Development of the Rolls-Royce Merlin from 1939 to 1945

A Lecture Delivered by Mr. A. C. Lovesey to the de Havilland Aircraft Company Technical Department in November, 1945

SINCE the war ended a number of British and American technicians have visited Germany and nearly all come back with the same story —the story of that army of German scientists who have been working with super equipment— supersonic wind-tunnels, high altitude plants— long term planning of most fantastic projects— and one is almost persuaded that we must have been a lot of amateurs in this country!

But when I feel despondent I cast my mind back to a night I spent at a certain aerodrome watching the Mosquitos take-off and speed on their way to Berlin with their 4,000 lb. bombs to return a few hours later, bomb up again, refuel, change crews and take-off again on the second mission in one night. And so in the end we won the war, in spite of the Germans' technical achievements.

Think again of this Mosquito on its way to Berlin—surely there must be some story at the back of it. The story is, I think, the work of our technicians and scientists who proved to be more than a match for their German counterpart—in fact I would say second to none.

I think the Mosquito is a good example of the part played by development in this country.

Now, unfortunately, from the aircraft de- signer's point of view the aeroplane has to have some sort of engine and I hope you will find some interest in a brief outline of the development of this engine, i.e. the Merlin.

It is well known that a completely new design of piston engine takes nearly five years from the date of its inception until it can start quantity production, and, while new designs and projects must continually go on, the development of existing types is of paramount importance during the war and it was largely due to such develop- ment that we were able to maintain technical superiority and eventually numerical superiority over Germany. Probably the statement numerical superiority requires qualification. One of the most effective methods of reducing production is the introduction of radical design changes, but by properly co-ordinated development necessary design changes can be planned ahead and filtered into the normal production flow.
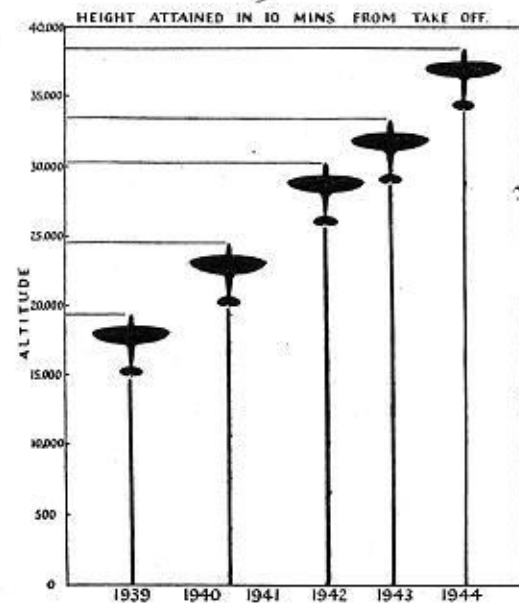

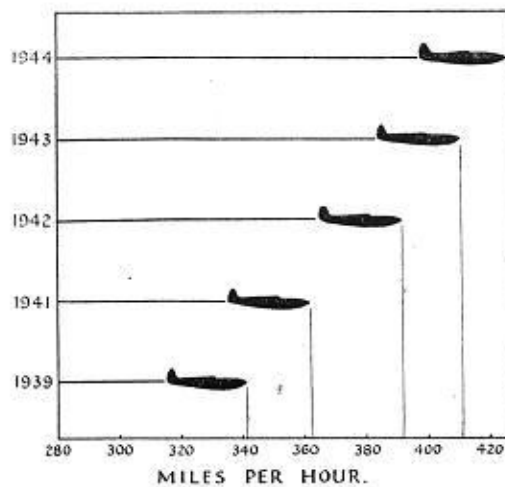Fig. 3.—Increase in rate of climb of Spitfire resulting from Merlin engine development

In the Rolls-Royce Company the principle of development is closely related to production, based on what we may term an "infiltration" technique; i.e. new features necessary for im- proved performance and mechanical reliability are introduced into production in digestible quantities so that after a period of time a com- pletely new Mark of engine is evolved without any break in production. The organization of the Rolls-Royce Group has been planned on this principle and the original Derby plant, which was not laid out for mass production, was always the first in the field with the new improvements and these eventually filtered out into the main pro- ducing plants after production difficulties had been overcome.

I think the best way to proceed with this talk is to take you on a quick excursion through the last six years of development on the Merlin engine, and then explain briefly the main develop- ment problems which have been tackled.

This development covered 52 different Marks of engines and you will see as we proceed that some very basic design changes were carried out without any major upheaval in the production programme.

Over this same period a total of 150,000 Merlin engines were produced, including those manu-

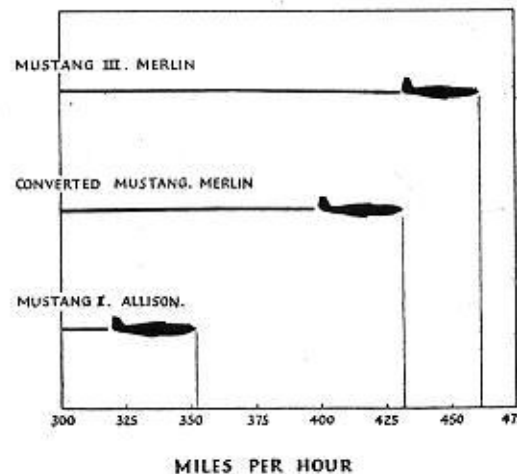Fig. 2.—Increase in speed of Spitfire mainly resulting from Merlin engine development

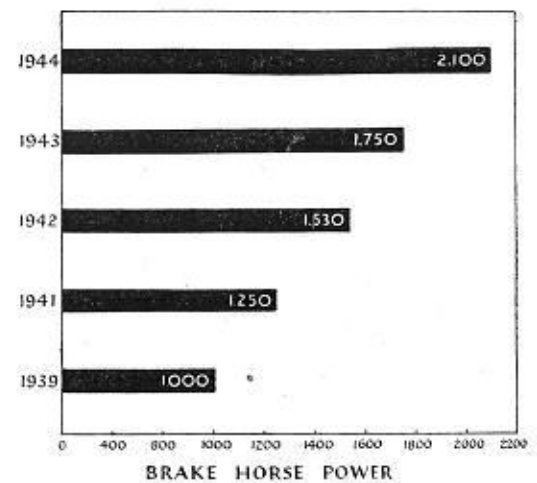Fig. 4.—Increase in speed of Mustang resulting from introduction of Merlin engine

Fig. 1.—Increase in brake horse-power of the Merlin engine

factured in the U.S.A. by the Packard Motor Company, but this total of 150,000 excludes those Merlin engines produced for United States Air Forces. The factories producing these engines were Rolls-Royce Derby, Crewe, Glasgow and the Ford Motor Company and Packards.

The first series of illustrations (numbers 1, 2, 3, 4 and 5) shows how the maximum power of the Merlin engine increased during the war period and the result of this upon aircraft performance.

A more detailed picture of this is given in illustrations numbers 6, 7, 8 and 9 which show how the rating of the Merlin engine was devel- oped to keep pace with the changing phases of the war.

Coming now to specific development items we can, for convenience, divide them into three general classes:

(a) Improvement of the supercharger.
(b) Improved fuels.
(c) Development of mechanical features to take care of the improvements afforded by (a) and (b).

Dealing with item (a) it can be stated that the supercharger determines the capacity, or in other words the output, of the engine. The impression still prevails that the static capacity known as the swept volume is the basis of comparison of the possible power output for different types of engine, but this is not the case because the output of the engine depends solely upon the mass of air it can be made to consume efficiently, and in this respect the supercharger plays the most important role. This principle applies equally to any engine but the engine has to be capable of dealing with
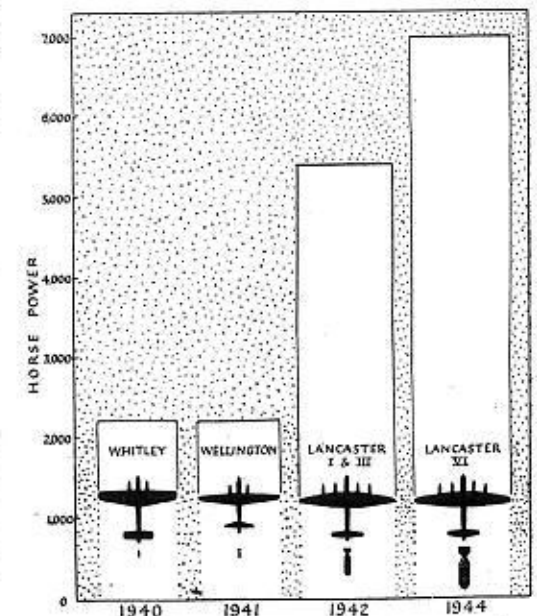

Fig. 5.—Merlin engine development for bomber aircraft with relative bomb loads which can be carried to Berlin
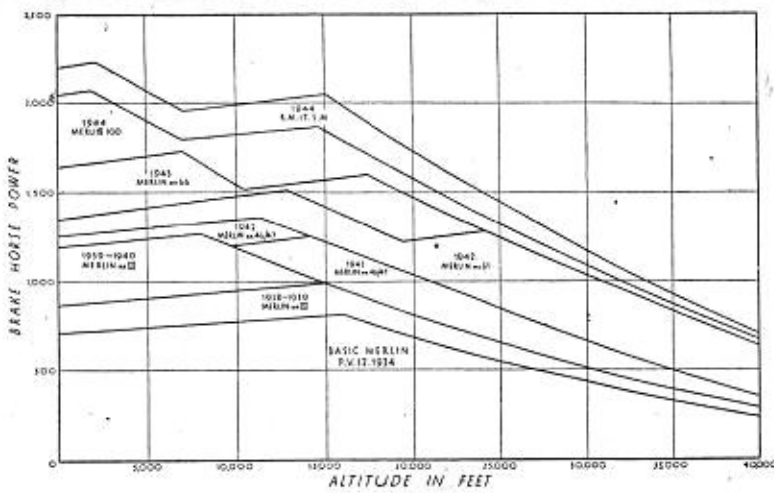
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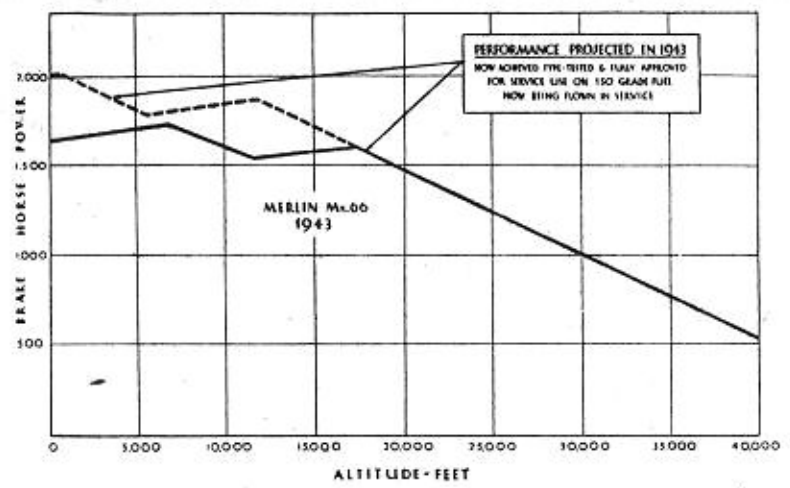Fig. 6.—Merlin power increase since the war began

Fig. 7.—Merlin Mk. II 66 development—engine performance projected and accomplished in 1943
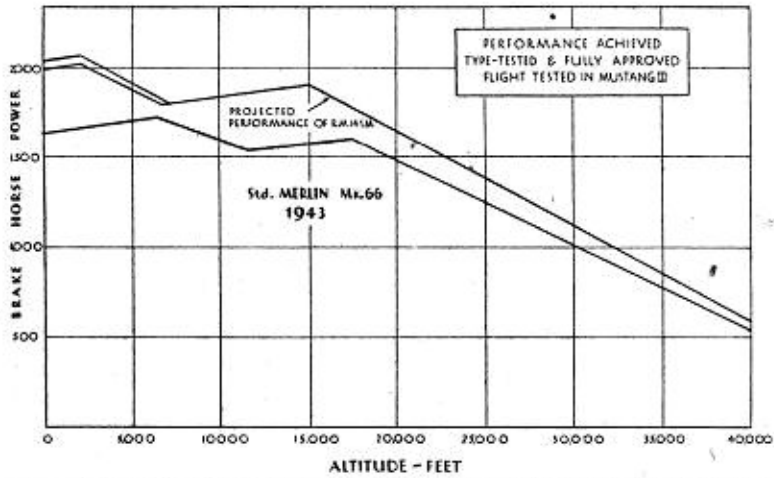

Fig. 8.—Merlin R.M.145.M. development—engine performance projected and achieved in 1943-44
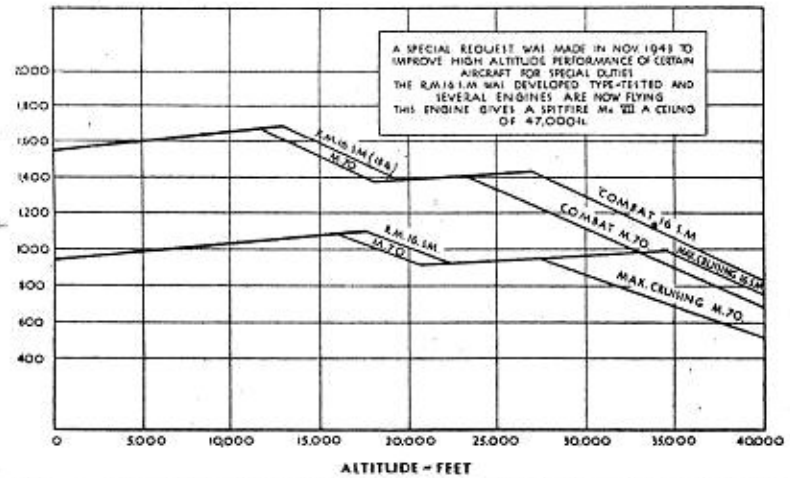

Fig. 9.—Merlin development to meet special high-altitude conditions

the greater mass flows with respect to cooling, freedom from detonation and capable of withstanding high gas and inertia loads (see illustration 10).

At this point I do not wish to make a case for the liquid-cooled engine, but in the case of fighter aircraft such as Mosquito, Spitfire and Mustang there is one thing I can say with complete confidence and that is that had the Merlin started this war as an air-cooled engine, the performance increase which I have shown you would not have been possible.

During the course of research and development on superchargers it became apparent to us that any further increase in the altitude perform-

Fig. 10.—Diagram showing saving in size and weight achieved by adoption of two-stage supercharger and intercooler

ance of the Merlin engine necessitated the employment of a two-stage supercharger. It is an easy matter to increase the compression ratio of the supercharger, in other words the boost pressure obtained at altitude, but naturally in order to get more horsepower out of the engine this has to be done efficiently in order to avoid wasted power in driving the blower and excessive temperature of the charge for the compression ratio obtained. It would appear that the useful limit of compression ratio for the single stage supercharger is about 4 : 1 and for compression ratios beyond this it is necessary to go to two stages. This is shown up clearly in illustration number 11.

I should point out that before the decision was made to adopt a two-stage mechanically drive blower, full consideration was given to the application of exhaust turbos and extensive analysis was made of this project. While it was attractive in respect of giving lower specific fuel consumptions under cruising conditions it had very little advantage in maximum power performance, particularly when one considers that with a turbo system we should lose practically the whole of our ejector exhaust effect which we know to be quite efficient at high speeds. This, of course, only holds good when we use simple ejector exhaust manifolds. The exhaust turbo system had a lot of disadvantages in respect of the installation in a fighter aircraft like the Spitfire. It came out heavier than the mechanically driven supercharger and the drag was estimated to be higher due to various cooling ducts supplied for the turbine. The system of control of the turbo blower was also a difficult one. It was quite evident that with regard to the Spitfire, which was the aeroplane under consideration at that time, the job of improving its performance could be done much better by means of a mechanically driven two-stage blower.
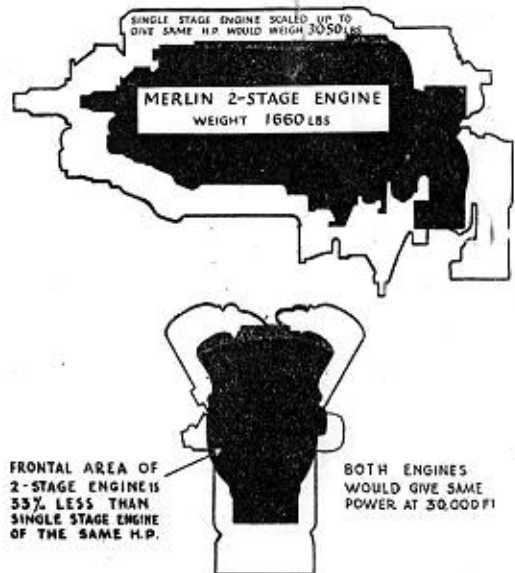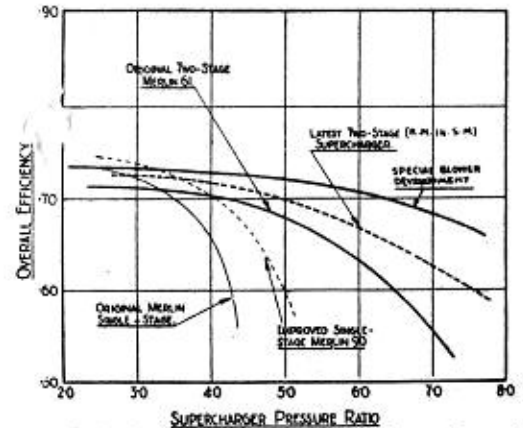
The basic development for the two-stage

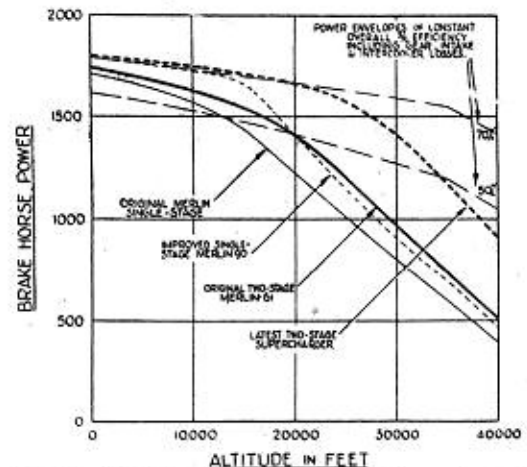Fig. 11.—Relation between compression ratio and overall adiabatic efficiency for single and two stage Merlin superchargers

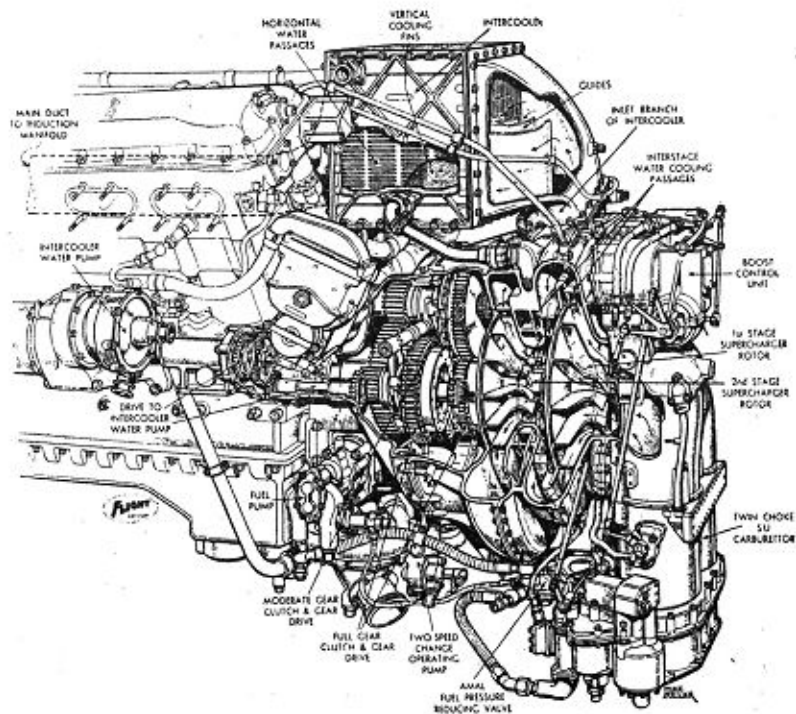Fig. 12.—Full throttle power of Merlin engines at altitude

Fig. 13.—Cut away of two-speed, two-stage supercharger. (*Courtesy Flight*)

blower was carried out on the supercharger rig which could accommodate two test blowers simultaneously. For the first stage we used a modified Vulture engine blower and for the second stage a Merlin 46 blower. On the supercharger rig the outlet from the Vulture blower was coupled up to the inlet of the Merlin 46 blower and the rig could operate the blower at different speeds if necessary. The performance characteristics of each blower were taken when running in combination and from these results all the necessary data was obtained with regard to matching the two stages so that the design of the two-stage unit could be commenced.

The two-stage blower was constructed and was subjected to development on the rig and when applied to the engine the results obtained were as shown in illustration number 12. The gain in engine power at 30,000 ft. with the two-stage supercharger was 300 h.p. compared with the Merlin 46, or a gain of nearly 50 per cent of power. (Merlin 61, 1,020 h.p. at 30,000 ft.;

Merlin 46, 720 h.p. at 30,000 ft.)

The result in the all-round performance of the Spitfire was considerable. At 30,000 ft. the speed of the Spitfire IX was 70 m.p.h. faster than the Spitfire V with the Merlin 46. This may be somewhat of an unfair comparison because the Spitfire V was nearing its ceiling at 30,000 ft., but comparing both aircraft at their respective full throttle heights the Spitfire IX with the Merlin 61 was some 40 m.p.h. faster than the Spitfire V.

The next problem to tackle was intercooling. The charge temperature rise relative to the intake was 205 deg. C. at maximum revs. in the F.S. gear and it was necessary to reduce the temperature in order to get an increased density of the charge and avoid detonation. Both air-cooled and liquid-cooled intercoolers were investigated and flight tested, but it became evident from the data obtained that the water cooled type was most suited to our particular design of two-stage supercharger. In a single seat fighter it was practically impossible to use an air-cooled intercooler in

the space available, and the air ducting involved in this form of intercooler was a serious limitation to the pilot's view. Having decided on a liquid-cooled intercooler a considerable amount of both engine and rig work was carried out in order to arrive at the most suitable matrix to give the maximum heat dissipation without an undue pressure loss in the induction system. Following on this a lot of endurance testing was necessary to prove out the mechanical reliability of the system. Illustrations 13 and 14 show the arrangement of the intercooler system of the Merlin engine.

In practice we find that about 40 per cent intercooling gives about the best overall results. Naturally, the more intercooling we get, or the lower the charge temperature, the more power the engine gives; but this has to be balanced up against increase of drag as the intercooler radiator becomes larger. Generally it is found that there is a rapid gain in performance up to about 35 per cent intercooling, but after this the gain is less rapid. I should explain that for convenience we express intercooling as a percentage of the temperature rise taken out by the intercooler.

The blower development I have outlined brought us up to the time of the introduction of the Merlin 61 and, with regard to aircraft performance, gave a very marked improvement over the previous single stage engines. Illustration 15 shows the improvement in performance of a bomber aircraft due to the fitting of two-stage engines.

We were now able to build up a lot of flight experience and we could see that there were great possibilities of obtaining further improvements with two-stage superchargers. One thing was very evident—that in order to obtain any appreciable improvement in compression ratio we should have to get rid of the entry losses caused by the carburetter. We had about reached the limit of carburetter size consistent with satisfactory metering and were forced to look for alternative methods of supplying fuel to the engine in the correct proportions.

As a result of our study of factors affecting the performance of a supercharged engine we were able to derive the laws covering the mass flow of air through the engine. It therefore became apparent that if we could control the fuel flow by these various factors to give the same relationship we should have an ideal fuel metering system.
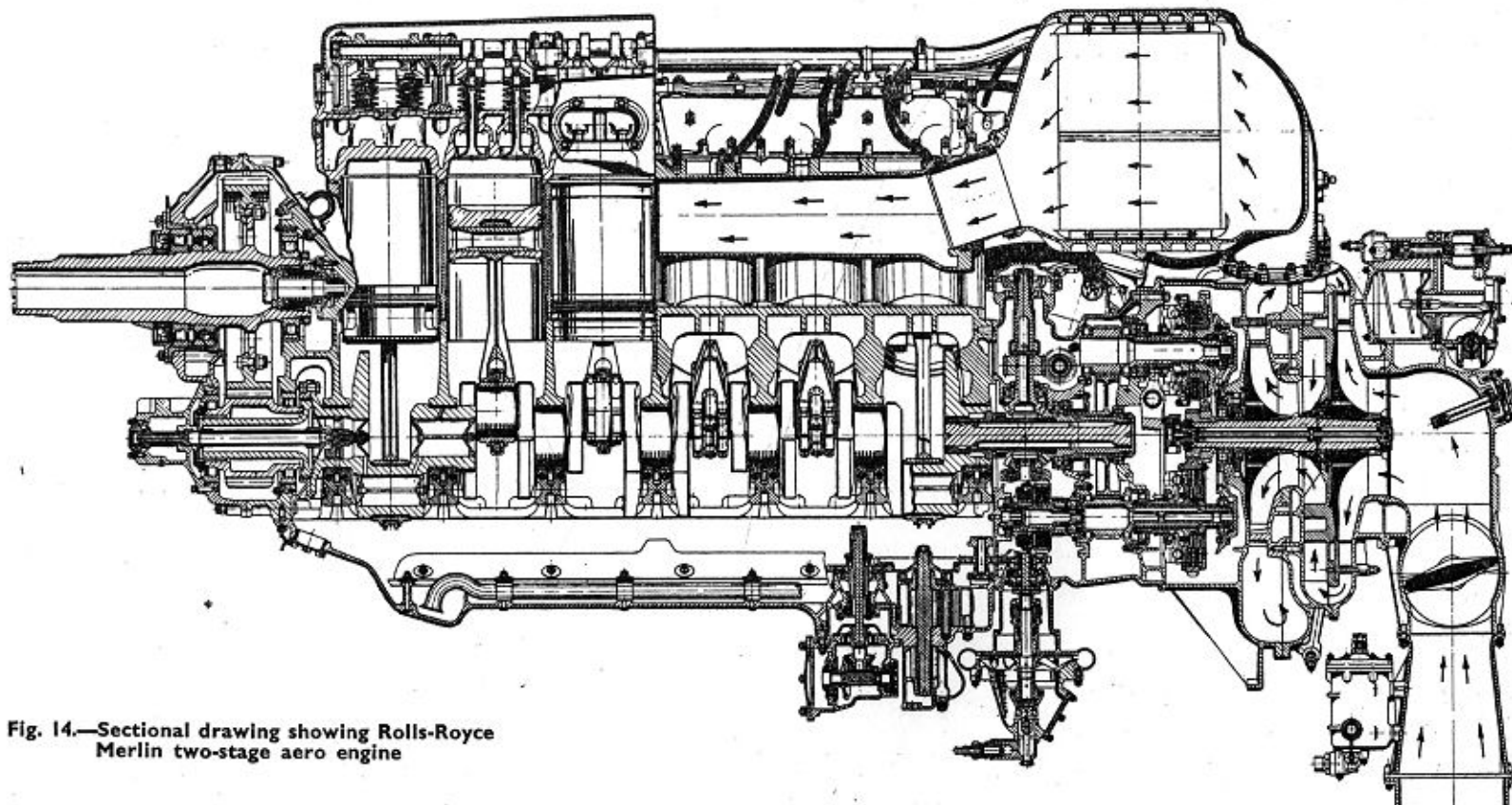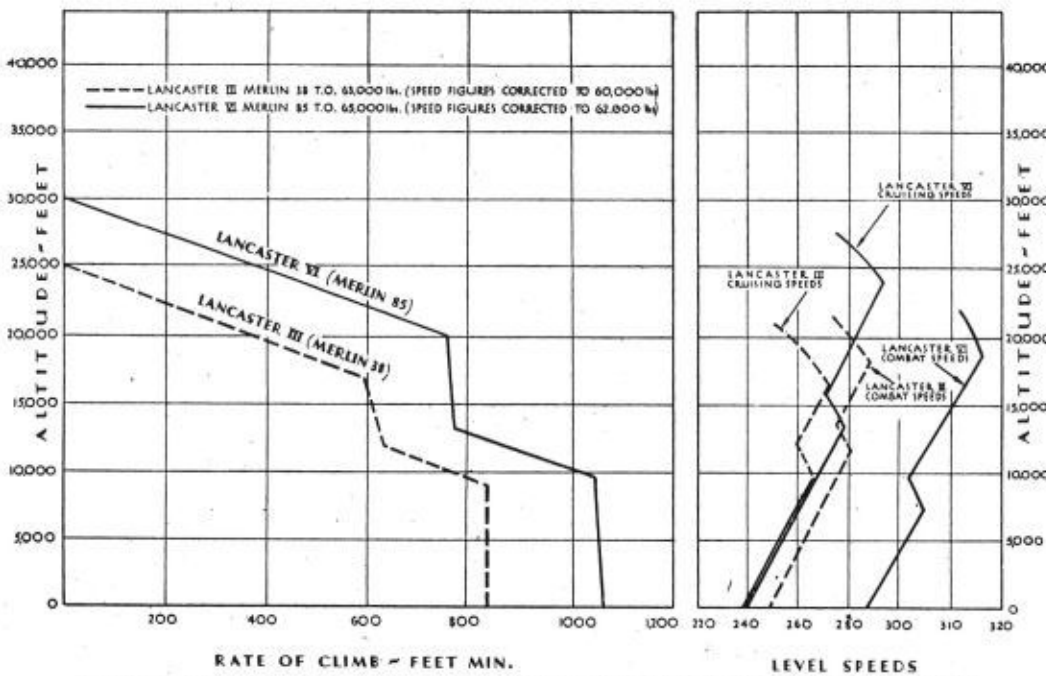

Fig. 14.—Sectional drawing showing Rolls-Royce Merlin two-stage aero engine

Fig. 15.—Improvement in bomber aircraft since July, 1943, due to fitting Merlin M.85's
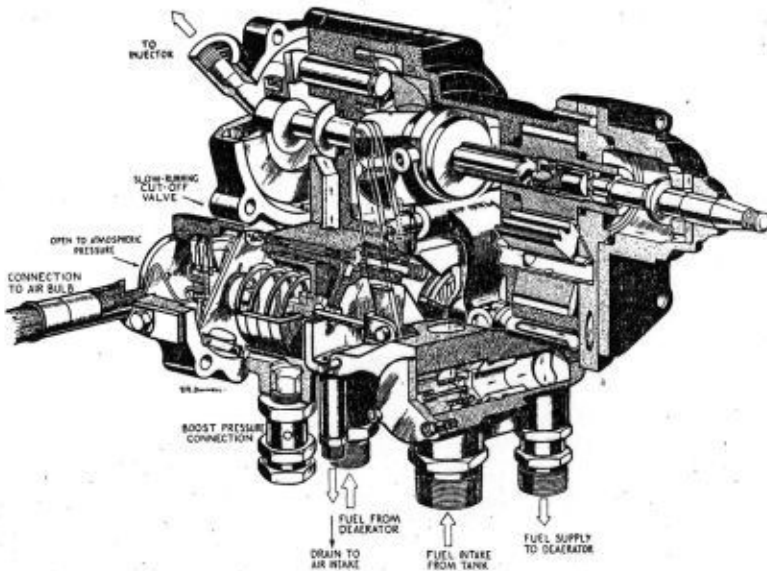(two-stage engines)

Fig. 17.—All-metal capsule control unit

Fig. 16.—S. U. injection pump

Fig. 18.—Layout of S. U. injection pump on Merlin engine

Now the principal factors affecting the charge flow are engine r.p.m., boost pressure, boost temperature and exhaust back pressure and this can be expressed by the formula:

$$W_e = K.N. \ \frac{P_e - \frac{1}{6}P_e}{T_e}$$ where W_e is in lb./min. and $K = \cdot 422$ for Merlin.

For the metering device we therefore wanted a pump driven at some ratio of the engine speed in which the stroke was proportional to the boost pressure minus one-sixth of the exhaust back pressure divided by the charge temperature.

A variable stroke pump of suitable type already existed in an experimental form produced by the S.U. Carburetter Company. It now remained to develop the control mechanism in which the stroke was controlled by boost pressure, atmospheric pressure and charge temperature. You will note that I have stated atmospheric pressure instead of exhaust back pressure, but with open exhaust pipes this is a near enough approximation. Illustration 16 shows the general arrangement of this pump which briefly consists of five plungers operated by a swashplate, the stroke of which can be varied by axial movement of an inclined shaft. This movement is produced by engine oil pressure operating a servo piston and the oil pressure is regulated by a small spill valve. This spill valve is in turn controlled by a stack of capsules responding to changes of boost pressure,

boost temperature and atmospheric pressure (Illustration 17). The complete metering pump has a built-in petrol pump supplied for the purpose of charging the plunger pump which does the metering. The pump can be driven in any convenient position on the engine and the metered fuel can be injected anywhere in the induction system (Illustration 18). Actually we selected the eye of the supercharger as in this position we gained about 7 per cent improvement in compression ratio of the blower due to the temperature drop from fuel evaporation.
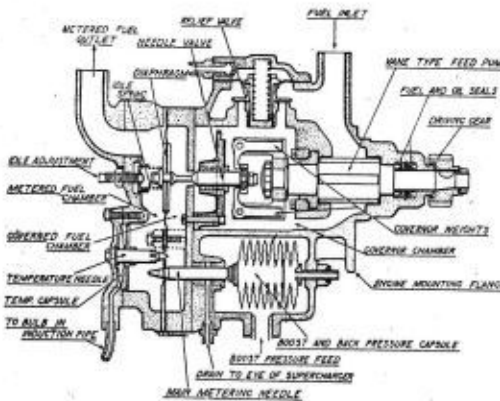

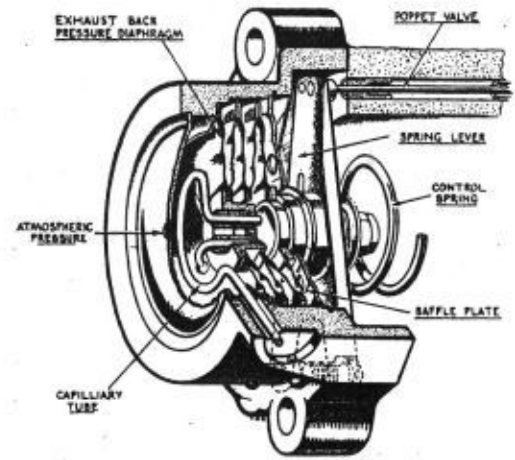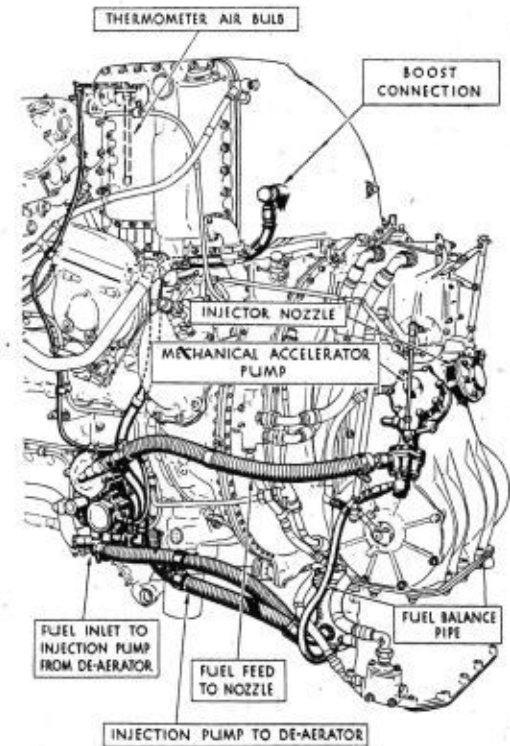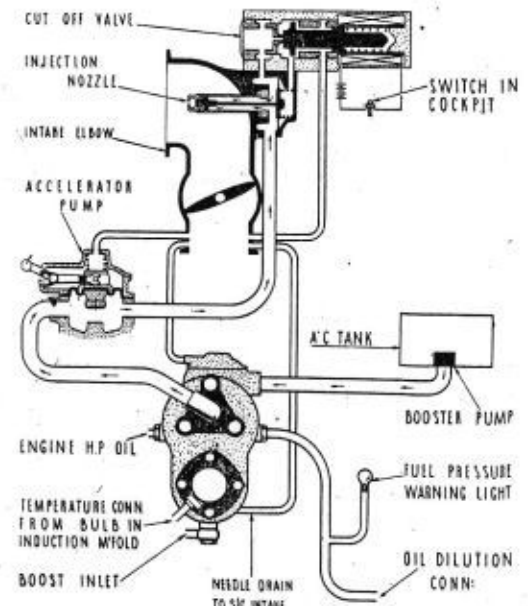Fig. 20.—Diagram of Rolls-Royce governor-controlled injection pump

Fig. 19.—Diagram of injection-pump system

In accordance with our policy of having an alternative insurance item we developed in parallel a centrifugal injection pump which actually does just the same job (Illustrations 19 and 20). In this pump we used centrifugal weights operating a poppet valve balanced against a diaphragm. Increase in speed tends to open the poppet valve and allow the pressure to build up on the other side of the valve. This pressure in turn reacts on the diaphragm with the result that the pressure in the chamber after the poppet valve increases proportionally to the square of the speed. For a given position of the main metering needle and the temperature metering needle, the flow through this orifice is proportional to the square root of the pressure; therefore, we get a flow from the outlet proportional to speed. The stack of capsules attached to the main metering needle regulates the fuel flow in correct proportion to the boost pressure and atmospheric pressure, while the small temperature needle corrects the flow for charge temperature (Illustration 17).

Returning now to superchargers; with either of the metering pumps I have described we are at last able to eliminate the major source of pressure loss at the inlet and without any other change to the blower this represents maintaining the boost pressure for another 2,000 feet in altitude (Illustration 21). We now carried out a number of changes to the blower. Further improvements were made to the shape of the intake elbow, the supercharger rotors were increased in diameter, diffusers were modified, pressure loss between the first and second stages was considerably reduced with the result that we were able to obtain a compression ratio of 7·2 at 30,000 ft. with an overall efficiency of 62 per cent which on the Merlin represents at 30,000 ft. an increase in horsepower of 400 b.h.p. compared with our first two-stage engine (Illustrations 22 and 11). Since these curves were drawn further improvements have been made which increase the efficiency to 65 per cent at a C.R. of 8·2.

Improved Fuels

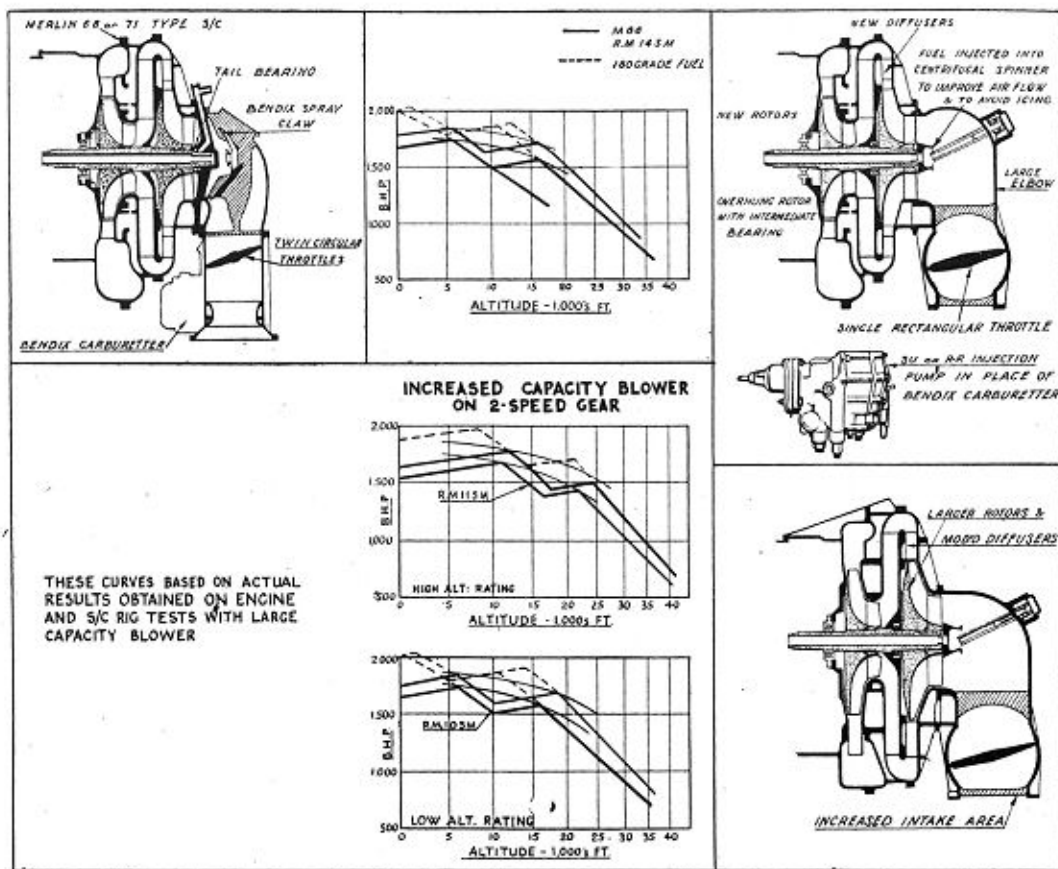The development steps I have outlined looked after the performance at high altitudes, but at the same time there was a great demand for improved performance at low altitude. Now the chief limitation (apart from mechanical ones) was detonation at high boost pressures. We had plenty of boost pressure in the Merlin engine available at low altitude but with 100 octane fuel we were limited to a safe boost pressure of about 20 lb./sq. in. At this boost pressure we could get about 1,850 h.p. in the M.S. gear (Illustration 23).

Fig. 21.—Increased performance of Merlin two-stage engine

Fig. 22 (left). — Large capacity blower and three-speed gear

Fig. 23 (right). — Effect of fuel on maximum power as limited by detonation

Obviously better fuels were required. In order to stimulate interest we proceeded to carry out overload tests on the Merlin with fuels containing higher percentages of T.E.L. which were mixed by ourselves. All this was done in order to demonstrate both on the test bed and in flight the improvement in performance which could be obtained if we had better fuels, also that the engine was capable of dealing with these higher ratings under combat conditions. The first tests were run with 100 octane fuel plus an additional 6¼ cc. T.E.L./gallon, bringing the total lead content up to 11¼ cc., and with this we were able to carry 25 lb. boost with a safe margin from detonation. This increased the rating of the engine up to 2,050 horsepower, which in turn increased the performance of the Spitfire at sea level by about 30 miles/hour and brought up the speed of the Mustang P.51B to over 400 miles/hour at sea level.

It was obvious that a fuel containing such a high percentage of T.E.L. would not be a practical proposition for service use due to lead fouling difficulties encountered under low power cruising conditions. Some single cylinder work was carried out at the R.A.E. under Mr. Thompson who had found that the addition of 2½ per cent mono methyl aniline to 100 octane fuel increased its knock rating considerably. Supplies of this fuel were made up for a full scale engine test on the Merlin and main engine test results more than confirmed the R.A.E. tests. At this time there was no production of this M.M.A. either in this country or in America and, imme-
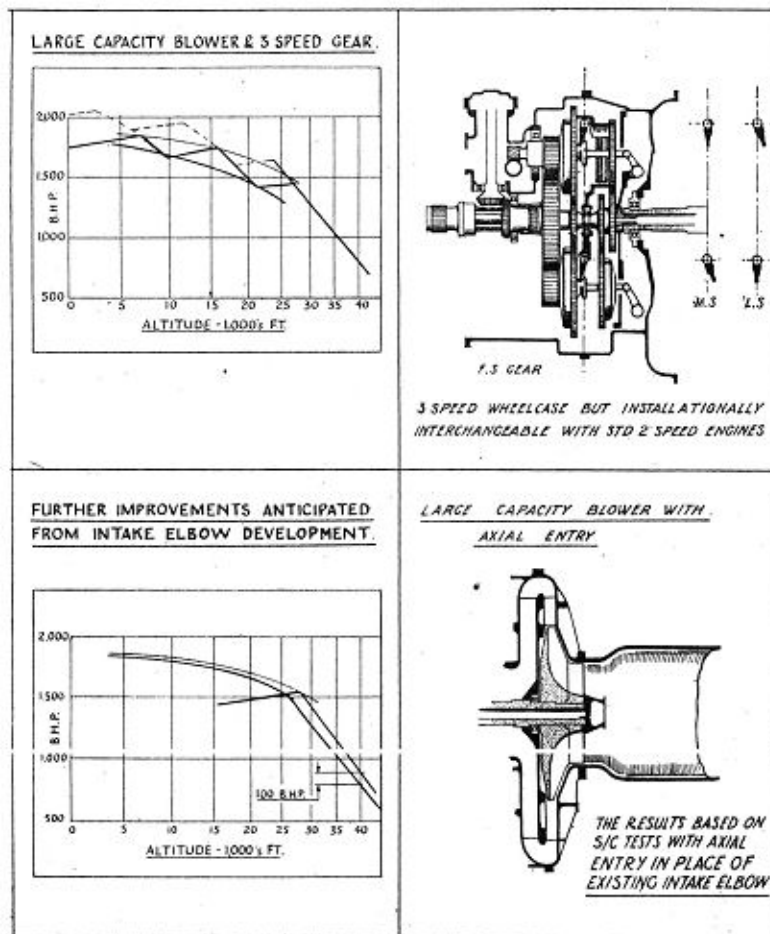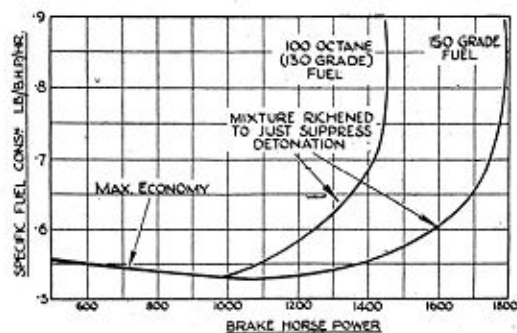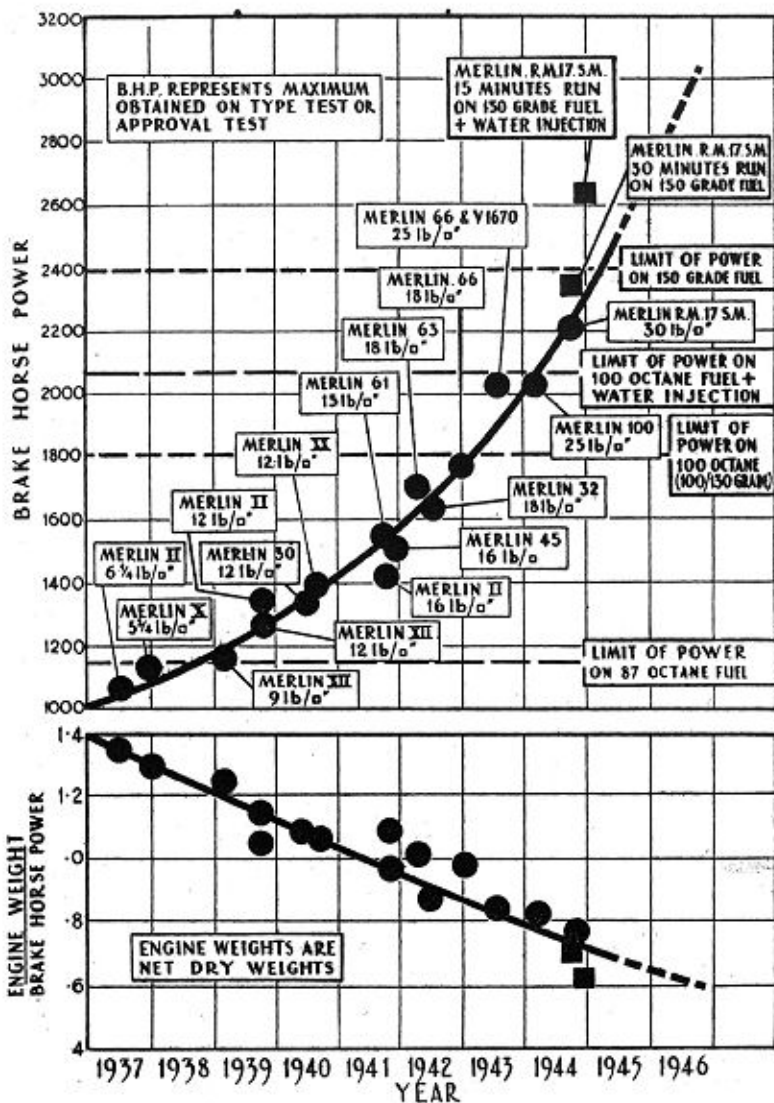
Fig. 24.—Rolls-Royce Merlin—progressive improvement in power and weight/power ratio with time

Fig. 25.—Spitfire performance projected and achieved by Merlin Mk. 66 engine development in 1943

Fig. 27.—Endurance at 3,000 r.p.m. with 18 lb./sq. in., or higher, boost —cumulative total for all experimental and development Merlin engines

Fig. 26.—Improved performance of Mustang III with Merlin R.M.14 S.M. (Mk. 100)

diately its value was realized, steps were taken to produce sufficient supplies in this country to cater for the whole fuel consumption of Fighter Command. By the time of the introduction of this fuel into the R.A.F., the whole range of Merlin engines were approved to operate at higher boost pressures on this fuel.

The first operational use of this fuel was against the flying bombs in the middle of 1944. Subsequently the whole of A.D.G.B. was put on to this fuel. Later it was used by the Second Tactical Air Force during and after the invasion of the Continent. The Americans promptly followed suit and used this British produced fuel in their escort fighters of all kinds.

The top curve of illustration 24 shows the progressive improvements in power of the Merlin engine over the years of war. The circles show the date on which the type test proved the various ratings. You will see we have drawn a line at 1,800 h.p. which represents a practical maximum power free from detonation on the Merlin engine on 100 octane fuel. The line at 2,050 h.p. represents about the best which can be done with 100 octane fuel plus water injection. The line at 2,400 h.p. represents the limit on 150 grade fuel.

Short endurance tests were carried out nearly a year ago using 150 grade fuel plus water injection and a power of 2,640 b.h.p. was obtained from the Merlin engine at 36 lb. boost. (B.M.E.P. 404 lb./sq. in. I.M.E.P. 535 lb./sq. in.)

It is only reasonable to expect that appreciable mechanical changes had to be made to the Merlin engine from time to time to take care of this power increase. Practically the whole of the engine has changed over this period, including the strengthening up of the crankcase, pistons, connecting rods, cylinders, etc., but it is interesting to refer to the curves shown in the bottom curve of illustration 24. Here we see that in spite of the general strengthening up of the engine, which, of course, involves the addition of weight, the curve shows a steady improvement in the specific weight.

At the time illustrations 25 and 26 were drawn we were still in the midst of war and we could see the possibility of still keeping alive and improving the performance of the Merlin engined fighter aircraft. Since that time, however, the picture has changed for two reasons—the advent of the
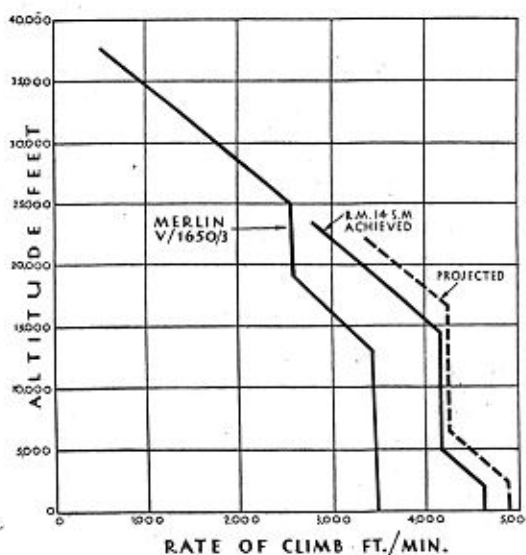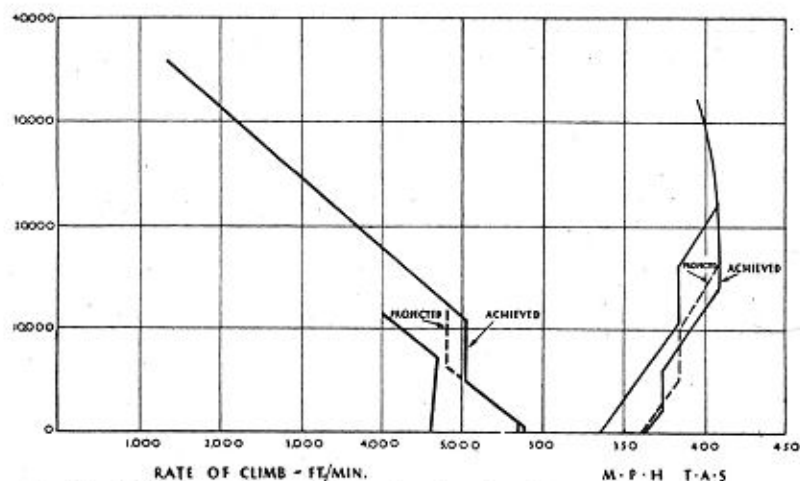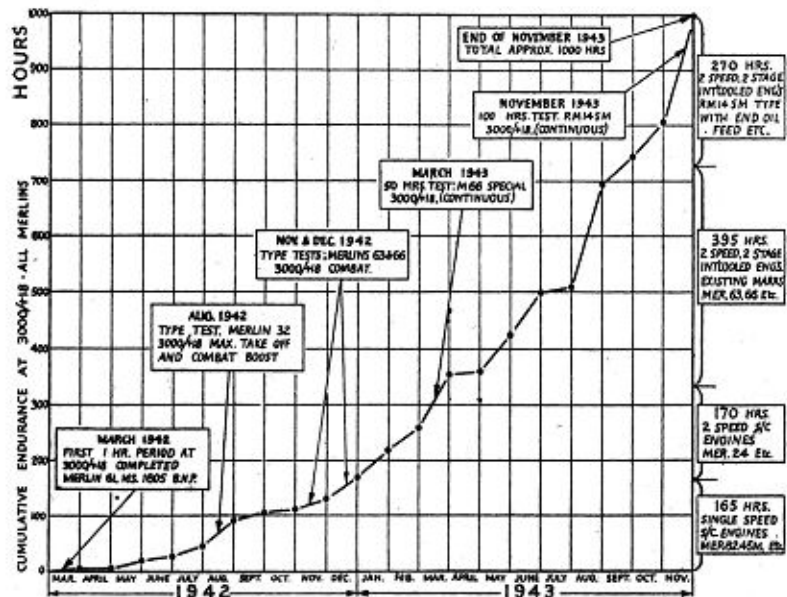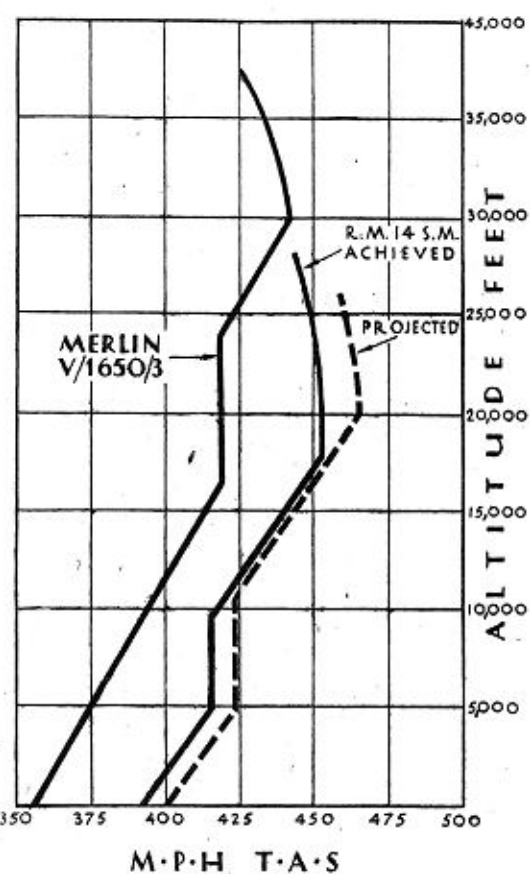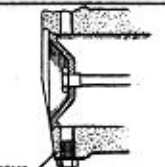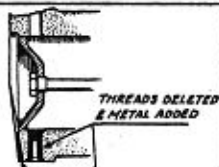
LIMITATIONS OF STANDARD COMPONENTS.		EXPERIENCE OF IMPROVED PERFORMANCE.	
MAIN BEARING PANEL FAILURE	FAILURE OF CRANKCASES IN MAIN BEARING PANELS AFTER ENDURANCE SHOWN TESTS (1)-(2) 27¾ Hrs. (3) 21½ · (4)-(6) 79¾ · STANDARD CRANKCASE	DEEPER BOSSES AND STUDS / STRENGTHENED MAIN BEARING CAPS	NO FAILURES CRANKCASES SERVICEABLE AFTER:- TESTS (7)-(13) 148 Hrs. (CONVENTIONAL OIL FEED) TESTS (14) 87½ Hrs. (15) 100 · (END FEED OIL FEED) STRENGTHENED CRANKCASE
OIL GROOVES AND HOLES TO FEED CONN. ROD BEARINGS.	REJECTED FOR EXCESSIVE WEAR AFTER:- TESTS (4)-(6) 79¾ Hrs. STANDARD MAIN BEARINGS	OIL GROOVES AND HOLES DELETED WITH END FEED	NO WEAR MEASUREABLE AFTER:- TESTS (14) 87½ Hrs. (15) 100 · STRENGTHENED MAIN BEARINGS.
CRACK	BROKEN THROUGH No.4 CRANKPIN BY FATIGUE CRACK STARTING FROM THREADS. TEST (14) 87½ Hrs. END OIL FEED CRANKSFT. FIRST DESIGN	THREADS DELETED & METAL ADDED	NO FAILURE: CRANKSHAFT SERVICEABLE AFTER:- TEST (15) 100 Hrs. END OIL FEED CRANKSFT. STRENGTHENED.
3 NARROW GAS RINGS / 2 SCRAPER RINGS.	SOME RING GUMMING AFTER:- TEST (1) 9¾ Hrs. (2) 7½ · (3) 21½ · (5) 20 · (6) ·50 · STANDARD PISTONS	DEEP TOP LAND / 3 STANDARD GAS RINGS / TOP SCRAPER RING DELETED	NO RING GUMMING: PISTONS IN GOOD CONDITION AFTER:- TEST (14) 87½ Hrs. (15) 100 Hrs. DEEP TOP LAND PISTONS

Fig. 28.—Development of R.M.14 S.M. mechanical features for improved reliability and increased rating

jet propelled fighter and the ending of the war.

Instead of trying to follow along this curve we have reluctantly called a halt to power development beyond what we have shown and the development on the Merlin is taking the course of long-term reliability under commercial operating conditions.

Development of Mechanical Features to Take Care of Increased Power

It was realized that the normal service type test, far from being a good proof of the reliability of the engine at its particular rating, was not sufficiently arduous to reveal quickly the mechanical limitations at the projected increased ratings. Therefore a basic overload test was adopted, first with the object of finding the mechanical weaknesses of existing Marks of engines and secondly with the object of arriving at a specification which would satisfactorily pass this test. The overload test was to consist of 100 hours endurance at 3,000 r.p.m. and 18 lb. boost pressure and our object was to complete this test without any adjustment or replacements.

We started this overload testing with a standard production Merlin 66 but failed due to cracks in the crankcase after 27 hours. Just to make sure that this was not a rogue failure we put another engine up for a similar test but again failed the crankcase after about the same running time. This led to some strain gauge investigation of the crankcase on a rig and as a result of the information obtained a modified design was put in hand.

In order not to hold up the work we continued our testing by replacing the failed parts and continued the endurance running on the serviceable features until such time as modified designs were available for testing.

To cut a long story short we completed a total of 1,000 hours running under these conditions on various experimental engines before eventually achieving our target of 100 hours on an engine which completed the test in a very satisfactory condition (see illustration 27). By this time the engine had reached what we call the Mark 100 specification. The test was completed successfully in six days and the engine ran perfectly throughout. There were no involuntary stops and the usual routine maintenance was omitted entirely, even the valve, plugs and tappets being untouched throughout the whole of the test. The only incident was the change of one magneto after 50 hours, due to a defect revealed by the single ignition check. The condition of the engine when stripped was excellent. The engine was then rebuilt without any replacement parts being fitted and given 100 hours' endurance testing in a Spitfire.

The illustrations 28, 29 and 30 show some of the problems encountered during this overload development. The second design change shown on the list calls for a little explanation. The normal system of lubrication of the bearings consists of admitting oil to each journal bearing and by means of suitable drilling and grooving the oil is induced into the journal and flows under pressure to the big-end bearings, assisted by the centrifugal force of the column of oil in the crankshaft. The inherent disadvantages of this system are that as wear takes place there is an increased leakage of oil from the journals with less oil supply to the big-ends. As oil has to be forced into the crankshaft against the C.F. pressure it gives a reduction in lubrication to the big-ends with increased rotational speed. This, of course, is all wrong as we should like an increase of oil flow with increase of r.p.m. The limit of life on bearings is the time when the journal clearances have increased to the extent that the big-ends get insufficient oil, although the journal bearings can run on quite satisfactorily with the increased clearance.

In order to overcome this defect we introduced what we called the end-to-end oil feed system (see

CRANKCASE and MAIN BEARINGS

FRONT OIL FEED FROM RELIEF VALVE.

① ② ③ ④ ⑤ ⑥ ⑦

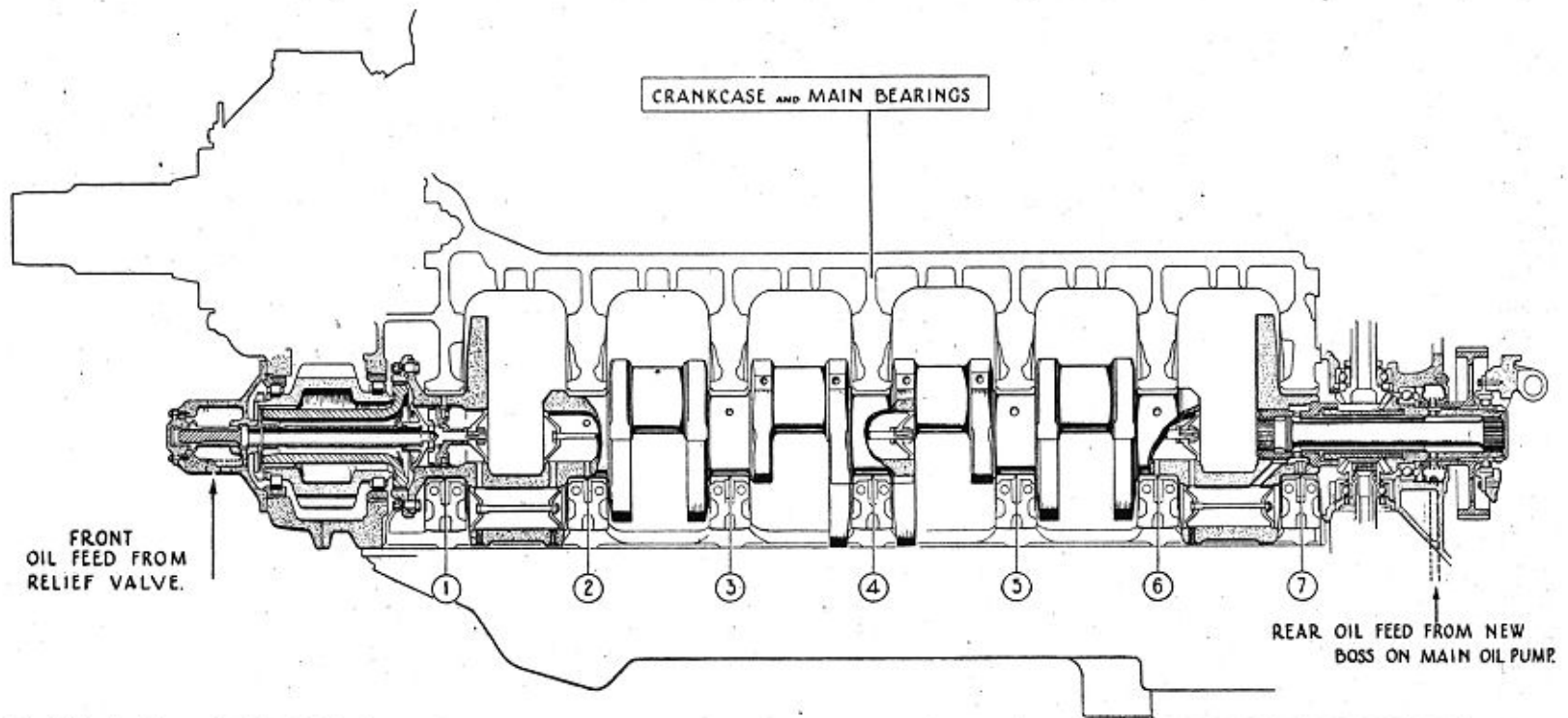REAR OIL FEED FROM NEW BOSS ON MAIN OIL PUMP.

Fig. 29.—End-to-end oil feed, Merlin crankshaft

illustration 29) in which we admit oil to the crankshaft at each end and it is fed out into both journal and big-end bearings by pressure and C.F. force. This possesses several additional advantages. It makes possible the correct proportioning of oil between the journal and big-end bearings which cannot be done with the previous system. It permits a reduction in total oil flow because with the old system excess oil was given to the journal bearings in order to provide enough for the big-end bearings. It gives excellent centrifusion and cleaning of the oil, and it permits deletion of grooves and holes in the journal bearings, thereby very considerably increasing their load carrying capacity.

We fell into a nasty trap with regard to reducing the oil flow and found that although bearing lubrication was excellent we ran into trouble with piston ring gumming.

Piston temperature measurements showed that a reduction in oil flow appreciably raised the piston temperature which explained the reason for ring gumming. We overcame this trouble by the simple device of putting some "flats" on the oil hole drillings of the journals and so permitted an increased oil discharge. A more logical way of looking after the piston rings is to introduce oil jets under the pistons fed by a separate gallery pipe and economize on the oil spilt out from the bearings. This system is under test and has proved most effective, giving a reduction in piston temperature of as much as 90 deg. C.

Another item which has given rise to a lot of trouble under civil operating conditions is the burning of exhaust valves due to the high lead content in the fuel. We have carried out a considerable amount of work on this problem, and I am pleased to say that after a long struggle we appear to have arrived at the answer.

Illustration number 31 shows the new features embodied in the Merlin 100 engine.
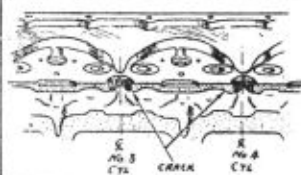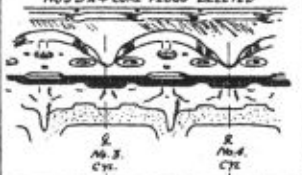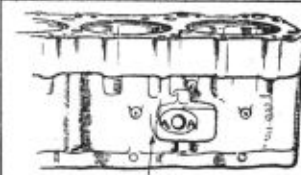
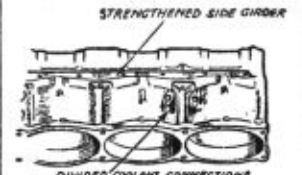As you all probably know, the present 100

Fig. 30.—Development of R.M.14 S.M. mechanical features for improved reliability and increased rating

octane fuel contains $5\frac{1}{2}$ ccs. of T.E.L. per gallon together with an amount of ethylene dibromide in the form of an inhibitor. The object of the inhibitor is to convert the products of combustion of the T.E.L. from non-volatile lead oxides to volatile lead bromides which pass out with the exhaust gases.

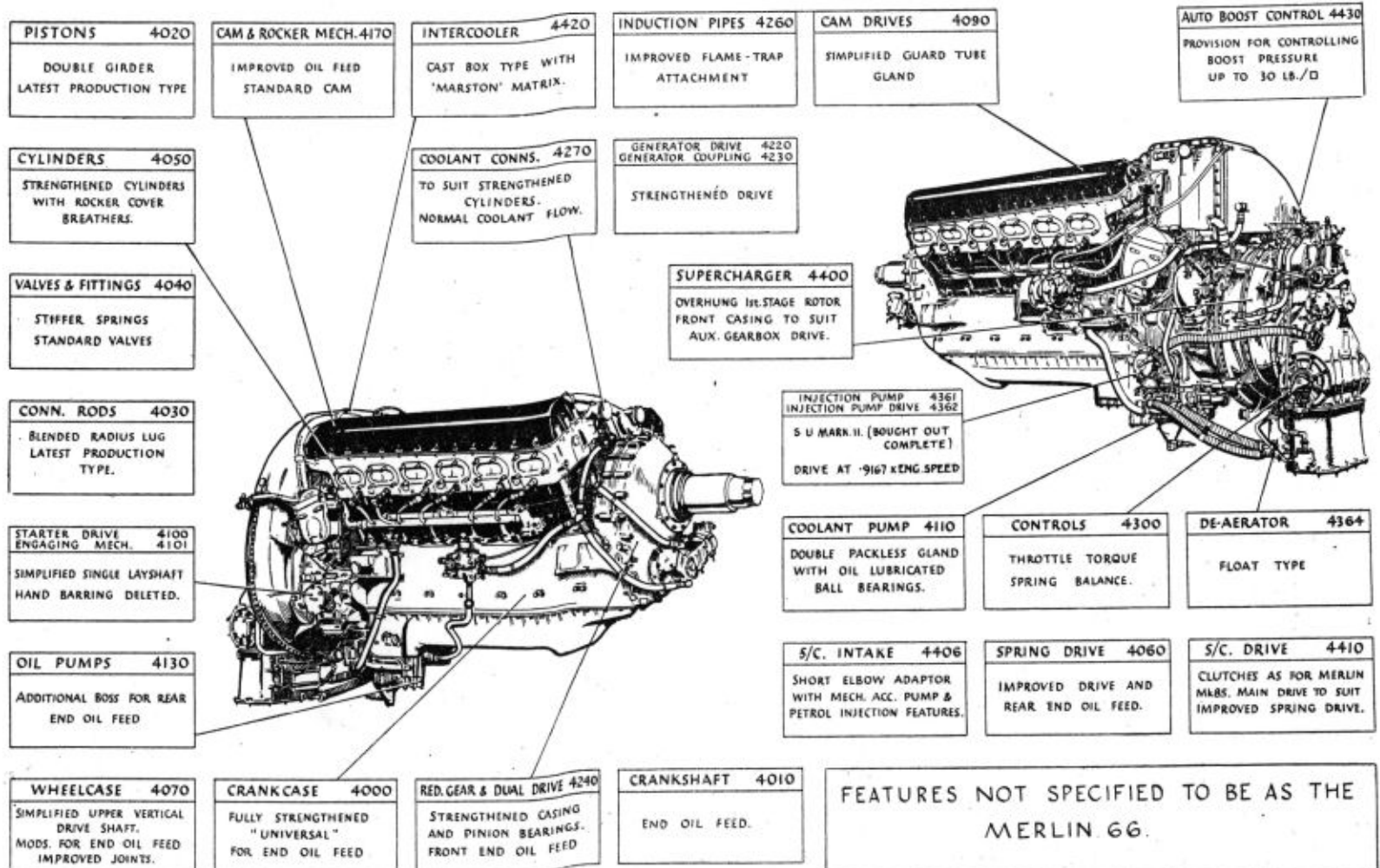The difficulty arises, however, under low tem-

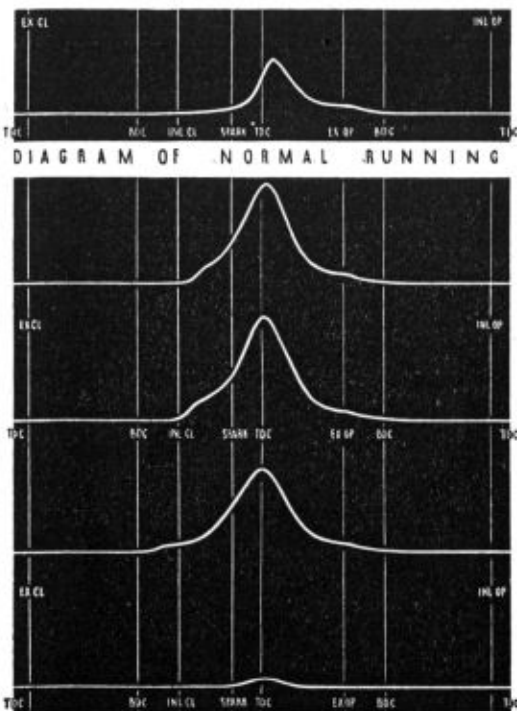Fig. 31.—Principal new features of the Merlin Mk. 100 engine

Fig. 32.—Progressive increase of pre-ignition resulting in backfire

perature conditions in the induction manifold due to the boiling point of T.E.L. and ethylene dibromide being widely different. The boiling point of the lead being 200 deg. C. and that of the dibromide only 132 deg. C. Therefore, under cold conditions the inhibitor tends to part company with the lead. Under adverse conditions we have found as much as two to three times as much T.E.L. per gallon present in certain cylinders with practically no lead dibromide to neutralize it. (At 25 deg. C. maximum T.E.L. 8 cc., minimum T.E.L. 3·2 cc., average T.E.L. 5 cc.) This, of course, results in very rapid attack of the exhaust valves.

On other cylinders which get an excess of ethylene dibromide and very little lead the exhaust insert erosion is very bad, resulting in rapid loss of tappet clearance. Spark plugs are affected in a similar way to the valves.

Obviously the first approach to the problem is to get the lead distribution right. We find on the Merlin that this lead distribution is excellent down to about 30 deg. charge temperature in the induction manifold but after that it becomes very erratic.

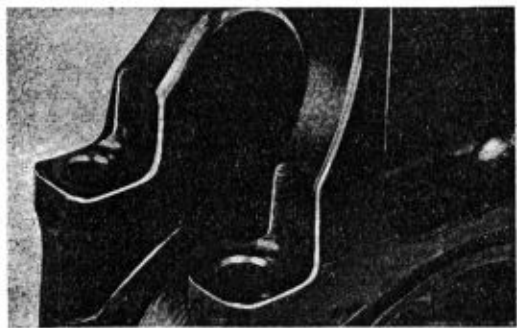A great deal can be done with regard to the fuel. The use of acetylene-tetrabromie, which

Fig. 33.—Early type Merlin connecting-rod bolt lugs

has a boiling point slightly higher than the T.E.L., greatly assists in keeping the two constituents together under low temperature conditions. Tests with this on the bench have been very promising and flight tests are about to commence. If after flight tests the results are found to be good it is possible that sufficient quantities can be produced in this country. No doubt the Americans will follow suit if the results are satisfactory.

On the other hand the Russians used ethyl-bromide which has a boiling point of 34 deg. C. and also has a low freezing point. On one of our heavy bomber raids our aircraft had to refuel in Russia and the sparking plugs were nearly solid with lead on their return to England.

This problem of lead distribution at low charge temperatures is also being catered for on inter-cooled engines by making the intercooler a heat exchanger, i.e. as well as cooling the charge at the higher temperature conditions it is automatically coupled into the engine cooling system at low temperature and prevents the charge falling below 40 deg. C. On the non-intercooled engines we are adding a small heat exchanger to do this job.

A more fundamental solution to this problem is, of course, fuel injection, and at the present moment we have this in the course of development.

When the distribution is as good as possible we still get failures over long running periods and the main reason for this is found to be slight valve seat wear and valve distortion due to temperature gradients in the cylinder head. The distortion has the effect of slight blow-by together with local high stressing and raising of the temperature of the valve. The result is the formation of a gutter across the valve face. It is interesting to note that lead attack becomes very rapid in the region of high stress concentration.

Careful temperature checks made of exhaust valves where distortion has been present have shown a rise in temperature of nearly 200 deg. C. where slight blow-by has occurred.

This problem is being attacked on the Merlin by a redesign of the cylinder head which ensures more uniform distribution of water round the exhaust valve seats. The result has been a considerable lowering of the average valve face temperature, and getting a uniform temperature round the valve face.

The remaining illustrations show a few items of interest. For example, pre-ignition, shown in illustration 32.

As you know the Merlin is fitted with flame traps with the object of preventing the lesser degrees of blow-back getting into the induction system and so resulting in violent backfires when running at high boost. The flame traps look after these conditions very satisfactorily but they will not cater for pre-ignition. This picture shows at the top a normal indicator diagram with an engine running at 3,000 r.p.m. and 18 lb./sq. in. boost. The point at which ignition takes place is marked and the diagram shows a smooth increase in pressure after the point of ignition. The second diagram shows a jump up in pressure before the spark occurs, which is actually the point where the charge is fired. This is accompanied by a sharp rise in pressure and you will observe that the peak pressures are about twice as high as with a normal diagram. It is also evident that there is a large amount of negative work being done in compressing the burning charge.

The third diagram shows a still earlier increase in pressure as ignition occurs from the hot plug;
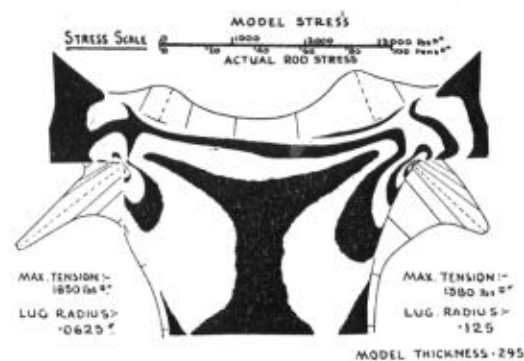

Fig. 34.—Photo-elastic test of connecting-rod

in fact it occurs very soon after the inlet valve closes.

The fourth diagram shows the point of firing to have taken place before the inlet valve closes, which immediately ignites the charge between the flame traps and the cylinders.

It requires only one or two such cycles to heat the flame traps sufficiently for ignition to take place in the main trunk pipe giving rise to a complete engine cut-out.

It is a lot to ask of the flame traps to cater for these conditions and the fundamental thing is to remove the source of the hot spot giving rise to pre-ignition. The most prevalent sources of trouble are as follows:

(1) Spark plug insufficiently tightened.
(2) Internal gas leakage in the sparking plug between the insulator and body of the plug, resulting in the plug rapidly heating up.
(3) Unsuitable type of plug.

If we could provide flame traps which could cater for these conditions it would be an extremely dangerous move and would ultimately result in some other failure such as piston burning.

The last illustrations (numbers 33, 34 and 35) show some features of the connecting rod design. The first picture shows the relatively sharp shoulder left between the lug for the connecting rod bolt and the connecting rod, resulting in high stress concentration and ultimate failure unless particular care is given to the finish and radius between the lug and the rod. Intensive photo-elastic tests were carried out and the next illustration shows how the stress concentration can be reduced by suitable blending the bolt and rod with the lug. The next picture shows the result of this work in the form of a production connecting rod.

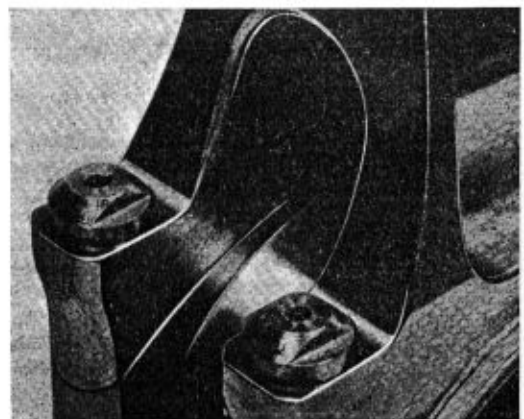This, I think, concludes some of the high spots in the development of the Merlin engine.

Fig. 35.—New design of Merlin connecting-rod

PROFESSIONAL PUBLICATIONS

Under this heading are given each month the principal articles of aeronautical interest appearing in the current issues of the Journals of the leading Professional Societies and Institutions.

The Royal Aeronautical Society
JOURNAL (Monthly)
    Vol. 50, No. 426, June, 1946
    Recent Aerodynamics Developments (34th Wilbur Wright Memorial Lecture). E. F. Relf.
    Method of Accident Investigation and Prevention Adopted By Air Transport Auxiliary. P. A. Wills

The Institute of Welding
TRANSACTIONS (Semi-Monthly)
    Vol. 9, No. 2, April, 1946
    Metallurgy of Aircraft Welding. R. S. Tew
    Welding of Thermoplastics. G. Haeim and H. P. Zade

The Engineering Institute of Canada
THE ENGINEERING JOURNAL (Monthly)
    Vol. 29, No. 4, April, 1946
    Trans-Canada Air Lines' Radar Installation. W. A. Cole

The Institute of the Aeronautical Sciences
JOURNAL (Monthly)
    Vol. 13, No. 5, May, 1946
    Ground Vibrations of Helicopters. M. L. Deutsch
    Landing Gear Strength Envelopes. J. F. McBrearty and D. C. Hill
    The Application of Established Automatic Control Methods to the Study of Basic Flight Problems. O. B. Johnston and J. M. Anderson
    Some Experiences in Full-Scale Power-Plant Testing. M. U. Clauser
    Auditory Signals for Instrument Flying. T. W. Forbes
    The Effect of Notches on Static and Fatigue Strength. D. W. Drake
    Roadability and Landing Ability in Aircraft Undercarriages. R. M. Rosenberg