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Summary.—This report describes a theoretical investigation using conventional component characteristics to discover that division of work between the low and high-pressure compressors of a double-compound simple-jet gas turbine of 12 : 1 design pressure ratio which is likely to result in the most desirable equilibrium operation over the normal engine speed range. Having decided in favour of a pressure ratio of 3 : 1 in the low-pressure compressor and 4 : 1 in the other, a study is then made using more realistic compressor characteristics to determine the probable performance of such an engine under all flight conditions when the design maximum temperature is 900 deg C (1173 deg K). The equilibrium running conditions of the engine are investigated with special reference to the problems introduced by the double-compound type of design.

PART I

Simplified Investigation

1. *Introduction.*—From a study of the overall performance of the gas turbine cycle for a simple jet engine with a maximum temperature of about 1200 deg K it can easily be deduced that, whereas the specific thrust per lb/sec of air flow of an engine with a compressor pressure ratio of 12 : 1 would be little different from that of engines of 4 or 5 to 1 pressure ratio, the specific fuel consumption would be as much as 25 per cent lower than that of the lower pressure ratio engines, assuming similar component efficiencies in both cases. Further, in a comparison of the economy at some arbitrary cruising condition, an engine with a maximum pressure ratio of 12 : 1 under sea level static conditions, would show a considerable improvement upon the cruising fuel consumption of a lower pressure ratio engine. For a duty where good overall efficiency is required, therefore, the 12 : 1 pressure ratio engine appears to be a promising project, and the purpose of this report is to predict the probable performance of such an engine and to carry out a theoretical investigation into the equilibrium operation of a double-compound engine such as this would have to be.

2. *Advantages of the Higher Pressure Ratio Engine.*—Since lightness and simplicity are often regarded as major advantages in an aero-engine and the double-compound engine of 12 : 1 design pressure ratio envisaged in this investigation will be both heavier and intrinsically more complex than present-day aircraft gas turbines, it follows that appreciable improvements in efficiency must be forthcoming by the use of the higher pressure ratio if any overall advantage is to be gained. If reference is made to the performance calculations for a simple-jet gas turbine cycle, using estimates of 87 per cent for both the polytropic efficiency of the compressor and the

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total head efficiency of the turbine, together with other small loss factors, the following comparison between an engine of 12 : 1 compressor pressure ratio at sea level static and one of 4 : 1 pressure ratio may be made.

2.1. *Performance at Sea Level Static.*—The compressor temperature rise in the two engines at design speed is 360 deg and 164 deg respectively and for a maximum temperature of 1200 deg. K for sea level static (take off) conditions the specific thrust of the two cycles would be 66 and 64 lb/lb/sec of air respectively. Thus for a given thrust the design mass flow of the higher pressure ratio engine would be only very slightly smaller than that of the lower pressure ratio one. The specific fuel consumption estimates in the two cases, however, are 0·82 and 1·15 lb/hr/lb, representing an improvement in economy of nearly 30 per cent to be obtained using the higher pressure ratio.

2.2. *Cruising Performance.*—Taking as a possible cruising condition, a forward speed of 500 m.p.h. in the stratosphere and assuming for this condition a maximum turbine temperature of 1000 deg K and a reduction in the compressor temperature rise from the design valve in the same proportion as the turbine inlet temperature reduction, the cycle performance is estimated as follows.

		12 : 1 *Engine*	4 : 1 *Engine*
Compressor Temperature Rise	deg C	300	137
Specific Thrust	lb/lb/sec	45	46
Specific Fuel Consumption	lb/hr/lb	0·98	1·28

Thus at this cruising condition, with approximately the same ratio of cruising thrust to take-off thrust in the two engines, (for the specific thrusts are almost equal and the cruising mass flows will be approximately the same proportion of the respective take-off values) a reduction in specific fuel consumption of about 25 per cent can be expected by increasing the design pressure ratio of an engine from 4 to 12. The value of 0·98 lb/hr/lb attainable with the larger pressure ratio engine is only about 6 per cent greater than the minimum attainable at 500 m.p.h. in the stratosphere with the component efficiencies of 87 per cent assumed. The attainment of this minimum would require a pressure ratio at take-off conditions of about 20 : 1, which would probably mean a big increase in the complexity and weight of the engine as well as a loss in specific thrust for only a small saving in fuel consumption. Increasing the design pressure ratio of a pure jet engine with these temperature limits above about 12 : 1 could, therefore, hardly be profitable.

3. *Division of Pressure Rise between Low- and High-pressure Compressors.*—To obtain an overall pressure ratio of 12 : 1 will almost always require two compressor rotors, and hence the division of work between the two compressors which is likely to give the best-matched characteristics over the running range must be estimated, before a detailed study of the engine performance can be begun.

3.1. *Arrangements Considered.*—Four schemes are considered in this comparison, which, using the notation Type A-B, where

A Pressure ratio of low-pressure compressor at sea-level static

B Pressure ratio of high-pressure compressor at sea-level static

are referred to as Types 6-2, 4-3, 3-4, and 2-6.

The turbine inlet temperature at design conditions (sea-level static) is assumed to be 900 deg C (1173 deg K).

3.2. *Characteristics and Efficiencies.*—For a general comparison of this nature it is considered to be sufficiently accurate to use conventional compressor characteristics[2], since the relative forms of the equilibrium running lines only are required, and, moreover, the performance calculations on the selected Type using more realistic characteristics will provide a check on the results of the approximate method. Horizontal compressor characteristics, therefore, are assumed, corresponding to a constant adiabatic efficiency of 80 per cent and a temperature rise proportional to the square of the rotational speed. The latter assumption makes it possible to use for the turbine characteristics a single curve out of the family of calculated curves usually assumed[3,4]. Typical single curves are chosen for both a single and double-stage turbine, previous investigations having shown that most probable designs of turbine would give only slightly different curves from the typical ones used. The total head efficiency of the turbines assumed is between 87 per cent and 88 per cent and remains constant for a particular turbine. The turbine characteristics can be combined with the normal jet-pipe characteristics,[5] once the design of the engine is fixed, to give curves from which the ratio of the high-pressure and low-pressure turbine temperature drops to the high-pressure turbine inlet temperature and also the quotient of the engine gross thrust and the ambient air pressure can be obtained for any known value of overall expansion pressure ratio. This greatly facilitates the performance calculation.

3.3. *Number of Turbine Stages.*—Without doing a design study, which would be outside the scope of the present investigation it is not possible to say with certainty how many stages a particular turbine would require, but in order to decide when to use single and when double-stage turbine characteristics the dividing line has been drawn, arbitrarily, at a ratio of total head temperature drop to turbine inlet temperature of 0·15. This results in the following number of stages for the various engine types.

	High-pressure Turbine	Low-pressure Turbine
Type 6-2	1	2
,, 4-3	2	2
,, 3-4	2	1
,, 2-6	2	1

Thus all the engines have 3 stages altogether except Type 4-3. The ratio of temperature drop inlet temperature for the low-pressure turbine in that case is 0·1572, which is only slightly above the limit imposed and a detailed design study might find it just possible to use a single-stage turbine.

3.4. *Results of Comparison.*—In Fig. 1 are plotted the equilibrium running lines on the low and high-pressure compressor characteristic fields for the four engine types at zero aircraft speed and with constant jet area, the co-ordinates of relative inlet mass flow parameter and relative (pressure ratio-1) being chosen to enable some sort of comparison to be made. The reference line shown in each case is intended to be an approximate surge line for the compressors, though the form of the actual surge lines might easily vary with the pressure ratio of the compressor. The reference line is known to be a reasonable approximation to the actual surge lines of compressors of about 4 : 1 pressure ratio especially in the region below the design pressure ratio.

3.41. *High-pressure compressor.*—From Fig. 1 it is clear that there is an appreciable difference in the form of the running lines on the high-pressure compressor characteristic, for the 6 : 1 design pressure-ratio compressor of Engine Type 2-6 shows a running line almost parallel to the reference curve, whereas the 2 : 1 design pressure-ratio compressor of Type 6-2 at the other extreme has an operating line in the form of a distorted S. Starting off at low speeds a long way from the design point this line passes almost vertically through the design point. before bending over again to approach the reference line rather obliquely. All the lines are extended to cover full-speed operation of the engine at the temperature of the stratosphere and it will be seen that the end point is much nearer the reference line in the case of Type 6-2 than in Type 2-6, though it is always possible that with actual surge-lines this effect may not be quite so marked. The lines for Types 4-3 and 3-4 occupy intermediate positions between those for Types 6-2 and 2-6.

On the assumption that the trend of these operating lines will not be greatly changed by the adoption of more practical compressor characteristics, it follows that the high-pressure compressors of Types 2-6 and 3-4 will be operating nearer their optimum efficiency zones than the other two at speeds below the design value, and will be less prone to surging at corrected speeds above the design value. This statement also assumes that, in the more practical characteristics referred to, the optimum efficiency zone will lie roughly parallel to the reference line shown and will include the design point.

3.42. *Low-pressure compressor.*—With all four types of engine the operating lines on the low-pressure compressor characteristic field show a tendency to 'bulge' out towards the reference line below the design pressure ratio and to swing away from the reference line after passing through the design point. This swinging away is least marked and the 'bulge' towards surging least violent in the case of Type 6-2, which has the very 'warped' high-pressure operating line, whilst they are worst in the Type 2-6, which has the smoothest high-pressure operating line.

3.43. *Best arrangement.*—It seems obvious from the foregoing results that if the engine operating lines on both the high and low-pressure compressors are to be as reasonable as possible the two intermediate types appear more suitable than Type 6-2 or 2-6. The final choice between the Type 3-4 and Type 4-3 on the evidence of this equilibrium running diagram is debatable, but on the grounds that it will perhaps be somewhat simpler to design the turbines for Type 3-4 (since the low-pressure turbine drives the lower pressure ratio compressor) this type is chosen for the more detailed investigation which follows.

4. *Performance using Conventional Characteristics.*—In order to obtain a pre-view of the characteristic features of double-compound engine operation the static performance of the selected Type 3-4 is first investigated over a range of jet areas using the conventional compressor characteristics to which reference has already been made. The operating lines for different conditions are shown on the low-pressure compressor characteristic in Fig. 2 and on the high-pressure characteristic in Fig. 3 whilst the overall performance of the engine under zero forward speed conditions is given in Fig. 4.

4.1. *Low-pressure Compressor Operating Lines.*—Fig. 2 is divided into four sub-diagrams in order to eliminate some of the confusion which would result from superimposing all the curves shown upon one figure. The notation used in the discussion which follows is detailed below.

Q	Mass flow			
P_1	Low-pressure	Compressor	Inlet Total Head Pressure	
P_2	,,	,,	Delivery ,, ,, ,,	
P_3	High-	,,	Inlet ,, ,, ,,	$= P_2$
ΔT_{12}	Low-	,,	Temperature Rise	
ΔT_{34}	High-	,,	,, ,,	
T_1	Low-	,,	Inlet Total Head Temperature	
T_3	High-	,,	,, ,, ,, ,,	
T_5	,,	,,	Turbine ,, ,, ,,	
t_1, p_1; etc.	$= T_1$, P_1, etc.	Relative to 288 deg C and 14·7 lb/sq in.		
N_L	Low-pressure	Rotor r.p.m.		
N_H	High-	,, ,,		

The curves of Fig. 2 are plotted against the corrected inlet mass flow of the engine expressed as a percentage of the design value of the parameter $Q\sqrt{T_1}/P_1$

4.11. *Variations of rotor speed.*—Fig. 2a shows plotted on the lines of constant $\Delta T_{12}/T_1$ the lines for constant $\Delta T_{34}/T_3$ for the high-pressure compressor. On the generalised assumption that for both compressors ΔT varies as N^2 these are, therefore, also lines of constant $N_L/\sqrt{T_1}$ and $N_H/\sqrt{T_3}$. At constant corrected low-pressure rotor speed ($N_L/\sqrt{T_1}$ the high-pressure speed parameter ($N_H/\sqrt{T_3}$ is seen to increase as the mass flow quantity $Q\sqrt{t_1}/p_1$ increases, so long as the low-pressure compressor pressure ratio is greater than about 1·4. At this pressure ratio approximately the lines of constant $\Delta T_{34}/T_3$ or N_H^2/T_3) cross over each other at an almost constant value of $Q\sqrt{t_1}/p_1$ and below this pressure ratio the converse of the preceding statement applies. At low-pressure compressor pressure ratios of the order of the design value of the lines of constant $\Delta T_{34}/T_3$ though still diverging are seen to be approximately parallel to the conventional surge line assumed for the low-pressure compressor.

In order to show the variation of absolute high-pressure rotor speed for constant inlet total head temperature to the engine as opposed to the variation of $N_H/\sqrt{T_3}$ which is a quantity of academic interest mainly, Fig. 2c shows lines of constant $\Delta T_{34}/T_1$ (*i.e.* proportional to N_H^2/T_1) on the low-pressure characteristic field. These are similar in general pattern to the N_H^2/T_3 lines but are more steeply inclined. This is deducible from the reasoning that if at constant engine inlet total-head temperature T_1 the high-pressure rotor speed is held constant whilst the low-pressure rotor speed is increased, the value of N_H^2/T_3 will decrease as a result of the rise in T_3 which is equal to T_2, the delivery temperature of the low-pressure compressor. Fig. 2a shows that the lines of N_H^2/T_1 would, therefore, cross over the lines of N_H^2/T_3 and be more steeply inclined on the characteristic.

4.12. *Variations in maximum temperature.*—Fig. 2b shows the variation of T_5/t_1 over the low-pressure compressor characteristic field, T_5 being the total head temperature after the combustion chamber and at inlet to the high-pressure turbine. When the low-pressure turbine is not choking (*see* below) the lines of constant T_5/t_1 have a gradient intermediate between those for constant N_H^2/T_3 and N_H^2/T_1 and they too cross over each other in the region of 1·4 low-pressure compressor pressure ratio. Above this pressure ratio the temperature ratio T_5/t_1 increases with increasing $Q\sqrt{t_1}/p_1$ at constant low-pressure speed, the converse being true below this pressure ratio. When the low-pressure turbine is choked lines of constant T_5/t_1 are also lines of constant N_H^2/T_1.

4.13. *Variation in jet area.*—Fig. 2c shows, in addition to the constant high-pressure rotor speed lines, the operating lines for the low-pressure compressor for different final nozzle areas. Curves for infinite jet area and for 2·8, 2·4 and 2·0 sq in. per lb/sec of design air mass flow (D.A.M.F.) are given, the design jet area being about 2·12 sq in. per lb/sec of mass flow. The infinite jet-area curve which lies for a greater part of its length in the surge region of the low-pressure compressor represents the limit at which, due to the falling maximum temperature of the engine, the expansion of the gas is only capable of providing sufficient power to drive the compressors with no surplus to provide thrust.

The lines for finite jet areas all show the tendency mentioned earlier to 'bulge' towards the surge line and then swing away again at higher rotor speeds. The line for 2·8 sq in. per lb/sec D.A.M.F., lies mainly in the surge region of the compressor, whilst that for 2·4 sq in. (13 per cent greater than design) coincides with the surge line between values of P_2/P_1 of about 2·3 to 2·9 before swinging fairly sharply away from it in the direction of increasing turbine inlet temperatures.

4.14. *Choking regions.*—In Fig. 2d the regions in which the two turbines and the jet-pipe are choked are indicated by shaded limiting lines. For the jet-pipe the choking limit corresponds to a Mach Number of 1·0 in the final nozzle and a ratio of 1·93 between total head pressure at inlet to the pipe and atmospheric pressure. (This allows for a small jet-pipe pressure loss). For the turbines the limits chosen are somewhat arbitrary but approximate to conditions which would give sonic velocities from the turbine nozzles. Thus the turbine swallowing capacities are assumed constant above a turbine total head pressure ratio of about 2·65 for the two-stage high-pressure turbine and of about 2·0 for the single-stage low-pressure turbine.

It will be noticed from Fig. 2d that the choking regions for the turbines lie on what might be termed the low temperature side of the limiting lines whereas that of the jet-pipe lies on the high temperature side of its limiting line. In very general terms this may be explained by saying that the lower the maximum temperature the greater the pressure ratios the turbines will require to give sufficient work to drive the compressors. These increased pressure ratios bring the turbines into their choking regions even though the work demanded by the compressors may at the same time be decreasing in an effort to reach a compromise. Pressure ratios in the turbine tend to be increased at the expense of the jet pressure ratio and vice versa. It is therefore the reverse procedure of the foregoing, namely increasing the maximum temperature of the engine, which causes an increase in jet pressure ratio and so causes jet-pipe choking.

By a comparison of Figs. 2c and 2d it will be seen that with a nozzle area of 2·4 sq in. per lb/sec D.A.M.F., the operating line of the conventional engine under discussion would, as the low-pressure rotor speed is increased, pass first into the region of high-pressure turbine choking then into the region where the low-pressure turbine chokes as well, until finally the jet-pipe too would choke, the maximum temperature in the engine increasing throughout. Once the low-pressure turbine is choked the pressure ratio across the high-pressure turbine is, under the present assumptions, fixed and thenceforth the temperature drop in this high-pressure turbine must be proportional to its inlet temperature. Similarly when the jet-pipe is choked comparable impositions are placed upon the operation of the low-pressure turbine.

In the case of the 2·0 sq in. per lb/sec D.A.M.F. nozzle the same effects occur with the exception that the low-pressure turbine choking region is not reached. The incidence of jet-pipe choking, however, causes the low-pressure turbine to operate in much the same manner as if it were choking but at a lower swallowing capacity than its maximum, with the result that the pressure ratios across both turbines are limited simultaneously and at lower values than when the low-pressure turbine is allowed to choke before the jet. Exactly the same arguments would apply if, by using an even smaller jet area, jet choking were to be reached before even the high-pressure turbine had choked.

It is not to be inferred that these choking-region boundaries restrict the practical operation of the engine in any way. They merely mark regions in which various temperature and pressure ratios remain constant.

4.15. *Surge regions*.—The compressor surge lines on the other hand do represent practical limits to the operation of the engine and their positions are important. The position of the low-pressure compressor surge line has already been considered with reference to the operating lines for constant final nozzle area. That of the high-pressure compressor only makes its appearance on Fig. 2 at low values of N_L^2/T_1 and comparatively high values of N_H^2/T_1 and T_5/t_1. Whilst it does not appear, therefore, that trouble with high-pressure compressor surging is likely to occur under normal running conditions it might be encountered by suddenly increasing the combustion temperature at low low-pressure rotor speeds.

4.2 *High-pressure Operating Lines* The operation of the high-pressure compressor is illustrated in Fig. 3. The most outstanding feature of this diagram is the line along which the high-pressure compressor operates whilst the low-pressure turbine is choking and to the left of which all operation of the engine must take place. From this line branch off progressively lines of constant low-pressure rotor speed and constant overall temperature ratio, the values of both these quantities increasing as the high-pressure compressor pressure ratio increases.

As would be expected from the observations made on the low-pressure characteristic, running lines for the larger propelling nozzle areas coincide with this low-pressure turbine choking line for much of their length whilst that for 2·00 sq in. per lb/sec D.A.M.F., lies so close to it as to be scarcely distinguishable from it. A further reduction in area would be required to move the operating line for constant jet area appreciably above the low-pressure turbine choking line. When finally, at low values of high-pressure compressor pressure ratio, the lines branch out of the low-pressure turbine choking line those for small nozzle areas lie closest to the high-pressure compressor surge line.

5. *Static Performance.*—Fig. 4 shows the performance of the engine as a whole when there is no forward motion of the aircraft. The sea level thrust is plotted against the low-pressure compressor temperature ratio $\Delta T_{12}/T_1$ for lines of constant $\Delta T_{34}/T_1$ (*i.e.*, equivalent to constant high-pressure rotational speed at constant altitude). The operating lines for the three jet areas are also plotted as are the contours of the specific fuel consumption of the engine and the lines of constant temperature, T_5.

It will be seen that along any particular constant jet area line there is a parallel increase in thrust, $\Delta T_{12}/T_1$, $\Delta T_{34}/T_1$ and T_5, whilst the specific fuel consumption falls to a minimum and then rises again. The lines for the larger jet areas, *i.e.*, up to 2·80 sq in. per lb/sec D.A.M.F., pass through the regions of lowest specific consumption under the static aircraft conditions considered here. The zero thrust axis is of course the line for infinite jet area and along it the specific fuel consumption would also be infinite.

5.1. *Effect of Decreasing Jet Area.*—At constant low-pressure compressor speed, denoted here by $\Delta T_{12}/T_1$ being constant, a decrease in jet area causes an increase in thrust, in high-pressure compressor speed, and in maximum temperature and in general causes a fall followed by a rise in the specific fuel consumption. When the high-pressure compressor speed is held constant and the jet area is decreased there is a drop in low-pressure compressor speed. The thrust usually falls, though may rise again, whilst the high-pressure turbine inlet temperature remains constant so long as the low-pressure turbine is choking and later rises a little. Again there is usually a fall and subsequent rise in specific fuel consumption.

Comparing these effects with those which occur in a simple jet engine with only one compressor when the final jet area is decreased at constant rotational speed, we find that the case where the low-pressure compressor speed is held constant gives changes comparable with those on the simple jet with the exception that the mass flow increases in the double compound engine, as can be seen from Fig. 2, whereas the mass flow of a simple engine decreases with decreasing jet area, thus moving the operating point towards surging. On the double compound engine the low-pressure compressor operating point is moved away from surging and the high-pressure compressor operation tends towards surging.

Reduction of the jet area keeping the high-pressure rotor speed constant produces none of the effects associated with reduction of jet area on the simpler engine type except that the mass flow through the engine is reduced in both cases.

5.2. *Temporary Thrust Increment by Variable Area Nozzle.*—Fig. 4 shows, therefore, the apparently anomolous result that at any chosen position, such as the design point, a temporary thrust boosting effect, say for take-off, could be obtained by either closing down or opening up a variable area propelling nozzle. The apparent anomaly is removed when it is appreciated that on one particular mode of governing a thrust increase is only obtained by altering the nozzle area in one direction. If the engine were governed at constant low-pressure rotor speed there would be a rapid thrust increase on reducing the jet area, but the high-pressure rotor would over-speed and the temperature at inlet to the high-pressure turbine would also increase fairly rapidly. If on the other hand the high-pressure rotor is governed then increasing the jet area will cause an overspeeding of the low-pressure compressor and there will again be an increase in thrust. But the temperature of the high-pressure turbine inlet will not increase and the thrust increase will not be so great as in the other case.

6. *Conclusions of Preliminary Investigation.*—This preliminary investigation has resulted in a decision that for a 12 : 1 pressure-ratio engine the division of work likely to give the best operation of the engine under equilibrium conditions is approximately that which corresponds to low-pressure and high-pressure compressor pressure ratios of 3 : 1 and 4 : 1 respectively. It has given some insight into what are likely to be the characteristic peculiarities of this type of design with regard to operating lines, choking regions, tendencies to surge and effect of changes in jet area and a first estimate of the performance of the engine under static aircraft conditions has been made.

It is, therefore, possible to go on to a more detailed analysis in Part 2, with a fair knowledge of what sort of equilibrium-running conditions are to be expected of the engine as a type. The danger of effects peculiar to the engine type being attributed to the sort of component characteristics chosen for the detailed investigation is therefore lessened.

PART II

More Detailed Investigation

7. *Introduction.*—This part consists of an investigation into the characteristics of a double-compound jet engine using realistic compressor characteristics as opposed to the conventional type used in Part I.

The effect of change of jet area on equilibrium running conditions and on net thrust and specific fuel consumption for various rotational speeds and flight velocities is also considered.

8. *General Description of Designs Considered.*—A diagrammatic arrangement of the unit is shown in Fig. 5. At maximum rotational speed under sea-level static conditions the pressure ratios of the low and high-pressure compressors are three and four respectively. This seems to be the most satisfactory arrangement from consideration of the results of the investigation using conventional characteristics given in Part I.

Two designs are considered and in the first, Design A, the compressor characteristics are such that no appreciable fall-off in efficiency is encountered at high altitudes, *i.e.*, at high non-dimensional rotational speeds, whilst the second design, Design B, has not such good operating qualities at altitude. The characteristics of Design A are considered in rather more detail than those of Design B which have only been included to indicate what losses might be incurred at high altitudes by using compressors of lower specific weight (reduced number of stages).

The design value of efficiency for both the low and high-pressure compressors under sea-level take-off conditions is 84 per cent and this applies to both designs. The high-pressure turbine has a maximum inlet temperature of 900 deg C (1173 deg K) and consists of two stages whilst a single stage is used for the low-pressure turbine. The design specific thrust is 65·4 lb/lb/sec and the specific fuel consumption 0·786 lb/hr/lb in both cases.

9. *Characteristics of Design A.*—9.1. *Sea Level Static Conditions (Fixed Jet Area).*—The equilibrium running lines for these conditions are shown in Fig. 6 and the design points of the compressors and of the engine are indicated on both compressor characteristics. There is a distinct tendency for the running line on the low-pressure compressor to move towards the surge line when the rotational speed of the compressor is reduced. After about 75 per cent full speed, however, on further reduction of speed, it tends to move away again slowly. The corresponding line on the high-pressure compressor runs approximately parallel to the surge line over the range considered.

9.2. *The Effect of Forward Speed and Altitude.*—The main effect of forward speed is to move the operating line nearer to the low-pressure compressor surge limit at reduced low-pressure compressor rotational speeds. This obviously occurs only in the region where the propelling nozzle is not choking under sea level static conditions. On the high-pressure compressor the effect of forward speed is to move the running line further away from the surge line. Above a low-pressure compressor rotational speed of $N_{LP}\sqrt{(288/T_1)}=0{\cdot}916$ of design value all the operating lines for any altitude and forward speed become coincident due to choking of the propelling nozzle. The same happens in the case of the high-pressure compressor, the corresponding speed being $N_{HP}\sqrt{(288/T_3)}=0{\cdot}923$ of the design value.

Increasing altitude tends to bring the running line on the high-pressure compressor nearer to its surge line but the reverse is true on the low-pressure compressor characteristics. The full rotational speed point at the tropopause under static conditions is shown for both compressors. Forward speed decreases the value of the non-dimensional parameter $N\sqrt{(288/T_3)}$ so that there would be less danger of surging the high-pressure compressor at high forward speeds in the stratosphere.

Lines of constant temperature ratio (T_5/T_1) are also plotted in Fig. 6 on both compressor characteristics. The diagram shows how, on the low-pressure compressor characteristics, the temperature ratio increases with the mass flow at a constant rotational speed throughout the range of operation covered. However, it can be seen that as the rotational speed is reduced the temperature ratio lines converge rapidly and they finally cross over at a relative $N_{LP}\sqrt{(288/T_1)}=0{\cdot}535$ and pressure ratio $P_2/P_1=1{\cdot}46$ so that the converse of the above is true at lower pressure ratios. (*See* Fig. 7). On the high-pressure compressor characteristics the temperature-ratio lines branch out of the low-pressure turbine choking line, which runs approximately parallel to the equilibrium-running lines but at slightly higher mass flows, and turn through roughly a right-angle before moving across towards the surge line.

When considering the performance at forward speed an intake efficiency of 90 per cent is assumed. 'Equivalent' parameters are used for the representation of thrust and specific fuel consumption so that the values under sea level conditions can be read off directly and those at any altitude readily found with a knowledge of the corresponding relative atmospheric conditions. These diagrams are shown in Figs. 8, 9. They cover the range from cruising to maximum rotational speed at any altitude. Superimposed upon the thrust diagram of Fig. 8 are lines of equivalent relative high-pressure compressor rotational speeds (Rel. $N_{HP}/\sqrt{(ta)}$ being relative to the design speed). This enables the relative speeds of the two rotors to be known for all conditions. At all times, within the range considered, the rate of change of the low-pressure rotor speed is greater than the corresponding change of the high-pressure rotor speed.

An initial fall off in thrust is experienced by increasing the value of the forward speed parameter $V/\sqrt{(ta)}$ from 0 to 600 m.p.h. for all rotational speeds. A minimum thrust is reached at a certain forward speed for the higher rotational speeds after which the thrust increases again, this minimum occurring at successively higher forward speeds as the rotational speed is decreased. For example, at a Rel. $N_{LP}/\sqrt{(ta)}$ of $1{\cdot}153$ minimum thrust occurs at a $V/\sqrt{(ta)}$ of about 370 m.p.h. whilst at Rel. $N_{LP}/\sqrt{(ta)}=1{\cdot}05$ the corresponding value of $V/\sqrt{(ta)}$ is slightly greater than 600 m.p.h.

When the pressure ratio of the engine becomes excessive for the maximum temperature being employed, as occurs in most jet engines at low rotational speeds, this minimum in the curve of thrust against forward speed at constant r.p.m. and the maximum which follows at even higher flight speeds deteriorate into a point of inflexion on the curve so that the thrust never increases with increasing forward speed but merely changes its rate of decrease. It follows that for a given maximum temperature a high pressure ratio engine will always be intrinsically worse in this respect than one of lower design pressure ratio.

The specific fuel consumption at the sea level static design condition is 0·786 lb/hr/lb thrust. Fig. 9 shows how it varies with forward speed $V/\sqrt{(ta)}$ and the low-pressure compressor rotational speed $N_{LP}/\sqrt{(ta)}$. As before the equivalent sea level values are plotted. The diagram clearly shows the increase of specific fuel consumption with forward speed at a constant rotational speed. Thus, at a Rel. $N_{LP}/\sqrt{(ta)}$ of 0·95 and a $V/\sqrt{(ta)}$ of 0 m.p.h. the specific fuel consumption is 0·755 lb/hr/lb thrust whilst the corresponding values at 300 and 600 m.p.h. are 0·935 and 1·115 lb/hr/lb thrust, the respective increases being 24 and 48 per cent. A combustion efficiency of 100 per cent has been assumed in presenting these results. The effect of altitude can be seen from the following illustration:— With a forward speed of 300 m.p.h. at sea level and a relative low-pressure rotor speed of 0·95 the specific fuel consumption is 0·935 lb/hr/lb thrust but with the same conditions (*i.e.*, identical N_{LP} and V) at the tropopause (36,090 ft) it may be deduced from Fig. 9 using $\sqrt{t_a}=0{\cdot}867$ that the specific fuel consumption falls to 0·895; a decrease of some 4 per cent. It must be remembered, however, that in practice the combustion efficiency may deteriorate with altitude so that little, if any, improvement in specific fuel consumption can be expected at altitude over the corresponding sea level value.

It may also be seen from Figs. 8, 9, that the engine speed has a greater influence on the thrust than forward speed while the converse is true in the case of specific fuel consumption.

9.3. *The Effect of Variable Jet Area.*—Fig. 10 shows the variation in the running line on both compressor characteristics brought about by either increasing or decreasing the jet area. Two constant area lines are shown besides that of design area, *viz.*, for an increase of 16 per cent and for a decrease of 20 per cent. The 16 per cent increase line is, on the low-pressure compressor characteristics, on the surge line side of the line for normal jet area, *i.e.*, in the low temperature region already mentioned in Section 9.2. and which is shown in Fig. 6.

A 16 per cent increase of jet area is chosen as the upper limit as it is coincident with the low-pressure compressor surge line between relative speeds $N_{LP}\sqrt{(288/T_1)}$ of 0·79 and 0·87. The high-pressure compressor surge limit is not encountered over the range shown until jet areas of less than 80 per cent design value are employed.

Cross-plotted on the low-pressure compressor characteristics (Fig.10) are lines of constant non-dimensional rotational speed of the high-pressure compressor $N_{HP}\sqrt{(288/T_3)}$ and, similarly, lines of constant non-dimensional rotational speed of the low-pressure compressor $N_{LP}\sqrt{(288/T_1)}$ are shown on the high-pressure compressor characteristics. By reducing the jet area from its design value a far greater effect on the position of the running line on the high-pressure compressor characteristics is obtained than by increasing the area by the same amount. This effect is not apparent on the low-pressure compressor characteristics where by increasing the area to 116 per cent design value an almost as great effect is obtained on the running lines as by decreasing it to 80 per cent. This can be explained by the fact that increasing the jet area at a constant low-pressure compressor rotational speed lowers the temperature and increases the pressure ratio thereby bringing the low-pressure turbine into its choking region. When the low-pressure turbine is choking any further increase in the jet area will have no effect on the running line of the high-pressure turbine. This tendency can be clearly seen in the way that the 116 per cent area running line converges into the design-area operating line which starts to choke in the region of the sea-level-static design point. The low-pressure turbine choking line is shown on the high-pressure compressor characteristics of Fig. 6 and it forms the limit to all the temperature-ratio lines (T_5/T_1) as operation at higher non-dimensional mass flows without varying rotational speed is impossible.

In a similar fashion to the temperature-ratio lines (T_5/T_1), shown in Figs 6,7, the constant jet area lines on the low-pressure compressor characteristic also converge and finally cross when the pressure ratio (P_2/P_1) has fallen to 1·46 so that below this point the areas increase with increasing mass flow at constant low-pressure-compressor rotational speeds. On Fig. 7 the zero-thrust line, *i.e.*, infinite area, and the high-pressure-compressor surge line are shown, the latter showing that there is a danger of high-pressure-compressor surging during the initial starting period. In the range covered by Fig. 7 the high-pressure-compressor surge line corresponds approximately to the line for equilibrium running with a jet area of 50 per cent design value.

9.31. *Variation of thrust and specific fuel consumption with jet area.*—The effect on the net thrust of varying the jet area by about $\pm$ 15 per cent is shown in Fig. 11 under static conditions and also with the forward speed parameter $V/\sqrt{(ta)}$ equal to 300 and 600 m.p.h. Over this range minimum area corresponds to maximum thrust. For constant values of the parameter $N_{LP}/\sqrt{(ta)}$ the rate of thrust decrease with area change increases slightly as forward speed is increased.

For example, the change of thrust by increasing the jet area from 90 per cent to 110 per cent design value at Rel. $N_{LP}/\sqrt{(ta)}=1{\cdot}0$ and $V/\sqrt{(ta)}=0$ m.p.h. is 31 per cent but at forward speeds of 300 and 600 m.p.h. the fall-off has increased to 36 and 41 per cent respectively. The variation of $N_{HP}/\sqrt{(ta)}$ with $N_{LP}/\sqrt{(ta)}$ and jet area is shown in Fig. 16b.

The corresponding specific fuel consumption diagram is shown in Fig. 12 and shows that, for a constant value of $N_{LP}/\sqrt{(ta)}$ if the jet area is increased from about 85 per cent design value the specific fuel consumption falls, reaches a minimum, and then rises again. The jet area at which the optimum value of specific fuel consumption occurs becomes smaller as the forward speed is increased. Thus, although the design area does not correspond to minimum specific fuel consumption with a relative low-pressure compressor rotational speed of 0·95 under sea level static conditions it does so if the forward speed is increased to 600 m.p.h. Altitude has the effect of moving the optimum condition to higher jet areas for the same values of rotational speed (N_{LP}) and forward speed (V).

10. *Characteristics of Design B.*—The characteristics of the low-pressure compressors are shown in Fig. 13. They would have correspondingly fewer stages than the compressors of Design A, the sea level static design points of the engine coinciding with the compressor design points. Equilibrium running lines for the forward speed parameter $V/\sqrt{(ta)}=0$, 300 and 600 m.p.h. which are plotted on both characteristics have similar trends to those of Design A discussed in Section 9.1. The essential difference between the two designs is the smaller rate of increase, in Design B, of pressure ratio at high non-dimensional rotor speeds, this being true of both compressors. The variation of thrust with rotational speed (both low-pressure and high-pressure rotors) and flight velocity for a fixed jet area is shown in Fig. 14. Approximately the same range is covered as for Design A, namely, cruising to maximum speed operating conditions at any altitude. The following table gives the comparison between the relative equivalent net thrusts of the two designs.

Relative Equivalent Net Thrusts

$N_{LP}/\sqrt{(ta)}$	DESIGN A			DESIGN B		
	$V/\sqrt{(ta)}$ (m.p.h.)			$V/\sqrt{(ta)}$ (m.p.h.)		
	zero	300	600	zero	300	600
1·153	1·50	1·38	1·42	1·38	1·22	1·27
1·10	1·33	1·21	1·21	1·25	1·10	1·12
1·05	1·17	1·04	1·01	1·12	0·98	0·93
1·00	1·00	0·86	0·82	1·00	0·86	0·84
0·95	0·82	0·69	0·63	0·88	0·75	0·71
0·90	0·66	0·52	0·46	0·75	0·62	0·58
0·85	0·50	0·37	0·31	0·61	0·49	0·44

From the above table the superiority of Design A over Design B at values of $N_{LP}/\sqrt{(ta)}$ exceeding unity is clearly indicated. If, however, $N_{LP}/\sqrt{(ta)}$ is less than unity the converse is true, giving Design B an improved performance under sea level static conditions. The reason for this is apparent from a study of Figs. 16a, c and d, which show the variation of compressor efficiency, compressor temperature rise and mass flow with relative low-pressure compressor rotational speed for both designs under static conditions. The assumed compressor efficiencies of Design B are on the optimistic side at relative rotational speeds below unity and result in the markedly improved performance of this design over Design A at these low speeds.

At relative rotational speeds greater than unity the reverse of the above is true. The actual compressor temperature rises of the two designs are approximately the same resulting in practically identical turbine work outputs per pound of air and consequently very similar turbine temperatures.

It follows, therefore, that the differences in thrust between the two designs result largely from the difference in the throughputs of the engines under nondesign conditions arising from the spacing of the compressor constant speed lines illustrated in Fig. 16d.

The changes in mass flow having an equal effect on both thrust and fuel consumption it is to be expected that the differences in specific fuel consumption between the two designs will be much smaller than the differences in thrust and will result mainly from the different compressor efficiencies in the two engines. That this is the case can be seen from a comparison of the differences in the tabulated thrusts with those shown in the following table which gives the specific fuel consumptions of the two schemes, deriving its information from Figs. 9 and 15 respectively.

Specific Fuel Consumptions

$N_{LP}/\sqrt{(ta)}$	DESIGN A			DESIGN B		
	$V/\sqrt{(ta)}$ (m.p.h.)			$V/\sqrt{(ta)}$ (m.p.h.)		
	zero	300	600	zero	300	600
1·153	0·89	1·04	1·21	0·92	1·08	1·26
1·00	0·79	0·96	1·13	0·79	0·94	1·11
0·85	0·70	0·93	1·15	0·68	0·86	1·03

11. *Reheat between Turbines.*—A little consideration has been given to the performance of the engine if a reheat chamber is introduced between the two turbines and the low-pressure turbine redesigned to cope with the higher volume flows which would result from reheating the gas to its original maximum temperature. It is found that an increase in specific thrust from 65·4 lb/lb/sec to 74·8 lb/lb/sec could be obtained at the design point for an increase in specific fuel consumption from 0·786 lb/hr/lb thrust to 0·967 lb/hr/lb thrust. If reheating to the same temperature as in the main combustion chamber is carried out at all operating conditions, then the running lines on the two characteristics are similar to those for the engine without reheat previously considered though of course the specific fuel consumptions remain high.

If at cruising the reheating is stopped and the final nozzle area is unaltered, there is a readjustment of conditions to enable the flow to adapt itself to the now oversize low-pressure turbine nozzles. This adaptation is done both by an increase in throughput and a rise in the temperature at outlet from the main combustion chamber, the low-pressure rotor speed being assumed to be held constant. The low-pressure compressor operating point therefore moves down the constant speed line away from surging and into the region of low-compressor efficiencies. To cater for the increased mass flow and the rise in maximum temperature the high-pressure rotor has to overspeed and also runs into low-compressor efficiency regions. The result is that the thrust is almost the same as that given at the same low-pressure speed when reheat is employed at cruising powers, but at the same time there is a saving in specific fuel consumption. Because of the low-compressor efficiencies, however, the specific consumptions are higher than on the original no-reheat engine at comparable cruising conditions.

Conversely an attempt to introduce reheat between the turbines without re-designing the low-pressure turbine to try and obtain a take-off boost only, results in a reduction in mass flow, in maximum temperature from the main combustion chamber, and in high-pressure rotor speed with consequently little increase in thrust and an increased danger of low-pressure compressor surging.

Reheating in the jet-pipe is not considered in the present report, because as in the case of the simpler single-rotor engine by the use of a variable area propelling nozzle reheating in the jet- pipe may be carried out without altering the running conditions in the rest of the engine.

12. *'Aerodynamic Locking'*.—When the report was discussed by the Power Plants Committee of the Aeronautical Research Council, Dr. A. A. Griffiths drew attention to the danger, in a double-compound engine of this type, of a fixed ratio between the speeds of the two rotors being imposed by the limitations restricting turbine operation when the jet-pipe is choking. It was suggested, therefore, that with this 'aerodynamic locking' occurring the engine would be comparable to a single-rotor engine of similar pressure ratio, which, it was generally agreed, would not operate without severe surging difficulties.

The theory of 'aerodynamic locking' follows from the approximations used in Part I of the report. In Section 4.14 it is shown that the high-pressure and low-pressure turbine temperature drops will be proportional to the respective turbine inlet temperatures whilst the jet-pipe is choking. Hence the turbine temperature drops will be proportional to each other. It follows that the temperature rises in the two compressors will also remain proportional to each other, and as these rises are assumed to vary as the square of the appropriate rotor speeds, then the ratio of the rotor speeds must also be fixed.

However, a comparison between the running lines shown in this report with those which would be obtained if the rotors were assumed to be mechanically coupled to give a fixed speed ratio, shows several features which are in favour of the un-coupled engine. It is on the low-pressure compressor that surging is most likely to be encountered and the discussion centres on the running lines on this compressor characteristic.

12.1. At zero flight speed the jet-pipe does not choke until the operating line has begun to swing away from the low-pressure surge line (*see* Fig. 2). Below this point an increase in flight speed causes the operating line of the uncoupled engine to move towards surging until, because of the increase in pressures within the engine due to the ram pressure rise in the intake, the jet-pipe is again choked. With the assumptions of Part I, this limiting line is the same as for the coupled engine under exactly similar conditions. However, for lower flight speeds, the low-pressure compressor of the coupled engine operates to the low mass flow or 'surge' side of this limit. It is, therefore, intrinsically more prone to surging than the uncoupled scheme.

12.2. The coupled scheme also shows the tendency, common in single-rotor engines, for the operation of the compressor to move temporarily towards surging during acceleration of the engine. It is pointed out in both parts of this report that a temporary increase in turbine temperature above that for equilibrium at a given low-pressure rotor speed will move the operation of the low-pressure compressor away from surging. The un-coupled scheme is likely to be prone to surging, therefore, only during deceleration at high flight speed under low thrust conditions, a condition likely to be met much more rarely than an acceleration at low or zero flight speed at low thrust conditions.

12.3. When 'typical' characteristics for the compressors are used, as in Part II of the report, the strict assumption of temperature rise in the compressor varying as the square of the speed is no longer valid and rigid aerodynamic locking can no longer be expected to occur. Fig. 8 shows in fact that even with the jet-pipe choked the low-pressure rotor speed varies more rapidly than the high-pressure rotor speed does. This feature is noted in Section 9.2 of the report. Moreover, it would appear that this is not an effect introduced fortuitously by the particular compressor characteristics chosen. For all normal axial and centrifugal compressors will have characteristics in which, as mass flow is increased along a constant speed line, there is a decrease in the work done for unit mass flow, represented by the temperature rise in the compressor. This non-uniformity of the relationship between temperature rise and speed in a compressor, combined with the fact, amply demonstrated in the report, that the compressors of a double-compound jet engine tend to operate in different regions of their respective characteristics creates an effect which can perhaps best be described as a 'slipping' of the aerodynamic locking which would otherwise occur under jet-pipe choking conditions. This slipping serves to lessen the tendency towards low-pressure compressor surging in the double-compound jet engine.

13. *Conclusions.*—The main effect of the increased pressure ratio in the double-compound type of jet engine compared with a single-rotor type is to reduce the specified fuel consumption although the change in specific output is negligible. The extra weight involved by adopting a 12 : 1 pressure ratio, especially if the operating criterion is good performance at high altitude, makes the engine only suitable for long range work.

The subdivision of the engine into two compressors independently driven gives rise to a new arrangement of equilibrium running lines. This applies especially to the low-pressure compressor characteristic, in which the order of increasing temperature-ratio lines is the reverse of that for the single-compressor type of jet unit for all normal flight conditions although during the initial starting period the above does not hold.

Care should be taken during the initial accelerating period to avoid the possible surging of the high-pressure compressor. On the other hand, rapid deceleration might cause low-pressure compressor surging especially at high forward speeds. This effect can, of course, only be realised when the value of the temperature ratio lines decrease towards the surge line.

The performance at altitude is dependent on good compressor characteristics at high non-dimensional speeds, though this in practice might require the addition of extra compressor stages.

The use of reheat between the two turbines might be considered if increased specific output is required, and an increase in specific fuel consumption can be tolerated. The cutting of this reheat process for cruising appears to present difficulties in the form of overspeeding and increased temperatures in the high-pressure turbine and a movement of the compressor operating points to bad efficiency regions.

Finally a comparison between the results of Parts I and II of the report will show that the conventional characteristics are sufficiently accurate for a good insight into the probable trends of operating lines for a new engine type to be investigated with reasonable reliability.

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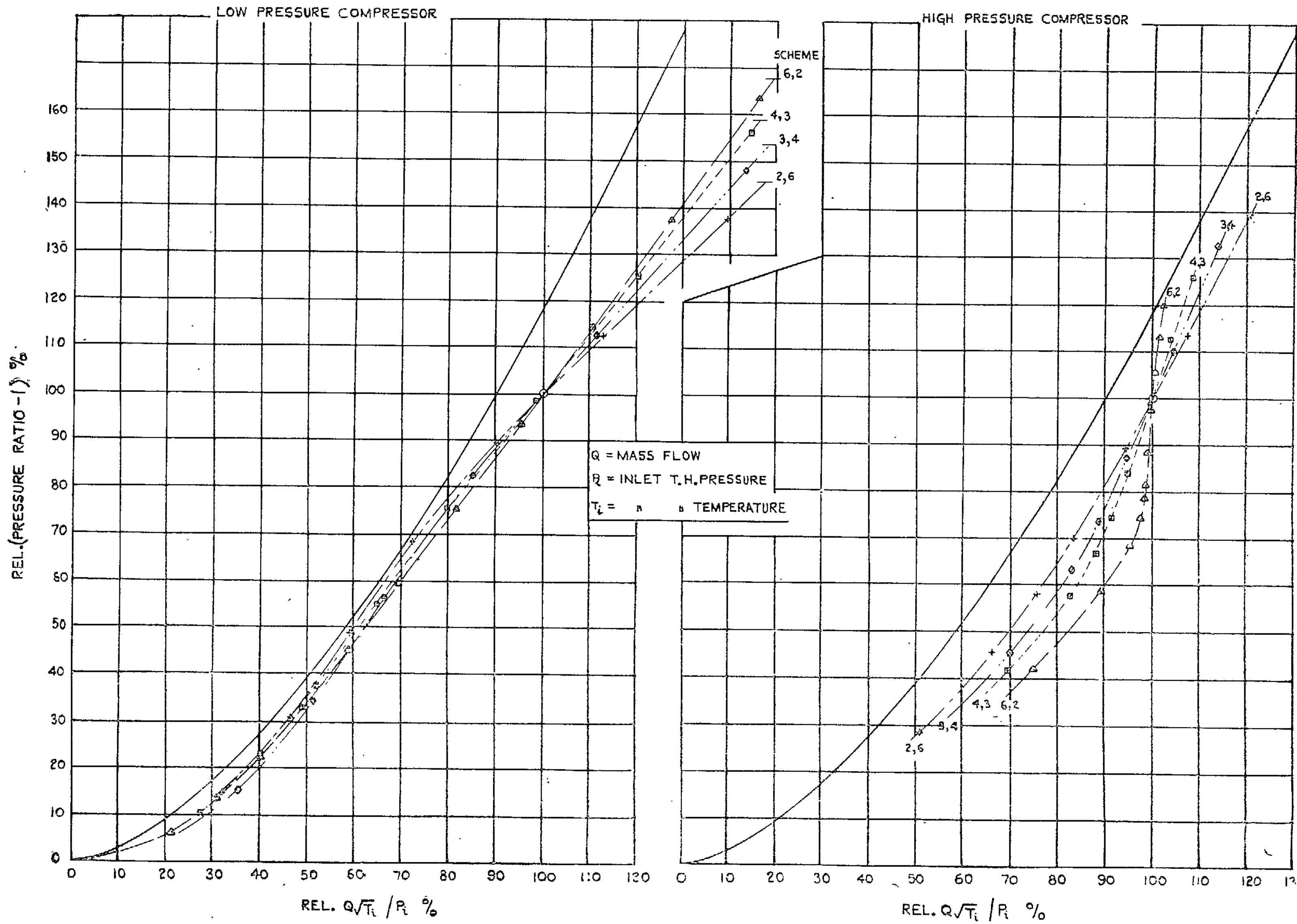

FIG. 1. Simplified investigation. Comparison of compressor operating lines for different low and high-pressure ratios.

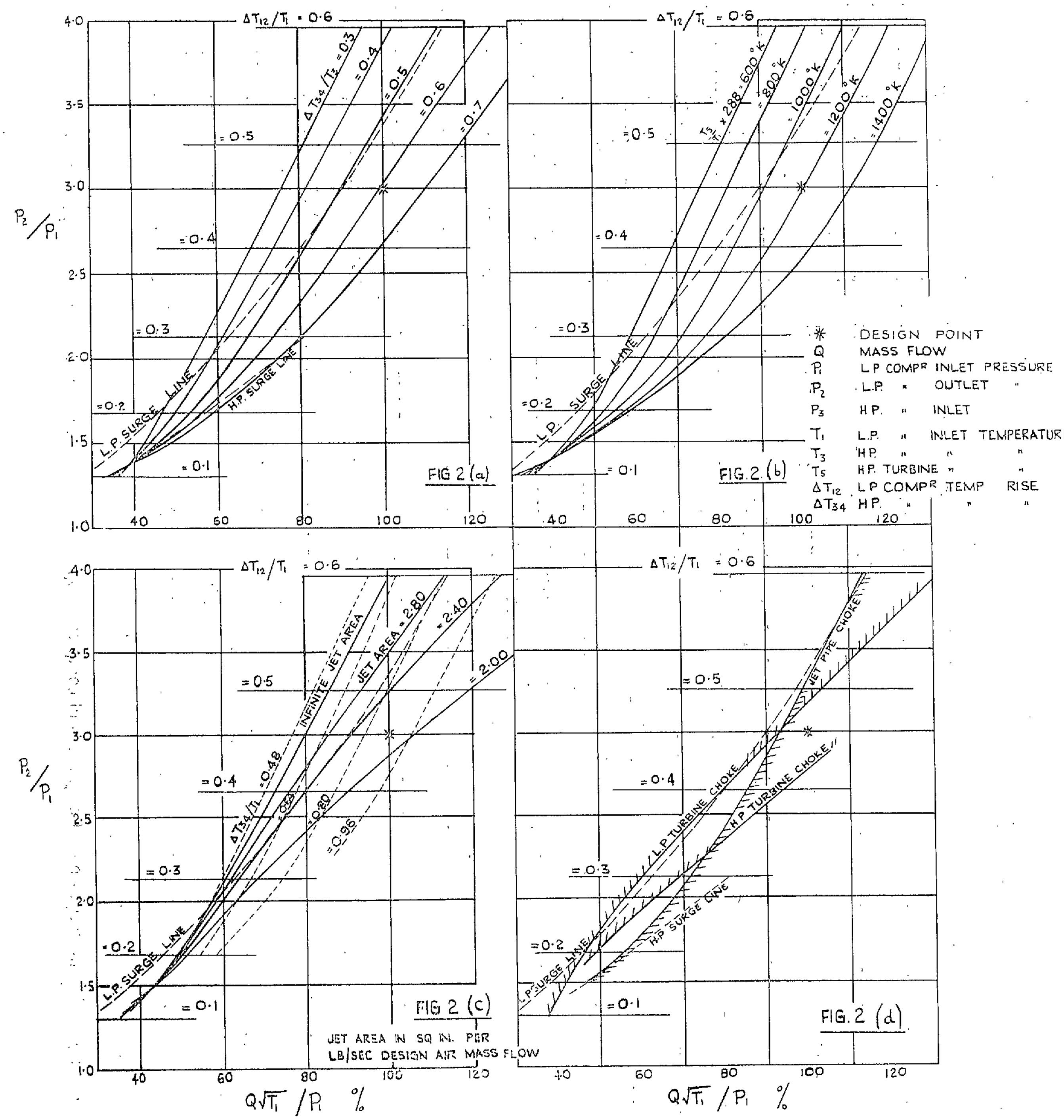

FIG. 2. Scheme 3-4. Low-pressure compressor characteristics.

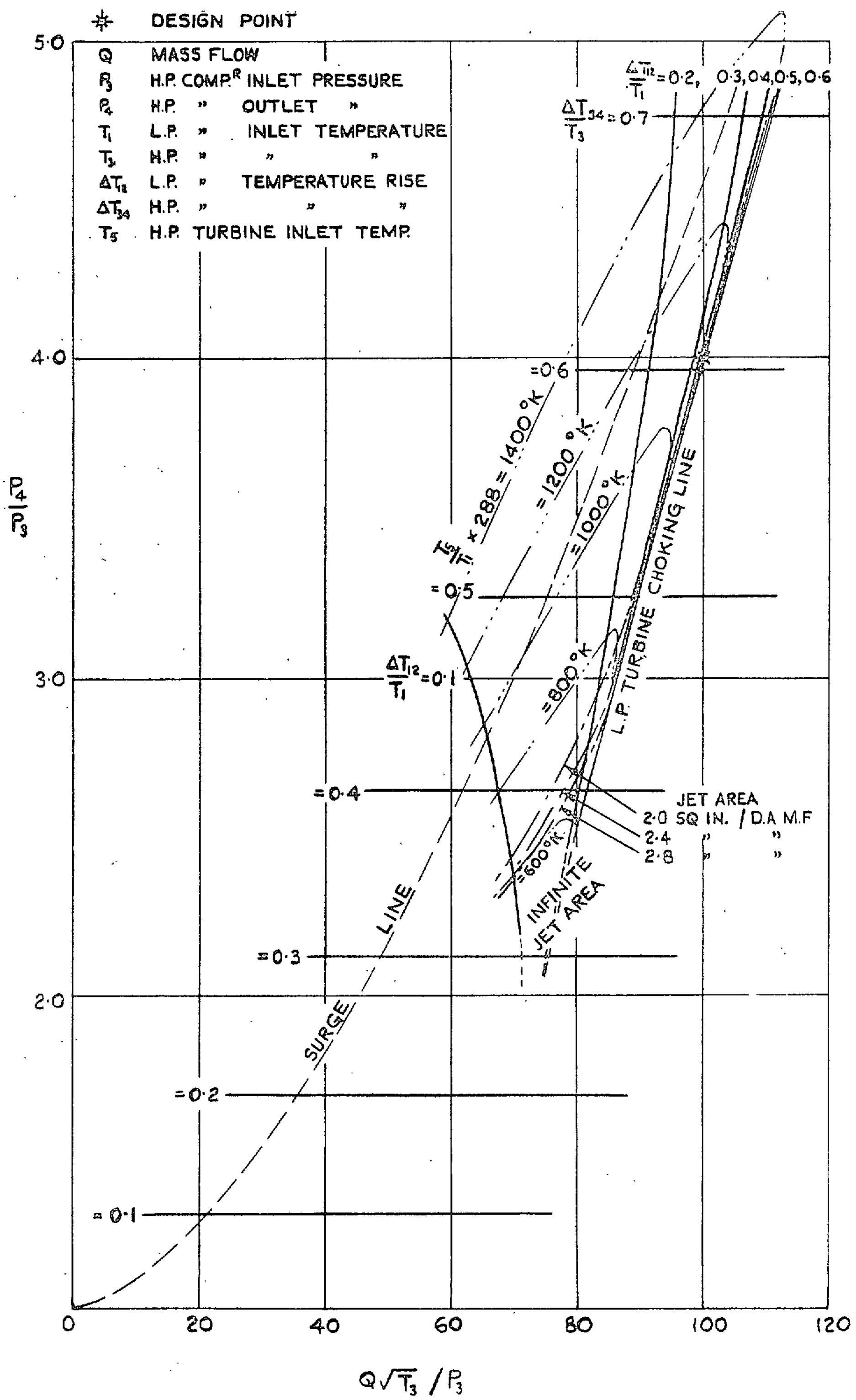

FIG. 3. High-pressure compressor characteristics.

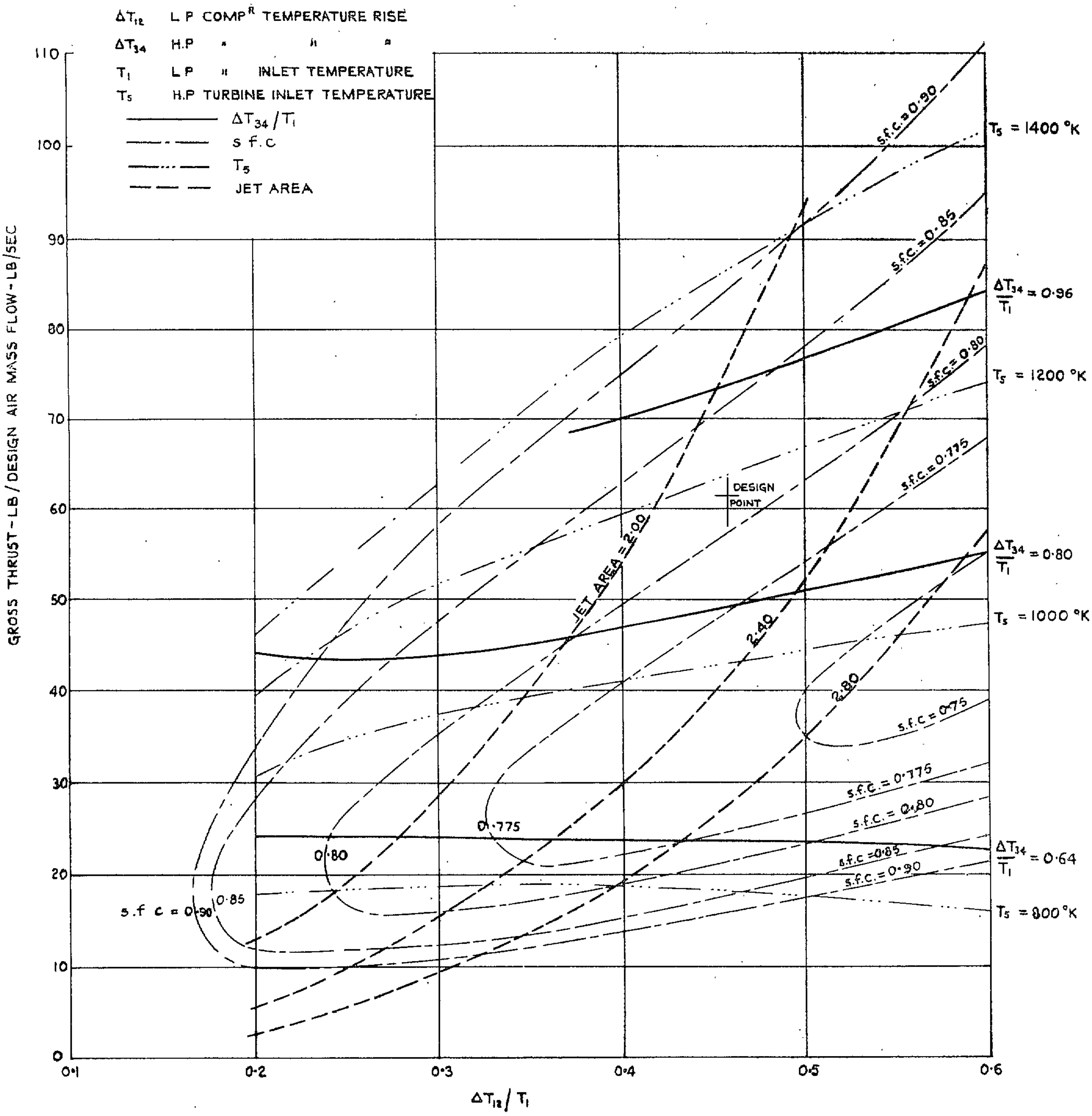

FIG. 4. Simplified investigation. Sea level static performance.

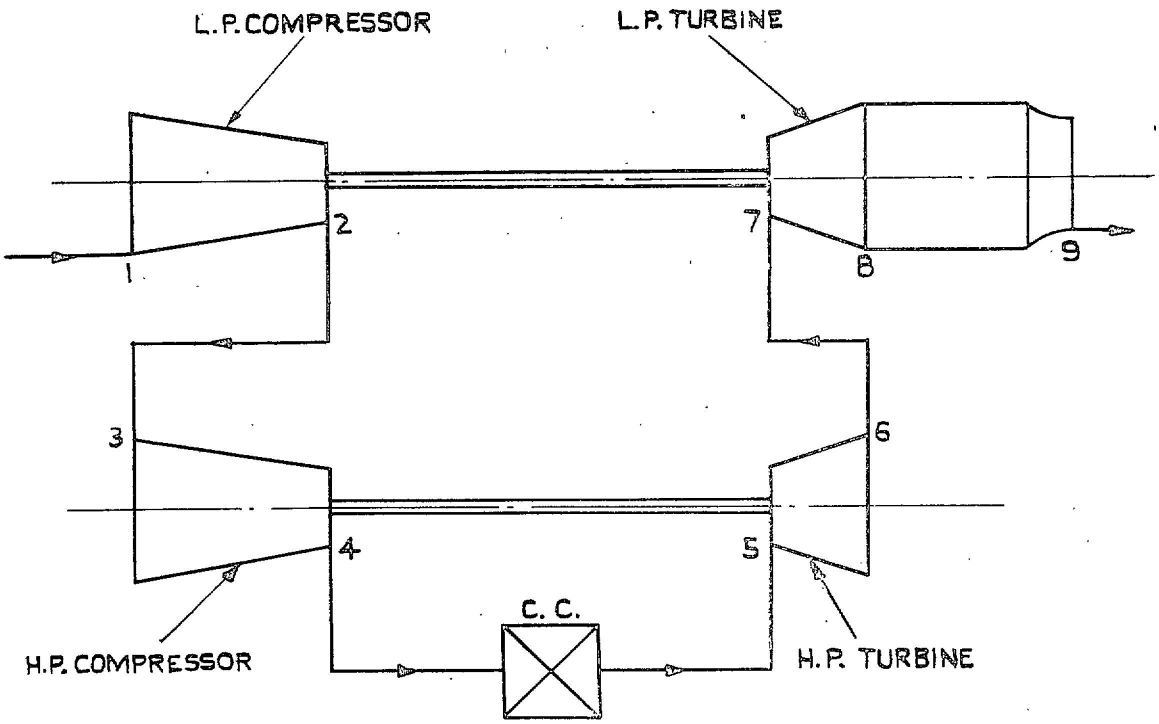

FIG. 5. Diagrammatic arrangement of unit.

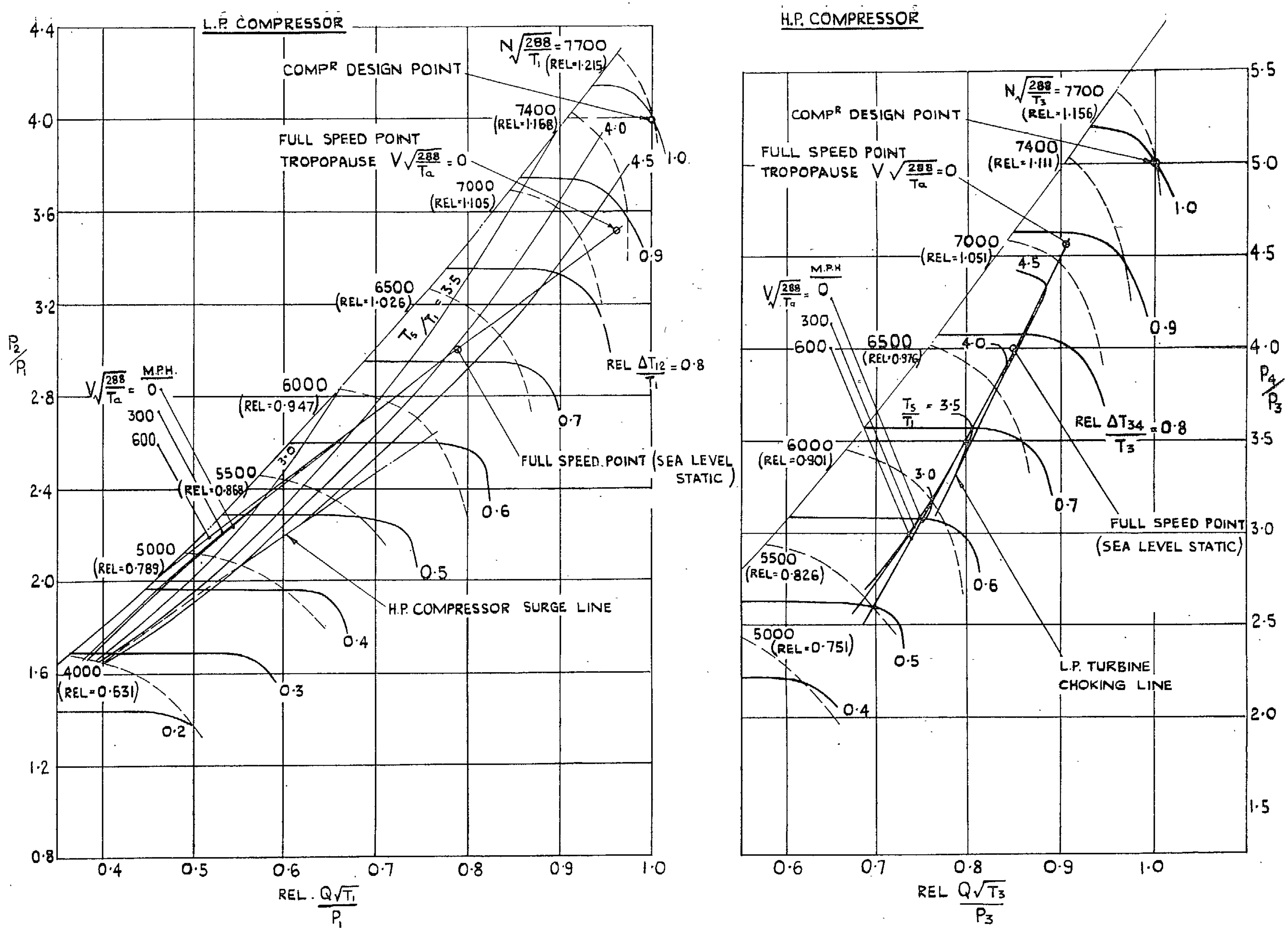

FIG. 6. Equilibrium running lines. Fixed jet area. Design A.

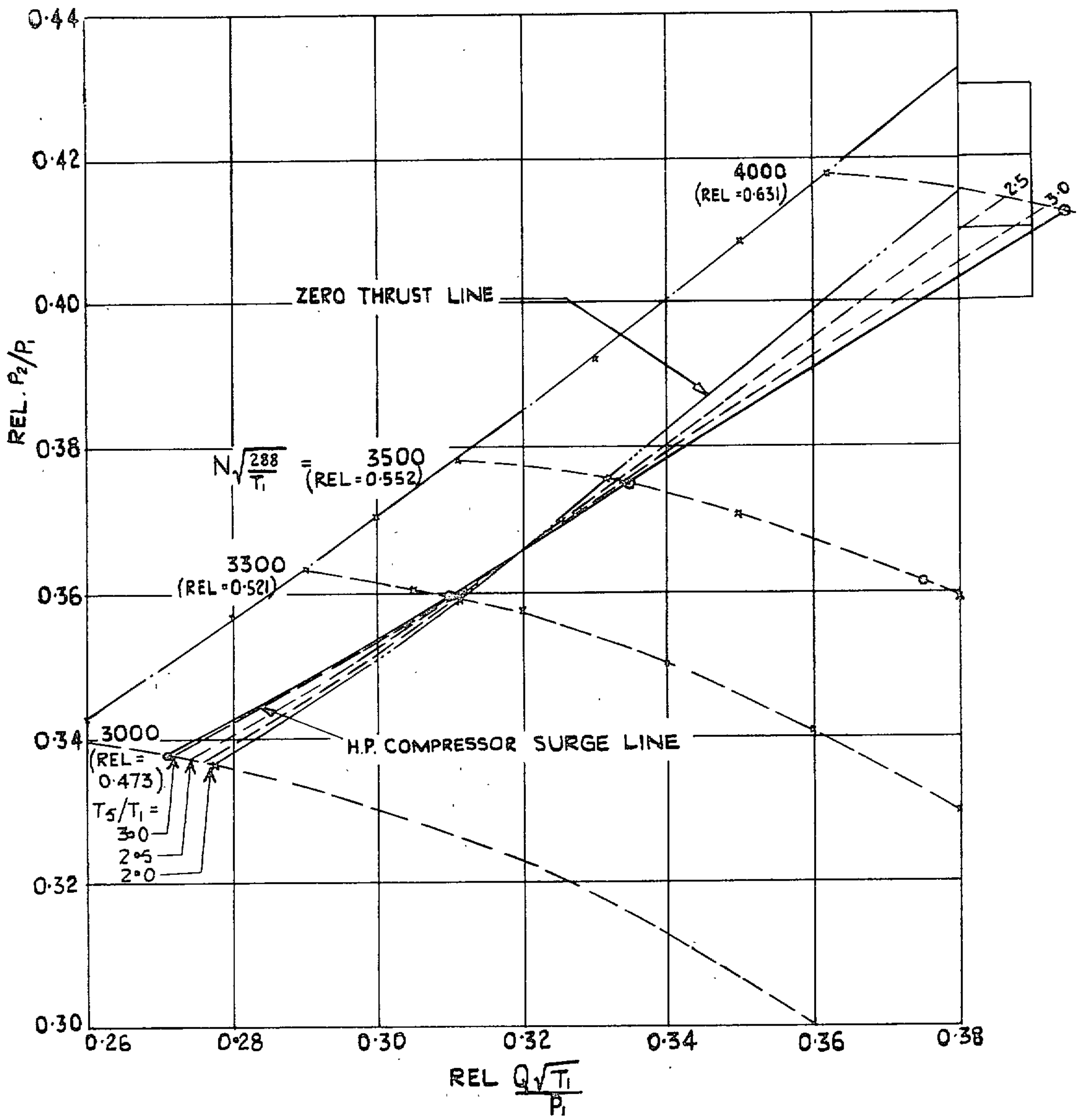

FIG. 7. Design A. Low speed operation of low-pressure compressor.

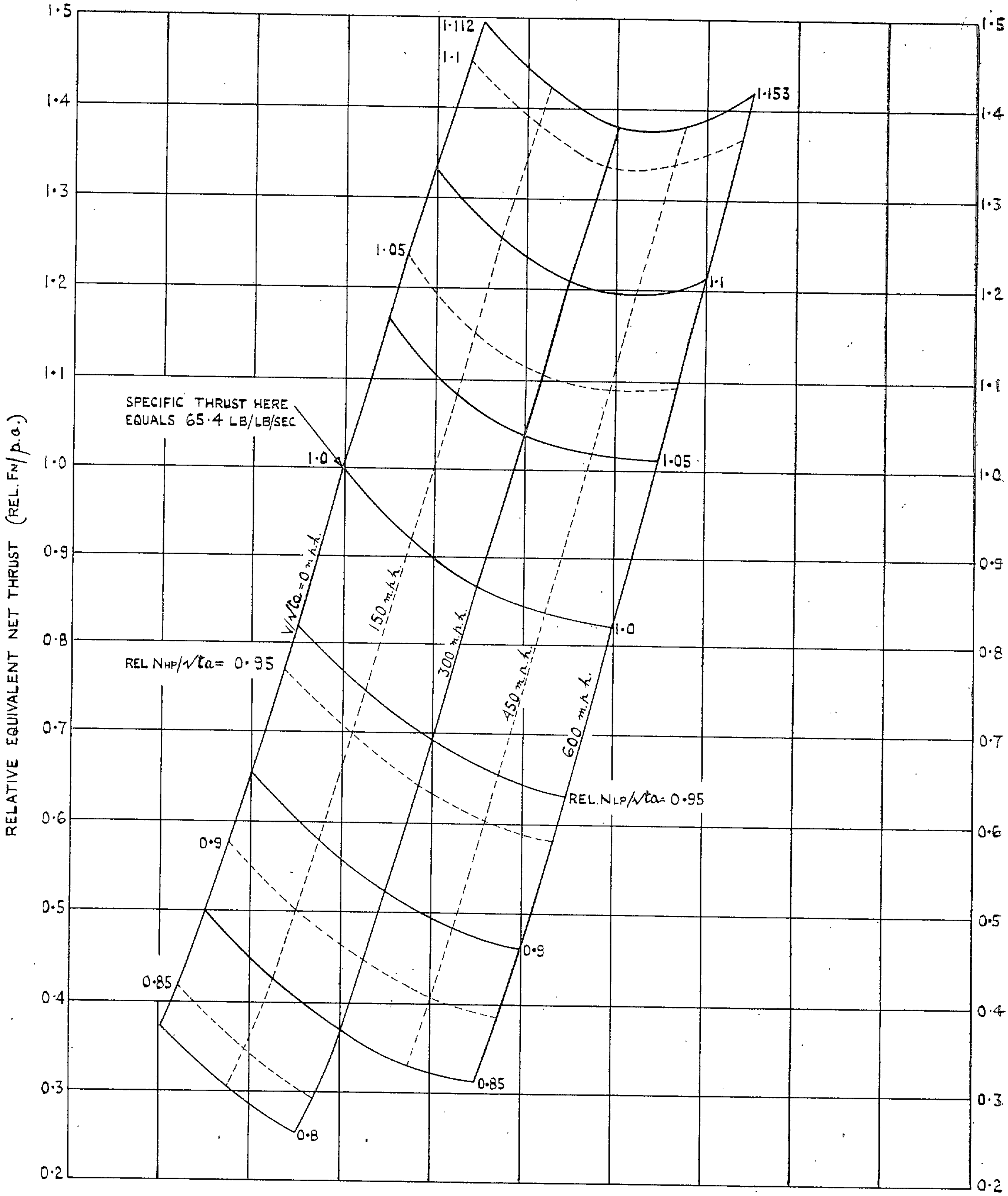

FIG. 8. Variation of thrust with rotational speed and flight velocity expressed as equivalent sea level values. Fixed jet area. Design A.

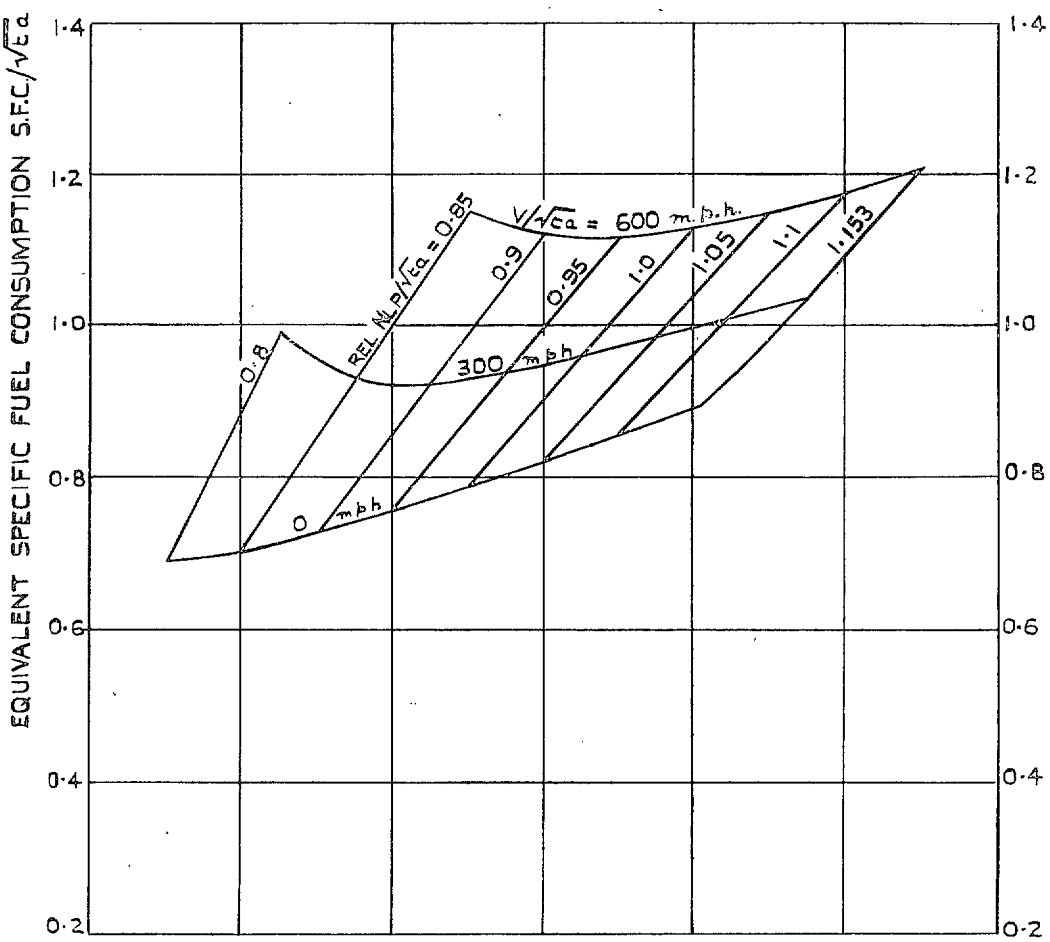

FIG. 9. Variation of specific fuel consumption with rotational speed and flight velocity expressed as equivalent sea level values. Fixed jet area. Design A.

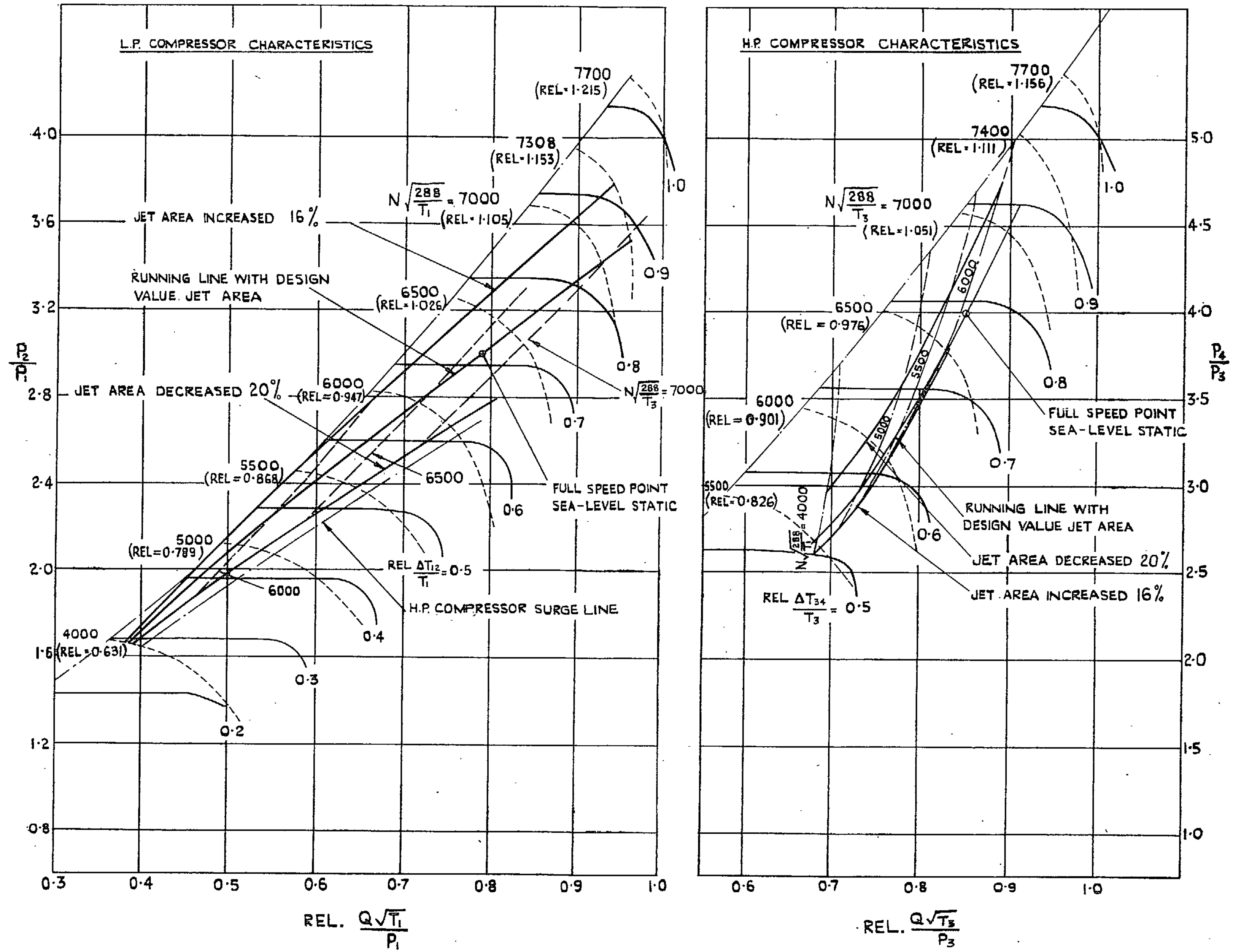

FIG. 10. Equilibrium running lines for different jet areas. Design A.

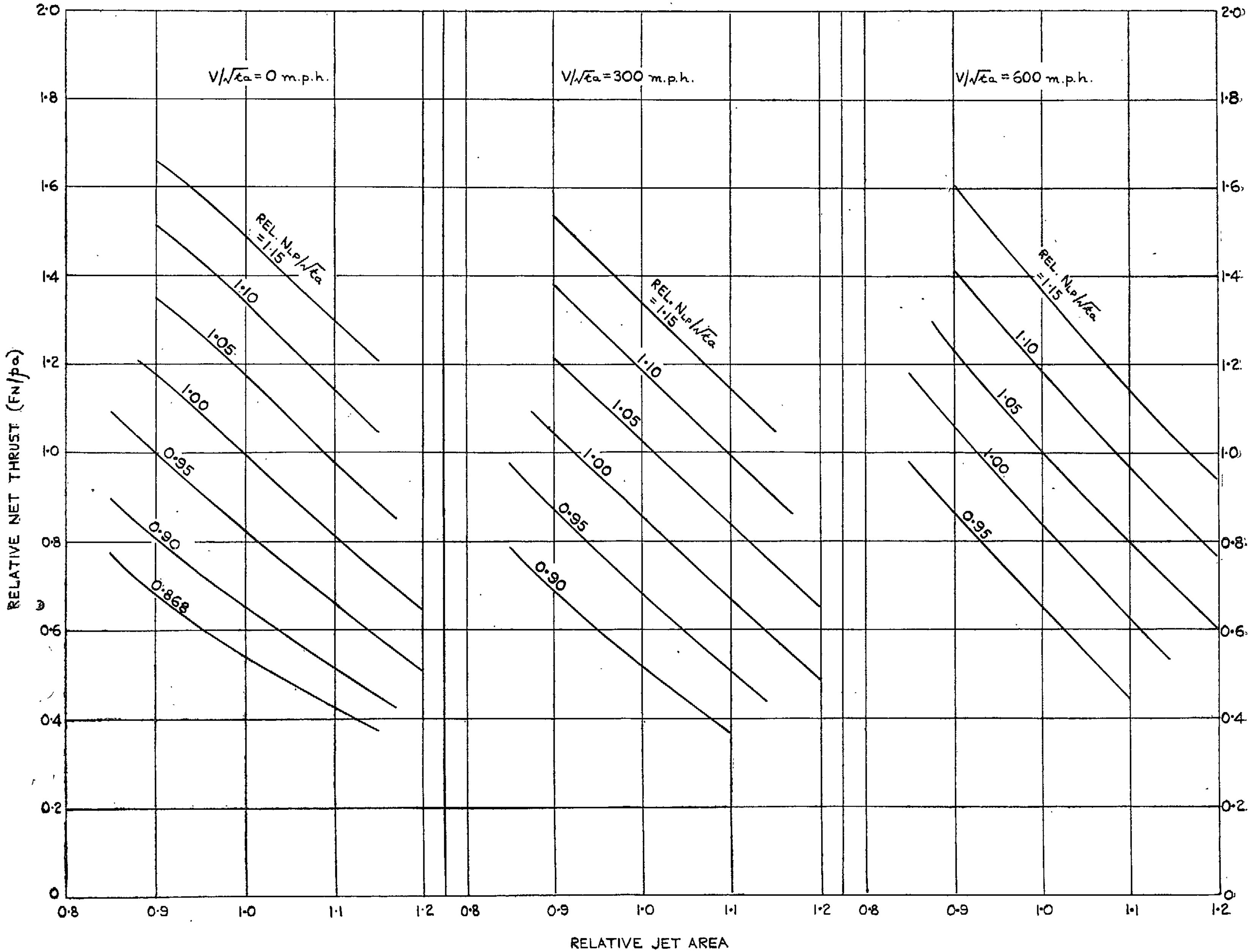

FIG. 11. Variation of net thrust with jet area, rotational speed and forward speed. Design A

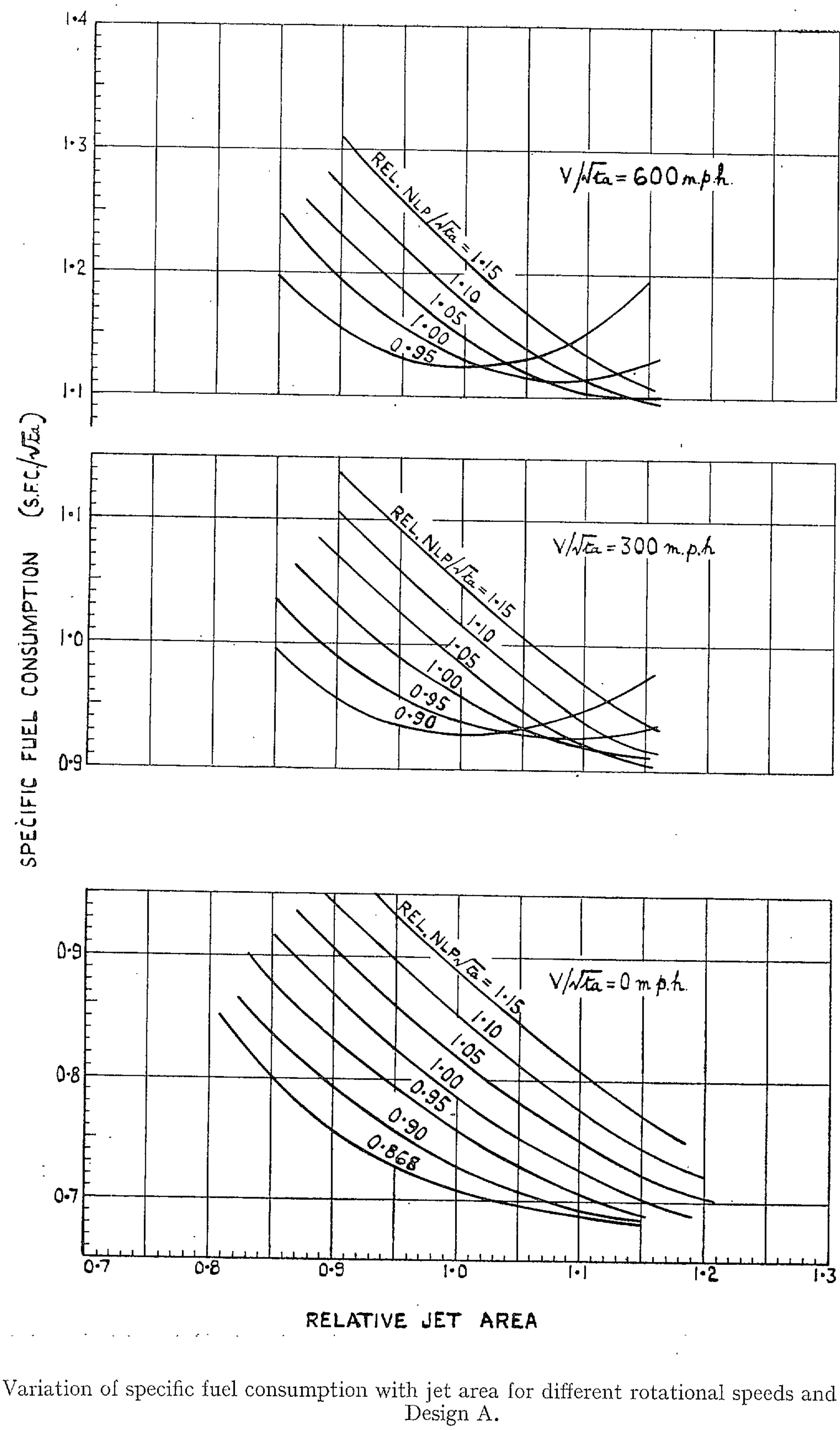

FIG. 12. Variation of specific fuel consumption with jet area for different rotational speeds and flight velocities. Design A.

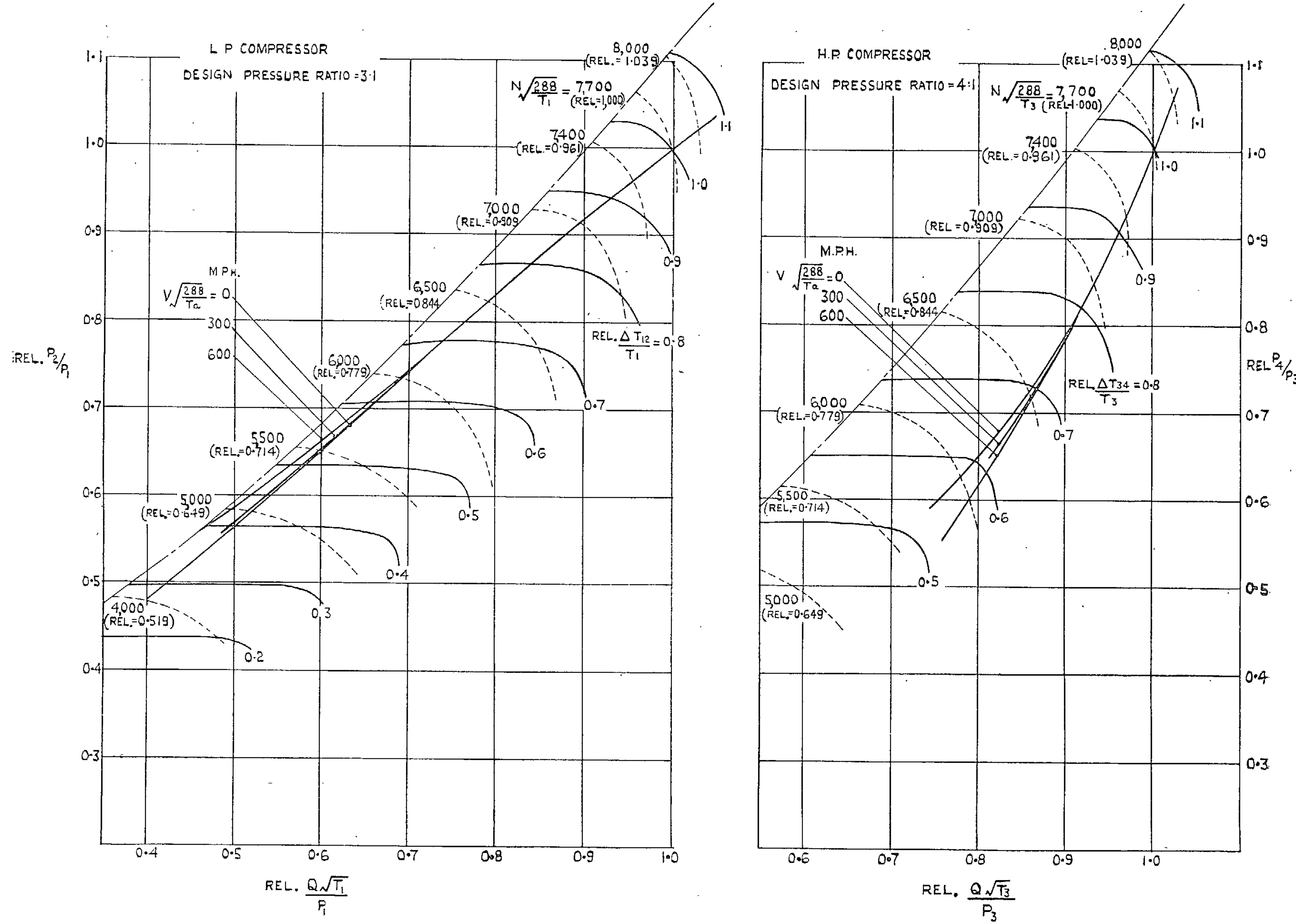

FIG. 13. Equilibrium running lines. Design B.

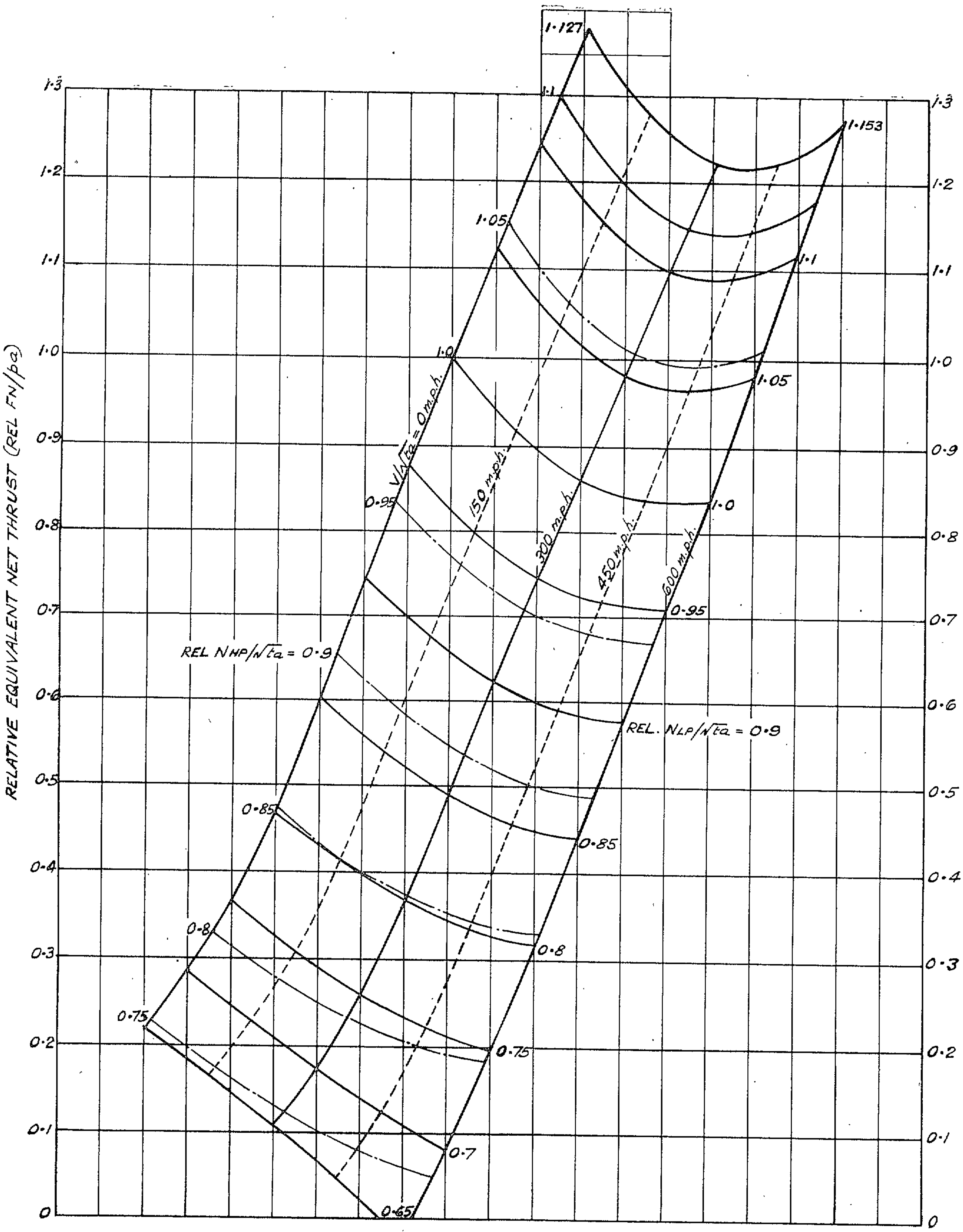

FIG. 14. Variation of thrust with rotational speed and flight velocity expressed as equivalent sea level values. Fixed jet area. Design B.

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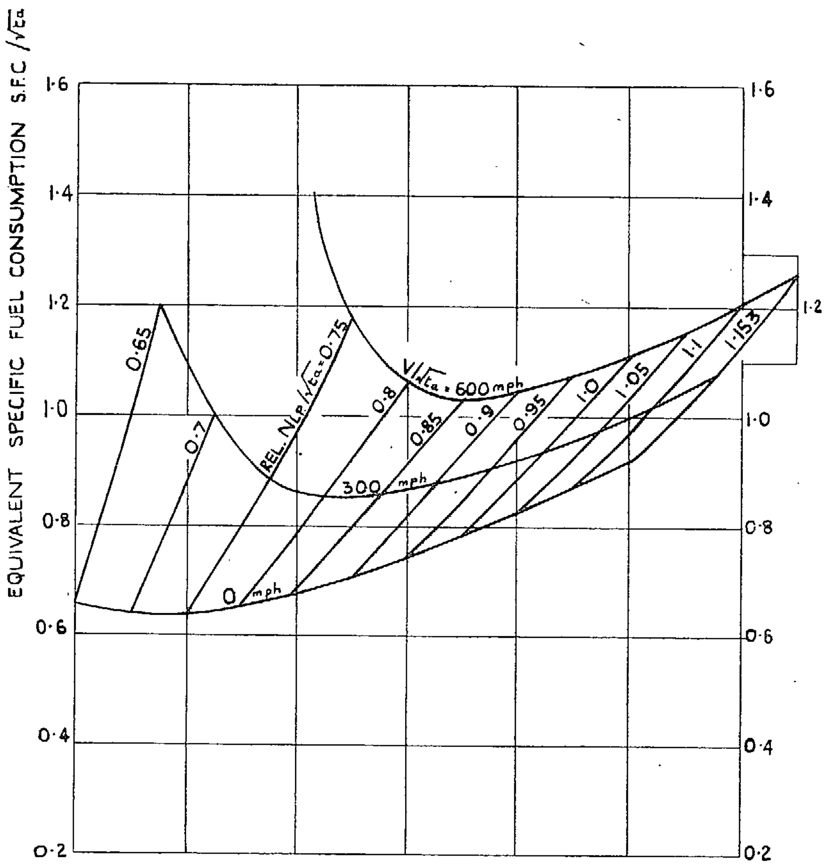

FIG. 15. Variation of specific fuel consumption with rotational speed and flight velocity expressed as equivalent sea level values. Fixed jet area. Design B.

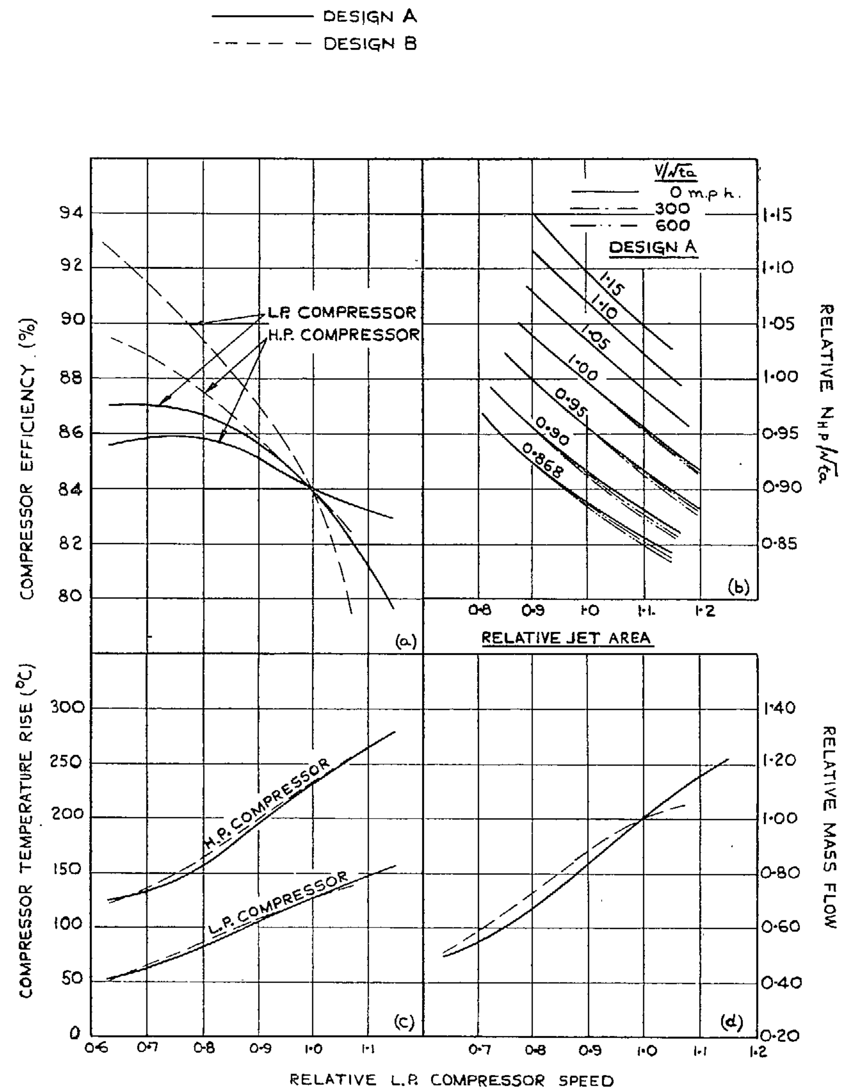

FIG. 16. Temperature rise and mass flow with low-pressure compressor speed (a), (c) and (d).

Variation of Rel. $N_{HP}/\sqrt{(ta)}$ with Rel. $N_{LP}/\sqrt{(ta)}$ and jet area (b).

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