
The early history of the Whittle jet propulsion gas turbine

Air Commodore F. Whittle

James Clayton Memorial Lecture 1945

The copyright of this paper is the property of the Institution of Mechanical Engineers. Apart from any fair dealing for the purpose of private study, research, criticism or review, as permitted under the Copyright Designs and Patent Act 1988, no part may be reproduced in any form or by means without permission. Enquiries should be addressed to:

Director of Publications and Information Services, the Institution of Mechanical Engineers,
1 Birdcage Walk, London SW1H 9JJ, Telephone: + 44 (0)20 7222 7899

The Institution is not responsible for any statement contained in these papers. Data, discussion and conclusions developed by the authors are for information only and are not intended for use without independent substantiating investigation on the part of potential users. Opinions are those of the author and not necessarily those of the Institution of Mechanical Engineers.

THE FIRST JAMES CLAYTON LECTURE

The Early History of the Whittle Jet Propulsion Gas Turbine

By Air Commodore F. Whittle, C.B.E., R.A.F., M.A., Hon. M.I.Mech.E.*

"I do not endeavour either by triumphs of confutation or pleadings of antiquity, or assumption of authority, or even by the veil of obscurity, to invest these inventions of mine with any majesty . . ." *Francis Bacon.*

PART I. INTRODUCTION AND GENERAL OUTLINE

Introduction. My purpose is to tell you briefly the early history of the development of the jet propulsion gas turbine in Great Britain, concentrating chiefly on the story up to the first flight tests in May 1941.

The preparation of this lecture has not been easy, for in it I have tried to give you as clear a picture as possible of many years of work. In order not to fog you with detail, much of the story must be omitted, whilst in some passages the work of months must be dismissed in a single paragraph in order to preserve an accurate general impression.

I will try to give some idea of the difficulties encountered and be frank about the mistakes that we made. Difficulties were by no means confined to the engineering side of the story; but of the large financial, administrative, and political problems which faced us from time to time I propose to say practically nothing. I shall say little about the aircraft side of the work, or of the more serious manufacturing problems which had to be solved.

There have been many attempts to solve the gas turbine problem in the past. I will not attempt now to give the background of the early history of the gas turbine as a prime mover, for that has already been done many times. The records in the Patent Office would probably show that the problem of the gas turbine has engaged the attention of inventors almost to the same extent as perpetual motion. It will suffice to say that the constant pressure gas turbine is an old idea, and that there have been many attempts to produce a practicable engine of this sort, but at the time I started thinking about the subject, i.e. in 1928-9, the many failures had led to a general belief in the engineering world that it had no future.

I now know that, apart from myself, there were others who refused to conform to the prevalent view and believed that the problems of the gas turbine were not insuperable. They included Dr. A. A. Griffith, Mr. H. Constant, and certain others at the Royal Aircraft Establishment, and engineers of the Brown-Boveri Company led by Dr. Meyer.

The main argument against the gas turbine was that the maximum temperatures permissible with materials available, or likely to be available, was such that the ratio of positive to negative work in the constant-pressure cycle could not be great enough to allow of a reasonable margin of useful work to be obtained, after allowing for the losses in the turbine and compressor. There seemed to be a curious tendency to take it for granted that the low efficiencies of turbines and compressors commonly cited were inevitable. I did not share the prevalent pessimism because I was convinced that big improvements in these efficiencies were possible, and, in the application of jet

The MS. of this lecture was first received at the Institution on 21st June 1945. For the Minutes of Proceedings of the meeting on 5th October 1945, at which this lecture was delivered, see p. 379 *ante*.

* Special Duty List, R.A.F., attached to Power Jets (Research and Development), Ltd., Whetstone, Leicester. The statements and opinions expressed herein are the personal views of the lecturer, and are not to be taken as in any way representing the opinions of the Air Ministry or the Ministry of Aircraft Production.

propulsion to aircraft, I realized that there were certain favourable factors not present in other applications, namely:—

- (1) The fact that the low temperatures at high altitudes made possible a greater ratio of positive to negative work for a given maximum cycle temperature.
- (2) A certain proportion of the compression could be obtained at high efficiency by the ram effect of forward speed, thereby raising the average efficiency of the whole compression process.
- (3) The expansion taking place in the turbine element of such an engine was only that which was necessary to drive the compressor; and therefore only part of the expansion process was subject to turbine losses.

In order to make my story as clear as possible, I propose now to tell it in outline first, and then to fill in certain parts of it in greater detail by describing the design and testing of the three editions of the first experimental engine; then dealing with the design and testing of the first flight engine (the W1), and an experimental version of it (the W1X); and ending with a few brief notes on two or three of the later engines.

Outline. I first started thinking about this general subject in 1928, in my fourth term as a Flight Cadet at the R.A.F. College, Cranwell. Each term we had to write a science thesis, and in my fourth term I chose for my subject the future developments of aircraft. Amongst other things, I discussed the possibilities of jet propulsion and of gas turbines; but it was not until eighteen months later, when on an Instructors' Course at the Central Flying School, Wittering, that I conceived the idea of using a gas turbine for jet propulsion. I applied for my first patent in January 1930. The principal drawing of the patent specification as filed is reproduced in Fig. 1. It may be seen that I tried to include the propulsive duct, or "athodyd" as it has since been called, but this had been anticipated at least twice, so the upper drawing and relevant descriptive matter had to be deleted from the specification.

The idea was submitted to the Air Ministry, but was turned down on the ground that as it was a gas turbine the practical difficulties in the way of the development were too great.

During 1930 I tried to interest various firms in the scheme, but met with no success; for the most part they thought the same way as the Air Ministry. It is probably also true that in their view the prevalent industrial depression made it anything but a favourable moment for expensive ideas of this sort.

Nothing very much happened for a few years. I gave up hope of ever getting the idea to the practical stage, but continued to do paper work at intervals, until, in May 1935, when I was at Cambridge as an Engineer Officer taking the Tripos Course, I was approached by two ex-R.A.F. officers (Mr. R. D. Williams and Mr. J. C. B. Tinling), who suggested that they should try to get something started. Though I had allowed the original patent to lapse through failure to pay the renewal fee, and though I regarded them as extremely optimistic, I agreed to co-operate. I thought that there was just a bare chance that something might come of it.

We eventually succeeded in coming to an arrangement with a firm of investment bankers (Messrs. O. T. Falk and Partners) which led to the formation of Power Jets, Ltd., in March 1936. Before Power Jets was formed, O. T. Falk and Partners obtained the opinion of a consulting engineer (Mr. M. L. Bramson) who gave a wholly favourable report. The initial sum subscribed was £2,000, and with this we cheerfully went ahead.

FIG. 1.

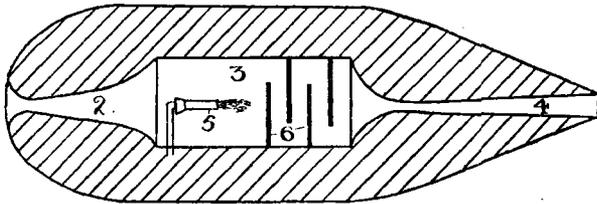


FIG. 2.

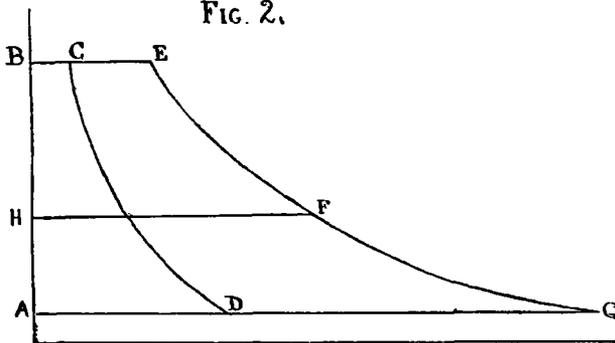


FIG. 3

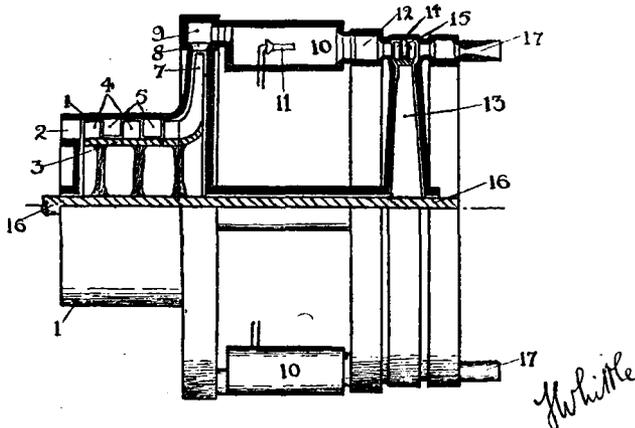


Fig. 1. Reproduction of Drawings Illustrating British Patent No. 347,206, filed 16th January 1930

The upper drawing—the thermo-propulsive duct—had to be deleted from the specification.

The President of the Air Council was a party to the agreement which resulted in the formation of Power Jets, and the Air Ministry was a shareholder from the start in that a proportion of the shares allotted to me was held in trust for the Department.

During the negotiations leading to the formation of Power Jets, I was working on the designs of an experimental engine. Messrs. O. T. Falk and Partners placed an order with The British Thomson-Houston Company, Ltd., for engineering and design work in accordance with my requirements in advance of the formation of the new company. Power Jets placed the order for the manufacture of the engine (except the combustion

chamber, instruments, and some accessories) with The British Thomson-Houston Company in June 1936.

The engine was to be a simple jet propulsion gas turbine having a single-stage centrifugal compressor with bilateral intakes, driven by a single-stage turbine directly coupled. Combustion was to take place in a single combustion chamber through which the working fluid passed from the compressor to the turbine.

We were going beyond all previous engineering experience in each of the major organs. We were aiming at a pressure ratio of about 4/1 in a single-stage centrifugal blower when at the time, so far as we knew, a ratio of 2½/1 had not been exceeded. We were aiming at a breathing capacity in proportion to size substantially greater than had previously been attempted. The combustion intensity we aimed to achieve was far beyond anything previously attempted. Finally, we had to get over 3,000 s.h.p. out of a single-stage turbine wheel of about 16½ inches outside diameter, and to do it with high efficiency.

At first, our intention was to do the job stage by stage—that is, to make a compressor and test it; then to add a combustion chamber to the compressor; then to test a turbine alone; and finally to build an engine—but we very soon realized that this was likely to be a long and costly process and we decided to go for a complete engine right away.

This first engine was based on a design for flight, but was not intended for flight; and though it was designed to be very light by normal engineering standards, we did not put forth special efforts to make it as light as possible.

I was fairly confident in the compressor and turbine elements but felt rather out of my depth with the combustion problem, and so (in 1936) I visited the British Industries Fair with a view to enlisting the aid of one of the oil burner firms, but the requirements I specified were considered to be far too stringent by most of them until I met Mr. Laidlaw, of Laidlaw, Drew and Company. Though he recognized that we were aiming at something far in advance of previous experience in this field he considered the target possible of attainment, and so it was with his help that we attacked the combustion problem.

While the engine was in course of design and manufacture, we carried out a number of combustion experiments on the premises of The British Thomson-Houston Company, with apparatus supplied by Laidlaw, Drew and Company, until we considered that we had enough information to design a combustion chamber. Power Jets therefore placed the contract for the design and manufacture of the combustion chamber with Laidlaw, Drew and Company.

By this time the Tripos Examinations at Cambridge were over, and the Air Ministry had agreed that I should stay for a post-graduate year. This was really a device to enable me to continue work on the engine, and so a considerable proportion of my time was spent at The British Thomson-Houston Company's works in Rugby.

Testing of the engine commenced on 12th April 1937, and continued intermittently until 23rd August. These early tests made it clear that the combustion problem was by no means solved, and that the compressor performance was far below expectations. Nevertheless they were sufficiently encouraging to show that we were on the right track.

Testing was then stopped in order to carry out a major reconstruction; and once more The British Thomson-Houston Company did this work for Power Jets.

At this time it was also decided that no further running should take place in the Rugby factory, as it was considered too dangerous, and so Power Jets came to an arrangement with The British Thomson-Houston Company by which they rented part of that firm's old foundry at Lutterworth (Ladywood Works) for their future testing.

At this point I think it will be of interest to explain the basis on which I was working with The British Thomson-Houston Company. I was allowed virtually complete access to all parts of their turbine factory and its contributory departments, and as time passed I was given an increasingly free hand. I was provided with an office and had access at all times to Mr. F. Samuelson, M.I.Mech.E., Chief Turbine Engineer, to Mr. R. H. Collingham, M.I.Mech.E. (who succeeded Mr. Samuelson as Chief Turbine Engineer when the latter retired), to his staff

of specialist engineers, and to the Drawing Office. I spent much time following the manufacture and investigating costs (as all the work was being done on a "cost-plus" basis) and I handled the controls whenever the engine was tested. All this was very valuable experience for me and, I believe, helped the work along very considerably.

The story from this point becomes increasingly complex, so to help me to tell it clearly I will refer you to Fig. 2. This shows the time relationship of some of the major events in the history.

After the first series of tests in 1937 the Air Ministry (on the recommendation of the Aeronautical Research Committee) began to take more notice of the work and decided to place contracts with Power Jets for a report on the first series of tests

While the reconstruction of the engine was in progress we carried out another series of combustion tests until once more we thought we had solved the combustion problem.

The reconstructed engine was ready to run again on 16th April 1938, and the testing (at Lutterworth) continued intermittently until 6th May, on which day the engine was severely damaged by a turbine blade failure. Though the total test running time was only about five hours, it was evident that the combustion problem was by no means solved.

A second major reconstruction was decided upon, and the work was once more carried out by The British Thomson-Houston Company, but this time the Air Ministry agreed to bear the cost (by contract with Power Jets). Once more we

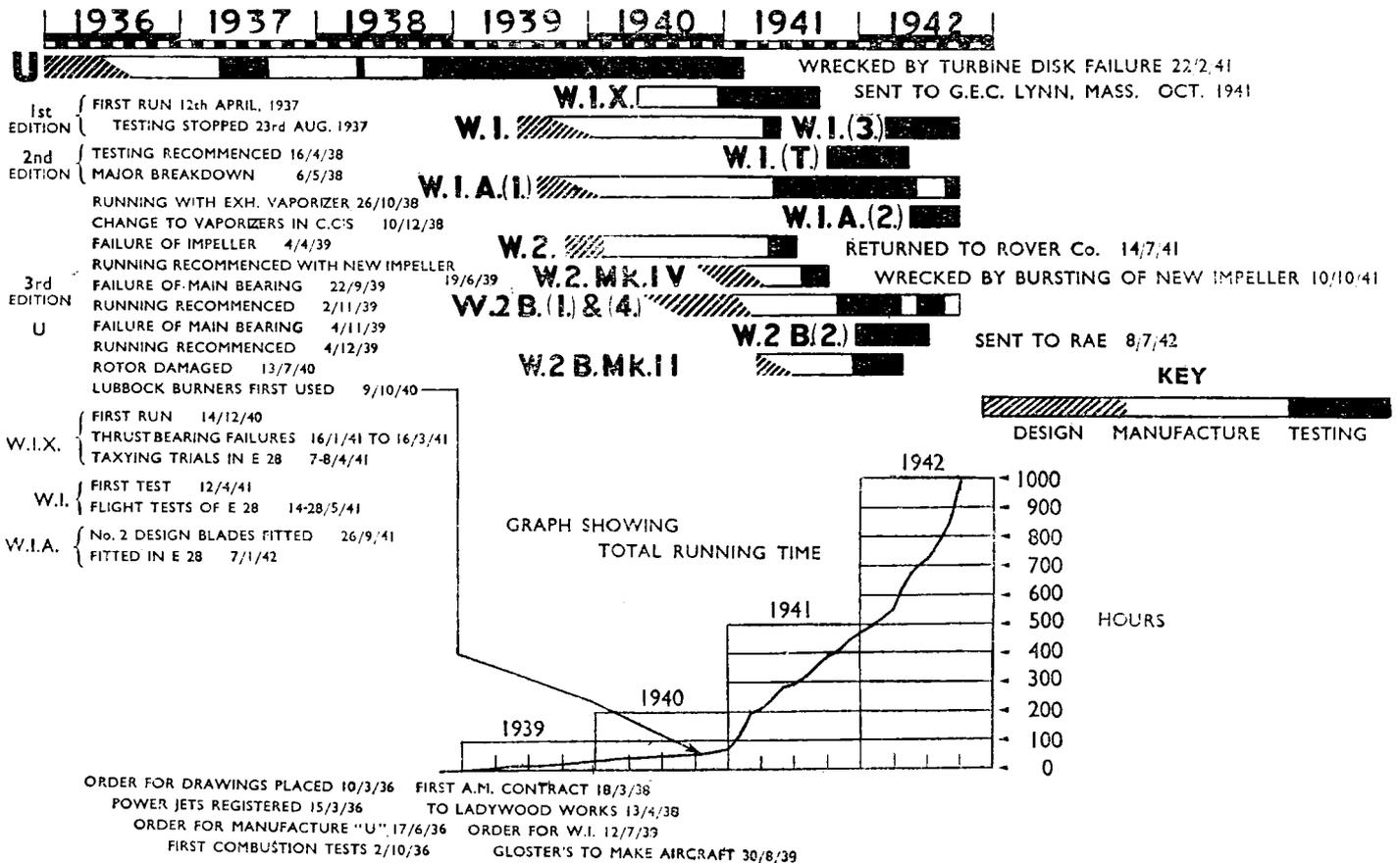


Fig. 2. Diagram Illustrating the Principal Events in the Early History of the Jet Propulsion Gas Turbine

and for further research running. However, the work was still regarded as "long-term research". At the same time further private money was being raised; but the total financial resources available were still very small and the work had to be done on the basis of the most stringent economy. This proved expensive in the end, because it meant that we were continually having to use parts which really ought to have been scrapped.

So far, there had been no official secrecy requirement on the work; but secrecy was a condition of the Air Ministry contracts, and when it was imposed it naturally made the raising of private money very difficult. (Incidentally, we received rather a shock when in 1939 we found that about six of my patent drawings had been reproduced in an article in the German journal *Flugsport*, but there was nothing very surprising in this because there was nothing to stop anybody from seeing the published patent drawings. As a matter of interest some of these are reproduced with their German captions in Fig. 3.)

The Air Ministry further helped the project by placing me on the Special Duty List at the completion of my post-graduate year in the summer of 1937, to enable me to continue work on the engine on a full-time basis.

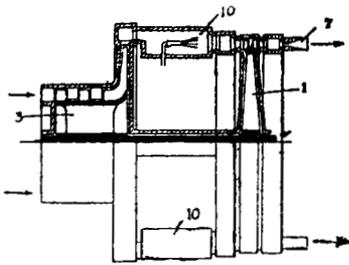
embarked on a further series of combustion tests while the reconstruction was in progress.

Testing of the third model of the engine commenced at the end of October 1938 and continued intermittently until February 1941 when it was damaged beyond repair by a turbine failure. It had by then served its purpose, and had provided an enormous amount of information on which subsequent designs were based.

In the summer of 1939 the Air Ministry ceased to regard the development as a matter of long-term research and came to accept the fact that we had the basis of a practicable aero-engine. As a result, Power Jets received a contract for a flight engine, and a short time afterwards a contract was placed with the Gloster Aircraft Company for the manufacture of an experimental aeroplane to specification E28/39. Thereafter, Power Jets and the Gloster Aircraft Company worked in close collaboration. The Ministry also agreed to purchase the experimental engine, and to cover all test running by contract.

Power Jets subcontracted the drawing and manufacture of the flight engine with The British Thomson-Houston Company. The design team now included a few engineers recruited by Power Jets as well as British Thomson-Houston engineers

Abb. 14. Whittle 1935. Brennstahl treibt Kompressor-Gasturbine.



Translation

Abb. 14.

Fig. 14. Whittle 1935. Exhaust Jet Drives a Gas Turbine Compressor

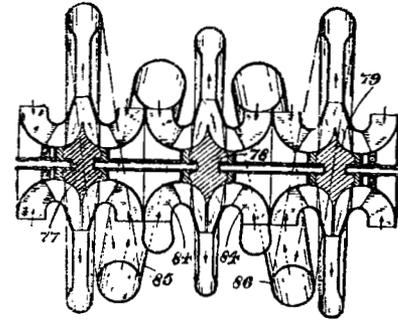


Abb. 65.

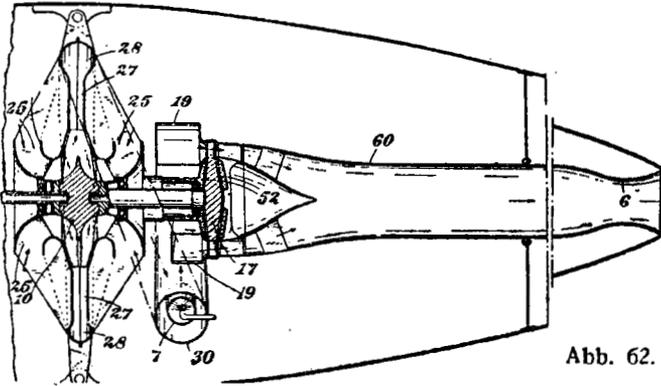


Abb. 62.

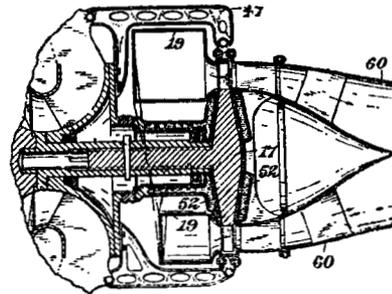


Abb. 63.

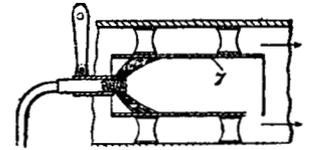


Abb. 64.

Abb. 62-65. Whittle 1935: Heizluftstrahltriebwerk mit Axialturbine.

Translation Figs. 62-65. Whittle 1935: Thermal Jet Propulsion with Axial Turbine

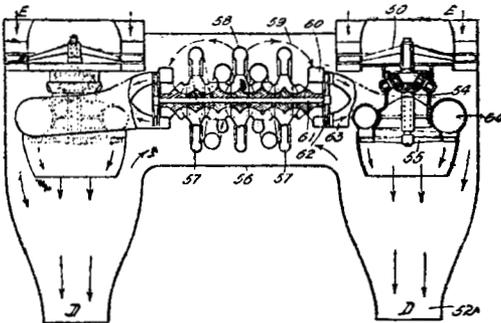


Abb. 66. Whittle 1936: Zwillingstriebwerk.

Translation

Fig. 66. Whittle 1936: Twin Propulsion System

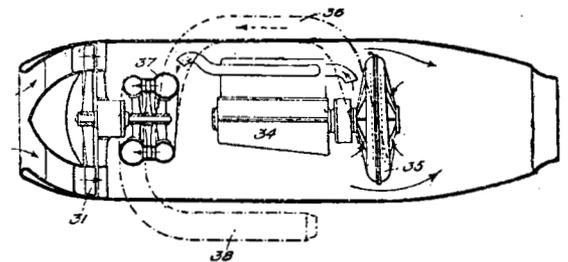


Abb. 67. Whittle 1936: Heizluftstrahltriebwerk mit Kolbenmotor und Turbine.

Translation

Fig. 67. Whittle 1936: Thermal Jet Propulsion with Piston Engine and Turbine

Fig. 3. Reproductions of Illustrations from *Flugsport* (1939)

and myself. This first flight engine was known as the "W1".

In the course of manufacture of the W1, certain major components were considered to be unairworthy on completion, and it was decided to use these—with certain spare components made for the first experimental engine—to build an "early edition" of the W1. This was known as the "W1X". The W1X was delivered, loosely assembled, in November 1940. Power Jets had by this time begun to build up a small sheetmetal shop as well as the nucleus of an engineering team. They had also installed combustion test apparatus at the Ladywood Works; this work also was covered by contracts from the Ministry of Aircraft Production.

The W1X, though falling short of expectations, proved to be far in advance of the experimental engine, and a number of tests were carried out on it which provided experience on which modifications to the W1 were based. When the W1 was delivered,

it was stripped by Power Jets, and was modified to incorporate the latest experience gained with the W1X. Eventually, after certain preliminary testing, the W1 was put through a 25-hours' special category test to clear it for flight. Meanwhile the E28 aeroplane was completed by the Gloster Aircraft Company, and the W1X was installed in it for taxi-ing trials in April 1941. In the course of these trials the aircraft did in fact leave the ground for a short straight hop.

Flight trials with the W1 began on 14th May 1941. The engine had been cleared for ten hours' flying, and the programme of flight testing laid down was completed in fourteen days without special incident. The test pilot was the late Flight-Lieutenant P. E. G. Sayer.

I have now to take you back a year to explain that at the beginning of 1940 the Air Ministry (later the Ministry of Aircraft Production) began to work on the assumption that there was a good chance of getting jet propelled fighter aircraft into

production in time for use in the war. As a result the following steps were taken:—

- (1) Power Jets were authorized to go ahead with a more advanced engine (the "W2").
- (2) The Gloster Aircraft Company was authorized to proceed with the design of a twin-engined interceptor fighter (the "F9/40"—prototype of the *Meteor*).
- (3) Direct contracts were placed with The British Thomson-Houston Company and other firms for the manufacture and development of jet propulsion gas turbines.
- (4) It was decided that Power Jets should become a research and development organization and that they were to supply all other firms engaged with all necessary drawings and any other information they needed to assist them in their work.

I refer you once more to Fig. 2 for the relationship in time of the first few of the types subsequently made, and would add the following series of notes to amplify Fig. 2:—

(1) By arrangement between the British and American Governments, the W1X, a set of drawings of the W2B, and a small team of Power Jets' engineers, were flown over to America in the autumn of 1941, and this initiated the intensive development of the jet propulsion gas turbine at the General Electric Company's works at Lynn, Mass.

(2) The "W1(T)" was a modified W1 built for bench development from spares.

(3) The "W1(3)" was also a modified W1.

(4) The "W1A" was an engine incorporating most of the features of the W1 but it also had in it certain of the special features of the W2 which it was desired to test in advance. This engine was manufactured by The British Thomson-Houston Company to Power Jets' requirements. (Power Jets were contractors to the Ministry of Aircraft Production.) It was flown in the E28.

(5) The "W1A(2)" was a modified W1A.

(6) "W2". Drawings of this engine were handed over to the Rover Company who made it as direct contractors to the Ministry of Aircraft Production. As made, it differed from the Power Jets' design in certain mechanical features. We realized before this engine was completed (as a result of doing more detailed calculations) that if the design assumptions in respect of component efficiencies were not achieved, the penalty would be very severe. This in fact proved to be the case. It was a failure.

(7) The "W2 Mk. 4". Power Jets, having received a direct contract for the W2, subcontracted the manufacture to The British Thomson-Houston Company, but when it was realized that the design was extremely sensitive to the design assumptions, it was changed by stages to bring it nearer to that of the W2B, and when it was delivered by the subcontractors it was further modified by Power Jets so that when testing commenced it differed only in detail from the W2B design. This engine was totally wrecked by the bursting of a faulty impeller forging, though not before a fair amount of useful testing had been done.

(8) The "W2B" was originally designed by Power Jets, and complete sets of Power Jets' drawings were passed to the several firms by then engaged. The first and second W2Bs to be tested by Power Jets were manufactured by the Rover Company, and (like the W2) differed from the Power Jets' design in certain mechanical features. The W2B was the prototype of the Welland engines (which subsequently powered the *Meteor I* in this country) and of the "Type I" (the corresponding engine made by the American General Electric Company which powered the Bell *Airacomet*, and which was the forerunner of a series of similar engines made by the American General Electric Company).

(9) The "W2B Mk. 2" was a modified W2B, and was the first engine in which Power Jets did the bulk of their own manufacture.

The whole project received a powerful stimulus from the successful flight trials of the E28. The Ministry of Aircraft Production decided to plan for production of the W2B and the *Meteor*. Many sceptics were converted. The firms already en-

gaged increased their activities considerably, and other firms which had practically ignored the gas turbine suddenly evinced a lively interest.

A noteworthy event was the formation by the Ministry of Aircraft Production of the Gas Turbine Collaboration Committee in November 1941. The Ministry of Aircraft Production, the Admiralty, the Royal Aircraft Establishment, the National Physical Laboratory, and the firms engaged on aircraft gas turbines were all represented on this Committee. Dr. H. Roxbee Cox, who as an official of the Ministry of Aircraft Production had been closely associated with gas turbine development from early in 1940, was primarily responsible for the formation of this Committee and was its chairman from its formation until he became Chairman and Managing Director of Power Jets (Research and Development), Ltd., in April 1944. The Committee proved to be an institution of great value, and it served to ensure a large measure of co-operation amongst the firms engaged. This leavening of competition with co-operation is a very healthy thing and worthy of preservation in peace time.

I will conclude this outline by saying that the types of engines which trace their descent directly from the W2 and W2B have undergone continuous development, and the original design performance for that size of engine has been far exceeded.

PART II. THE DESIGN AND TESTING OF THE EXPERIMENTAL ENGINE

The Design and Testing of the First Model. (a) *Design.* The first engine was designed with a specific target in mind. It was a very optimistic one, but nevertheless it formed the starting point and is worth recording. The aim was to propel a very "clean" little aeroplane of about 2,000 lb. "all up" weight at a speed of 500 m.p.h., at a height of the order of 70,000 ft. This speed was estimated to correspond to that of minimum drag at that height, i.e. this high speed was also the most economical speed for the height. It was estimated that a net thrust at this height of 111 lb. would be required.

The size of engine corresponding to these data was considered to be the smallest in which the necessary accuracy of machining could be obtained without excessive manufacturing costs.

The design assumptions and leading particulars are given in Table 1, and in the pressure-volume cycle shown in Fig. 4.

TABLE 1. LEADING PARTICULARS OF FIRST EDITION OF EXPERIMENTAL ENGINE
Dimensions are in inches.

<i>Compressor impeller—</i>	
Tip diameter	19
Tip width	2
Outer diameter of eye	10.75
Inner diameter of eye	5.5
Number of blades	30
Material	Hyduminium RR56
<i>Compressor casing—</i>	
Inner diameter of scroll	31
Material	Hyduminium RR55, DTD.133B.
<i>Turbine—</i>	
Mean diameter of blades	14
Blade length	2.4
Material of blades	Firth-Vickers Stayblade
Material of disk	Firth-Vickers Stayblade
Blade chord	0.8
Number of blades	66
<i>Maximum speed, r.p.m.</i>	17,750

Figs. 5, 6, 10, and 12 illustrate various features of the design, which are further amplified in Figs. 7, 8, 9, 11, and 13, Plates 1 and 2.

For the most part, I rely on Table 1 and Figs. 4–13 to convey the necessary information on the design; but my comments on certain special points are given below.

The assumption of 80 per cent adiabatic efficiency for a

centrifugal compressor running at a tip speed of 1,470 feet per sec. was very optimistic indeed, and received a good deal of criticism; but I felt confident that we could design to avoid many of the losses which were occurring in all centrifugal compressors of which I had knowledge at the time. The general

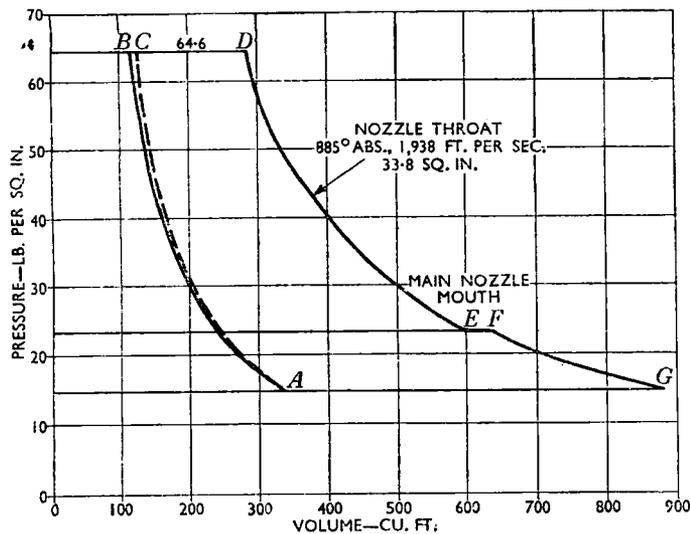


Fig. 4. The Pressure-Volume Diagram, Design Assumptions, etc., on which the Initial Design of the Experimental Engine was Based.

Sea level cycle.

- Assumptions:—Compressor efficiency, 80 per cent.
 Turbine (shaft) efficiency, 70 per cent.
 Axial velocity at turbine exhaust, 800 feet per sec. = 14 per cent of heat drop.
 Efficiency at final expansion, 97 per cent.
 Weight of air, 26 lb. per sec.
 Weight of fuel, 0.3635 lb. per sec. = 168 gal. per hr. approx.
 Power to drive compressor, 3,010 h.p.
 Static thrust, 1,389 lb.

Products of combustion, per sec.

- N₂ = 19.963 lb. = 0.713 lb. mol.
 O₂ = 4.763 „ = 0.149 „
 CO₂ = 1.122 „ = 0.0255 „
 H₂O = 0.516 „ = 0.0286 „

Total 26.364 „ 0.9161 „

Mean molecular weight = 28.78

Value of R (gas constant) = 96.5.

$\gamma = 1.4$ for compression and 1.379 for expansion.

$K_p = 0.24$ for compression and 0.25 for expansion and combustion.

Latent heat of fuel, 75 C.H.U. per lb.

Calorific value, 10,500 C.H.U. per lb.

State point	Pressure, lb. per sq. inch	Temperature, deg. C. abs.	Volume, cu. ft. .	Velocity, ft. per sec.
A	14.7	288.0	339.5	0
B	64.6	439.5	118.0	0
C	64.6	477.5	128.2	200
D	64.6	1,052.0	287.9	200
E	23.45	795.8	600.0	2,400
F after reheat	23.45	836.7	631.0	900
G	14.7	737.0	885.0	1,720

view was that we should be fortunate if we got 65 per cent adiabatic efficiency.

We went for the double-sided compressor because we wanted to get the greatest possible breathing capacity in proportion to size. I also counted on this feature to give a reduced proportion of skin friction losses.

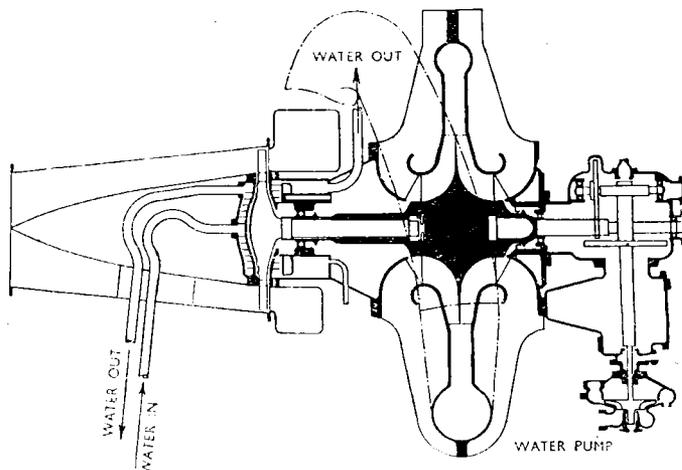


Fig. 5. Assembly of First Model of Experimental Engine

We aimed at having as many blades on the impeller as manufacturing limitations would permit, in order to keep the blade loading as low as possible. In particular, it was hoped that by keeping the pitch-chord ratio of the rotating guide vanes small we should avoid stalling at the intake, as I believed then—and still believe—that this is one of the main sources of loss in centrifugal compressors.

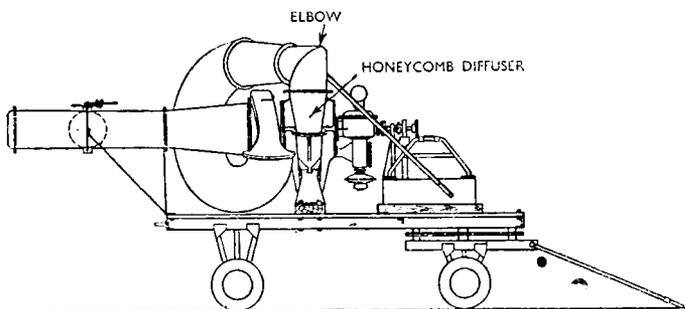


Fig. 6. Test Assembly of First Model of Experimental Engine

No diffuser blades were fitted to the blower casing at first. Two stages of diffusion were aimed at. The intention was to obtain partial diffusion in the bladeless vortex space between the impeller tips and the scroll and to convert most of the remaining kinetic energy into pressure in the "honeycomb" diffuser through which the air passed from the compressor scroll to the combustion chamber.

The turbine nozzle arrangement was very unorthodox, as no nozzle blades were used. The idea was that most of the expansion took place in the convergent-divergent entry to the

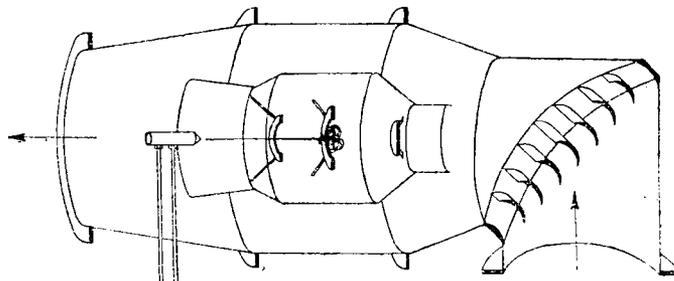


Fig. 10. Combustion Chamber Arrangement at Commencement of Testing of First Model of Experimental Engine
 The pilot jet and the igniter are omitted.

nozzle scroll which was shaped to cause the discharge of the gases through its annular mouth with constant axial velocity, the whirl velocity corresponding to that of a free vortex, i.e. constant angular momentum. This nozzle design was the source of considerable controversy; and though I am not very proud of it now, I thought it a good idea at the time. It is of considerable interest in retrospect, because it became evident, later, that I had not succeeded in conveying to others what I had in mind.

Air tests were made on a half-scale model of this nozzle, and though very rough, they seemed to show that it would behave approximately as expected.

The design of the rotor assembly needed much careful thought. It was considered necessary to use unbored forgings for both the turbine wheel and compressor impeller, also to use an overhung turbine rotor, as it was thought that the provision of a satisfactory bearing support on the exhaust side of the turbine would be very difficult. The bearing housing assembly which contained one of the two water jackets for the turbine cooling could not be split in the diametral plane. These considerations governed the rotor design.

I have already referred to my meeting with Mr. Laidlaw and to our collaboration in the design of the first combustion chamber and also in the preliminary testing which provided the basis

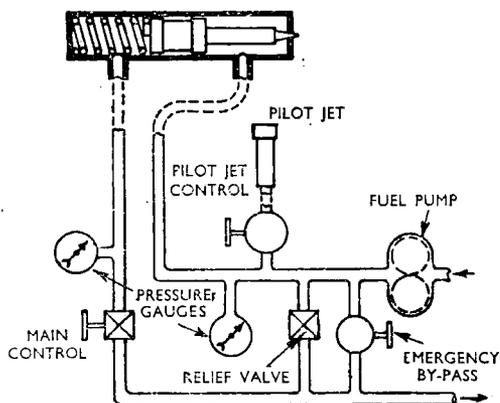


Fig. 12. The Fuel System used in the Early Tests of the First Model of the Experimental Engine

for the design. These tests were done on a site just outside the British Thomson-Houston turbine factory, using air supplied by a larger blower in the factory. The "set-up" for these tests is shown in Fig. 14, Plate 2. The tests were very crude but they did at least show that the required combustion rate could be obtained, though (as it proved) they were by no means sufficient to avoid combustion trouble in the engine subsequently.

(b) *Testing.* For test purposes the engine was mounted on a four-wheeled trailer. This trailer also carried the starter motor, instrument panel, and controls, making the whole set self-contained except for the fuel supply from the fuel tank and the water supply. It was intended to measure the thrust by a spring balance connecting the trailer to a fixed abutment, but in the testing of the first model no thrust measurements were taken.

The original intention was to start the engine by means of a two-cylinder air-cooled aero-engine, but the torque fluctuations with this engine were found to be too severe, and a 20 kW. d.c. motor was used instead. This was mounted on the trailer, and because of its weight the wheels of the trailer were removed and the axle supported on blocks. The drive was direct to the main rotor and operated through an automatically releasable dog-clutch in which a driving pin was forced out of engagement as soon as the engine overran the starter motor.

Preliminary motoring tests were carried out by using a special air nozzle to drive the turbine with the compressed air supply available in the British Thomson-Houston turbine factory. We obtained sufficient power this way to motor the engine up to 10,000 r.p.m. with the compressor intakes blanked off. In the first of these tests the blower impeller fouled its casing, but the

slight damage was made good and the test was subsequently repeated satisfactorily. It was, however, a rather depressing start.

As already mentioned, the testing of the engine under its own power began on 12th April 1937. The very first attempt to start was successful in that the engine ran under its own power, but it accelerated out of control up to about half its designed full speed. This happened several times; and altogether it was a very alarming business, so much so that in the early days the individuals in the vicinity did more running than the engine.

The starting procedure was as follows. The engine was motored at about 1,000 r.p.m. and the pilot jet (which injected an atomized spray) was switched on and ignited by means of a sparking plug and hand magneto. The motoring speed was then raised to about 3,000 r.p.m. and the main control opened slowly. The engine would then accelerate under its own power; but, as I say, not always under control. The explanation of the first few uncontrolled accelerations was simple when we found it, and may be understood by reference to the diagram of the early fuel system shown in Fig. 12. If the spill line from the burner was not full of fuel the needle valve of the burner would be forced into the fully open position when the fuel pump ran. We were frequently breaking the fuel line and doing various motoring tests so that often, unknown to us, there was a "lake"

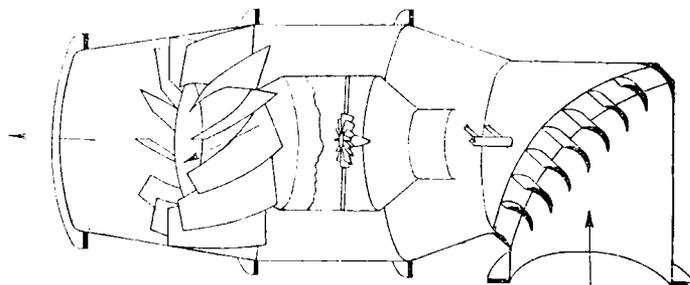


Fig. 15. Experimental Engine (First Model): Arrangement of Combustion Chamber when converted to Downstream Injection

The pilot jet and the igniter are not shown.

of fuel in the combustion chamber. Other uncontrolled accelerations were caused by the sudden opening of the burner needle valve after initial sticking; by loss of temper in the burner spring through overheating, etc. Fortunately none of these uncontrolled accelerations took the engine beyond about 9,000 r.p.m.

No trouble was ever experienced in starting except when the ignition failed through cracked electrodes, or when mistakes were made in the assembly of the fuel lines.

The overheating of the burner already referred to was a serious problem; and as a result of it a fairly drastic change in the combustion system was made. We changed over to downstream injection as shown in Fig. 15. Five runs were then made with this system up to maximum speeds of about 8,500 r.p.m., but the combustion was so bad that this speed could not be exceeded. Any further opening of the control seemed to result only in the burning of more fuel aft of the turbine.

One attempt was made to use the "Primus" principle in the combustion system, i.e. the combustion chamber was fitted with a vaporizer, and we changed from Diesel fuel to kerosene. The pilot jet was relied on for the initial heating of the vaporizer. Only one attempt to run was made with this arrangement and once more there was uncontrolled acceleration, believed to be due to priming of the vaporizer through insufficient heating surface. Though we changed back to liquid injection after this one effort at vaporized injection, we continued to use kerosene as fuel.

Many attempts to improve the combustion were made by a series of modifications to the combustion chamber; and some improvement was achieved—we managed to get up to a speed of 11,000 r.p.m. for ten minutes. This series of runs ended when the compressor impeller fouled the casing after running for four minutes at 12,000 r.p.m.

The damage to the compressor and impeller casing was only

slight; but as it had now become clear that the delivery pressure from the compressor was much below expectations, we decided to fit diffuser blades (Fig. 16) in an effort to improve the blower performance before further testing. We then managed to attain a speed of 13,000 r.p.m., but the compressor performance still left much to be desired. Moreover, the combustion had

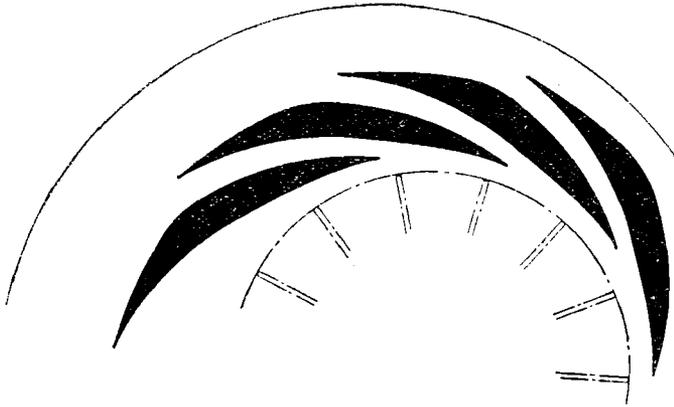
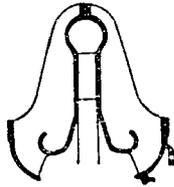


Fig. 16. Diffuser Blades fitted in Course of Tests on First Model of Experimental Engine

deteriorated, and as this was believed to be due to the nature of the flow from the compressor scroll to the combustion chamber, many modifications to improve this flow were made, but without noticeable improvement. There was evidence of a flow reversal in the elbow, but we did not realize how severe this was until (in one test late in the series) flames were seen through a small hole which had been drilled in the neck of the blower casing scroll.

A series of rapid modifications to the diffuser system of the

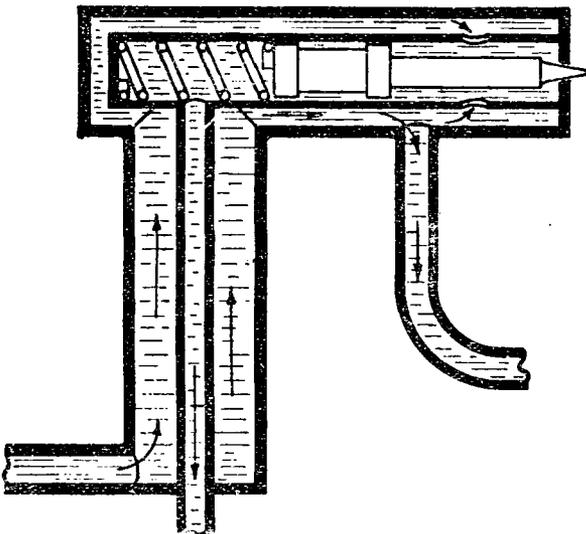


Fig. 17. Burner for Upstream Injection, insulated from Overheating by Cooling Jacket of Fuel: First Model of Experimental Engine

blower, combustion chamber, and the flow path between the compressor scroll and the combustion chamber was made, most of them with little improvement, but subsequently we succeeded in reaching a speed of 13,600 r.p.m. with the blower fitted with a modified set of diffuser blades.

At this point in the tests the Chief Engineer of The British Thomson-Houston Company considered it unwise to run at speeds higher than 12,000 r.p.m. in the open factory, and this was the speed limit for the remaining tests of the first model.

A return to upstream injection was made, the burner now being insulated against overheating by using a fuel cooling arrangement as shown diagrammatically in Fig. 17. Combustion appeared to be improved and for the first time no part of the casings reached glow heat at speeds of up to 12,000 r.p.m.

Testing was now suspended for the following reasons: first, because the speed restriction of 12,000 r.p.m. made it necessary to find a new site for running at higher speeds; and second, because it was decided to make major modifications to the general arrangement.

The tests so far had been very disappointing, but there were many encouraging features. We had demonstrated that there was no particular difficulty in starting or in control. There was also plenty of evidence which suggested that the whole scheme was well worth developing, though it had become obvious that much hard work lay ahead.

The principal defects of that particular arrangement were shown to be:—

- (1) Poor compressor efficiency.
- (2) Excessive preheating of the air to the rear intake, owing to the disposition and temperature of the combustion chamber.
- (3) Very unsatisfactory combustion.
- (4) Excessive frictional loss in the unorthodox turbine nozzle scroll.

No readings of sufficient reliability had been obtained from which any estimate of the efficiency of the turbine could be made, but it seemed practically certain that it was well below that assumed in the design.

The Design and Testing of the Second Model. (a) Design. The main aims of the reconstruction were to obtain a single straight combustion chamber and to provide a much improved diffuser system for the blower. In particular complete symmetry about the axis was aimed at.

Features of the new arrangement are shown in Figs. 18 and 20, and are further amplified by Figs. 19, 21, and 22, Plate 3. It should be noted especially that the flow through the turbine was reversed and that we hoped to get a certain degree of heat exchange by passing the ten exhaust pipes through the annular space between the outer casing and the combustion tube.

We used as much as possible of the original engine because we could not afford to do anything else. For example, the same compressor casing was used with the scroll machined off and replaced by ten fabricated discharge pipes (Fig. 21). I have no doubt now that it would have been cheaper and quicker to have had a new blower casing.

We had decided to use the "Primus" principle for combustion, and while the reconstruction was proceeding we carried out a further series of tests on combustion chambers at the British Thomson-Houston factory, once more with the assistance of Mr. Laidlaw. Many arrangements were tried before we decided to proceed with one having a vaporizing coil with a cluster of ten vapour nozzles injecting upstream towards the mouth of the flame tube. The primary air entered the flame tube through two concentric rings of swirl vanes of opposite hand. Excess air entered the flame tube through a system of holes in its side.

There was another important difference in the turbine design, apart from the fact that the direction of flow through it had been reversed. Hitherto I had left the detail design of the turbine blades almost entirely to the British Thomson-Houston engineers but now, by a strange chance, I discovered that there was a fundamental difference between my ideas and those of the steam turbine world in general.

I have already said that the original bladeless turbine nozzle scroll was intended by me to provide a rotating annular flow of

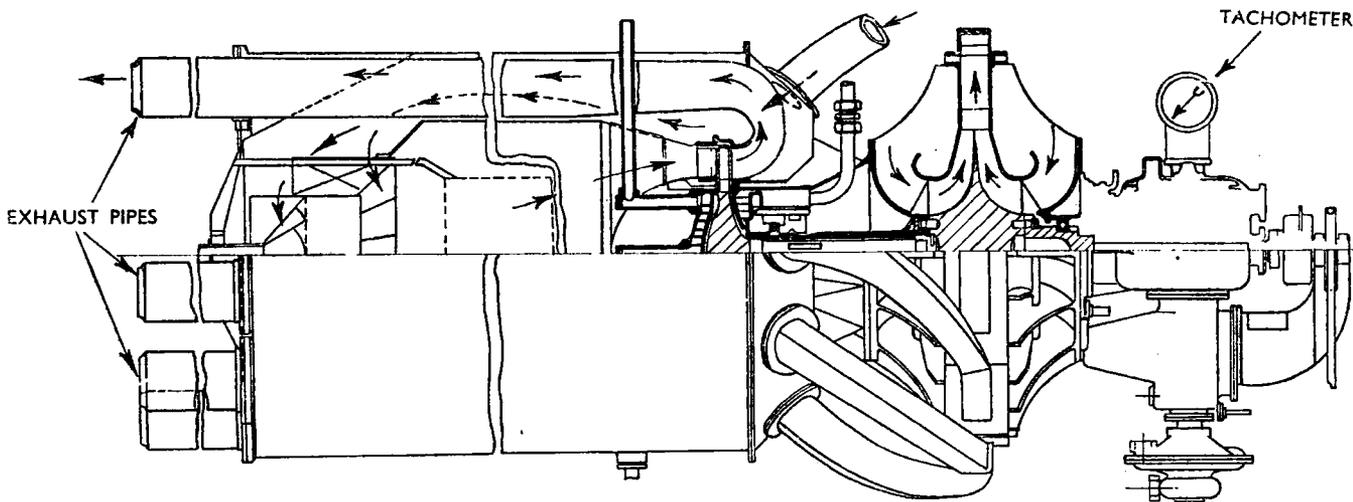


Fig. 18. Assembly of Second Model of Experimental Engine

constant angular momentum. I believed that this was the effect aimed at in any case in normal practice. Working from first principles I had taken it for granted that it was well known that, in theory at least, the ideal flow from a complete nozzle ring should be one of constant angular momentum. I was astounded to find that on the contrary it was the general practice to assume that the flow from a turbine nozzle ring was considered to be a series of straight jets of substantially constant velocity and

angular momentum from the nozzle ring. This meant that there was about twice as much twist on the blades as there was before.

I do not want to elaborate on this very important point; it will suffice to say that the concept of vortex flow is now fairly well established and it has remained the foundation of Power Jets' practice in turbine design. It is only fair to add that I subsequently found that the engineers of the Royal Aircraft Establishment had already accepted this concept, and there is now evidence that more than one turbine firm was thinking similarly at that time.

In the redesign of the engine, the design assumptions were substantially modified. A blower efficiency of 70 per cent was now assumed, and the revised pressure-volume diagram is shown in Fig. 20. The revised figure for the thrust was 1,240 lb. at full speed.

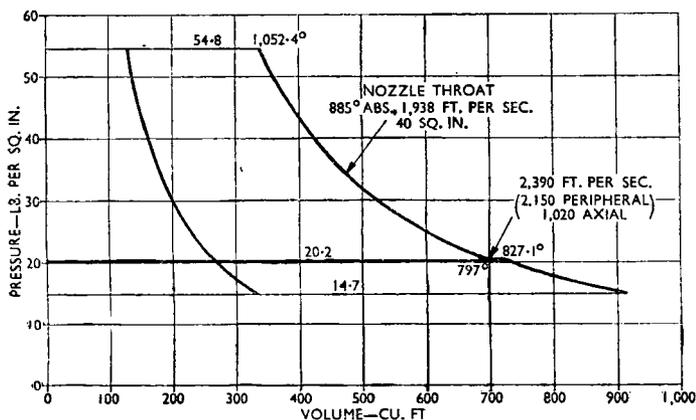


Fig. 20. Revised Pressure-volume Diagram and Design Assumptions on which the Second Model of the Experimental Engine was Based

Sea level cycle.

- Assumptions:—Compressor efficiency, 70 per cent.
 Turbine (shaft) efficiency, 70 per cent.
 Axial velocity at turbine exhaust, 1,020 feet per second.
 Efficiency of final expansion, 90 per cent.
 Weight of air, 26 lb. per sec.
 Weight of fuel, 0.3635 lb. per sec.
 $\gamma = 1.4$ for compression = 1.379 for expansion.
 $K_p = 0.24$ for compression = 0.25 for combustion and expansion.
 Static thrust, 1,240 lb.

pressure. My discovery of this difference in outlook made much clearer to me why there had been so much argument over the original nozzle scroll.

It appeared, therefore, that the blades of the first turbine had been provided with angles based on standard practice; and that though they had a substantial twist, this was only to allow for the radial variation of blade speed. I therefore took care to ensure that the nozzle and turbine blades used in the second model were designed to conform to a flow of constant

(b) *Testing.* All further testing was done at the Ladywood Works at Lutterworth, though Power Jets continued to rely on The British Thomson-Houston Company to a very large extent for labour and modifications. I frequently drove over to the British Thomson-Houston factory to collect test hands, fitters, sheetmetal workers, etc., as the situation required from time to time (though by now Power Jets employed an assistant engineer and a watchman).

We were now using a 10 h.p. motor car engine as starter motor, which was mounted on the trailer complete with its own radiator, petrol tank, etc.

Only nine test runs were made on the second model of the experimental engine, because the ninth test was brought to an end by a turbine failure which caused fairly extensive damage.

For eight of these test runs the speed never exceeded about 8,500 r.p.m., but in the last run of the series a speed of 13,000 r.p.m. was maintained for half an hour, at the end of which the failure occurred. A thrust of 480 lb. was recorded.

Many troubles were encountered, many of them due to defects in the fuel system. There were failures of the separately driven fuel pump, hunting due to faulty relief and control valves, etc., but the main trouble was due to a serious fault in the design for which I was wholly to blame. The nozzle ring assembly was not adequately supported against the difference of pressure between the combustion chamber and the turbine housing, and though modifications to stiffen it were made in the course of the tests these were inadequate, and when the engine was dismantled after the turbine failure it was found that the nozzle assembly had rubbed very heavily on the turbine wheel at the blade roots.

It was thought at first that the blade failure was due to the heavy rub mentioned above, but subsequent examination of the blades led to the conclusion that they had been subjected to very uneven gas temperature, of such a nature that there was a narrow annular belt of extremely hot gas impinging on the blades at the point of failure, and that the failure was therefore due to the running stress combined with excessive temperature.

Until this uneven temperature distribution became evident, the combustion had seemed to be fairly satisfactory. The flame never appeared to be more than about 2 feet long, and combustion seemed to be complete; but it was now evident that the mixing of cool secondary air and hot combustion products was very inadequate.

Apart from a considerable amount of secondary damage resulting from this failure, it was also found that there were a large number of cracks in the buttress ribs of the impeller blades.

The Design and Testing of the Third Model. (a) Design. Another major change in the arrangement of the engine was decided upon. This was in many ways a compromise between the two arrangements already tried. The main feature was the use of multiple combustion chambers. The general design of the engine is shown in Fig. 23, and also in Figs. 24 and 25, Plate 4.

The compressor remained the same as in the second model,

Testing began at the end of October 1938 and continued with increasing intensity until the engine was wrecked by the failure of the turbine disk in February 1941.

Practically the whole of the testing was dominated by the combustion problem. Not only were a great many combustion modifications tested in the engine, but these were supplemented by a much greater number of rig tests which took place in parallel, at first (as before) on the premises of The British Thomson-Houston Company and later at the Ladywood Works at Lutterworth.

For two years we struggled with a combustion system based upon the pre-vaporization of the fuel, but eventually had to abandon it. I cannot possibly give an adequate picture of that heartbreaking period. What I have to say below is a bare outline only. Even if the whole lecture were confined to this period of testing, it would still be no more than an outline.

We began with a coil type vaporizer mounted in the exhaust pipe. The vapour was led to a cluster of vapour nozzles in each

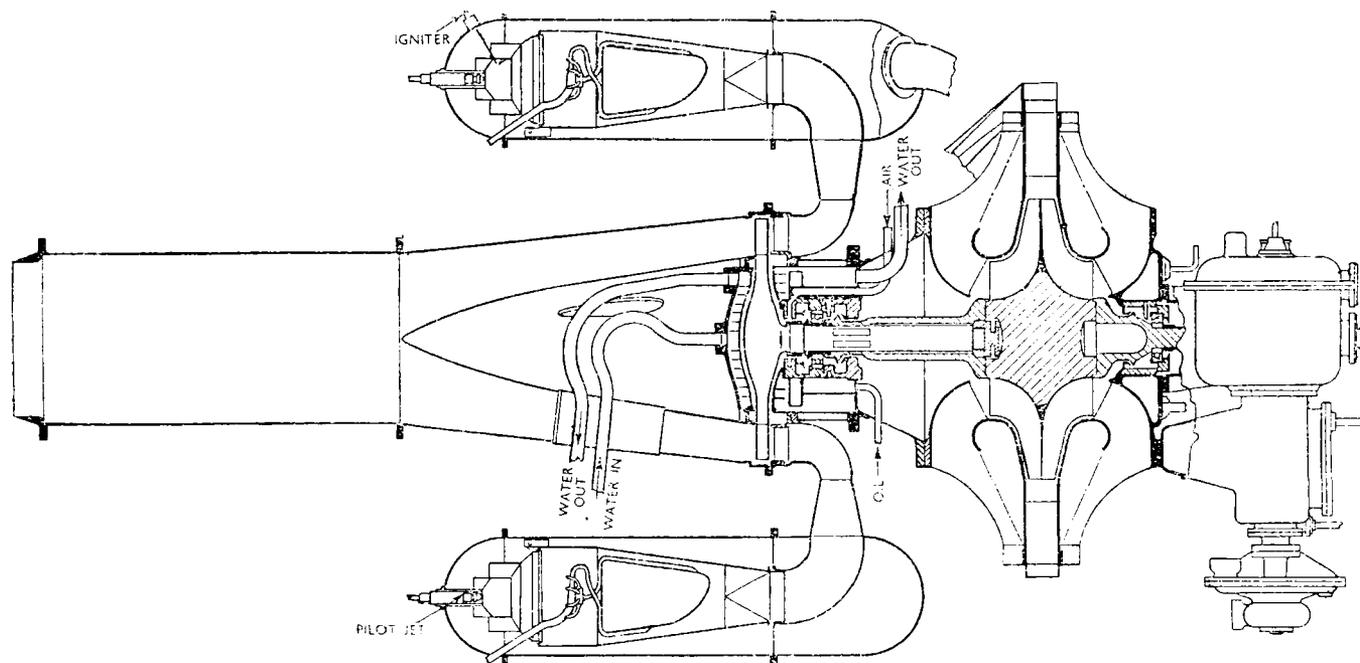


Fig. 23. Assembly of Third Model of Experimental Engine

except that the impeller was modified by machining away the cracked buttress ribs and by thinning off the blades. Once more we were being penny wise and pound foolish.

Each of the ten combustion chambers was basically similar to the one combustion chamber of the second edition, but approximately $1/\sqrt{10}$ times the size. The counterflow arrangement was preserved for the following reasons:—

- (i) The outer casings were insulated against high temperatures by relatively cool air from the blower.
- (ii) Serious modifications to the rotor assembly were avoided.
- (iii) A number of expansion and assembly problems were avoided.

An important feature of the combustion chamber arrangement was the provision of interconnecting ducts between both the air casings and the flame tubes. The main purpose of these was to make it possible to light up all combustion chambers by providing ignition in one only. It was also hoped at that time that they would act to some extent as pressure balancers.

The turbine design remained, in principle, the same as in the second model, but of course the direction of flow was reversed.

The exhaust assembly of the first model was brought back into use with (at the beginning of testing) a vaporizer mounted within it.

(b) Testing. To describe the testing of the third model in detail would take a long time, and I do not propose to attempt it.

combustion chamber. Each combustion chamber was provided with a pilot jet of atomized spray type for the initial heating of the vaporizer. However, it was soon found that to obtain the necessary amount of heating surface resulted in a serious restriction in the exhaust, and we were forced to fit each combustion chamber with its own vaporizer.

The effort directed to the combustion problem grew steadily in intensity until by August 1940 four combustion rigs were in operation at Ladywood. Power Jets had recruited more engineers, and had built up a small sheetmetal shop. They were aided by the loan of Dr. Hawthorne and two other young engineers from the Royal Aircraft Establishment.

We paid many penalties in the early days for the primitive nature of the tests. It was very much a case of "more haste, less speed". The solution always seemed to be just around the corner, and I have to admit that we were very slow to realize just how big was the problem we were attacking.

The problem was one in which reason did not help much; there were too many variables. It was a case for continued trial and re-trial. Our efforts fell under the following main heads:—

- (i) Tests of many different types of vaporizer.
- (ii) Modifications to the flame tubes.
- (iii) Modifications to the baffle system.
- (iv) Modifications to the position and direction of spray of the vapour nozzles.

To give an idea of the rate at which changes were being made,

even in the early part of the testing, it is sufficient if I tell you that in January 1939 ten types of vaporizer were tried in the combustion rig, also nine flame tube modifications (most of these modifications consisting of variations in the position and size of secondary air holes). These were by no means the only changes tried.

A factor which dominated the testing for a very long time was that seemingly good results achieved on the combustion test rig could not be repeated in the engine. For some time we attributed this to the fact that the combustion test rigs ran at, substantially, atmospheric pressure, whereas in the engine the pressure was much higher, and so was the temperature of the air entering the combustion chamber. The need for a high-pressure combustion test rig was ultimately met when the Ministry of Aircraft Production made arrangements by which we were able to do combustion experiments with an air supply from a large compressor used in the construction of the Dartford tunnel. This testing was done at Dartford. These experiments confirmed the results in the low-pressure rigs rather than in the engine, so that for some time we were still left with the problem of why the combustion in the engine was so much worse than it was in rig tests.

We now have a fairly clear idea of the reasons for the difference. I summarize them as follows:—

- (1) We now know that the combustion problem is very largely an aerodynamic one, and despite the fact that on rig tests we endeavoured to simulate the ducting from the compressor to the combustion chamber, the way in which the air flowed into the combustion chamber in the engine was not reproduced on the rigs sufficiently closely.
- (2) Small differences as between a given combustion chamber in the engine and on the rigs were having a much greater effect on combustion behaviour than we realized.
- (3) Lack of accuracy in manufacture and distortion in service caused differences in the combustion behaviour of the different combustion chambers of the engine, also to a much greater degree than we realized. This factor was, of course, aggravated as lack of uniformity increased through distortion and repeated modification.

The troubles we encountered from time to time were:—

- (1) Severe surging in the fuel system.
- (2) Severe out-of-balance in the fuel flow to each of the ten vaporizers.
- (3) Blockage of the vaporizers and vapour nozzles with carbon.
- (4) Local overheating and burning of the vaporizers.
- (5) Local overheating of the casings through bad temperature distribution.
- (6) Heavy deposits of carbon in the flame tube.

The burning-out of the vaporizers and blocking of the vapour nozzles was very unsystematic. We would, for example, find practically all the vapour nozzles blocked in one combustion chamber, while in another none would be blocked. Some of the vaporizers had a life of about half an hour only; others would last much longer. About thirty-one different types of vaporizer were tested in the rigs, many of them with several sub-variations, and nine of these types were tried in the engine. A typical arrangement used early in this period is shown in Fig. 26, whilst the last of the vaporizer types is illustrated in Fig. 27, Plate 5. This last was the most successful, and with it we were able to get the engine nearly up to its design speed, but it suffered from the troubles of the earlier types in lesser degree.

A good deal of the trouble with the vaporizers was attributed to the "cracking" of the fuel, and we tried to overcome this by using different fuels. In this we received advice and assistance from the Asiatic Petroleum Company, who were very helpful in making special fuels available.

It became clear from rig tests that a factor contributing to local overheating of the vaporizers and to bad temperature distribution of the gases at the discharge of the combustion chamber was the very poor distribution of the air flow into the combustion chamber. The bad temperature distribution was

serious from the turbine point of view, because almost invariably the hotter gases passed through the roots of the turbine blades. Many attempts were made to rectify this by fitting various kinds of baffles between the flame tube and the outer casing and at other places in the path of the air flow into the flame tube. Innumerable alterations were also made in the number and distribution of the secondary air holes in the wall of the flame tubes.

The flame tube shown in Fig. 27, Plate 5, is typical of the type used throughout this phase of the testing. The system of

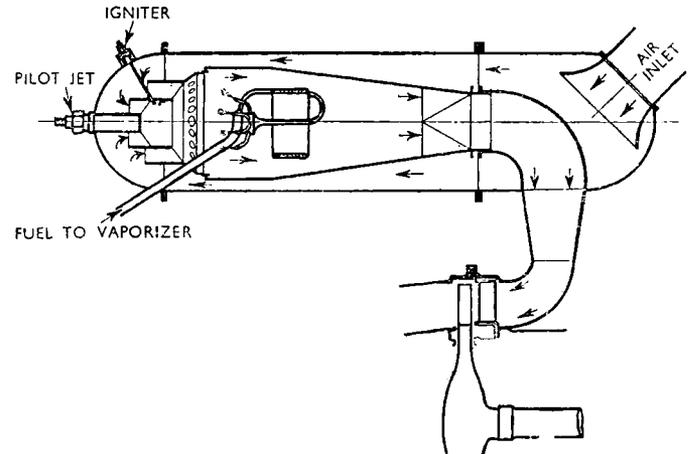


Fig. 26. Typical Combustion Chamber with Vaporizer

swirl vanes through which the primary air entered the combustion chamber remained substantially unchanged. It consisted of two concentric rings of swirl vanes of opposite hand, the vapour nozzles being set to inject approximately along the plane of separation of the oppositely rotating streams of primary air.

Many changes in the fuel lines were made. We tried different types of fuel pump, different types of relief valves, control valves, etc. Frequently we were in trouble with dirty fuel or through foreign matter getting into the fuel line during modifications. For a large proportion of the testing the fuel pump was

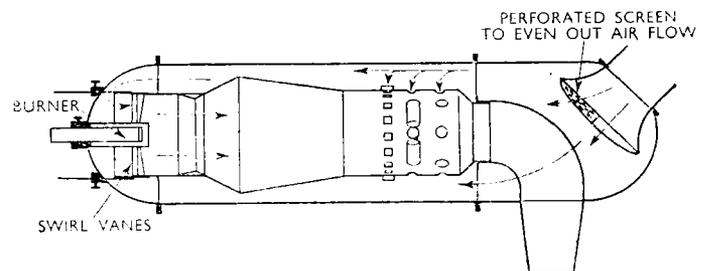


Fig. 28. The Shell Type Combustion Chamber adapted for Use in Engine

not mounted on the engine, but was driven by a separate electric motor; but it was subsequently mounted on the engine without producing any abnormal features.

Among the more important modifications to the fuel line were:—

- (1) The introduction of an air bottle to damp out pressure fluctuations and to provide initial "boost pressure" for starting. (This was later replaced by a Dowty accumulator, but the scheme was eventually abandoned by Power Jets.)
- (2) In order to try to provide equal flow of fuel to each of the ten combustion chambers, a flow-balancing device was introduced into the fuel line.

Fortunately the need to continue our struggle with this system of combustion disappeared in the autumn of 1940. For a long

time Mr. I. Lubbock, of the Asiatic Petroleum Company, had been helping us by advice and by obtaining special fuels, etc., but at this stage in the development he did something much more important; he and members of his team produced a combustion chamber using atomized spray injection and tested it at the Fulham Laboratory of the Asiatic Petroleum Company. The "Shell" combustion chamber is shown in Fig. 28, and this was the starting point of a new phase in the development. (We had made several attempts, on the combustion rigs, to get a satisfactory system using liquid injection in parallel with the development of the vaporizer system but with little success.) Power Jets now commenced intensive development both on the controllable atomizing burner and on the other features of the "Shell" combustion chamber. Of the several arrangements tried on the rigs and in the engine, the most successful (the one in use in the engine at the end of its life) is shown in Fig. 29, Plate 5.

Though the first tests on the engine with this system were disappointing, it nevertheless ultimately proved to be the turning point. Once more many of the combustion troubles were subsequently found to be due to lack of accuracy, especially in the manufacture of burners. We continued to use kerosene as the fuel, though gas oil was tried. The main reason for persisting with kerosene was its low freezing point.

Though the combustion problem was by far the greatest, and though much work still lay ahead, we were over the worst by the time the experimental engine gave up the ghost. At least it was possible to say that the combustion problem had ceased to be an obstacle to development. The atomized liquid spray system had outstanding advantages over vapour injection in respect of the simplicity of the fuel system and of the simplicity of the starting procedure. A disadvantage was that much higher fuel pressure had to be used.

Needless to say, our troubles were not confined to combustion. In March 1939 one of the impeller blades cracked near the tip. In order to keep running, we cut off the tip of that blade and also the tip of the opposite blade, to maintain balance. We only managed to get one more test run out of this impeller before many other blades failed in a similar manner, one blade tip passing right through the engine. Fortunately the damage to the turbine blades was relatively slight.

It was now considered that the combination of ten diffuser blades and thirty impeller blades was unfortunate; so the new impeller, which had been ordered from The British Thomson-Houston Company, was to have twenty-nine blades; also the central disk was not to be cut away between the blades at the tips.

While waiting for the new impeller, the opportunity was taken to modify the diffusers, to try to improve the compressor performance, which was still much below expectations. This modification did in fact produce a marked improvement in blower performance, in spite of the fact that, due to faulty assembly, there was a substantial variation in the throat widths of the diffuser passages.

A crack appeared at the tip of one of the blades of the new impeller where it joined the central disk, at a place where there had been damage in heat treatment; and because of this and a rub on the casing, a further new impeller was ordered. Nevertheless this impeller continued in use for all further testing with this engine (except for a short period) because the crack did not extend beyond $1\frac{1}{2}$ inches in length.

We made a further attempt to improve the blower performance at the end of 1939 by fitting guide vanes in the blower intake to help the air round the corner (see Fig. 30). This modification did not increase the delivery pressure but seemed to have improved the compressor efficiency as the measured compression temperature rise was reduced. New diffuser blades were fitted to the blower in March 1940, in a further attempt to improve the blower performance. Many other modifications to the same end were made, briefly as follows:—

- (1) We attempted to prevent warm air from being drawn into the rear intake of the blower by fitting heat shields between the elbows of the "starfish" assembly and the rear intake of the blower.
- (2) We modified the side clearances.
- (3) We attempted to stop leaks in the blower casing which were present as a result of progressive distortion (mainly caused by numerous rubs).

- (4) We scalloped the tips of the impeller blades as shown in Fig. 31, with the object of imparting more energy to the air near the walls of the casing, in order to neutralize skin friction effects.

All except the last of these modifications seemed to produce some improvement, but the last one caused a substantial reduction in delivery pressure for a given rotational speed, as it

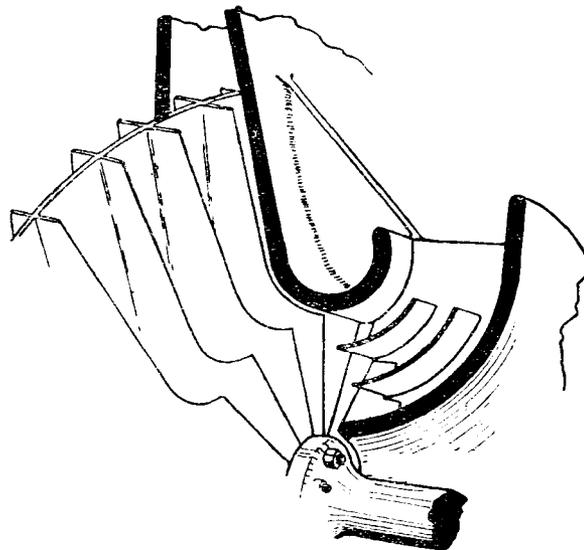


Fig. 30. Guide Vanes fitted to Blower Intakes during Testing of Third Model of Experimental Engine

constituted an effective reduction in diameter. Uncertainty as to the exact values of the temperature rise made it difficult to say what the effect on efficiency was.

A complete new rotor assembly was fitted in July 1940; but the impeller of this assembly was withdrawn from service after a few runs and replaced by the old one, as the new one was required for the flight engine, the impeller for which had been scrapped in manufacture.

We had to fit the new rotor assembly when a turbine blade

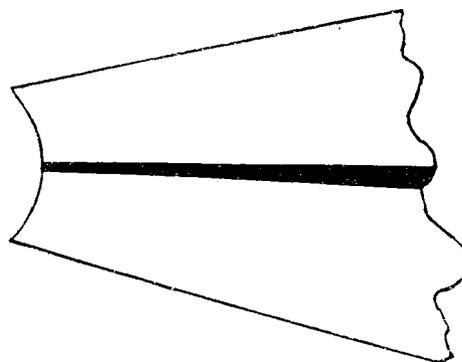


Fig. 31. Modification to Tips of Impeller Blades in Third Model of Experimental Engine

failed by tearing off about 1 inch from the tip. Until then, little had been done to the turbine in the course of testing (except light overhauls after numerous incidents inflicting minor damage). This turbine wheel had had a rough time in the course of its history. Apart from the effects of bad combustion, there were many tip rubs, partly through distortion and partly through yielding of the disk, and both nozzle blades and turbine blades had sustained progressive damage through impact with foreign bodies, including pieces of impeller blade. The turbine had also survived two main bearing failures (each due to foundry sand in the lubricating oil: each time the engine ran there was a fine rain of sand from the roof of the building).

The replacement turbine was of the same design, except that the blades were made of "Rex 78" (Firth-Vickers) instead of "Stayblade". A new nozzle ring was fitted at the same time as the new rotor assembly.

There was gradual yielding of the disk of the second wheel, of the same kind as with the first. This yielding occurred mainly at the shoulders of the bulb roots of the blades, which became progressively looser in their sockets as a result. For some time before the new wheel was used it had become obvious that the De Laval type of root fixing was unsatisfactory, and a wheel was ordered with the "fir tree" fixing, as used in the W1, but it was never used in the experimental engine.

The disk ultimately failed completely and wrecked the engine in February 1941 after a very useful running time of 169 hours. The failure is shown in Figs. 32 and 33, Plates 5 and 6.

Further points of interest connected with the test running of the experimental engine are:—

- (1) Some useful experiments were made on starter motors. Successful starting was achieved with a small single-cylinder two-stroke petrol engine, and also with the electric starter motor of the 10 h.p. motor car engine which had been used for starting during most of the testing.
- (2) We found that we could eliminate the rear water jacket without deleterious effects; and as a result, the W1X and W1 engines were modified to dispense with the rear water jacket.
- (3) Towards the end of its life, several non-stop runs, lasting up to ten hours, were done at cruising speed (14,000 r.p.m.).

PART III. THE DESIGN AND TESTING OF THE W1X AND W1 ENGINES

The leading particulars of the W1 engine are given in Table 2, and the general design is illustrated in Fig. 34, and in Figs. 35-38, Plates 6 and 7.

As already mentioned, the W1X was built from components ordered for the experimental engine and from certain parts

TABLE 2. LEADING PARTICULARS OF W1
Dimensions are in inches.

<i>Compressor impeller—</i>	
Tip diameter	19
Tip width	2
Outer diameter of eye	10.75
Inner diameter of eye	5.5
Number of blades	29
Material	Hiduminium RR59
<i>Compressor casing, Material</i>	Mg. Alloy No. 299 DTD.350
<i>Turbine—</i>	
Mean diameter of blades	14
Blade length	2.4
Material of blades	Firth-Vickers Rex 78
Material of disk	Firth-Vickers Stayblade
Blade chord	0.8
Number of blades	72
<i>Maximum speed, r.p.m.</i>	17,750

made for the W1 which were rejected as "unairworthy". The W1X differed from the W1 only in respect of the necessary adaptations.

The general design of the W1 was very similar to the third model of the experimental engine, except that much lighter scantlings were used. Other important differences were as follows:—

- (1) A very different and much lighter design of auxiliary drive box was used.
- (2) The number of turbine blades was increased from sixty-six to seventy-two, and the fir-tree root fixing was used.
- (3) The blower casing carried four mounting points for attachment to the tubular engine bearer structure of the aircraft.

Testing of the W1X. When the engine was delivered by The British Thomson-Houston Company, the combustion system was modified in accordance with the latest experience on the experimental engine.

For test purposes the engine was now carried on a frame which was suspended from the roof of the test house by four swinging rods. At this time a spring balance was still used for measuring thrust, though it was later replaced by hydraulic thrust-measuring devices. Testing was carried out in the new test houses which had been built at the Ladywood Works.

We succeeded in reaching a speed of 16,500 r.p.m. within a day or two of the beginning of tests on the W1X, and though the performance was somewhat below expectations there was a very great improvement as compared with the experimental engine.

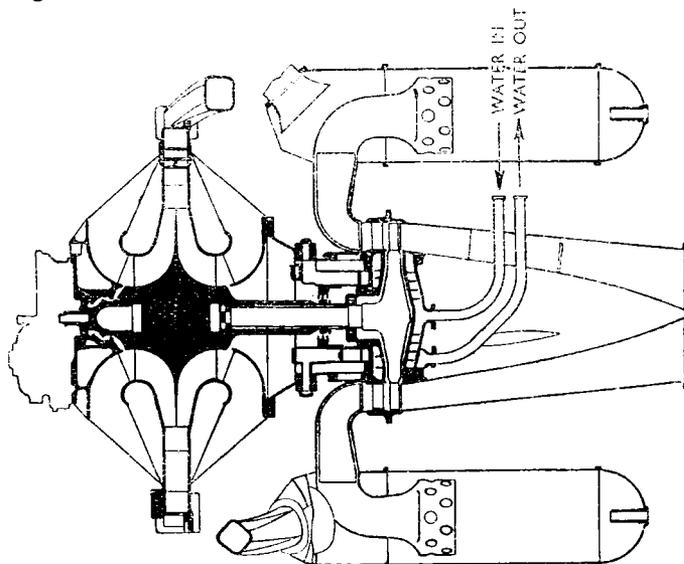


Fig. 34. Assembly of W1 Engine
Combustion chamber details not shown.

Bearing failures were our main trouble in the early testing of the W1X. These failures were not due to the inability of the bearings to carry the load imposed, but to faults in the installation, either because the design was unsatisfactory or because the assembly was faulty. One was due to malalignment of the bearing on the shaft; another to a failure in the lubrication system; another to foreign matter getting into the bearing housing; one at least was due to an oversight through sheer fatigue on the part of the people doing the work (we were working at very high pressure and for very long hours).

The intensive testing of the W1X resulted in a series of modifications to the W1 (and the other engines then in course of design and manufacture). It was a most useful engine, and we did 132 hours of test running with it in nine months. After that it was sent to the General Electric Company of America, where it was used for demonstration purposes.

The Testing of the W1. There is little to be said about the testing of the W1 without going into excessive detail. There were early "teething troubles" of course, but serious troubles at speeds up to the rating at which it was decided to fly were avoided by virtue of our experience with the W1X; and though testing of the engine did not begin until 12th April 1941, we succeeded in getting through a 25-hour special category test to clear it for flight, installed it in the aircraft, and completed the ten hours of flight trials, all in 46 days.

The engine was cleared for flight at a static thrust of 850 lb. at 16,500 r.p.m. Typical performance curves are given in Figs. 39 and 40.

A hydraulic starter motor was designed for the W1 and W1X engines, but was never used. The starter motor for both bench and flight tests was a 7 h.p. motor car engine mounted on a hand truck and fitted with a long flexible drive which could be

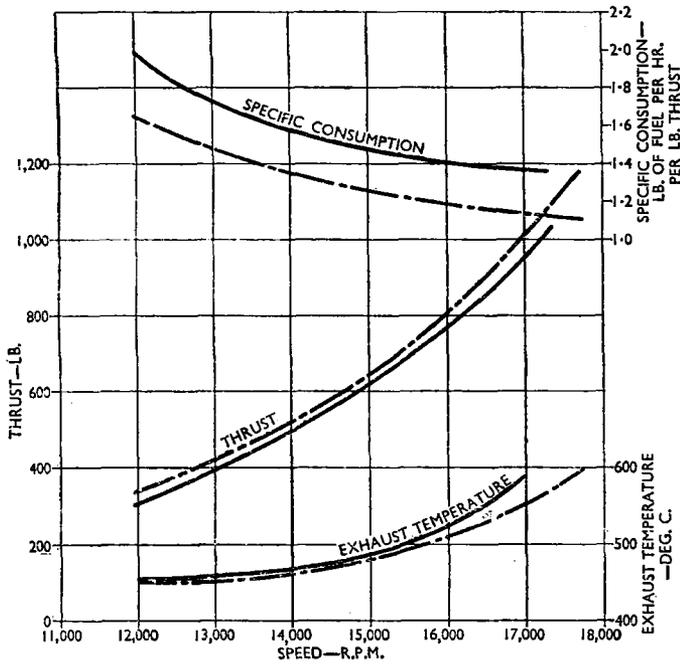


Fig. 39. The W1 Engine: Curves of Thrust, Specific Fuel Consumption, and Exhaust Temperatures plotted against Speed

— Test results.
 - - - "Design" performance.

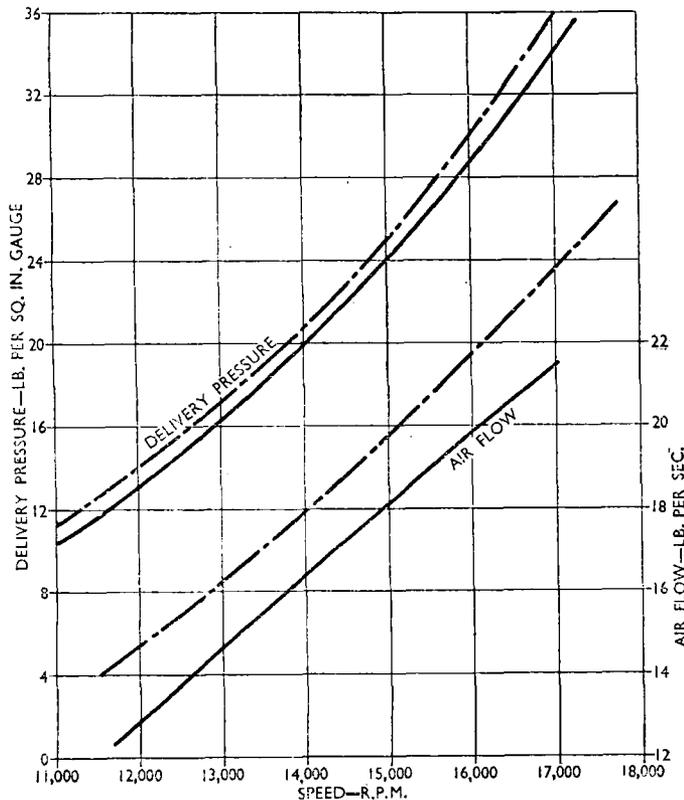


Fig. 40. The W1 Engine: Curves of Blower Delivery Pressure and Air Mass Flow

Air flow readings are now known to be low.
 — Test results.
 - - - "Design" performance.

connected to and disconnected from the engine by hand. It was also intended that each of these two engines should be fitted with a governor to prevent overspeeding. Such a governor is necessary, because the fuel required for full speed diminishes with height; hence for a given setting of throttle—which itself consists of a needle valve—engine speed increases with height. However, a satisfactory governor was not ready in time for the flight trials and so we did without. All later engines were provided with a governor and a barostat relief valve (by means of which the maximum fuel-line pressure was made a function of the height—as height was increased, the fuel pressure was reduced). We received much valuable help from Dr. H. R. Ricardo, F.R.S., M.I.Mech.E. (*Past-President*), and his team in the design and development of these and other fuel-line accessories.

The general arrangement of the aeroplane is shown in Fig. 41, Plate 7, and in Fig. 42.

PART IV. SOME BRIEF NOTES ON THE W1A, W2, AND W2B ENGINES

The W1A Engine. The W1A engine was designed for a thrust of 1,450 lb. The general design is illustrated in Fig. 43, also in Figs. 44 and 45, Plate 7.

The general arrangement, as may be seen, has many features in common with the W1, but air cooling was used for the turbine instead of water cooling, the fins of the air cooling fan being machined integral with the turbine disk. Another important difference was that stationary guide vanes were mounted at the entry to the blower intakes to give the air a "pre-whirl" in the direction of rotation.

Initial tests with the W1A were very disappointing, primarily because of low turbine efficiency. Surging of the blower was experienced for the first time, but in the case of this engine it was cured by dispensing with the air cooling system at the rear side of the turbine wheel. (The cooling air to the rear side of the wheel discharged into the exhaust annulus and being relatively "stagnant" it caused "choking" of the exhaust. This lowered the capacity of the expansion system below the surge point of the blower.)

A substantial improvement in turbine efficiency was achieved by fitting a redesigned set of blades. The unsuccessful blades had profiles based on aerofoil sections. With the new ones we returned to more conventional profiles, though still conforming to angles appropriate to vortex flow. Eventually, though this engine fell short of its design performance, it was relatively successful and it powered the E28 aeroplane in flight trials.

The W2 Engine. An illustration of this engine is shown in Fig. 46, Plate 8.

As I have already said, this engine was a failure. It was too ambitious. Of the many serious faults in the design, perhaps the worst was that we had designed for an exit velocity from the turbine much too near the speed of sound, so that when the assumed component efficiencies were not realized the exhaust velocity reached the critical value at speeds well below the design full speed. Both the compressor and turbine efficiencies were substantially lower than the expected figures, the net result being that surging of the blower and high exhaust temperatures made it impossible to run at more than 75 per cent of the design r.p.m. The corner vane system at the blower casing discharge ports was a much-criticized feature of this design, but this same feature has been embodied in later designs with considerable success.

We had realized before we started to test the W2 that the design was very critical in respect of design assumptions, and therefore no serious attempt was made by Power Jets to develop it. We relied on the revised design known as the W2B to give us what we wanted.

The general design of this engine is illustrated in Fig. 47 and in Fig. 48, Plate 8. A great deal of development work was required before the W2B gave its design performance, but that is a story which must be told later. As already mentioned, this was the parent design of the Rolls-Royce *Welland* engines which powered the *Meteor* fighter, and of the American General Electric Company's engines which powered the Bell P.59 A (or *Airacomet*).

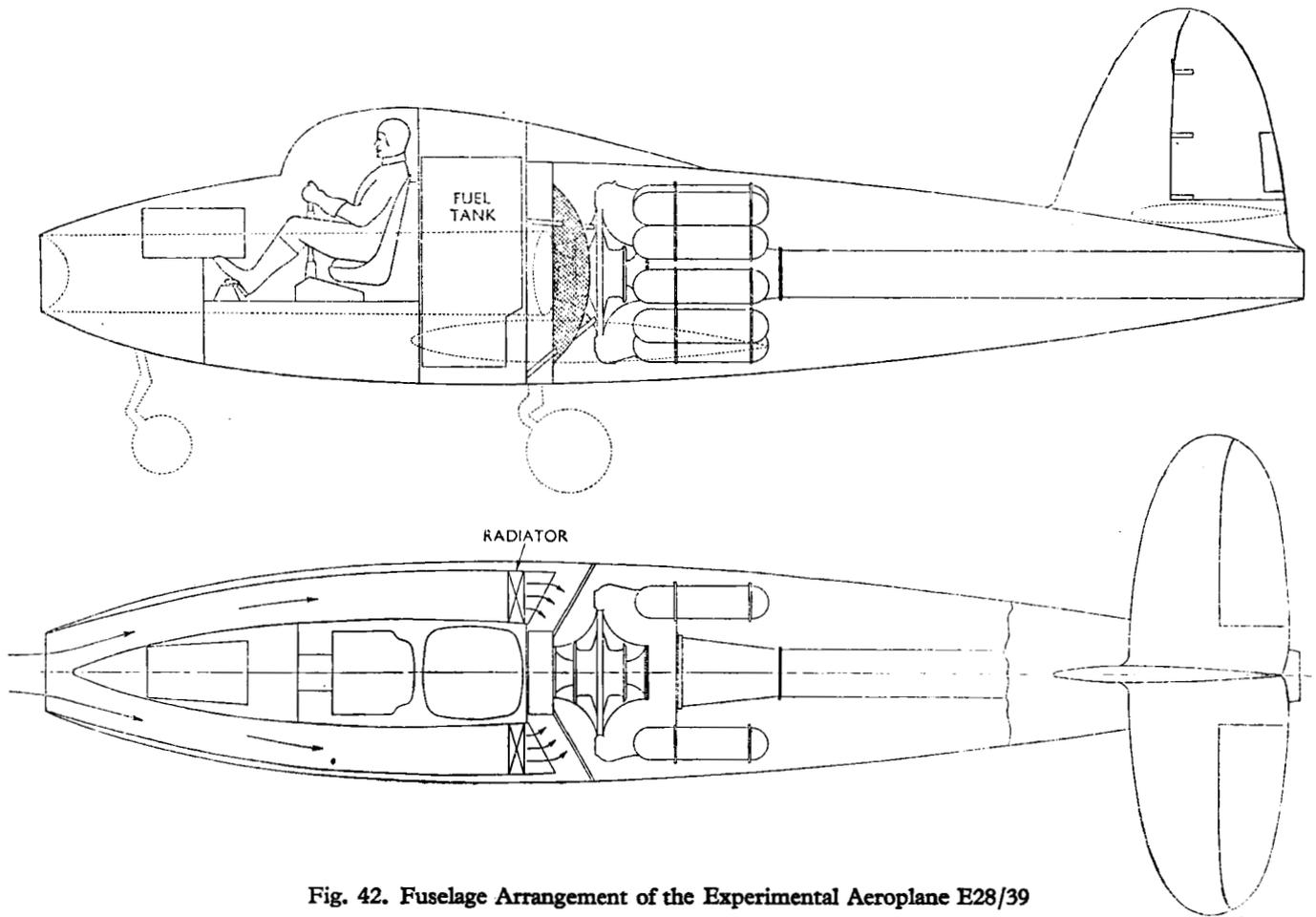


Fig. 42. Fuselage Arrangement of the Experimental Aeroplane E28/39

CONCLUSIONS

If the foregoing account has caused mental indigestion, my excuse is that it could scarcely do otherwise when the intensive work of about six years has to be compressed into so short a

Company, and the other firms engaged. I have not been able to mention many individuals and firms who have given great help. Acknowledgement will, I hope, be made in due course.

I certainly hope I have not conveyed the impression that this has been a one-man job. No big engineering task ever is a one-man job. As every engineer knows, it is always the work of a team. At first the team working in this field of engineering consisted of The British Thomson-Houston engineers, Messrs. Laidlaw, Drew and Company, and myself. Later it was aug-

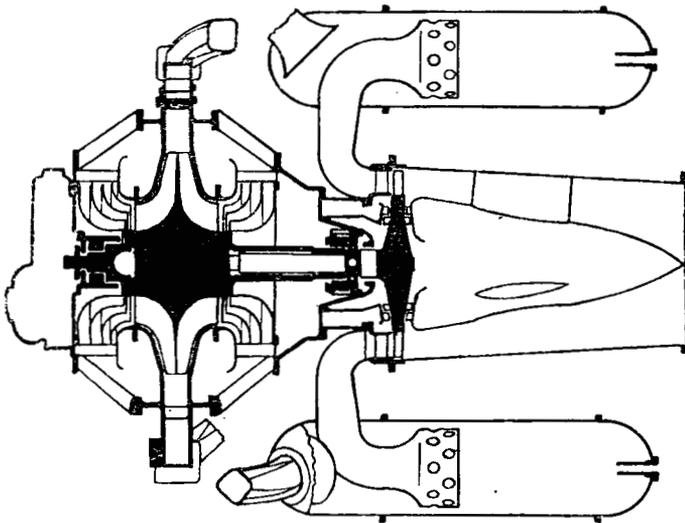


Fig. 43. Assembly of the W1A Engine

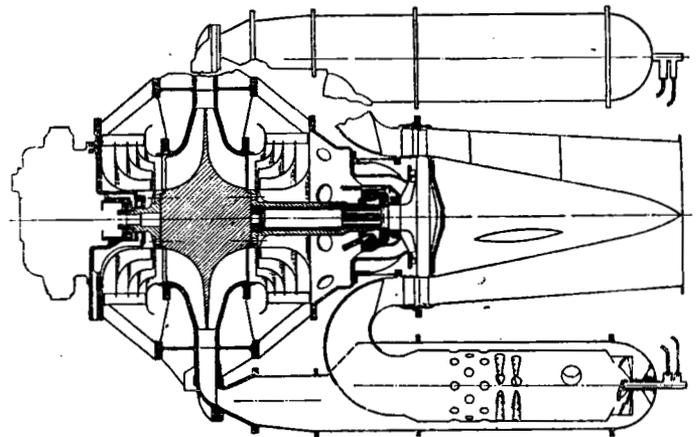


Fig. 47. Assembly of the W2B Engine

description. It is far from complete in many ways. I have been able only to hint at the complex relationships which existed from time to time between Power Jets, the Air Ministry (or Ministry of Aircraft Production), The British Thomson-Houston

mented by the excellent team that I helped to build up at the Power Jets' Works; and later still, as other firms began to share in the work, it would be true to say that the fruits were the product of a group of teams working in collaboration.

I feel that I must point out that a factor which has contributed greatly to the work has been the very fine training I have received in the Royal Air Force. Of my 21½ years' service, I have spent ten under training, mostly engineering. In this I regard myself as having been very fortunate, and I hope that the outcome will do something to suggest that such a degree of training should not be as exceptional in the future as it is at present.

A NOTE ON GERMAN WORK

Evidence from Germany recently obtained indicates that the Germans started practical work on jet propulsion gas turbines at about the same time as ourselves, i.e. 1936, but that they succeeded in flying with this system of propulsion before we did (believed to be a few days before the outbreak of war). However, the engine they used was of a type subsequently abandoned, and successful flight trials with the type of engine which they ultimately used in quantity did not take place until some time after the British flight trials in May 1941. The engine with which our first flight trials were carried out was the obvious parent of a successful series of British and American engines and so I think we can claim with justice that the E28/39 was the first successful aeroplane using the gas turbine jet propulsion engine.

The power plant of the Me.262—an aeroplane which the Germans used in considerable numbers towards the end of the war in Europe—was the Junkers 004 jet propulsion gas turbine having an axial flow compressor. They put this engine into production at a stage in its development history which would be considered far too early in this country, and it was technically a long way behind the British engines, being much heavier in proportion to its power, having a much bigger fuel consumption, and only a fraction of the life. Moreover it had the serious disadvantage of being very sluggish in response to the throttle. This, combined with the low reliability of the engine and the high wing loading of the aeroplane, represented a very dangerous combination, and it is believed that fatal accidents were so numerous as to affect the morale of the pilots very seriously.

A NOTE ON THE FUTURE

So far I have confined myself to the past, but a brief word about the future may not be out of place.

Jet propulsion is only one way of using the gas turbine in aircraft propulsion (incidentally, the gas turbine method is only one of about five systems of jet propulsion which have been developed to, or nearly to, the practical stage during the war). Up to now far too much emphasis has been placed on the jet propulsion aspect of this development. This particular mode of using the gas turbine has come first because it happens to be the simplest, but there is no doubt that the gas turbine will also be used in combination with a normal propeller (Fig. 59), and also with what has come to be called the "ducted fan", i.e. a low-lift axial flow compressor in a duct. The use of the jet propulsion gas turbine will probably be confined mostly to aircraft designed for high speeds and relatively short ranges. The other applications of the gas turbine will cover speed and range requirements unsuited to the plain jet. So wide is the possible range of application of the gas turbine in one form or another that it seems reasonably certain that within (say) 10–15 years the piston engine will have given way to the gas turbine in all aircraft except possibly the light aeroplane. I make the reservation about the light aeroplane because at present it appears to be far more difficult to design for the low power necessary than it is to design for much higher powers than we use at present.

The uses of the gas turbine will not of course be confined to aircraft. It has already been successfully used in locomotives in Switzerland, and in other ways. I expect to see it reach some prominence in the field of marine propulsion.

Acknowledgements. I am indebted to the British Thomson-Houston Company, Rugby, for permission to reproduce the photographs used in Figs. 7, 8, 9, 11, 13, 14, 21, 22 and 35, and to the Asiatic Petroleum Company for Fig. 28.

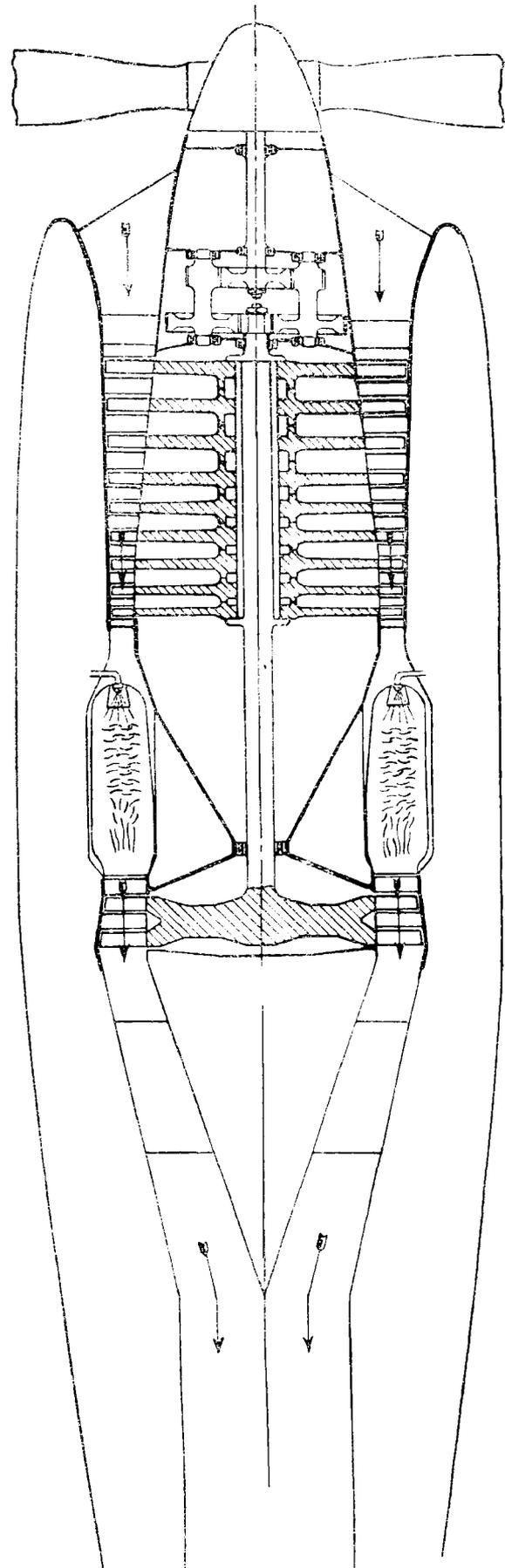


Fig. 59. Diagram of Gas Turbine-Propeller Combination

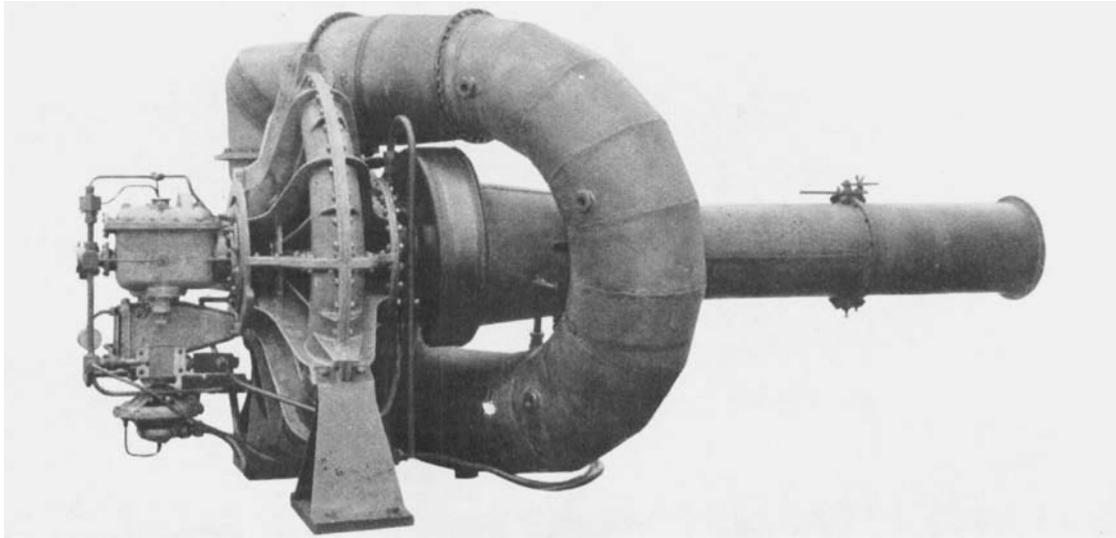


Fig. 7. First Model of the First Experimental Engine

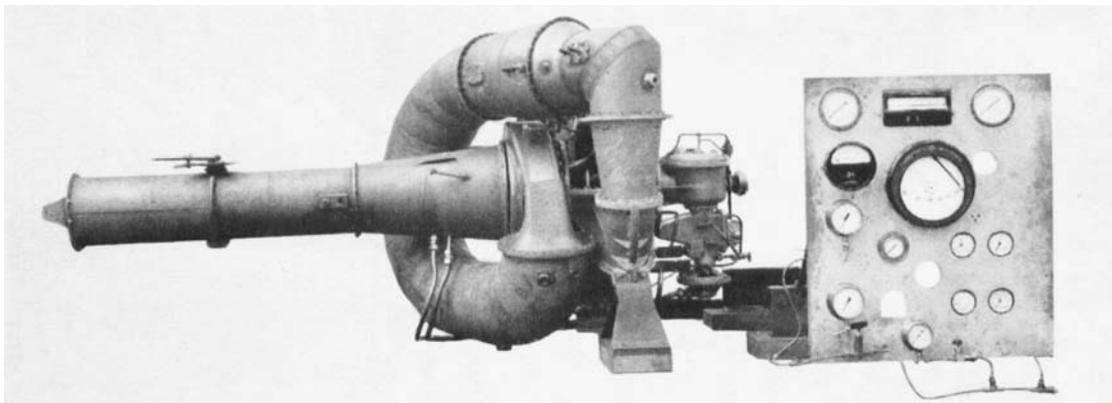


Fig. 8. Test Assembly of First Model of Experimental Engine
The truck and starter motor have been "blacked out" of the photograph.

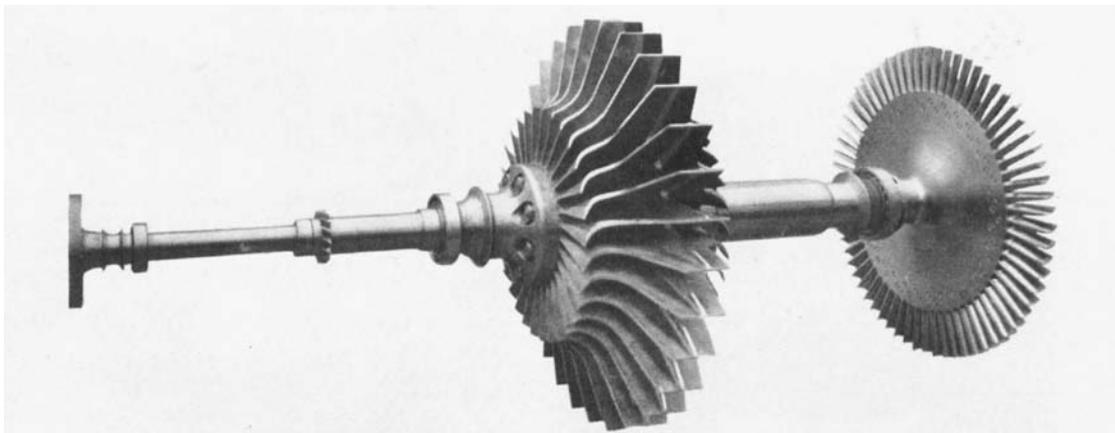


Fig. 9. Rotor Assembly of First Experimental Engine

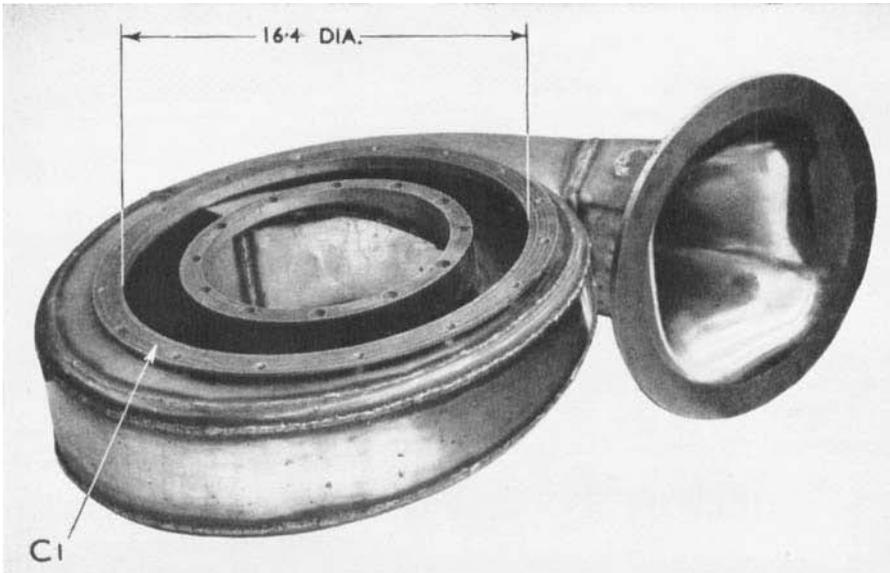


Fig. 11. The Unconventional Bladeless Turbine Nozzle Scroll in the First Model of the Experimental Engine



Fig. 13. The "Honeycomb" Diffuser used in the First Model of the Experimental Engine

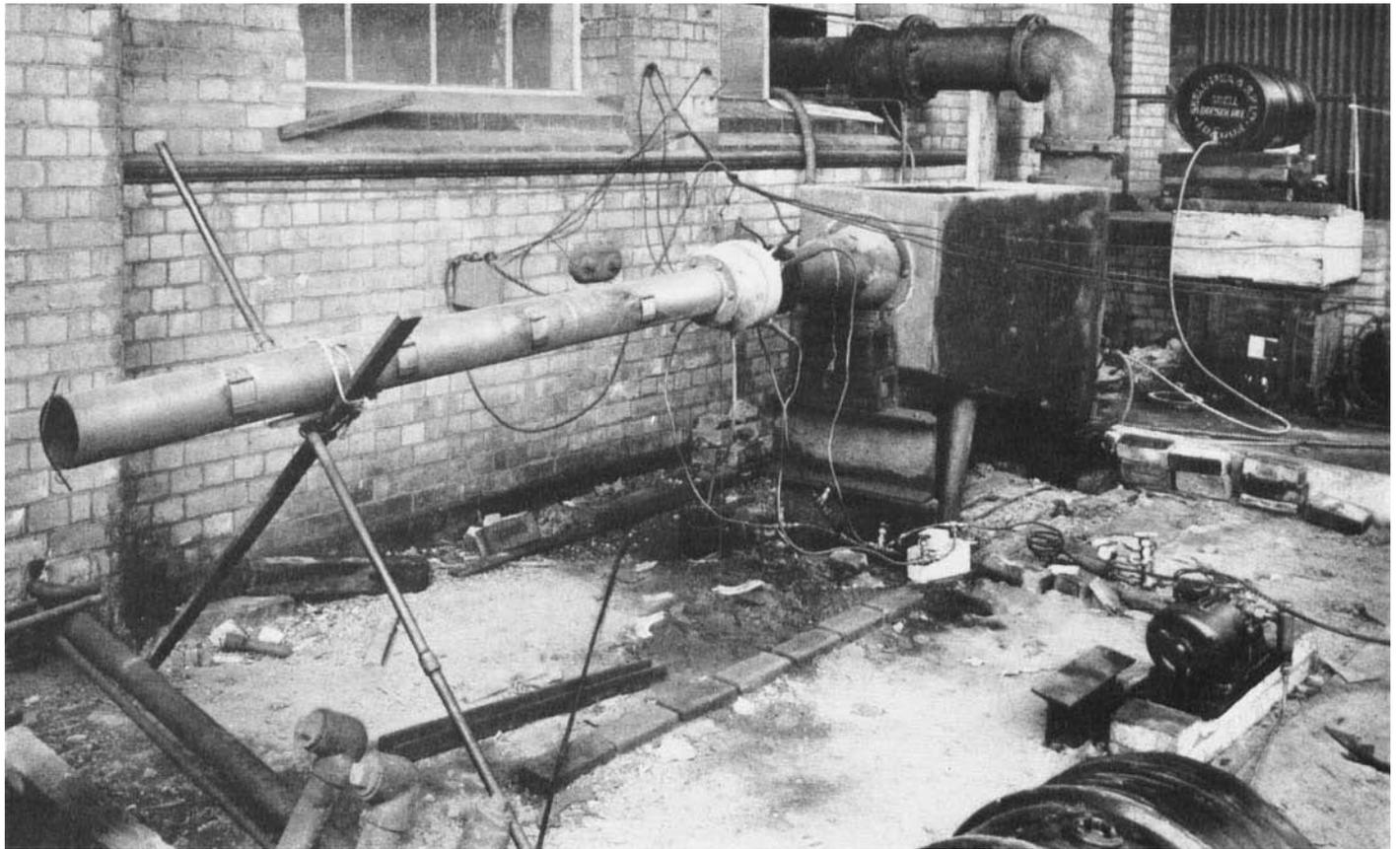


Fig. 14. Combustion Test Arrangements outside the British Thomson-Houston Factory, as used before the Completion of the Experimental Engine

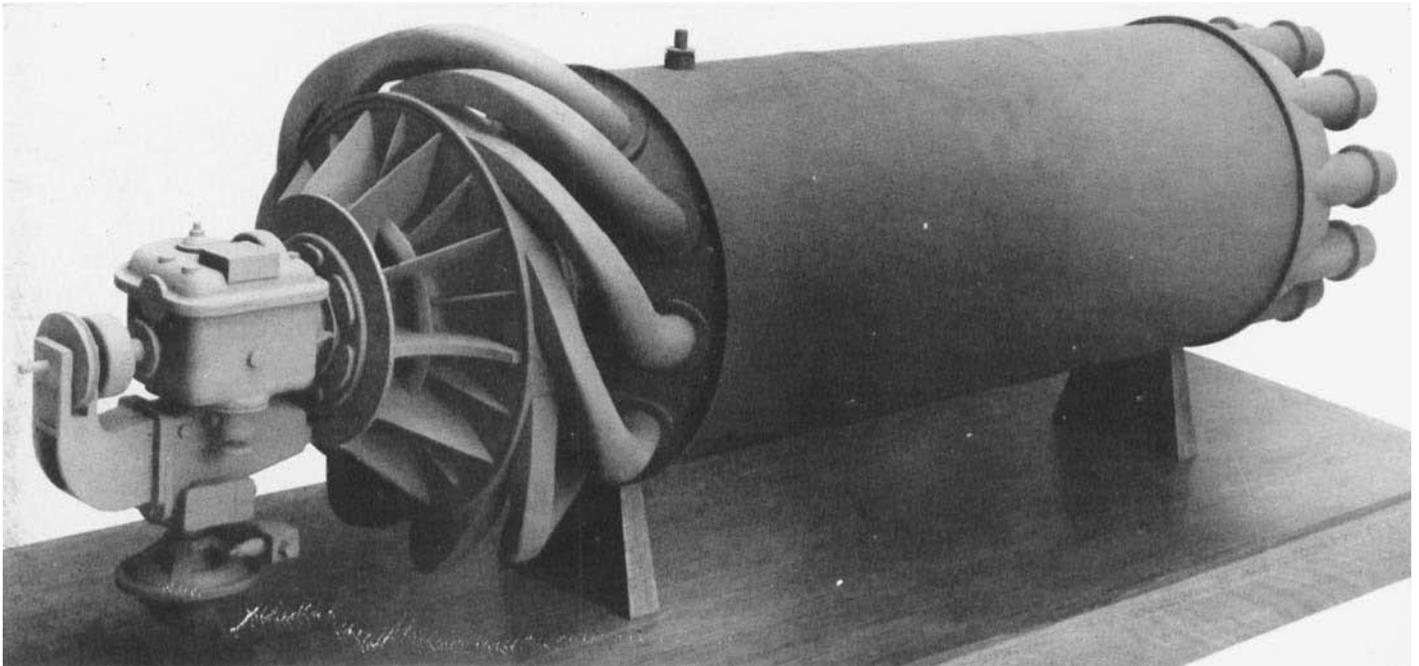


Fig. 19. Second Model of Experimental Engine : Wooden Model

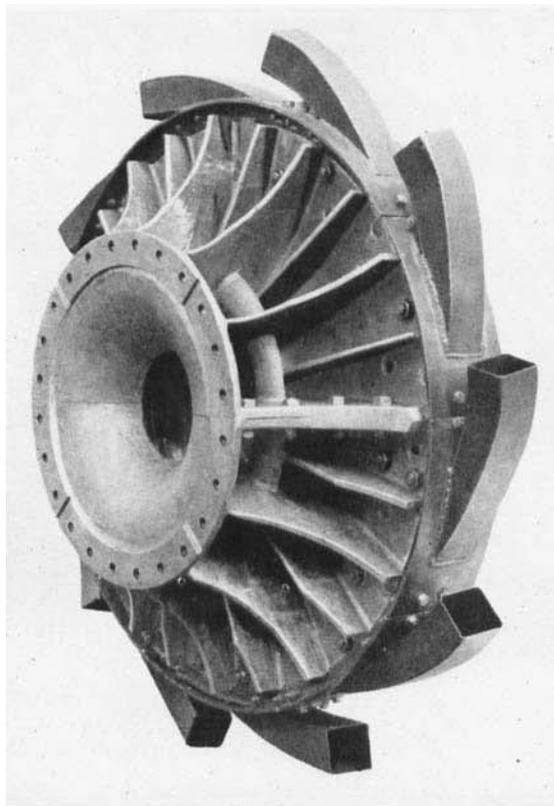


Fig. 21. Modification to Blower Casing, Second Model of Experimental Engine

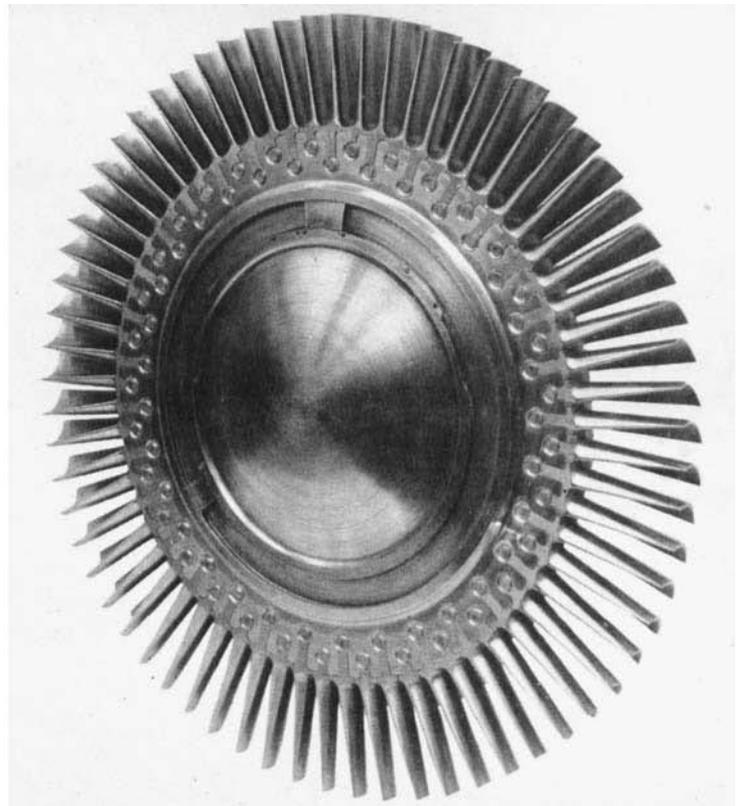


Fig. 22. Rebladed Turbine (Blades Designed for Vortex Flow) for Second Model of Experimental Engine

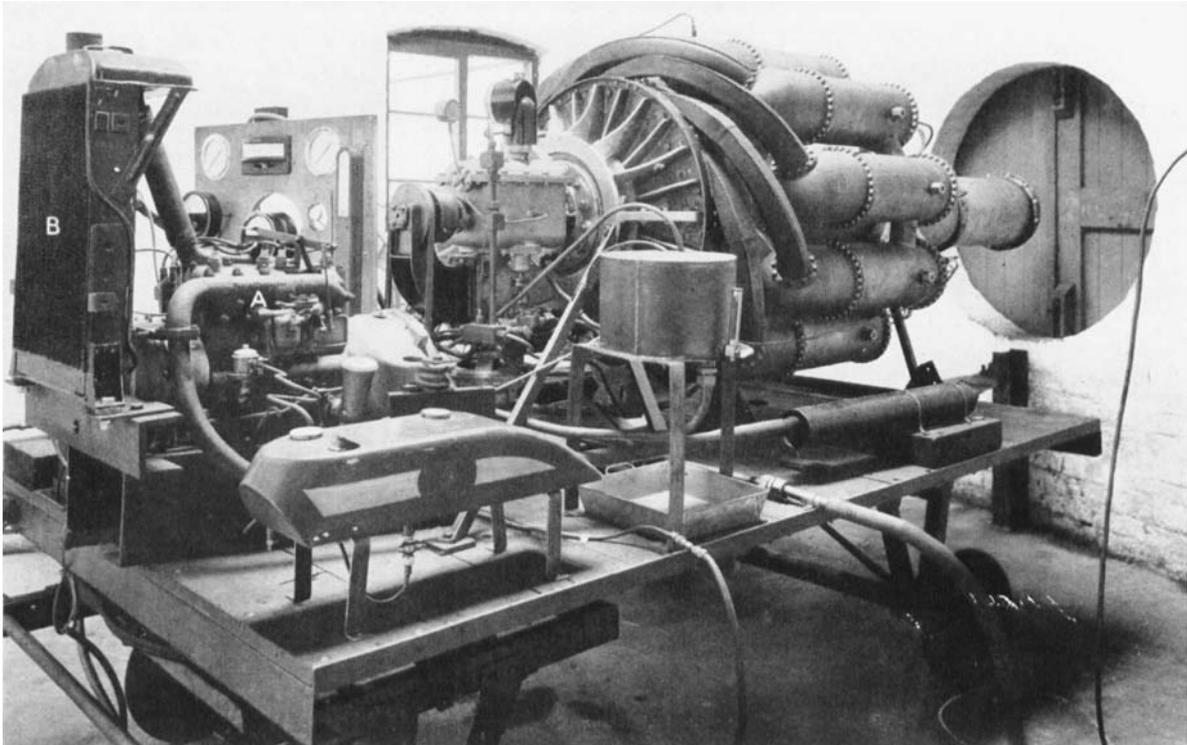


Fig. 24. Test Installation of Third Model of Experimental Engine at Ladywood Works, Lutterworth
A. 10 h.p. engine for starting. B. Radiator for starting motor.

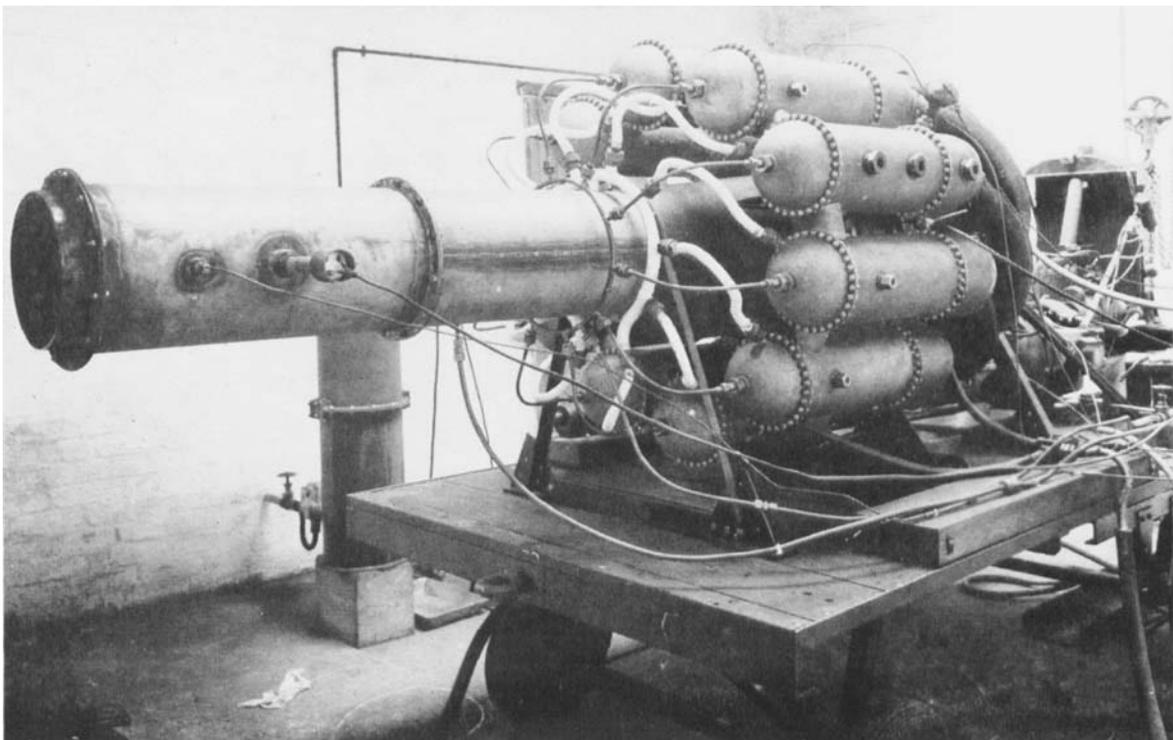


Fig. 25. Another View of Test Installation of Third Model of Experimental Engine at Ladywood Works, Lutterworth

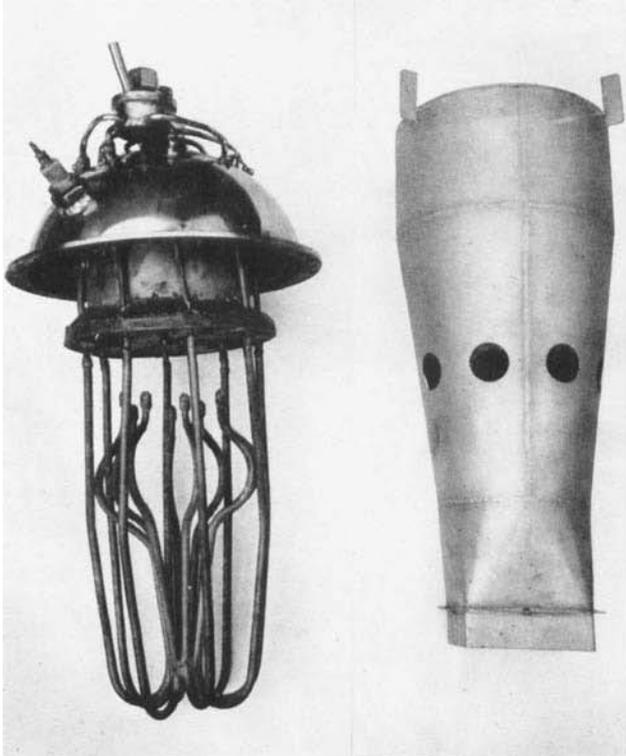


Fig. 27. Vaporizer Type 31, with Flame Tube

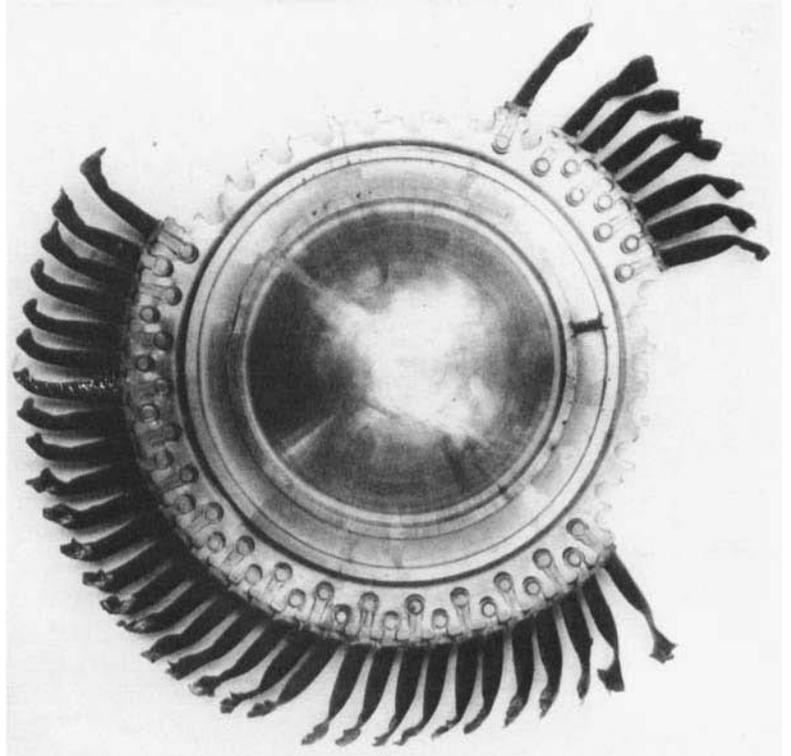
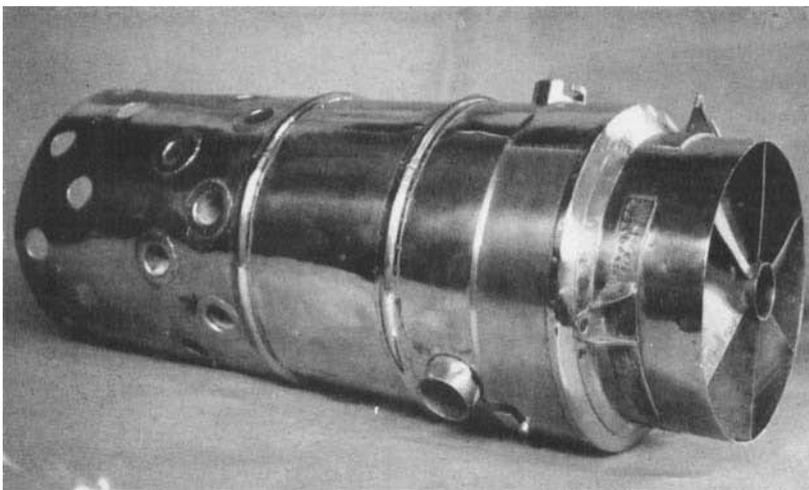
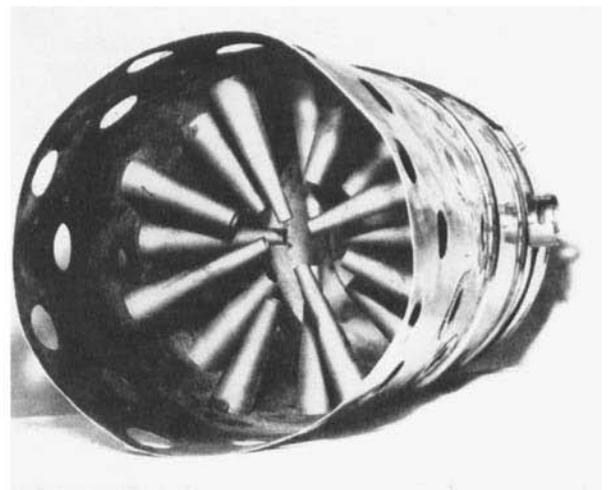


Fig. 32. Failure of Turbine Disk of Third Model of Experimental Engine (February 1941)



a



b

Fig. 29. Combustion Chamber Type 75
Type in use at end of testing.

[I.Mech.E., 1946]

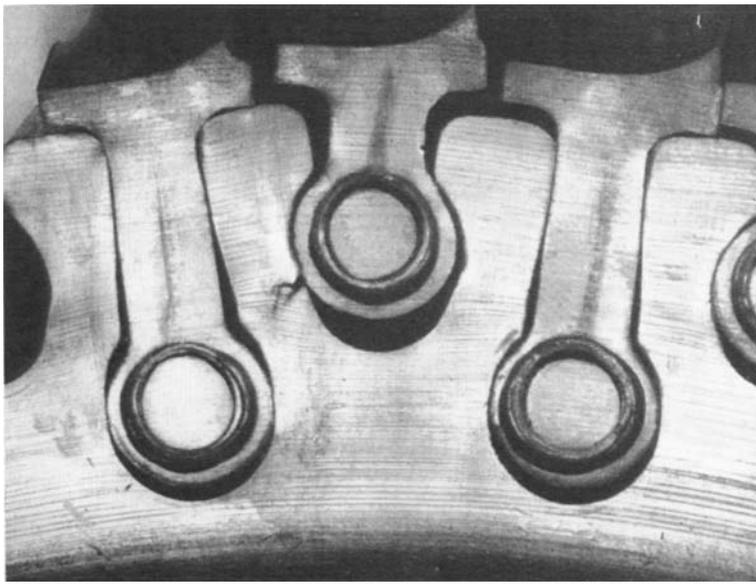


Fig. 33. Yielding of Turbine Disk of Third Model of Experimental Engine (February 1941)

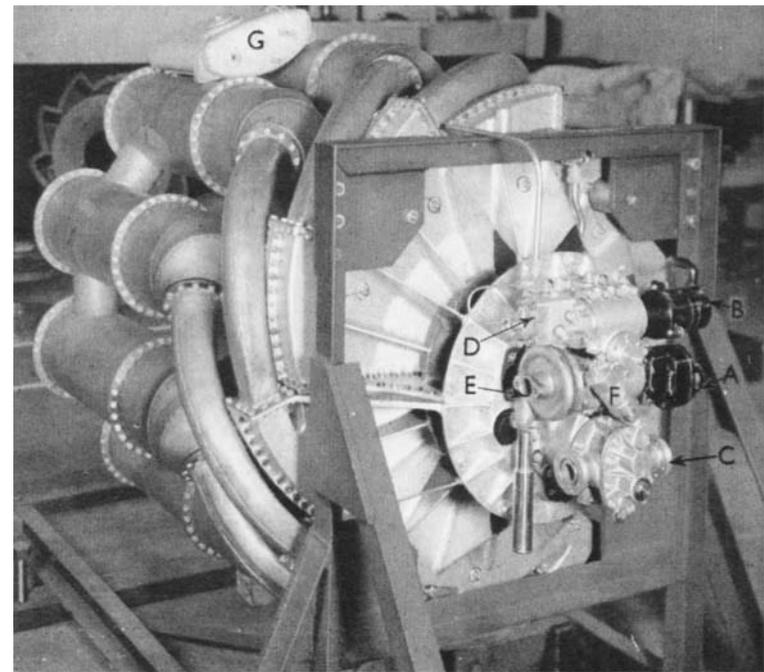


Fig. 35. View, from Gearcase End, of the W1, the First Flight Engine
A. Fuel pump. B. Tachometer generator. C. Oil starter motor.
D. Lubricating oil pump. E. Water pump. G. Oil tank.

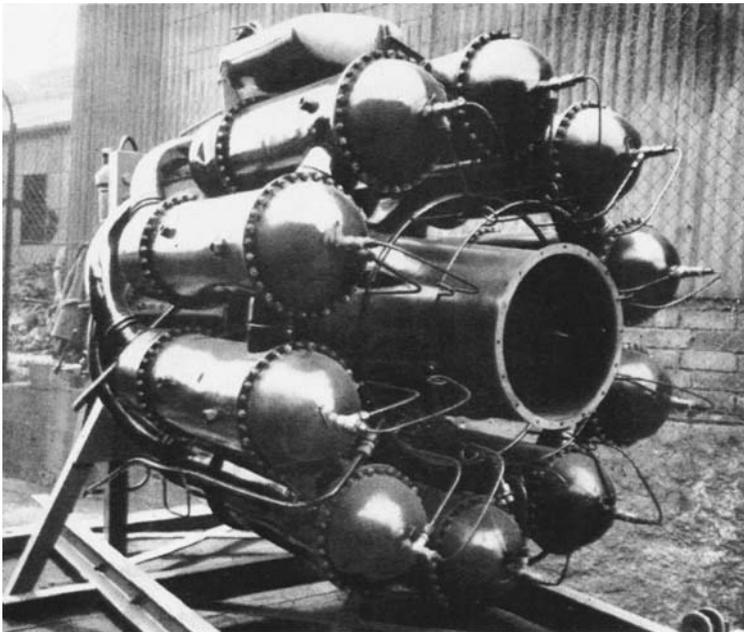


Fig. 36. View, from Exhaust End, of the W1, the First Flight Engine

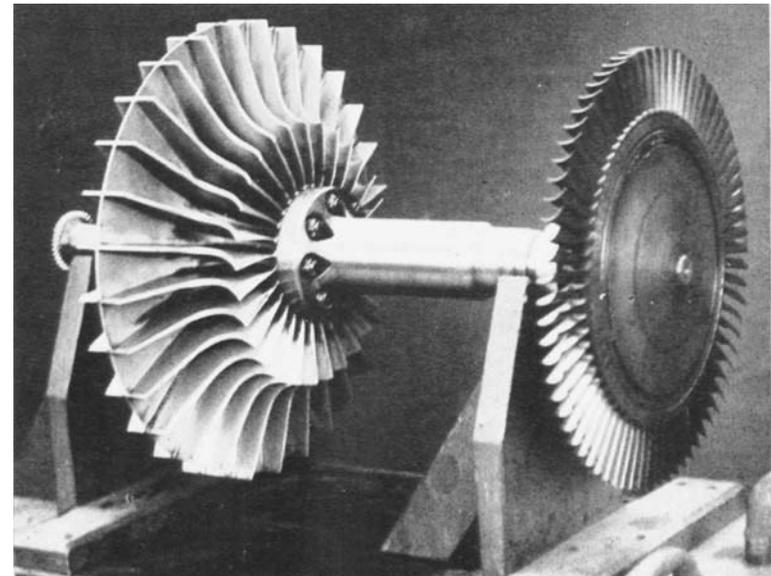


Fig. 37. Rotor Assembly of the W1 Engine

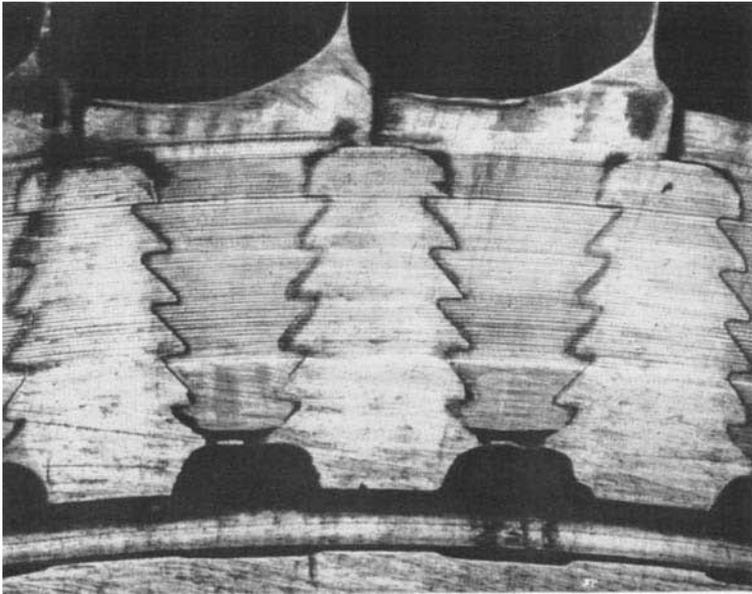


Fig. 38. "Fir Tree" Blade Root Fixing on the W1 Engine



Fig. 41. The Gloster-Whittle Experimental Aeroplane E28/39
(R.A.F. Official, Crown Copyright Reserved)

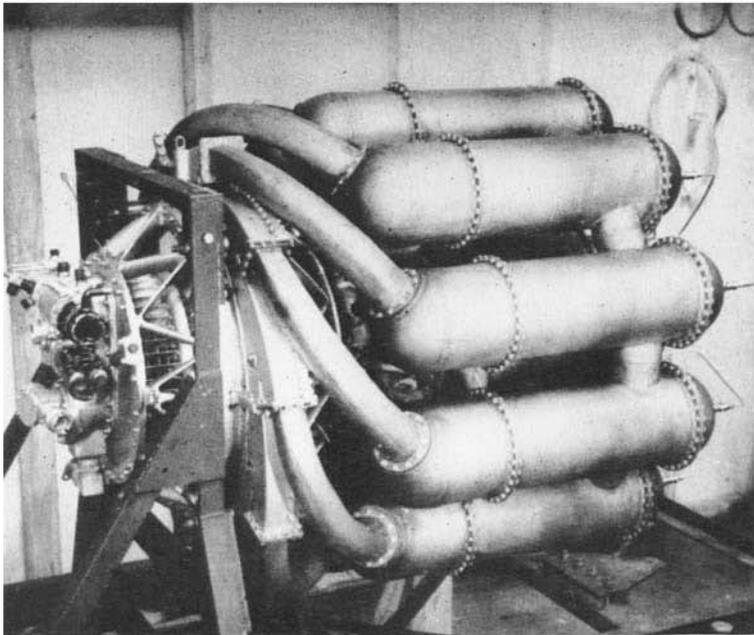


Fig. 44. View, from Gearcase End, of the W1A Engine

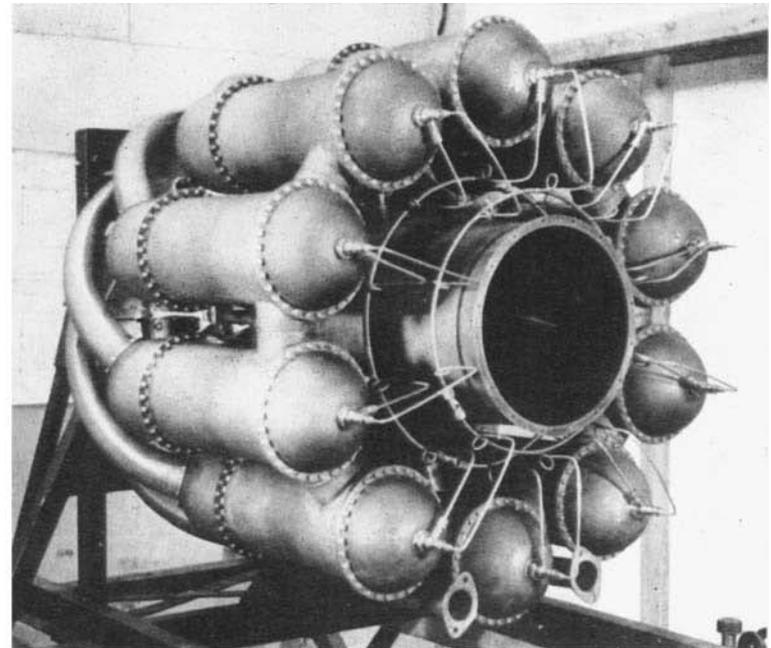


Fig. 45. View, from Exhaust End, of the W1A Engine

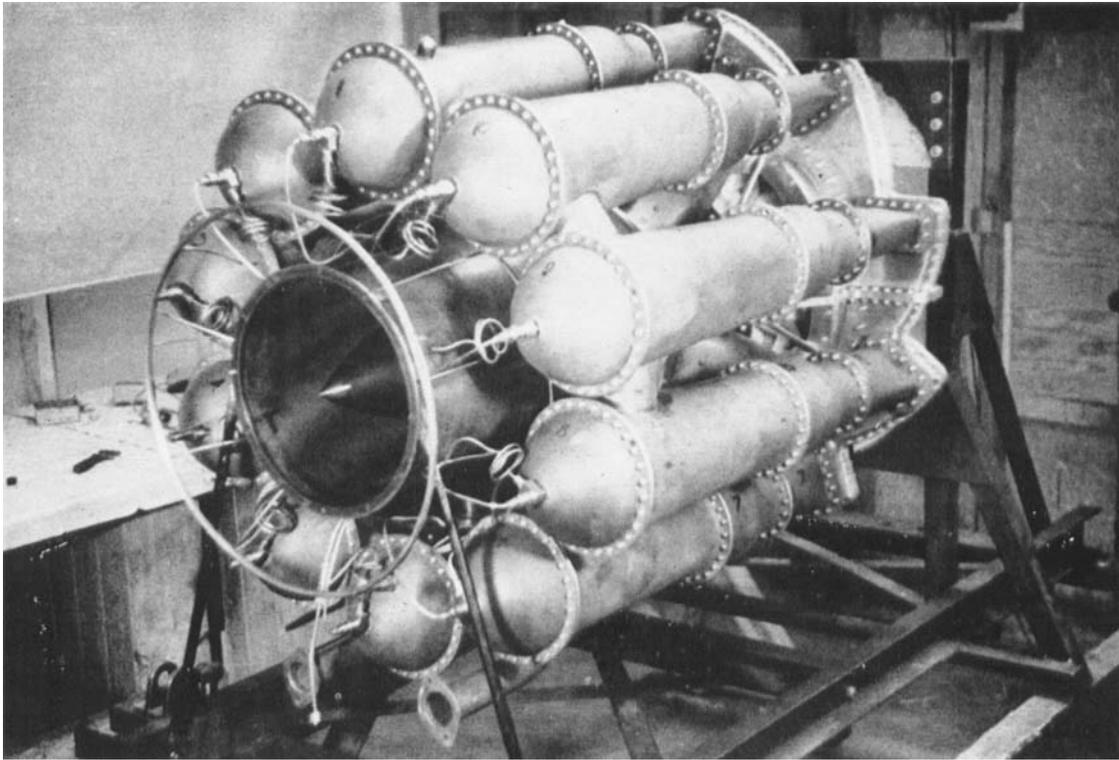


Fig. 46. View, from Exhaust End, of the W2 Engine

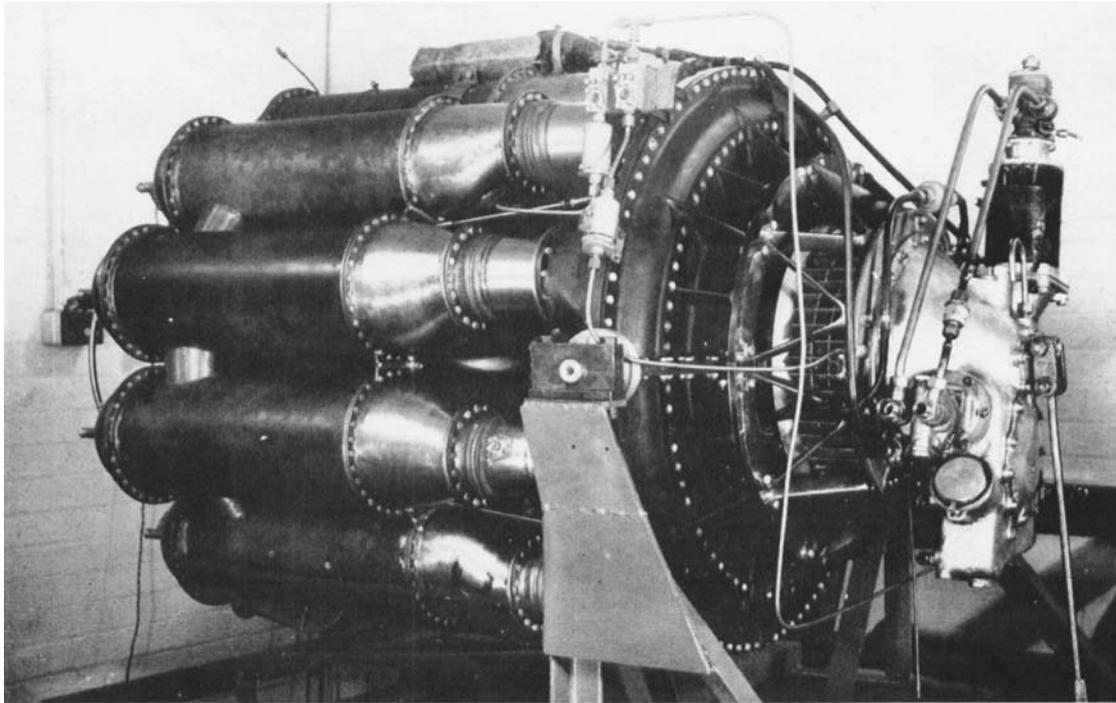


Fig. 48. View, from Gearcase End, of the W2B Engine

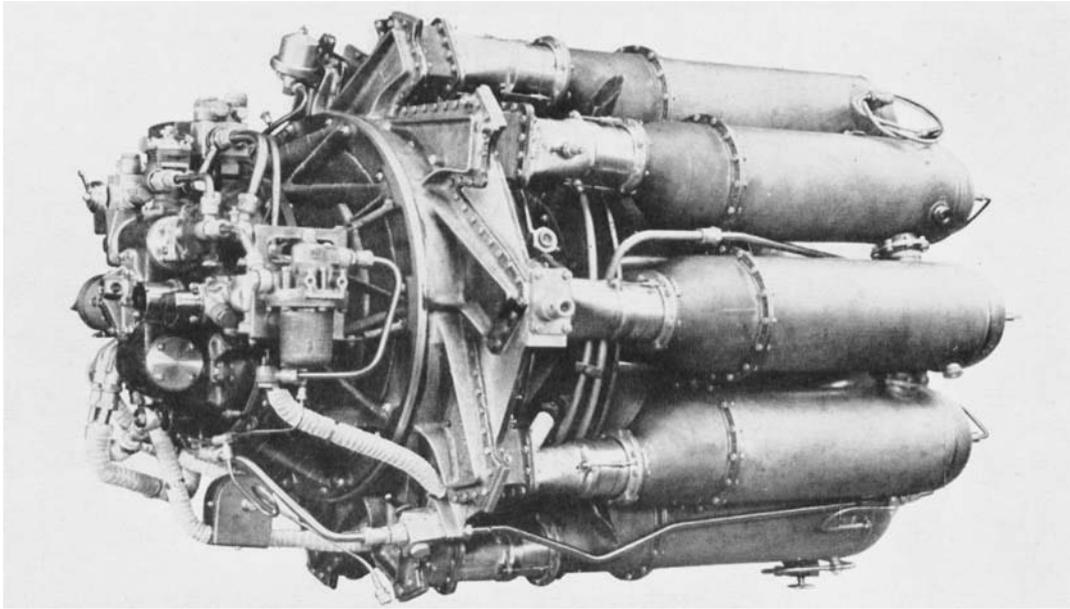


Fig. 49. Power Jets W2/700 Engine

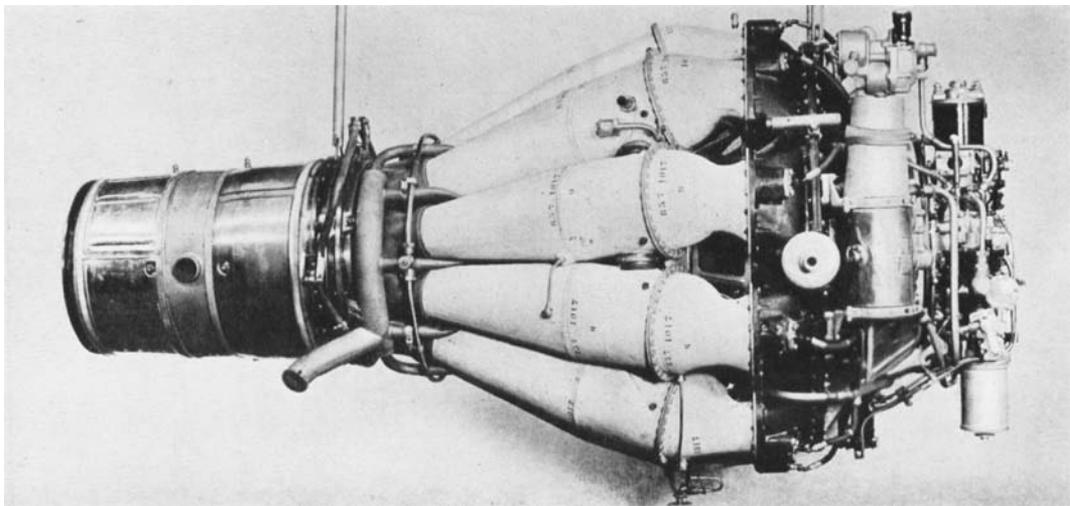


Fig. 50. Rolls-Royce *Derwent I* Engine

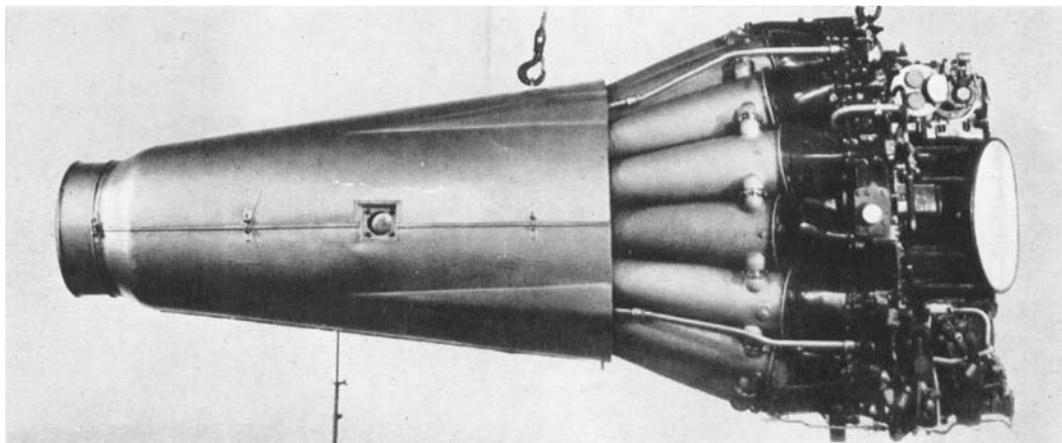


Fig. 51. De Havilland *Goblin* Engine

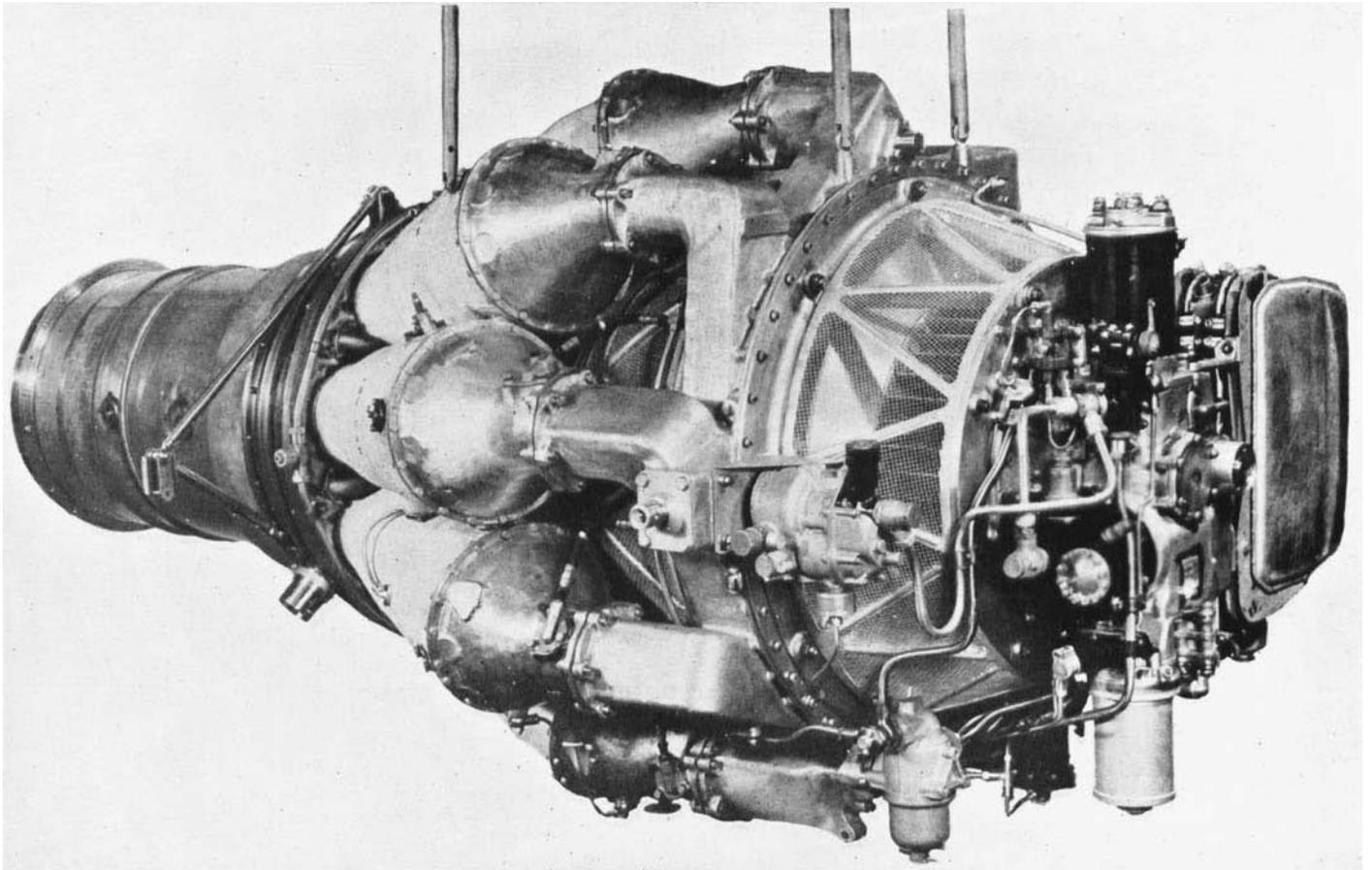


Fig. 52. Rolls-Royce *Derwent V* Engine

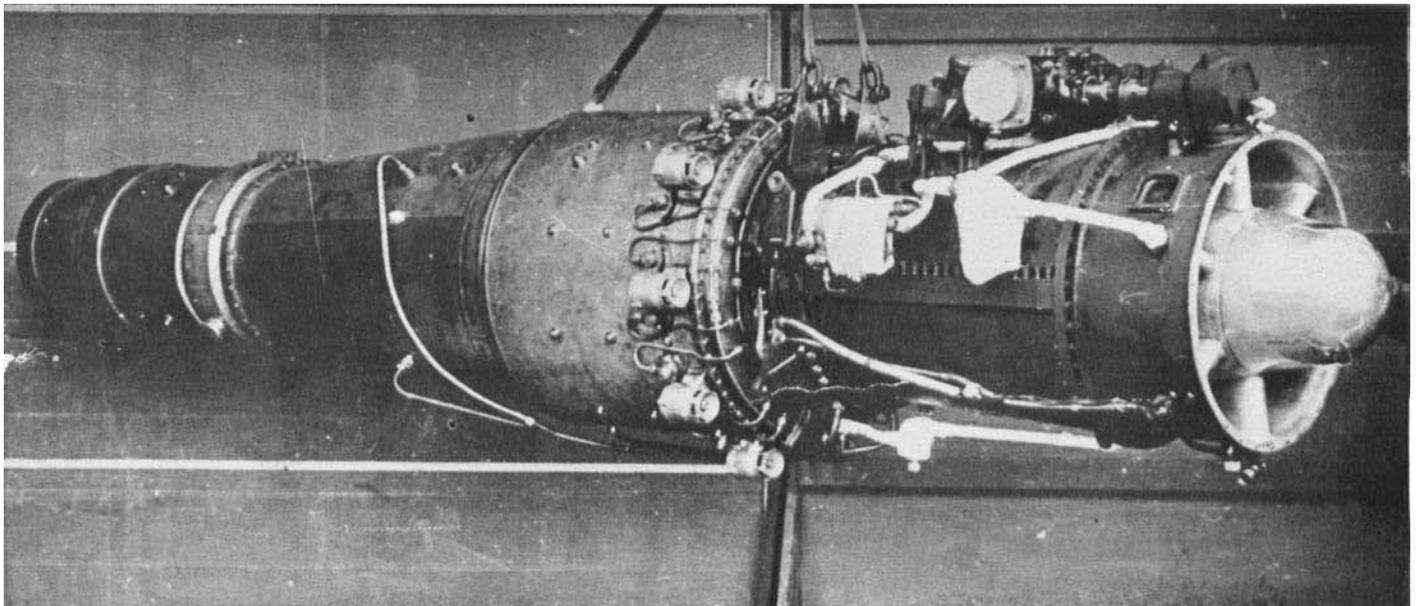


Fig. 53. Metropolitan-Vickers F2 Engine

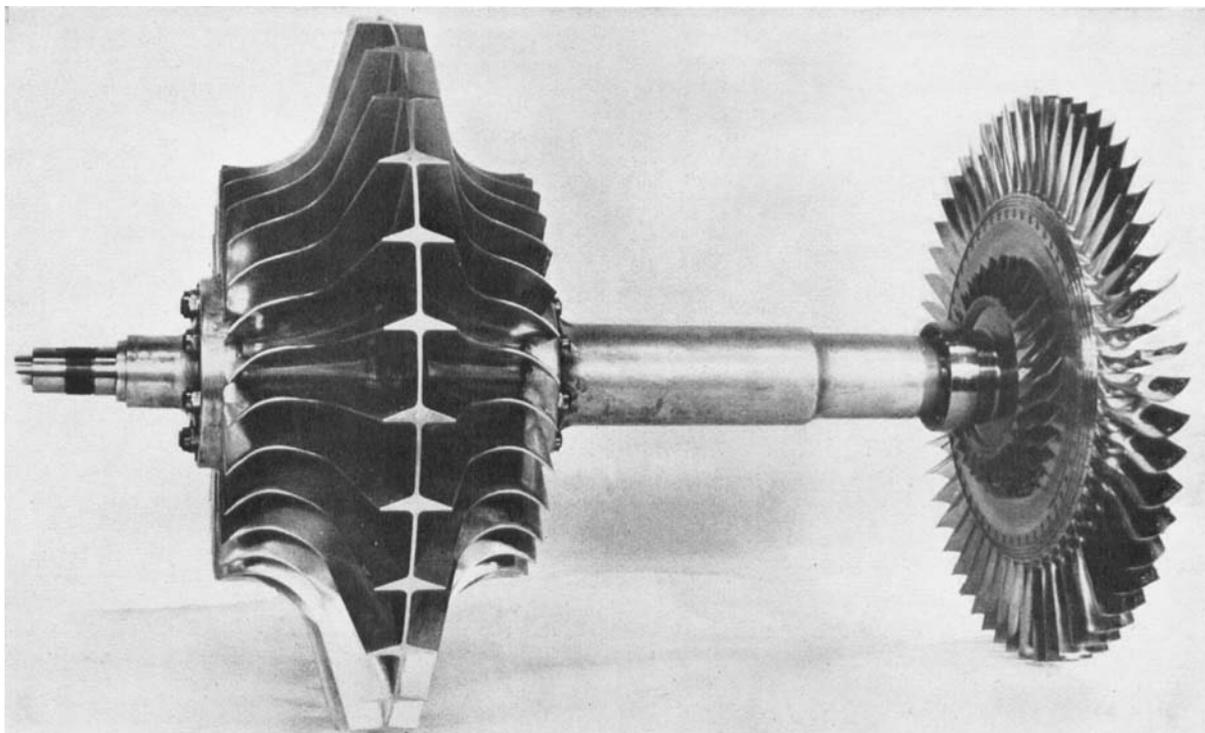


Fig. 54. Rotor of the Power Jets W2/700 Engine

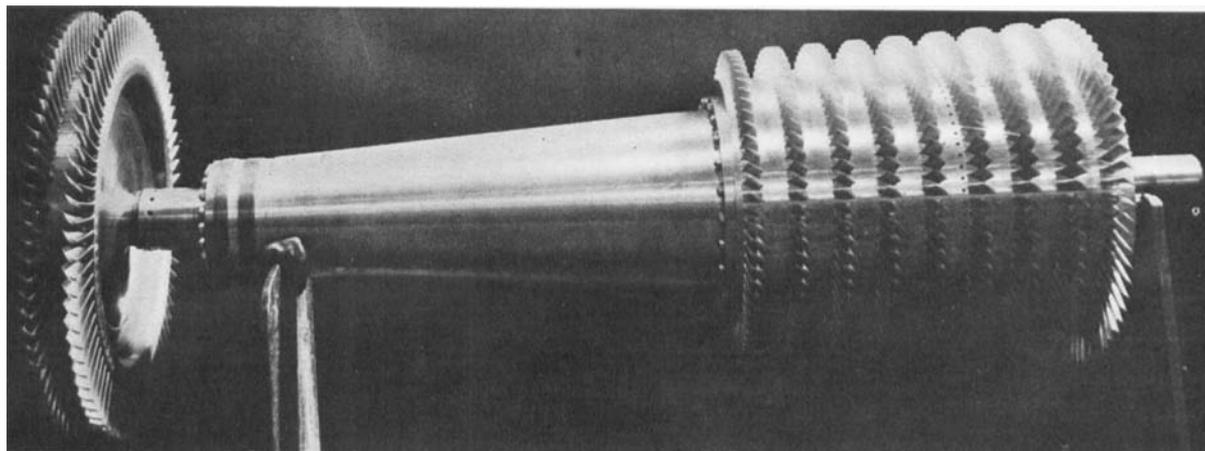


Fig. 55. Rotor of the Metropolitan-Vickers F2 Engine

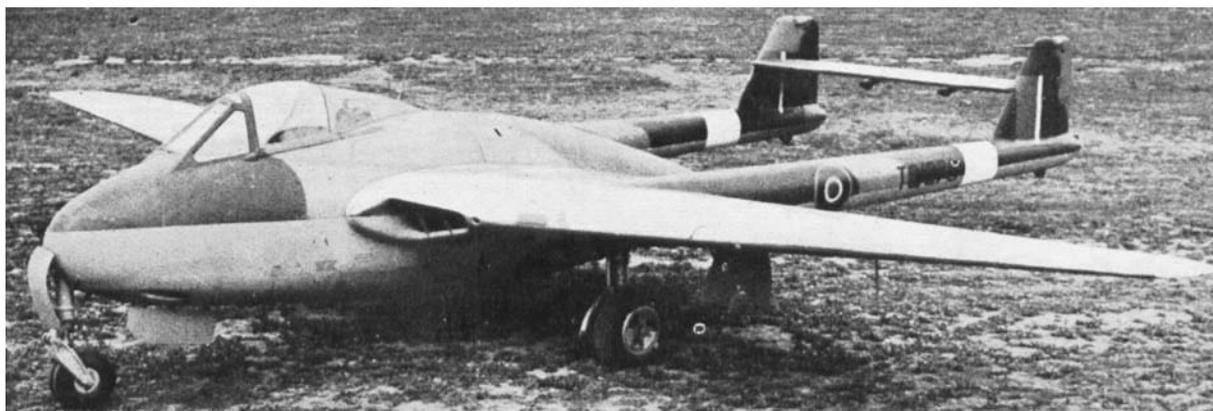


Fig. 56. De Havilland *Vampire* Jet-Propelled Interceptor Fighter with *Goblin* Engine

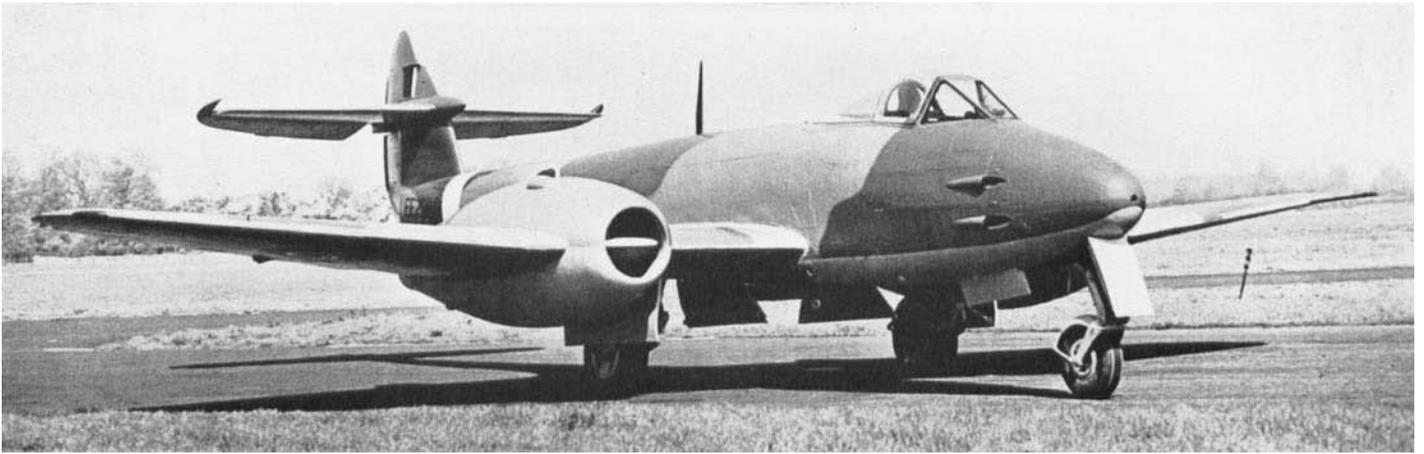


Fig. 57. R.A.F. Gloster *Meteor* Jet-Propelled Single-Seat Fighter
(M.A.P. Crown copyright reserved.)

Power unit: two *Welland* or *Derwent* engines; armour, four 20 mm. cannon in the nose. Span, 43 feet; length, 41 feet; height, 13 feet; wing area, 374 sq. ft.



Fig. 58. The R.A.F. Gloster *Meteor* Fighter in Flight
(M.A.P. Crown copyright reserved.)

ADDENDUM

Since the foregoing lecture went to press, details of several more recent types of turbo-jet engines and aircraft have been officially released for publication. Several of these were described in a subsequent lecture given before the Royal Institution, London, on 7th December 1945. Figs. 49-53, Plates 9 and 10, show views of the Power Jets W2/700 engine, the Rolls-Royce *Derwent I*, the Metropolitan-Vickers F2, and the de Havilland *Goblin*; while Figs. 54 and 55, Plate 11, illustrate typical rotors from centrifugal type (Power Jets W2/700) and axial type (Metropolitan-Vickers F2) turbo-jet engines respectively.

In these turbo-jet engines the jet velocities are of the order of 1,600 to over 2,000 ft. per sec., i.e. of the order of three times the forward speed of the aeroplane. The Froude efficiency corresponding to a 3/1 ratio is 50 per cent, so that the propulsive

efficiency is relatively poor, though at 600 m.p.h. the efficiency of the propeller is dropping to values little more than this. The efficiency of the engine as a heat engine for generating kinetic energy in a jet is about 34 per cent at heights where the temperature is very low, so that the absolute overall efficiency is of the order of 17 per cent.

Some more recent types of turbo-jet engined aircraft are illustrated in Figs. 56-58, Plates 11 and 12, which show the de Havilland *Vampire*, and the Gloster *Meteor III*. The former has its two air intakes in the leading edges of the wings. The *Meteor III* is fitted with Rolls-Royce *Derwent I* engines. The *Meteor IV*, which at present holds the world speed record of 606 m.p.h., has longer nacelles and is powered with two Rolls-Royce *Derwent V* engines. Another well-known single-engined interceptor is the Lockheed *Shooting Star*.