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Assessment of the Relative Performance of the By-pass Engine and the Orthodox Double Compound Jet Engine

By

E. A. BRIDLE, B.Sc., D.I.C.

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COMMUNICATED BY THE PRINCIPAL DIRECTOR OF SCIENTIFIC RESEARCH (AIR),
MINISTRY OF SUPPLY

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Summary.—The by-pass engine can be described as a form of ducted fan engine in which the fan boosts the main compressor.

Two possible forms of by-pass engine are described, and their estimated performance is compared with that of the orthodox double compound jet engine under various flight conditions, the calculations being extended to include the case of thrust boosting by means of exhaust reheat.

It is concluded that the by-pass engine can offer an appreciable gain in respect of fuel economy over the orthodox double compound jet engine even at 650 m.p.h. in the stratosphere, at the expense, however, of increased frontal area for a given thrust.

1. *Introduction*.—The by-pass engine is a double compound jet engine in which part of the air from the low pressure (L.P.) compressor is expanded as a jet without passing through the high pressure (H.P.) compressor and combustion system. It may therefore be regarded as a form of ducted fan engine in which the fan (L.P. compressor) boosts the main compressor. This gives rise to two forms of engine: one in which the by-pass air is allowed to mix with the exhaust from the L.P. turbine, the gases expanding as a single jet; and one in which the by-pass and main gas streams are exhausted through separate nozzles.

The purpose of this Report is to compare the performance of these two forms of by-pass engine with that of the orthodox double compound jet engine.

2. *Scope of Investigation*.—The main investigation deals with flight conditions at 45,000 ft, three forward speeds being considered at this altitude, namely, 450 m.p.h., 550 m.p.h. and 650 m.p.h. The 550 m.p.h. case is the design (cruise) condition laid down by the Ministry of Supply in certain specifications relating to jet engines for military and civil aircraft.

The effect of thrust boosting by means of reheat is considered for the altitude case at 450 m.p.h. and for the static condition at sea level.

3. *Basis of Comparison and Assumptions*.—The performance comparison between the different types of engine is based on the relative values of their specific fuel consumption and thrust per unit frontal area. These quantities are obtained from thermodynamic cycle calculations for a range of maximum cycle temperature, overall pressure ratio, L.P. compressor pressure ratio and by-pass ratio.

* N.G.T.E. Memorandum No. M.32, received 27th August, 1948.

A list of the various assumptions made for ducting losses, heating losses, etc., is given in an appendix, but the values for some of the main components may be quoted here.

It is assumed that 90 per cent of the dynamic head due to forward speed is available at the L.P. compressor intake. Other assumptions are as follows:—

Polytropic efficiency of both low pressure and high pressure compressors including intake and outlet diffuser losses	86 per cent
Overall total-head efficiency of turbines	87 per cent

The nozzle loss for the orthodox jet engine and in each nozzle of the dual jet engine is assumed to be 2 per cent, based on the jet energy, while a further 3 per cent is included in the mixed jet engine to allow for mixing of the two gas streams.

The assumptions made for the reheat pressure loss are based on available test data, and apply to a reheat system in which the entry Mach number is approximately $0 \cdot 3$.

4. *Results*.—In the mixed jet engine at a given forward speed and maximum cycle temperature the by-pass ratio is determined primarily by the L.P. compressor pressure ratio, by-pass ratio being defined as the ratio of the by-pass air mass flow to that passing through the H.P. system. The relationship between by-pass ratio and L.P. pressure ratio is shown in Fig. 1. The by-pass ratio is practically independent of overall pressure ratio, and the curves give the mean values for a range of overall pressure ratios from 8 to 12, the latter being the highest value used so far in projected designs. Maximum cycle temperatures of 1000 deg K and 1050 deg K are chosen as representative values for maximum cruise operation, while 1200 deg K is considered a reasonable maximum for take-off, climb and combat conditions.

Figs. 2 to 6 give the performance in terms of thrust per unit frontal area. In estimating the frontal area, two stations have been selected as being likely to yield the position of maximum engine diameter, namely,

(*a*) L.P. compressor inlet
(*b*) combustion system and surrounding by-pass duct,

it being assumed that with a good design, the diameter of the turbines is less than that of the combustion system. For any particular set of conditions, the overall areas at the two stations have been calculated for unit air mass flow through the engine, the larger of the two areas thus obtained being assumed equal to the overall frontal areas, irrespective of nacelle shape. From the calculated thrust per unit air mass flow, the thrust per unit frontal area has then been determined. In most cases, the frontal area is prescribed by the overall diameter of the combustion system and by-pass ducting, or by the combustion system alone in the orthodox jet engine. In some cases, however, the diameter is greatest at inlet to the L.P. compressor, and this is indicated on the curves in Figs. 4 and 5.

Fig. 2 shows specific fuel consumption plotted against thrust per unit frontal area for the three types of engine at 45,000 ft, 550 m.p.h., the maximum cycle temperature being 1000 deg K and the overall pressure ratio 10. L.P. pressure ratios of $1 \cdot 4$, $1 \cdot 8$ and $2 \cdot 2$ are considered for both types of by-pass engine, and for the dual jet engine the effect is shown of varying the by-pass ratio for a given L.P. pressure ratio. In the latter case, a further L.P. pressure ratio of $2 \cdot 6$ is considered, at which value it is not possible to use mixed jets. It will be appreciated that with a by-pass ratio of zero, either form of by-pass engine is equivalent to an orthodox jet engine. The estimated curves for the mixed jet case, however, will not pass through this point because the calculations assume a mixing pressure drop which is independent of the by-pass air mass flow. Also shown in Fig. 2 is the thrust per unit frontal area below which it is assumed that the engine cannot be completely buried in an aircraft wing. The chosen value of 130 lb/sq ft at 45,000 ft, 550 m.p.h. is based on a typical engine for installation in bomber aircraft.

Some comparison having been obtained between mixed jet and dual jet engines, the next series of curves is devoted mainly to the mixed jet case, both to reduce the amount of work and to avoid unnecessary complication. Figs. 3, 4 and 5 show specific fuel consumption plotted against thrust per unit frontal area for the various conditions shown on the curves. In Fig. 5 points are shown for the dual jet case at an L.P. pressure ratio of $2 \cdot 0$, using the same by-pass ratio as that obtained in the mixed jet engine with the same L.P. pressure ratio. The effect of forward speed on the performance of mixed jet and orthodox jet engines for one set of conditions is summarized in Fig. 6, where specific fuel consumption is plotted against forward speed for a constant L.P. pressure ratio of $2 \cdot 0$ with a maximum cycle temperature of 1050 deg K.

The effect of thrust boosting is considered for engines having an overall pressure ratio of 10 at sea level. In order to obtain some comparison between the relative performance at sea level and altitude it is assumed that the available pressure ratio increases to 12 at 45,000 ft, 450 m.p.h., the latter being considered a typical climb condition. The calculations are made for a main combustion outlet temperature of 1200 deg K with reheat in the exhaust systems to 1800 deg K. In Fig. 7, thrust per unit frontal area is plotted against by-pass ratio for the three types of engine, frontal area still being prescribed by the combustion system and by-pass ducting. Figs. 8 and 9 show the percentage thrust boost plotted against by-pass ratio and percentage increase in specific fuel consumption respectively.

5. *Discussion.*—Before entering into the general discussion it should be emphasized that the curves for a given type of engine indicate the relative performance obtainable by varying the design, and do not represent operating lines for a given design.

The primary effect to be noted from Fig. 1 is the dependence of by-pass ratio on L.P. compressor pressure ratio in a mixed jet engine. As the L.P. pressure ratio is increased the by-pass ratio falls, until when it becomes zero the engine reverts to the orthodox jet type. At a given L.P. pressure ratio, both an increase in the maximum cycle temperature and a decrease in forward speed require an increase in the by-pass ratio.

5.1. *Relative Performance with Mixed Jets and Dual Jets.*—Referring to the curve for the mixed jet engine in Fig. 2, it is seen that as the L.P. pressure ratio is reduced, thereby increasing the by-pass ratio, there is a marked fall in specific fuel consumption below that of the orthodox jet engine, but at the expense of a reduction in thrust per unit frontal area. Turning to the dual jet case, it is seen that increasing the by-pass ratio for a given L.P. pressure ratio gives curves which are similar to that for the mixed jet engine. If dual jets are employed, there is little to be gained in specific fuel consumption by reducing the L.P. pressure ratio, and in the case considered it will be seen that the dual jet performance is closest to that of the mixed jet engine when utilizing an L.P. pressure ratio of about $2 \cdot 2$. Nevertheless, on the assumptions made, the advantage lies with the mixed jet system, its specific fuel consumption at a thrust per unit frontal area of 130 lb/sq ft being $3 \cdot 5$ per cent less than that given by dual jets. The difference is less at higher thrusts, diminishing to zero as the orthodox jet engine case is approached.

On the basis of these calculations, therefore, it appears that a greater saving in specific fuel consumption over that of the orthodox jet engine is obtained from the use of mixed jets than with dual jets. This is only true provided that the mixing losses have not been greatly underestimated, and as this condition introduces some doubt it is recommended that the performance with mixed jets should be regarded as a theoretical maximum for by-pass engines, and liable to some reduction in practice.

5.2. *Comparison of Mixed Jet By-pass Engine with Orthodox Jet Engine.*—Fig. 3 may be regarded as an extension of the results for the mixed jet engine given in Fig. 2 under the specified 'cruise' conditions, *viz.*, 45,000 ft, 550 m.p.h. For a given maximum cycle temperature an increase in overall pressure ratio is accompanied in both types of engine by a decrease in specific fuel consumption and an increase in thrust per unit frontal area, the effects being less marked in the by-pass engine for a given L.P. pressure ratio. Keeping the overall pressure ratio constant, an increase in maximum cycle temperature causes an increase in both the specific fuel consumption and thrust per unit frontal area of the orthodox jet engine. With the L.P. pressure ratio constant, the specific fuel consumption of the by-pass engine decreases with increased maximum cycle temperature, while there is little change in thrust per unit frontal area. By varying the L.P. pressure ratio in the mixed jet by-pass engine, however, it is always possible to obtain both a reduction in specific fuel consumption and an increase in thrust per unit frontal area with increased maximum cycle temperature. Particular values for the by-pass engine at the L.P. pressure ratio of 2·0 are compared with those for the orthodox engine in the following table:

Type of engine	Mixed jet				Orthodox jet			
Max. cycle temperature	1000°K		1050°K		1000°K		1050°K	
Overall pressure ratio	8	12	8	12	8	12	8	12
By-pass ratio	0·62	0·56	0·85	0·85	0	0	0	0
Specific fuel consumption	0·979	0·939	0·968	0·909	1·087	1·020	1·111	1·033
Thrust/unit frontal area	154·2	175·2	155·5	171·9	198·9	246·0	215·4	271·2

With a maximum cycle temperature of 1000 deg K the saving in specific fuel consumption over the orthodox jet engine is 9·9 per cent for an overall pressure ratio of 8, and 7·9 per cent for an overall pressure ratio of 12, the corresponding reductions in thrust per unit frontal area being 22·5 per cent and 28·8 per cent. These quantities are somewhat larger with the maximum cycle temperature of 1050 deg K. The above figures confirm that the need for high overall pressure ratios is not so great in the by-pass engine as in the orthodox jet engine.

The general remarks of the above paragraphs apply to Figs. 4 and 5, which show specific fuel consumption and thrust per unit frontal area for the other forward speeds. Fig. 4 shows that at 450 m.p.h. the advantage of the by-pass engine in respect of fuel economy is appreciably greater than at 550 m.p.h. for a given L.P. pressure ratio. In addition, it is well known that the specific fuel consumption of the orthodox jet engine falls with decreasing forward speed, and the sum effect enables a very low specific fuel consumption to be obtained in the by-pass engine. The effect of increasing the maximum cycle temperature is emphasized in Fig. 4 by the curve for 1200 deg K and it is seen that at the higher temperatures and pressure ratios the frontal area is governed by the diameter at the inlet to the L.P. compressor.

Fig. 5 shows that at the higher forward speed of 650 m.p.h. the specific fuel consumption is generally increased, and the advantage of the by-pass engine is not so marked. The minimum thrust per unit frontal area allowable for buried engines will be higher than at 550 m.p.h. but even at a value of, say, 200 lb/sq ft the mixed jet by-pass engine shows an appreciable reduction in specific fuel consumption compared with the orthodox jet engine.

It has been shown that the specific fuel consumption of the dual jet engine is higher than that estimated for the mixed jet case, but if dual jets have to be used, the points in Fig. 5 still show an advantage over the orthodox jet engine if thrusts per unit frontal area of 160 to 190 lb/sq ft can be accepted. It will be noticed from these points that for the cases considered the effect of maximum cycle temperature on dual jet performance is not so marked as with mixed jets, and at low overall pressure ratios increased temperature has an adverse effect.

Fig. 6 is plotted for a maximum cycle temperature of 1050 deg K and an L.P. pressure ratio of 2·0 and shows that the specific fuel consumption of both types of engine increases almost linearly with forward speed. At 450 m.p.h. with an overall pressure ratio of 8, the specific fuel consumption of the mixed jet by-pass engine is 16·6 per cent less than that of the orthodox jet engine, and for an overall pressure ratio of 12 it is 15·6 per cent less. At 650 m.p.h. the savings are still appreciable, being 9·9 per cent and 8·1 per cent. These savings are, of course, accomplished at the expense of thrust per unit frontal area, and as mentioned above are liable to some reduction in practice.

5.3. *Performance with Reheat.*—From Fig. 7 it is seen that as the by-pass ratio increases, the thrust per unit frontal area obtainable with exhaust reheat in the by-pass engine decreases, and therefore never exceeds that obtainable from the orthodox jet engine with reheat to the same temperature. For the mixed jet engine under sea-level static conditions, the thrust per unit frontal area at a by-pass ratio of 0·5 is 7·3 per cent less than that of the orthodox jet engine, and 37·5 per cent less with a by-pass ratio of 2·0. The corresponding figures for 450 m.p.h. at 45,000 ft are 5·1 per cent and 24·4 per cent. The reduction in thrust per unit frontal area due to by-passing is therefore considerably greater for the sea-level static case. Both the above values for the mixed jet engine at the by-pass ratio of 0·5 are seen to be reasonably small, and up to this by-pass ratio there is no appreciable gain to be had from the use of dual jets. Above this value, however, the dual jet engine shows to some advantage at the higher L.P. pressure ratios, namely 2·2 at sea level, which is assumed to increase to 2·6 at 45,000 ft, 450 m.p.h. Under sea-level static conditions with a by-pass ratio of 1·5, for example, the reduction in thrust per unit frontal area from that of the orthodox jet engine is only 17·3 per cent in the dual jet engine, compared with 28·8 per cent for mixed jets. The advantage of dual jets is less at 45,000 ft, 450 m.p.h., the corresponding values being 12·8 per cent and 18·3 per cent. If lower L.P. pressure ratios are used, the advantage of dual jets over mixed jets is not so great, and even higher by-pass ratios are required before any advantage at all is obtained.

Fig. 8 shows that the percentage increase in thrust with reheat is considerably greater in the by-pass engine than in the orthodox jet engine. The effect is much greater for the 450 m.p.h. case at 45,000 ft than for the sea-level static condition, which is to be expected from the preceding paragraph. Despite this greater percentage increase in the thrust of the by-pass engine, the thrust per unit frontal area of the orthodox jet engine with reheat is not exceeded, owing to the relatively lower thrust of the by-pass engine in the unreheated condition.

It is seen from Fig. 9 that the increase in thrust with reheat is obtained at the expense of greatly increased specific fuel consumption. In the altitude case with a by-pass ratio of 1·5 (L.P. pressure ratio approximately 2·2 with mixed jets) the increase in specific fuel consumption is about 160 to 170 per cent over that for the by-pass engine without reheat, the increase in the orthodox jet engine being 66 per cent. With the same by-pass ratio in the sea-level static case, the corresponding increases are about 300 per cent for the by-pass engine and 100 per cent for the orthodox jet engine.

It should be noted that the calculations assume a reheat combustion efficiency of 98 per cent, and that the estimated performance is subject to a reduction of this value in practice.

6. *Conclusions.*—*a*. At a given forward speed, maximum cycle temperature and overall pressure ratio, the by-pass engine in either mixed jet or dual jet form offers an appreciable saving in specific fuel consumption compared with the orthodox jet engine, at the expense, however, of increased frontal area for a given thrust.

b. Theoretically, the use of mixed jets can yield a lower specific fuel consumption than that obtained with dual jets for the same maximum cycle temperature and overall pressure ratio. In the mixed jet engine, the greatest saving in specific fuel consumption over that of the orthodox jet engine is obtained in general at the lowest practicable L.P. compressor pressure ratio, with a correspondingly large by-pass ratio. For the specified 'cruise' condition, *viz.*, 550 m.p.h. at 45,000 ft, the performance of the dual jet engine is closest to that with mixed jets when utilizing an L.P. pressure ratio of about 2·2.

c. The need for high overall pressure ratios is not so great in the by-pass engine as in the orthodox jet engine.

d. With a given overall pressure ratio, an increase of maximum cycle temperature in the mixed jet engine can give both a reduction in specific fuel consumption and an increase in thrust per unit frontal area.

e. Compared with the orthodox jet engine the by-pass engine shows to greater advantage in respect of fuel economy as forward speed is reduced. The converse is also true, but even at 650 m.p.h. in the stratosphere the by-pass engine still shows a significant saving in specific fuel consumption.

f. With exhaust reheat, a larger percentage increase in thrust is obtained from the by-pass engine than from the orthodox jet engine, at the expense of a much greater percentage increase in specific fuel consumption. The thrust per unit frontal area of the by-pass engine, however, is less than that of the orthodox jet engine over the range of flight speeds considered (0 to 450 m.p.h.). The difference is greatest under sea-level static conditions, but is comparatively small with a by-pass ratio of less than 0·5. The dual jet engine can give a higher thrust per unit frontal area than the mixed jet engine with by-pass ratios above 0·5.

APPENDIX

Certain assumptions made in the calculations are given in Section 3 of the main report. Further assumptions common to the three forms of engine considered are as follows:—

Ratio $\frac{\text{inner diameter}}{\text{outer diameter}}$ at inlet to L.P. compressor	$0 \cdot 5$
Outlet angle from inlet guides	30 deg
Axial velocity at inlet to L.P. compressor	500 ft/sec
Flow area through combustion system	$0 \cdot 8 \times$ enclosing area
Velocity through combustion system based on inlet conditions	70 ft/sec
Combustion pressure loss	$0 \cdot 03 \times$ inlet total pressure
Combustion efficiency	$0 \cdot 98$
Outlet Mach number from L.P. turbine	$0 \cdot 65$
Turbine exhaust system loss	$0 \cdot 15 \times$ inlet dynamic head

Assumptions relating to the by-pass engine only are:—

Axial velocity at outlet from L.P. compressor	500 ft/sec
Velocity through by-pass ducting	200 ft/sec
Pressure loss in by-pass ducting	$0 \cdot 40 \times$ L.P. compressor outlet dynamic head

In the mixed jet engine, mixing is assumed to take place at the same total-head pressure, whereas in practice the two streams mix at the same static pressure. It is assumed, however, that both streams are diffused to a suitably low velocity before mixing, to reduce mixing losses, so that the above assumption introduces negligible error.

With exhaust reheat, the pressure loss is assumed to be of the form:—

$$\frac{P}{P_0}\left(f + h\,\frac{t-1}{t_0-1}\right)$$

where:—

P is total-head pressure at inlet to reheat system

P_0 do. for orthodox jet engine under sea-level static conditions

t reheat temperature/inlet temperature

t_0 do. for orthodox jet engine under sea-level static conditions

f friction loss

$= 0 \cdot 75$ lb/sq in. for orthodox jet engine, mixed jet engine and turbine exhaust system of dual jet engine

$= 1 \cdot 00$ lb/sq in. for by-pass duct of dual jet engine

h heating loss

$= 1 \cdot 25$ lb/sq in. for all types of engine.

Efficiency of combustion in reheat system $0 \cdot 98$.

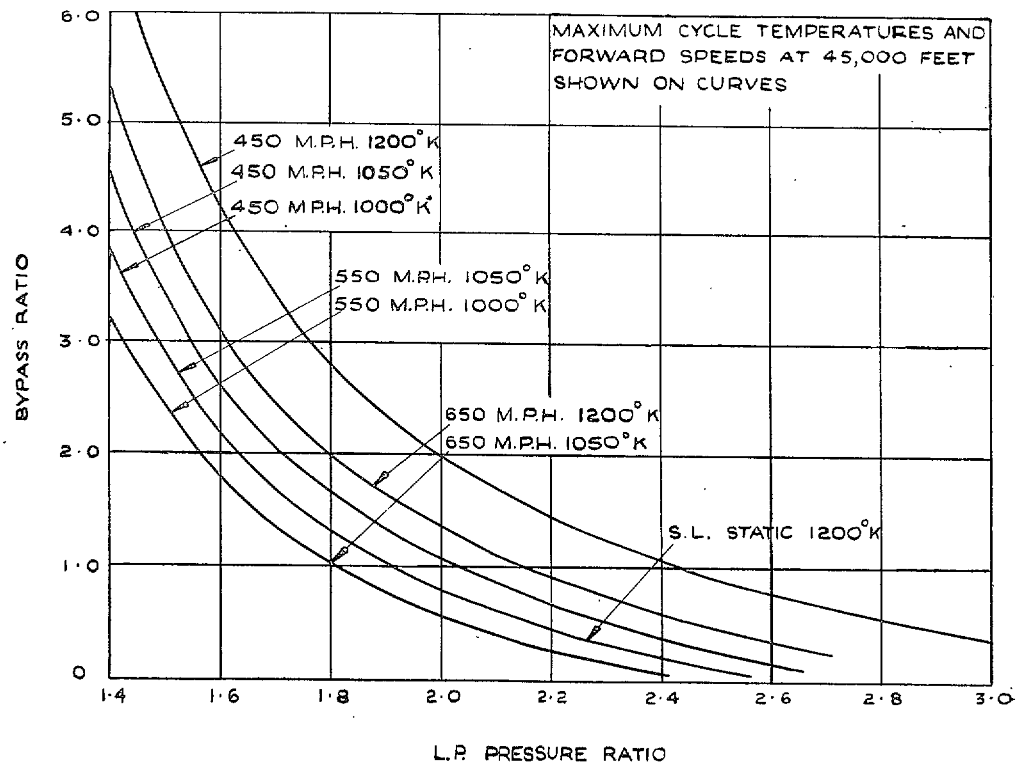

FIG. 1. Relationship between by-pass ratio and L.P. pressure ratio for mixed jets.

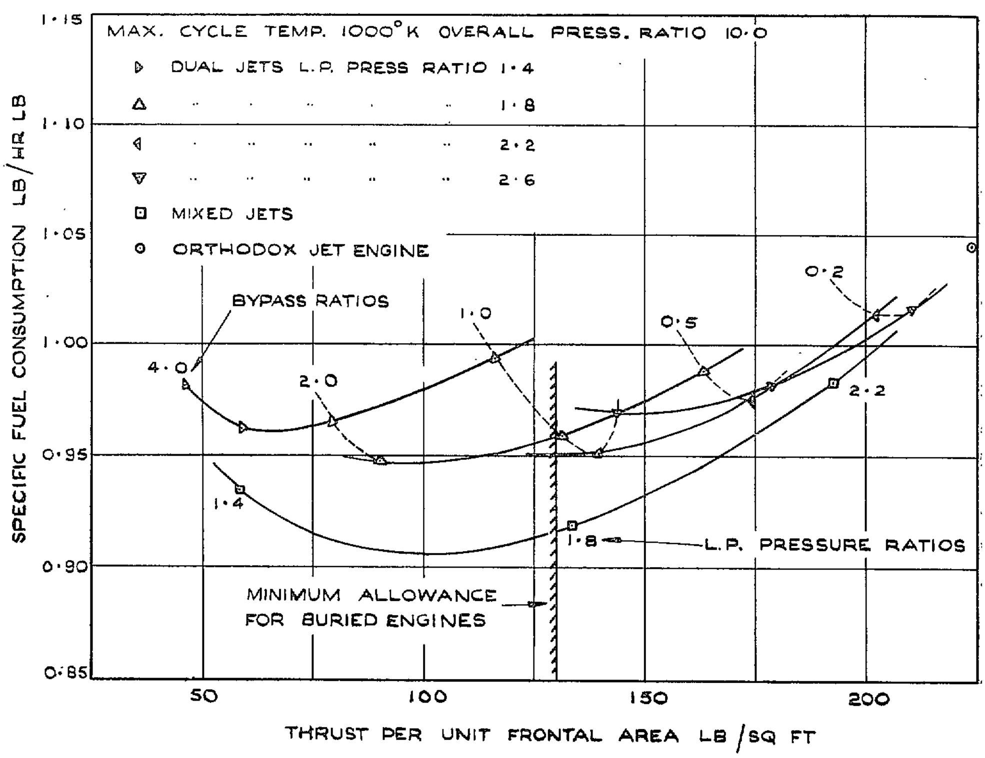

FIG. 2. Estimated performance 45,000 ft, 550 m.p.h. (cruise).

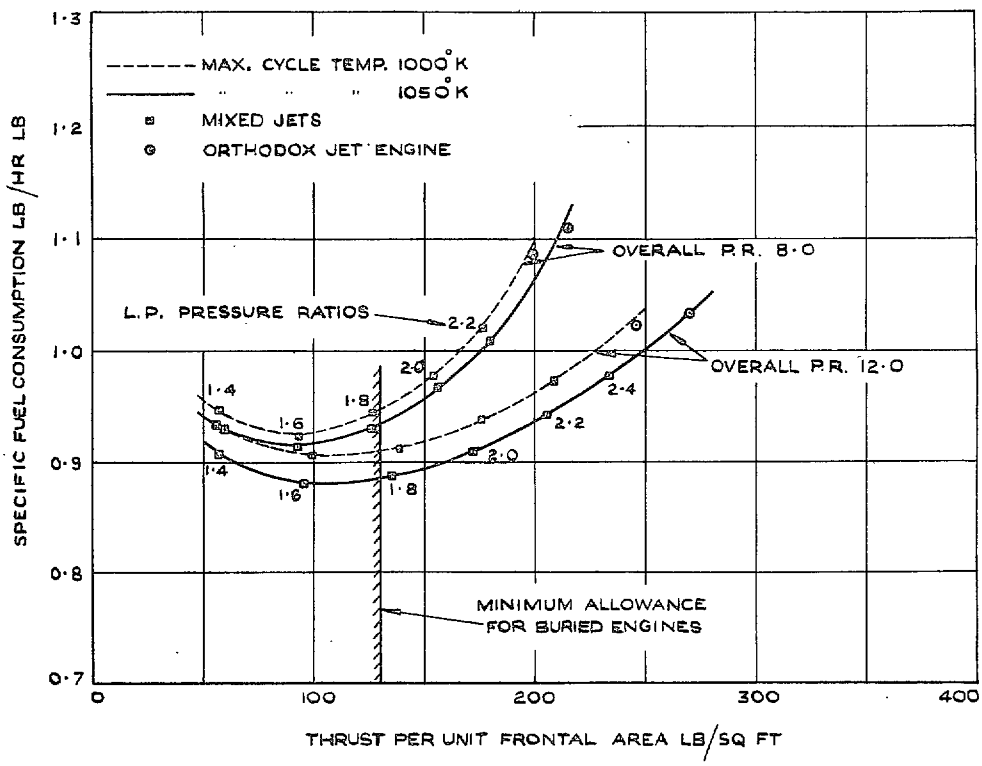

FIG. 3. Estimated performance 45,000 ft, 550 m.p.h. (cruise).

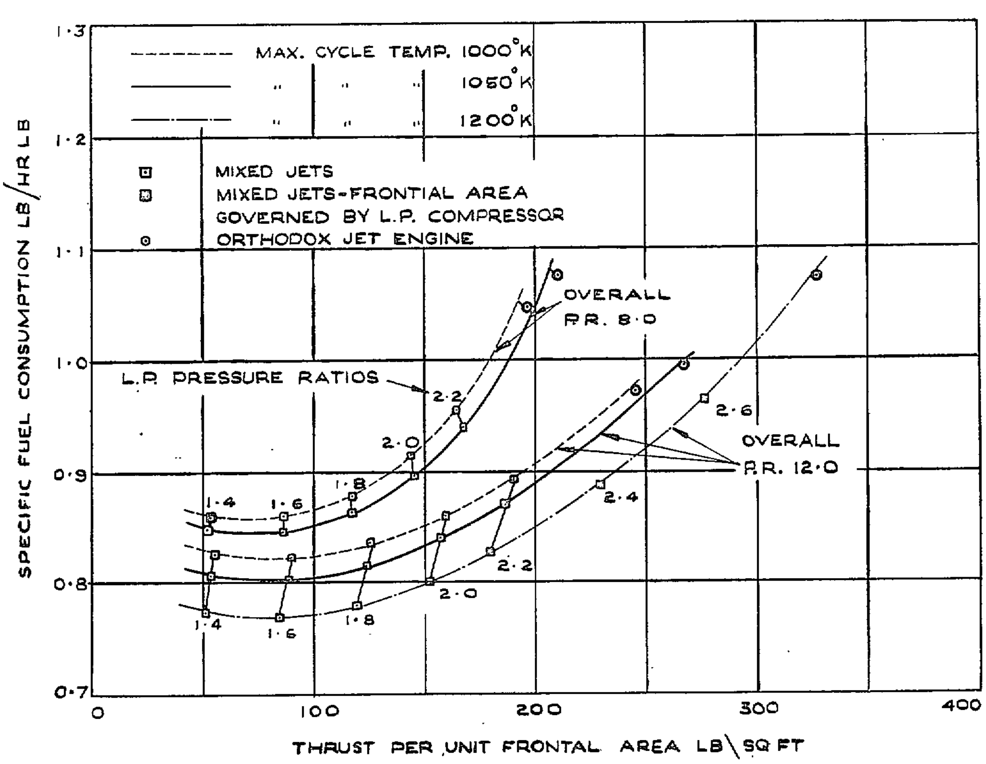

FIG. 4. Estimated performance 45,000 ft, 450 m.p.h.

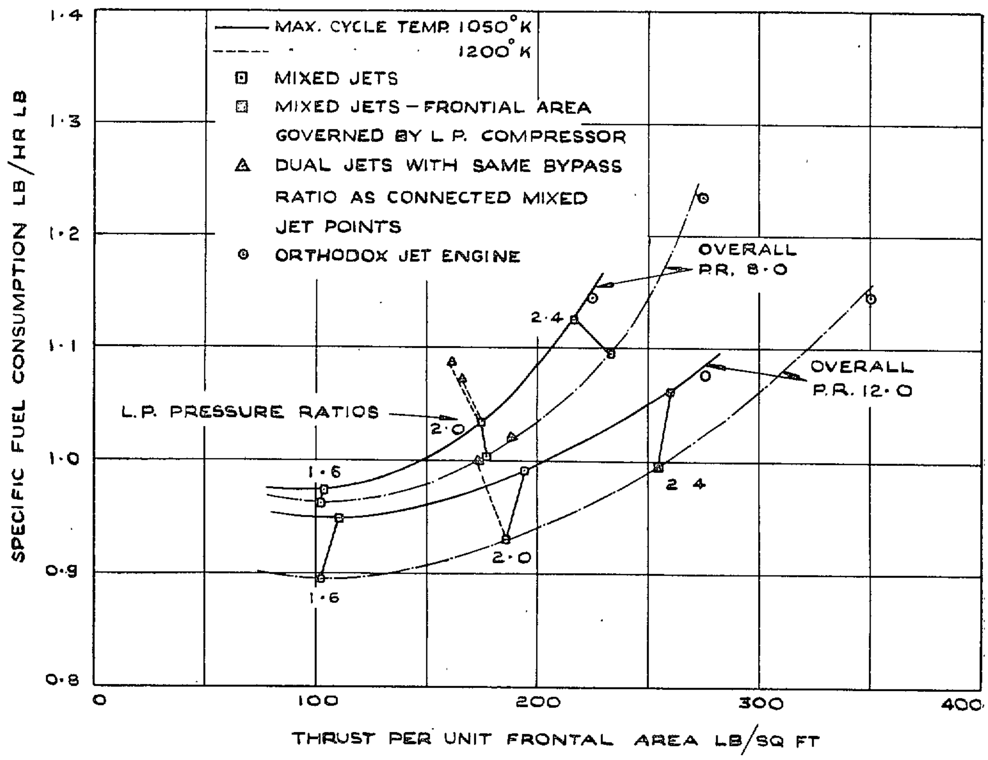

FIG. 5. Estimated performance 45,000 ft, 650 m.p.h.

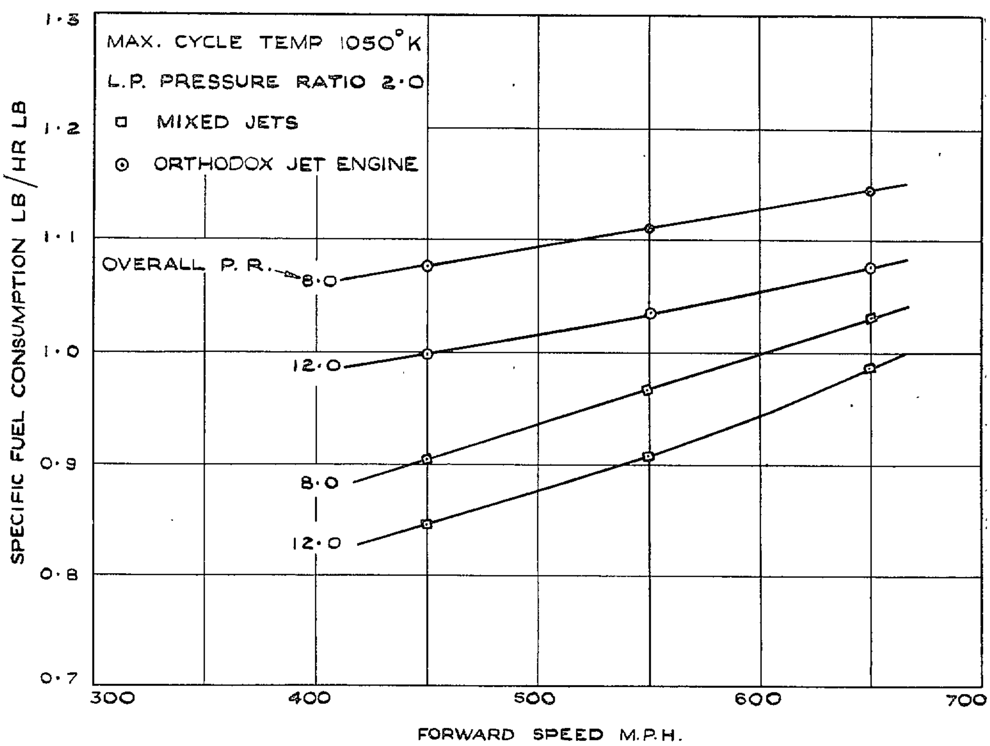

FIG. 6. Estimated performance 45,000 ft.

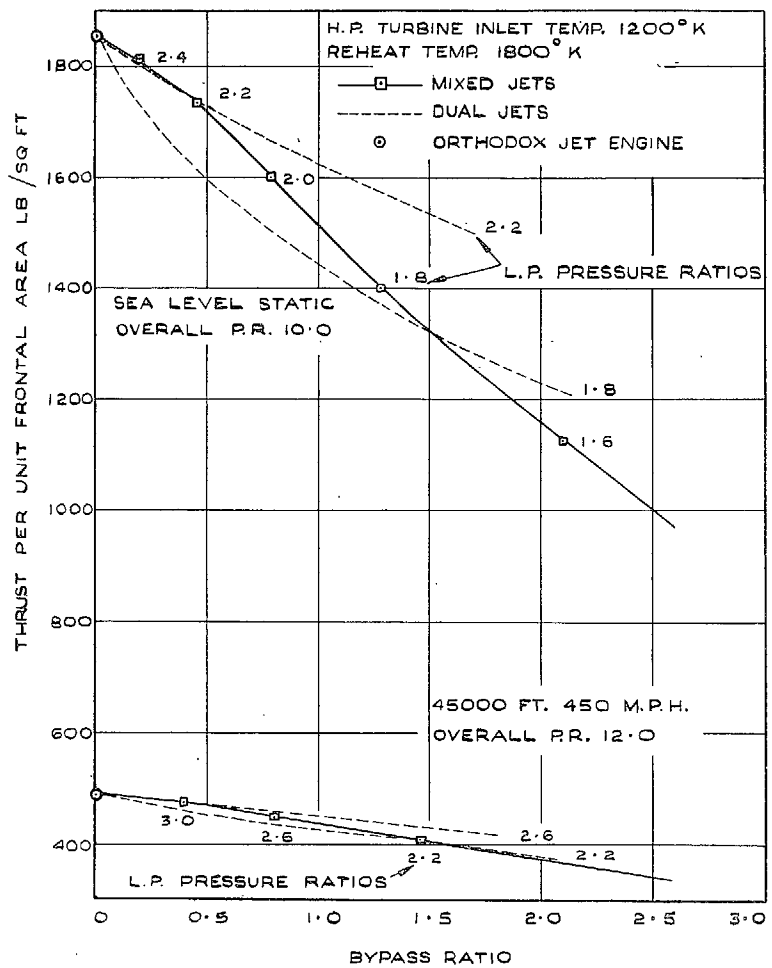

Fig. 7. Estimated performance with reheat.

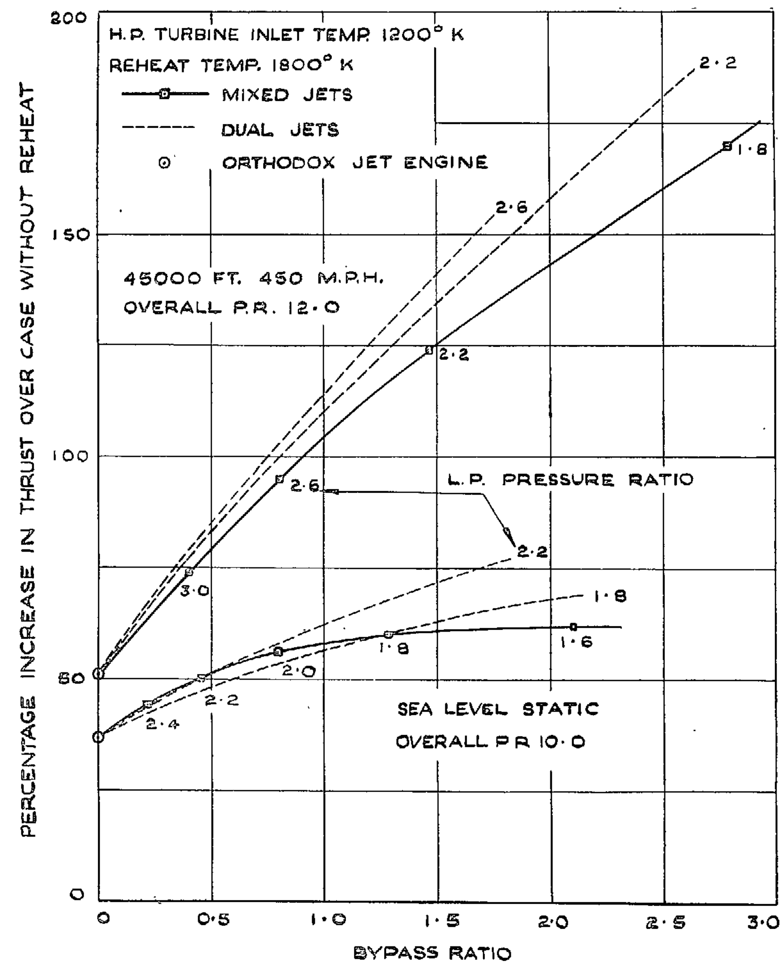

Fig. 8. Estimated performance with reheat.

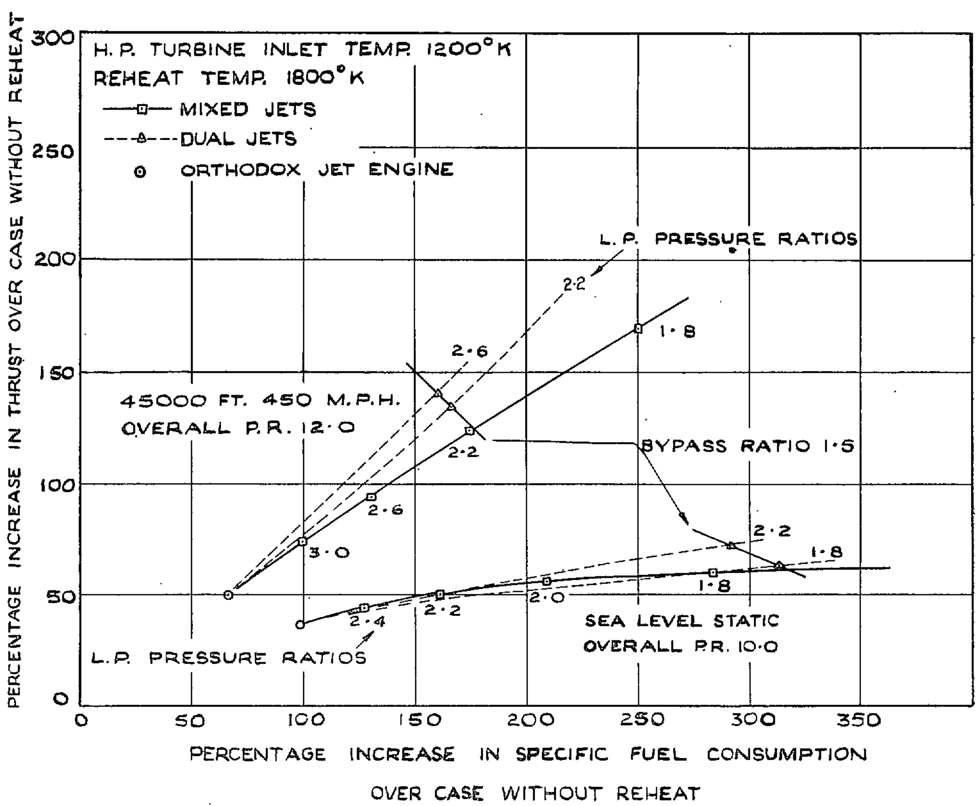

FIG. 9. Estimated performance with reheat.

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