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METHOD FOR DETERMINING COMPONENT MATCHING AND OPERATING CHARACTERISTICS FOR TURBOJET ENGINES

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16. Abstract

Maps are developed for matching the compressor and turbine components of a single-spool engine. Component pressure ratios and engine temperature ratios are determined which satisfy the matching requirements of flow, power, and rotative speed. The method of development is primarily graphic in form. Operating lines are constructed which illustrate two modes of engine operation for two types of missions. Transient operation is also considered. Included is the effect of varying the nozzle throat area on matching the components.

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METHOD FOR DETERMINING COMPONENT MATCHING AND OPERATING CHARACTERISTICS FOR TURBOJET ENGINES

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SUMMARY

A method is presented which graphically illustrates the fundamentals of matching the compressor, turbine, and primary nozzle components of a turbojet engine. For simplicity, the techniques and relations are developed for a single-spool nonafterburning engine. The method would be applicable, however, to the individual spools of a multispool engine.

Matching maps are developed from standard compressor and turbine performance maps which, when overlayed, identified the range of pressure ratios and inlet temperatures over which the power, flow, and rotative speed match between the two components. The maps are then used to locate graphically the operating points and operating lines for two example modes of engine operation which satisfy the propulsion requirements for either a subsonic or supersonic mission. The resulting effects on nozzle throat area requirements are also shown graphically.

The type of mission and mode of operation for which the engine is designed has a large effect on the operational flexibility required of the individual components. For the constant rotative speed, constant turbine inlet temperature operation commonly used for supersonic cruise missions, the turbine operated at essentially a fixed pressure ratio over the entire mission, the nozzle required only nominal changes in throat area, but the compressor had to operate over a wide range of pressure ratio, flow, and equivalent rotative speed. Conversely, modes of operation based on constant equivalent speed operation of the compressor required considerable variation in turbine pressure ratio, rotative speed, and nozzle throat area.

INTRODUCTION

A method has been devised which graphically illustrates the fundamentals of matching the compressor, turbine, and primary nozzle components of a single-spool turbojet engine. For our purposes here, matching is the designing, sizing, and manipulation of the operating characteristics of the components of an engine so that they will work together as a unit. There must be continuity of flow through the engine inlet, compressor, combustor, turbine, and exhaust nozzle; the turbine power must match that required for driving the compressor; the turbine and compressor rotative speeds must be the same; and the increase in static pressure across the inlet and compressor must match the drop in static pressure across the combustor, turbine, and exhaust nozzle.

The fundamentals of matching have been considered to varying degrees in references 1 to 4 as a part of the broader field of engine and component design. Various matching procedures were developed in these references, including many of the parametric relations and mapping techniques used herein. Our purpose is to present the basic concepts of matching in a brief, clear, complete, and graphic manner. Three general areas are considered:

(1) Development of compressor and turbine performance maps.

(2) Development of matching maps.

(3) Development of operating lines.

SYMBOLS

A	flow area
C_p	specific heat at constant pressure
f	fuel-to-air ratio
h	specific enthalpy
M_0	Mach number
N	rotative speed
P	power
p	absolute pressure
R	gas constant
T	absolute temperature
V	absolute velocity
w	weight flow
y	ratio of compressor bleed-flow not passing through the turbine to engine airflow
γ	ratio of specific heats
η	adiabatic efficiency

δ ratio of pressure to standard sea-level pressure, p'/p_{std}

θ engine temperature ratio, T_4'/T_2'

θ_{cr} squared ratio of critical velocity to critical velocity at standard temperature, $\left(V_{cv}/V_{cr,\,std}\right)^2 = \left[2\gamma/(\gamma + 1)\right]\left[gRT'/(1020)^2\right]$; approximately equal to the ratio of temperature to standard temperature, T'/T_{std}

Subscripts:

ax auxiliary power take-off

C compressor

cr critical

d bearing, seal, and windage drag

f fuel

std standard sea-level static condition

T turbine

2 compressor inlet

3 compressor exit

4 turbine inlet

5 turbine exit

6 exhaust nozzle throat

Superscripts:

' total state condition

— average between stations

COMPRESSOR AND TURBINE PERFORMANCE MAPS

In order to determine the performance and operational capability of a turbojet engine, it is necessary to work with the performance maps of the individual components. Such maps are shown in figure 1 for the compressor and turbine components.

Compressor

The curves shown in figures 1(a), (b), (d), and (e) illustrate graphically the develop-

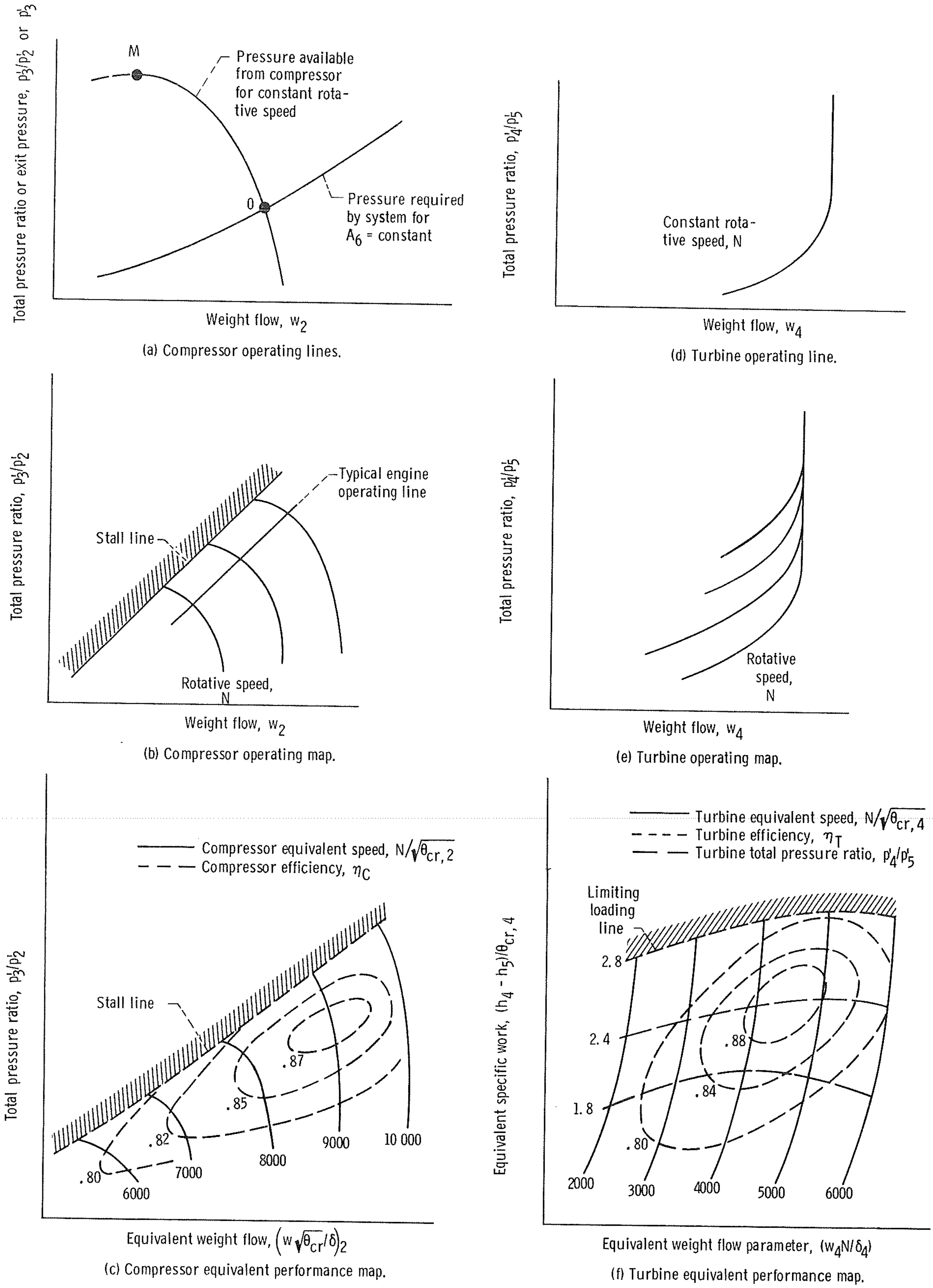


Figure 1. - Evolution of component performance maps.

ment of component maps. For instance, the solid line starting at point M in figure 1(a) shows the variation in flow, w_2, with discharge pressure p'_3 or pressure ratio p'_3/p'_2 for a compressor operating at a given rotative speed N. If the compressor came equipped with a valve at its exit and the valve was nearly closed, the compressor would operate near to point M. Then, as the valve was opened, the weight flow would increase, and the operating point would move down the line towards point O. The other line shown going through point O is generated by leaving the exit valve at the same position as it was for point O, and then increasing or decreasing the rotative speed. Increasing the rotative speed increases both the pressure and flow.

Figure 1(b) shows a series of lines of constant rotative speed N, each generated in the same manner as the line M-O by varying the resistance of the system the compressor must discharge to. For simplicity, the system resistance of an engine can be considered to be the exhaust nozzle. The valve analogy just described is equivalent to varying the throat area of the exhaust nozzle, A_6. In the real case, however, the pressure drop across the burner and turbine components also contributes to the system resistance. A typical system resistance line or operating line for an engine is shown on figure 1(b).

Too high a system resistance, or, in other words, closing down the valve or the nozzle throat area too far, will stall the compressor. Stall occurs to the left of point M in figure 1(a), and when plotted over a series of lines of constant rotative speed, as in figures 1(b) and (c), a stall or surge line is generated. Operation of the compressor at any point to the left of this line is to be avoided. Lines of constant compressor efficiency are then plotted over the lines of constant rotative speed to complete the map as shown in figure 1(c).

One additional requirement is that the values of weight flow and rotative speed be corrected to equivalent weight flow, $\left(w\sqrt{\theta_{cr}}/\delta\right)_2$, and equivalent rotative speed, $N/\sqrt{\theta_{cr,2}}$, as shown in figure 1(c), where $\delta_2 = (p'_2/p_{std})$ and $\theta_{cr,2} \approx (T'_2/T_{std})$. (The exact relation for θ_{cr} is noted in the SYMBOLS.) Otherwise, without referencing the weight flow and rotative speed to a given compressor inlet pressure and temperature, in this case p_{std} and T_{std}, the maps would shift as inlet conditions varied with changing flight speed and altitude. For instance, the location of line M - O in figure 1(a) would move to the left as the aircraft went up in altitude, reducing the pressure of the air entering the compressor. However, when referenced to an equivalent or standard inlet condition, as in figure 1(c), the line remains in a fixed position on the map as inlet pressure and temperature vary with flight conditions. The advantages of using corrected maps will become more apparent later when discussing the details of operating lines.

Turbine

The constant rotative speed line shown in figure 1(d) for the turbine was developed using the same valve analogy as in figure 1(a) for the compressor, however, the shape of the line is different. The vertical portion of the line which extends over all but the lowest pressure ratios indicates that the flow chokes across the turbine. At the lowest pressure ratios, analogous to a nearly closed valve at the exit of the turbine, or a closed-down nozzle throat area, A_6, the turbine unchokes and the flow drops off rapidly.

A series of lines of constant rotative speed are shown in figure 1(e), for a constant inlet pressure, p_4', showing that they all converge to a choked flow condition, but at progressively higher pressure ratios. In order to spread the lines apart so that contours of efficiency can be shown in the choked region, the weight flow term of the abscissa is usually multiplied by the rotative speed, $w \times N$. Also, convention has been to change the ordinate from pressure ratio to specific work using the relation

$$\Delta h_T = h_4 - h_5 = \bar{C}_{P,T} T_4' \eta_T \left[1 - \left(\frac{p_5'}{p_4'}\right)^{(\bar{\gamma}-1)/\bar{\gamma}}\right]$$

or by using values of enthalpy found from the appropriate gas tables. Pressure ratio is then plotted as an overlay on the map. Finally, the values of rotative speed, weight flow, and specific work are corrected to what they would be if the pressure and temperature of the gas entering the turbine were 14.695 psia (10.13 N/cm^2) and 518.7° R (288 K), respectively, or, in other words, $\delta_4 = (p_4'/p_{std})$, and $\theta_{cr,4} \approx (T_4'/T_{std})$. The results are then replotted, as shown in figure 1(f). The limiting loading line indicates the maximum amount of equivalent specific work that can be obtained from the turbine. Going to higher pressure ratios across the turbine produces no further increase in this work.

MATCHING MAPS

Observation of the component performance maps of figure 1(c) and (f) indicates that their ordinate and abscissa parameters are not consistent. One map cannot be placed over the other to find their common points or areas of operation. To match the two components in terms of weight flow, rotative speed, and power would require individual solutions for their common operating points over the entire area of the maps. Another way would be to reorient and replot the two maps to ordinate and abscissa parameters that would be consistent between the two components. Then the two maps could be overlayed and the common areas of matched operation determined graphically. Such maps are called matching maps, and the following equations and figures show how these matching maps can be developed from the component maps of figure 1.

For clarity, the development of the relations for the compressor and turbine components, equating weight flow, rotative speed, and power, are shown diagrammatically in table I. Equation (2) in the table equates, in terms of equivalent rotative speed and component inlet temperature, the requirement that the rotative speed of the two components

TABLE I. - DEVELOPMENT OF MATCHING PARAMETERS

Basic relations	Flow, $w_C = w_T$	Speed, $N_C = N_T$	Power, $P_C = P_T$
Assumptions for simplified matching relations	1. $p'_3 = p'_4$ 2. No fuel, $w_f = 0$ 3. No bleed flow, $y = 0$ 4. No flow leakage	1. $\gamma_C = \gamma_T$ 2. $c_{p,C} = c_{p,T}$	1. No auxiliary power takeoffs. 2. No bearing, seal, or windage drag.
Development	$\frac{w_C\sqrt{\theta_{cr,2}}}{\delta_2} = \frac{w_T\sqrt{\theta_{cr,2}}}{\delta_2}$ $\frac{w_C\sqrt{\theta_{cr,2}}}{\delta_2} = \frac{w_T\sqrt{\theta_{cr,4}}}{\delta_4}\sqrt{\frac{\theta_{cr,2}}{\theta_{cr,4}}}\frac{\delta_4}{\delta_2}$ $\frac{w_C\sqrt{\theta_{cr,2}}}{\delta_2}\frac{N_C}{\sqrt{\theta_{cr,2}}} = \frac{w_T\sqrt{\theta_{cr,4}}}{\delta_4}\frac{N_T}{\sqrt{\theta_{cr,4}}}\frac{p'_4}{p'_2}$	$\frac{N_C}{\sqrt{\theta_{cr,2}}} = \frac{N_T}{\sqrt{\theta_{cr,2}}}$ $\frac{N_C}{\sqrt{\theta_{cr,2}}} = \frac{N_T}{\sqrt{\theta_{cr,4}}}\sqrt{\frac{\theta_{cr,4}}{\theta_{cr,2}}}$ $\sqrt{\frac{\theta_{cr,4}}{\theta_{cr,2}}} = \frac{\frac{N_C}{\sqrt{\theta_{cr,2}}}}{\frac{N_T}{\sqrt{\theta_{cr,4}}}}$	$(w\Delta h)_C = (w\Delta h)_T$ $\Delta h_C = \Delta h_T$ $\frac{\Delta h_C}{\theta_{cr,2}} = \frac{\Delta h_T}{\theta_{cr,2}}$ $\frac{\Delta h_C}{\theta_{cr,2}} = \frac{\Delta h_T}{\theta_{cr,4}} \times \frac{\theta_{cr,4}}{\theta_{cr,2}}$
		$\frac{\theta_{cr,4}}{\theta_{cr,2}} = \frac{\frac{N_C^2}{\theta_{cr,2}}}{\frac{N_T^2}{\theta_{cr,4}}}$	
Simplified matching relations	$\frac{\frac{w_C N_C}{\delta_2}}{\frac{p'_3}{p'_2}} = \frac{w_T N}{\delta_4}$ (eq. (1))	$\frac{T'_4}{T'_2} = \left[\frac{\frac{N_C}{\sqrt{\theta_{cr,2}}}}{\frac{N_T}{\sqrt{\theta_{cr,4}}}}\right]^2$ (eq. (2))	$\left(\frac{\Delta h}{N^2}\right)_C = \left(\frac{\Delta h}{N^2}\right)_T$ (eq. (3))
Matching relations for no simplifying assumptions	$\frac{(1 - y)(1 + f)(wN)_C}{\left(\frac{p'_3}{p'_2}\right)\left(\frac{p'_4}{p'_3}\right)\delta_2} = \frac{w_T N}{\delta_4}$ (eq. (4))	$\frac{T'_4}{T'_2} = \frac{\gamma_2(\gamma_4 + 1)R_2}{\gamma_4(\gamma_2 + 1)R_4}\left[\frac{\frac{N_C}{\sqrt{\theta_{cr,2}}}}{\frac{N_T}{\sqrt{\theta_{cr,4}}}}\right]^2$ (eq. (5))	$\frac{1}{(1 - y)(1 + f)}\left(\frac{\Delta h_C}{N^2} + \frac{P_d + P_{ax}}{w_C N^2}\right) = \left(\frac{\Delta h}{N^2}\right)_T$ (eq. (6))

be equal at all operating points, $N_C = N_T$. In similar developments, equations (1) and (3) in table I equate the other matching requirements of equal weight flow, $w_C = w_T$, and power, $P_C = P_T$, for both components. These three equations (eqs. (1) to (3)) include the simplifying assumptions noted on the second line of the table. The effect of these assumptions is shown by comparing with equations (4) to (6).

The ordinate of both component maps of figures 1(c) and (f) was then converted to the power matching parameter of equation (3) using the expressions

$$\left(\frac{\Delta h}{N^2}\right)_C = \frac{\bar{C}_{P,C}T_2'}{\eta_C N^2}\left[\left(\frac{p_3'}{p_2'}\right)^{(\bar{\gamma}-1)/\bar{\gamma}} - 1\right]$$

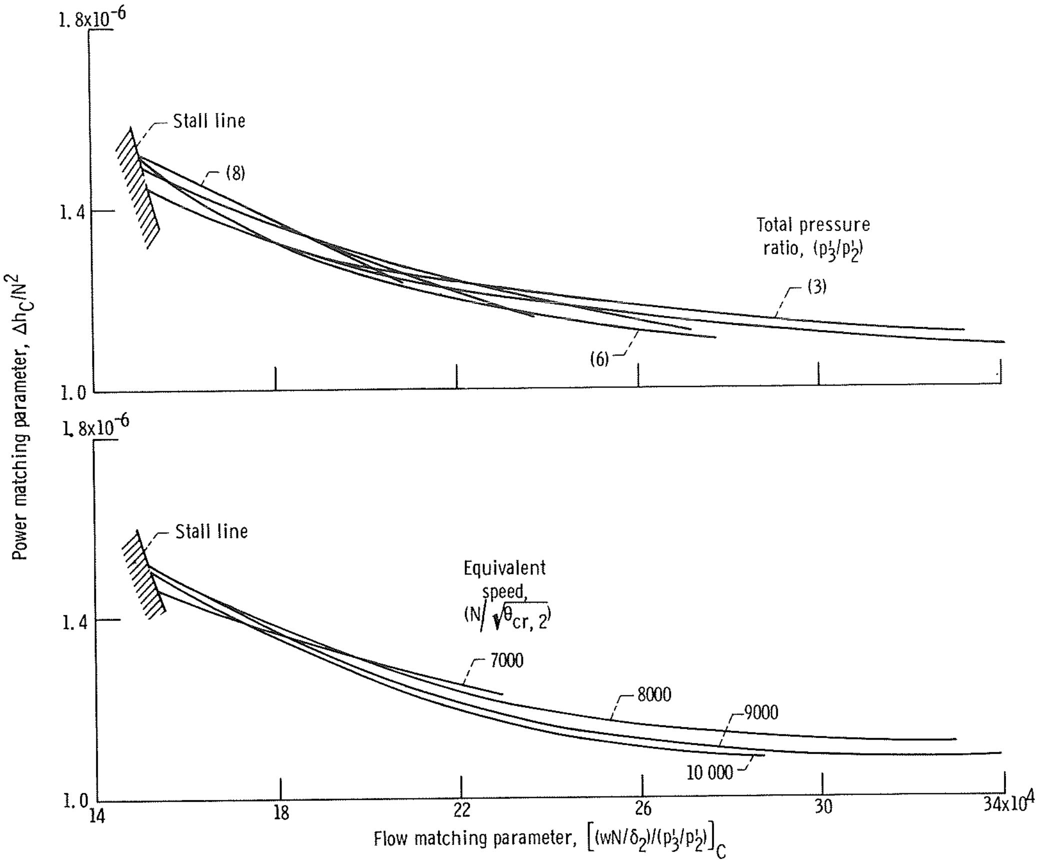
and

$$\left(\frac{\Delta h}{N^2}\right)_T = \frac{\dfrac{\Delta h_T}{\theta_{cr,4}}}{\left(\dfrac{N_T}{\sqrt{\theta_{cr,4}}}\right)^2}$$

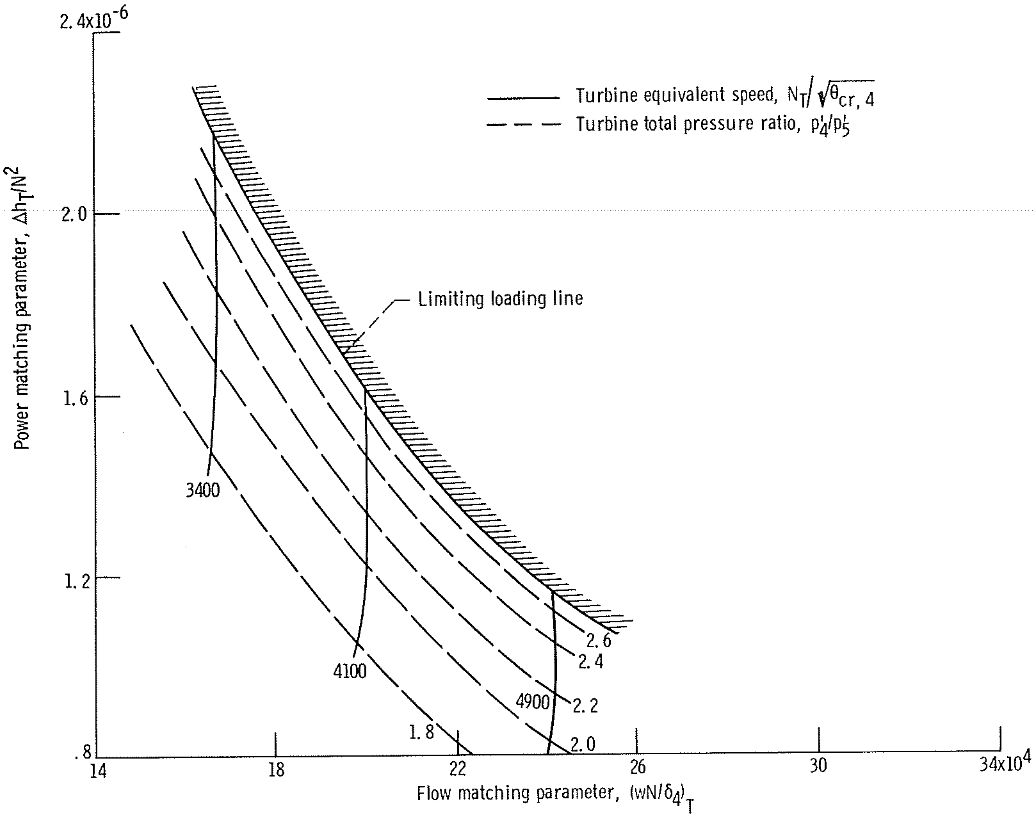
Similarly, the abscissa of figures 1(c) and (f) was converted to the flow matching parameters of equation (1) (table I) where it may be noted that the abscissa parameter for the turbine map is already in its correct form for matching, $w_T N/\delta_4$. The abscissa parameter for the compressor map must be multiplied and divided by its equivalent rotative speed and pressure ratio, respectively, to make it comparable with the turbine,

$$\frac{\left(\dfrac{w_C\sqrt{\theta_{cr,2}}}{\delta_2}\right)_2 \times \dfrac{N}{\sqrt{\theta_{cr,2}}}}{\dfrac{p_3'}{p_2'}} = \frac{\dfrac{w_C N}{\delta_2}}{\dfrac{p_3'}{p_2'}}$$

which may be shown to be equal to the matching parameter for the turbine (for the simplifying assumptions of $p_3' = p_4'$ and $w_C = w_T$), as follows



(a) Compressor.



(b) Turbine.

Figure 2. - Matching maps.

$$\left(\frac{\frac{w_C N}{\delta_2}}{\frac{p_3'}{p_2'}}\right)\left(\frac{\delta_2}{\frac{p_2'}{14.7}}\right)\left(\frac{p_3'}{p_4'}\right)\left(\frac{w_T}{w_C}\right)\left(\frac{\frac{p_4'}{14.7}}{\delta_4}\right) = \frac{w_T N}{\delta_4}$$

The resulting matching maps are shown in figure 2. They are plots of the power matching parameter for lines of constant pressure ratio and constant equivalent rotative speed for both components. Two plots are shown in figure 2(a) for the compressor map to distinguish between the lines of constant pressure ratio and constant equivalent rotative speed, since they both fall on top of each other. The plots are characteristic of this form of compressor matching map, which is actually no longer a map but a narrow band approaching a single line. The stall line still defines the lower flow and upper power limit for the compressor.

The matching map for the turbine, shown in figure 2(b), is likewise considerably changed from its form in figure 1(f), but unlike the single band for the compressor, the turbine still appears as a map. Lines of constant equivalent rotative speed and pressure ratio form a grid pattern, restricted only by the limiting loading characteristics of the turbine.

Figure 3 shows the matching maps overlaying one another. The figure shows the stall limit for the compressor, the limiting loading line for the turbine, and all the parameters required to describe the performance of the two components. The requirements can only be matched over the narrow operating band of the compressor, limited on the left end of the band by the compressor stall line, and on the right end by the turbine limiting loading line. Only a small portion of the turbine operating map is actually used. Note that the turbine has insufficient power or flow handling capacity to drive the compressor beyond the limiting loading line.

Another interesting characteristic noted on figure 3 is that it is possible to maintain the turbine at essentially a constant turbine equivalent rotative speed and pressure ratio while the compressor is operated over its entire range of equivalent rotative speed and pressure ratio. Use will be made of this characteristic in the next section of the report where the various modes of engine operation are discussed. Note also that matched values of equivalent rotative speed can be read directly from figure 3 for both the components. Therefore, the value of engine temperature ratio, θ, defined as the ratio of T_4'/T_2', required to operate the two components at any point over their common range of operation can be computed using equation (2) of table I.

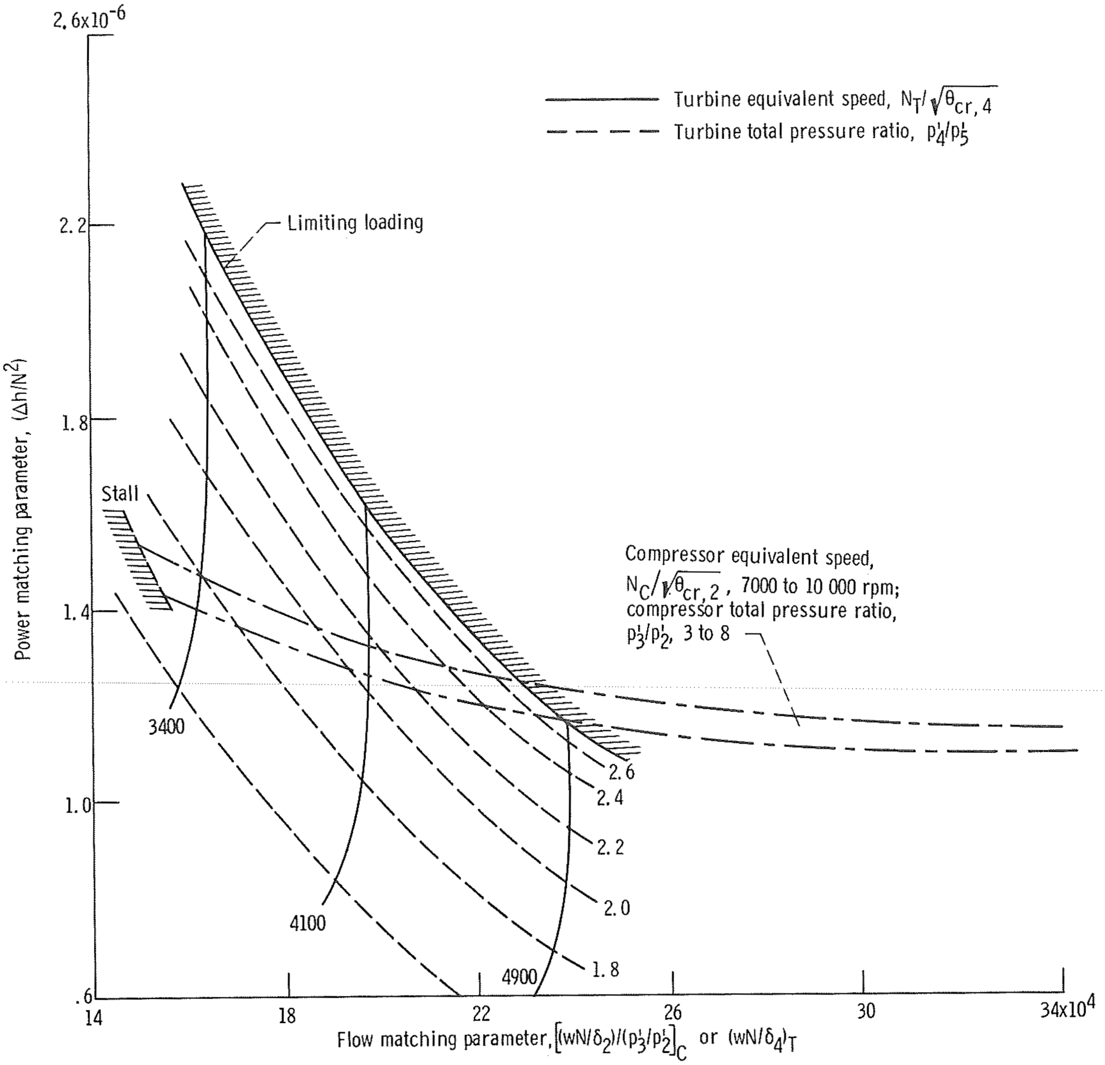
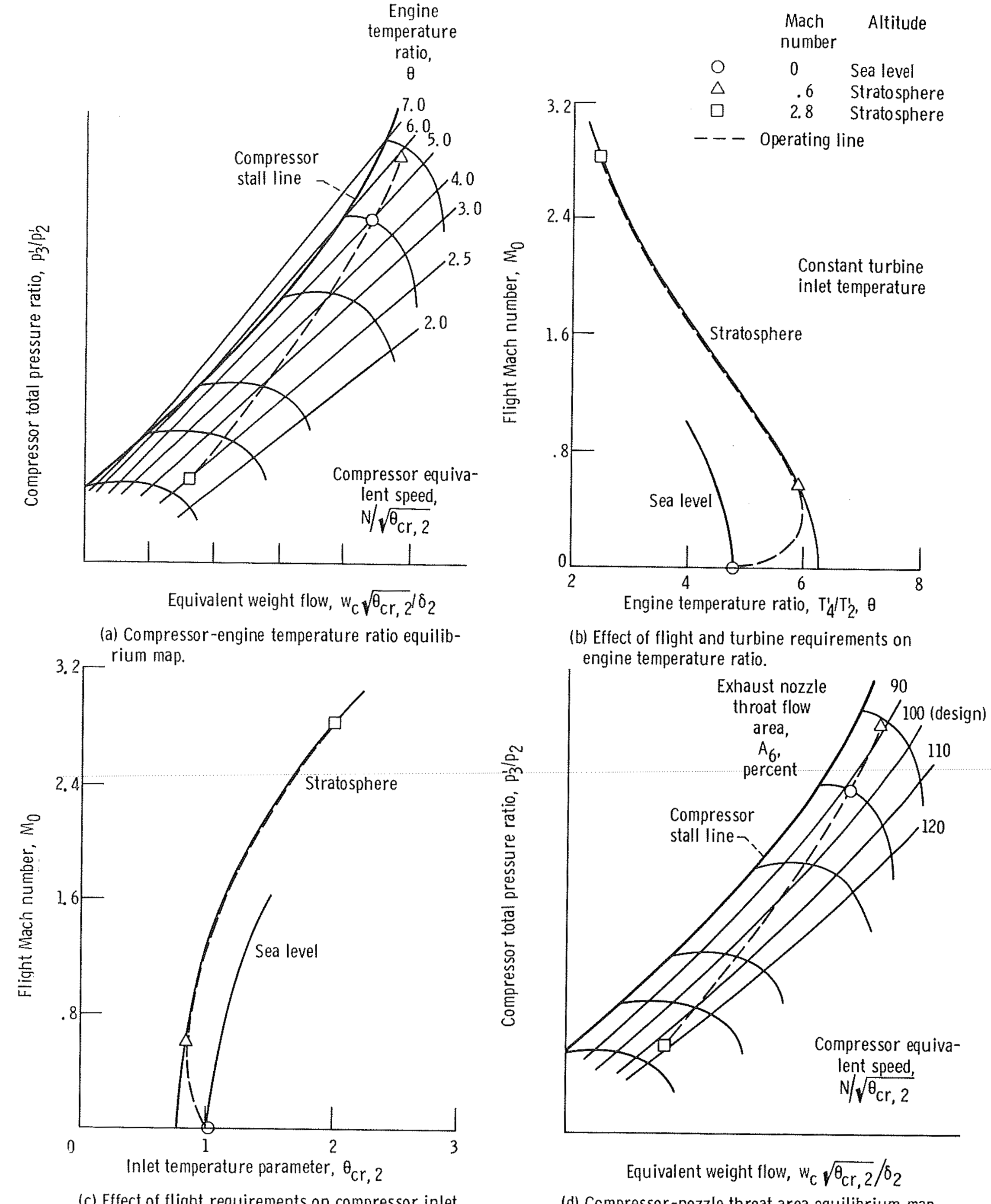


Figure 3. - Overlay of compressor and turbine matching maps.



(a) Compressor-engine temperature ratio equilibrium map.

(b) Effect of flight and turbine requirements on engine temperature ratio.

(c) Effect of flight requirements on compressor inlet theta.

(d) Compressor-nozzle throat area equilibrium map.

Figure 4. - Equilibrium operating maps.

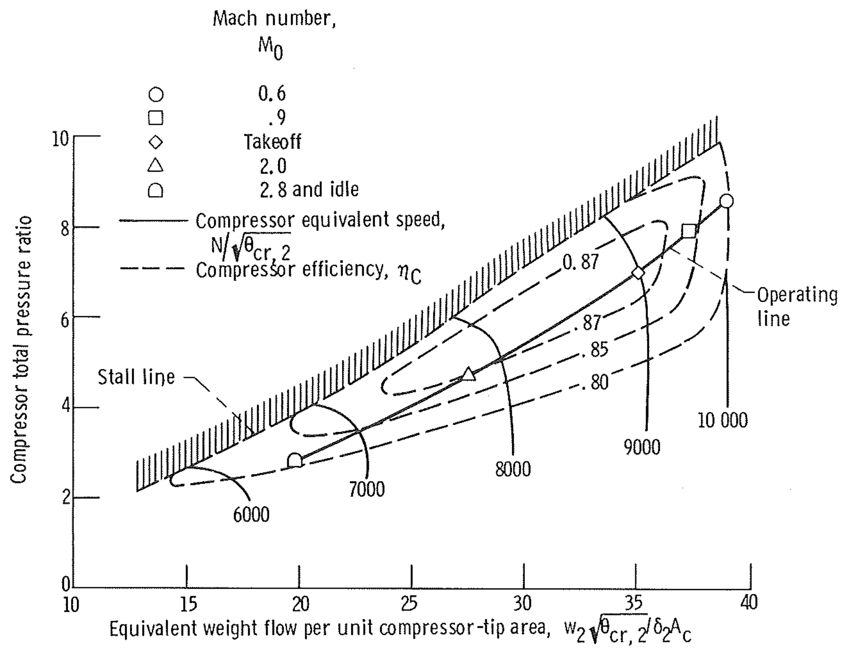
OPERATING LINES

Figure 4(a) shows lines of constant engine temperature ratio, θ, computed as just described in the previous section and plotted as an overlay on the compressor performance map. Reference 3 refers to this form of the map as an equilibrium operating map, and it is from the relations shown here that the operating points for the compressor, turbine, and engine can be determined at each point of the mission from takeoff to cruise. This can be seen with the aid of figures 4(b) and (c) where the relation of flight Mach number and altitude to the two engine parameters of θ (at a given turbine inlet temperature) and $\theta_{cr,2}$ is shown. At takeoff, the engine temperature ratio, θ, for a turbine inlet temperature of 2000° F (1367 K), and the inlet temperature parameter $\theta_{cr,2}$ are approximately 4.7 and 1.0, respectively, as shown by the example points. If a flight Mach number of 0.6 is reached above an altitude of 36 000 feet (10973 m) (stratosphere), such as a subsonic cruise engine, the two parameters become approximately 5.9 and 0.80, respectively. At Mach 2.8 for a supersonic engine, they become 2.4 and 2.0, respectively. Assuming the rotative speed N of the engine is known (it is usually held constant from takeoff to cruise at a value close to the mechanical speed limit of the compressor and turbine), the value of $N/\sqrt{\theta_{cr,2}}$ can be computed for each flight Mach number and altitude from figure 4(c). Then, with $N/\sqrt{\theta_{cr,2}}$ and θ known, each operating point can be plotted on figure 4(a). This procedure is noted by following the example points from figures 4(b) and (c) to figure 4(a).

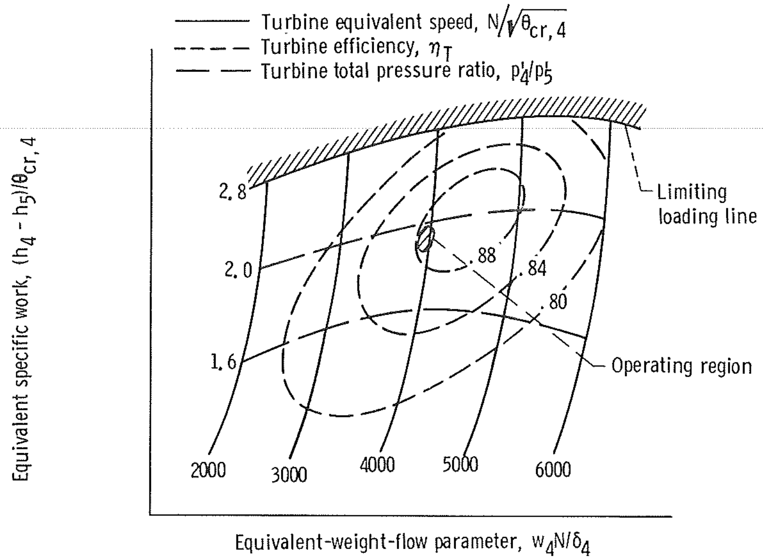
Figure 4(d) shows lines of constant nozzle throat area A_6 overlaying the same compressor performance map shown in figure 4(a). The method used to develop the lines was described in the valve analogy of figure 1(a). Figure 4(d) can then be used to determine what the throat area of the exhaust nozzle must be to operate the compressor at values of pressure ratio that will be consistent with the values of $N/\sqrt{\theta_{cr,2}}$ and θ obtained from figures 4(b) and (c). These areas can be determined graphically by transferring the operating points from figures 4(a) to (d).

Modes of Operation

In figures 5 and 6, a series of engine operating points are shown plotted on compressor and turbine performance maps. Two different modes of engine operation are considered. Figure 5 shows the operating points for the usual mode of engine operation where the rotative speed and turbine inlet temperature are held constant at their maximum values for all operating conditions except idle. This is the mode of operation that was described in the example of figure 4. Figure 6 shows the location of the same operating

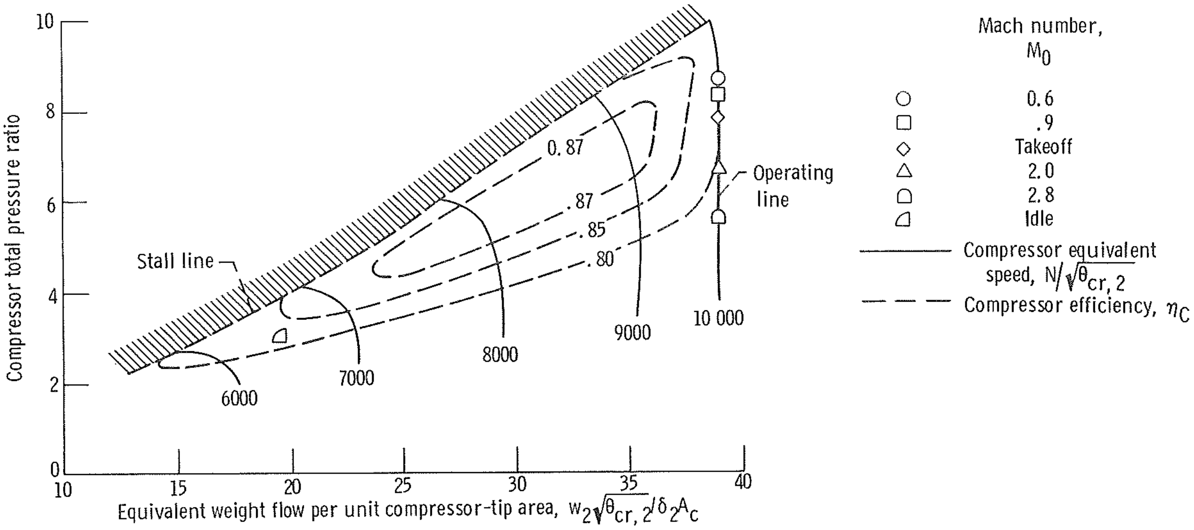


(a) Compressor operating map.

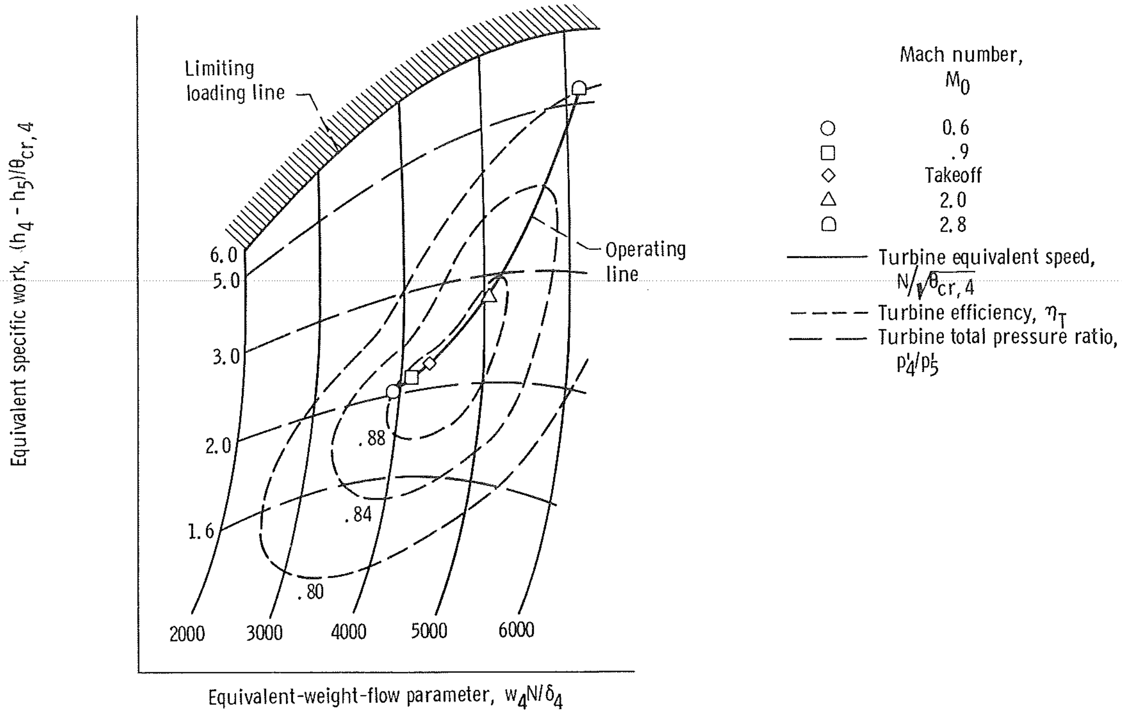


(b) Turbine operating map.

Figure 5. - Equilibrium operating maps for mode I operation (T_4' and N held constant).



(a) Compressor operating map.



(b) Turbine operating map.

Figure 6. - Equilibrium operating maps for mode II type of operation. (T_4' and $N/\sqrt{\theta_{cr,2}}$ held constant.)

points for a less used mode of operation where the equivalent rotative speed of the compressor, $N/\sqrt{\theta_{cr,2}}$, rather than its actual rotative speed is held constant.

The points plotted on the compressor maps define the operating lines for the engines. The line extends over much of the map for the mode I operation. Its extremes occur at the condition of subsonic cruise and supersonic cruise in the stratosphere. It may be noted in figure 5(a) that in going to the supersonic cruise condition there is a considerable reduction in compressor pressure ratio, equivalent weight flow, and equivalent rotative speed. However, there is almost no change in the turbine operating point over this range of engine and compressor operation, and this is noted in figure 5(b). The reasons for this are apparent. Since N and T_4' are held constant in this mode of operation, and since

$$\theta_{cr,4} \approx \frac{T_4'}{T_{std}}$$

then $N/\sqrt{\theta_{cr,4}}$ remains constant. Also, in figure 3 there is very little change in turbine pressure ratio, p_4'/p_5', over the portion of a constant $N/\sqrt{\theta_{cr,4}}$ line extending across the compressor matching map. Therefore, with little or no change in either its equivalent rotative speed or pressure ratio, the turbine operates at essentially one point on its performance map for all flight conditions.

As a matter of interest, figure 7 shows how the mode I type of operation appears on the matching maps repeated from figure 3. Also, in comparing the engine operating line of figures 4(a) and 5(a) for this mode of operation with the nozzle throat area lines of figure 4(d) there is only a nominal change in throat area required over the operating range of the engine. (In many fixed-nozzle engines, small changes in turbine inlet temperature or rotative speed are made in lieu of changing the nozzle area.) However, the above observation would only be true for nonafterburning engines. In an afterburning engine, nozzle throat areas must be increased at any point along the operating line where the afterburner is on to provide for the increase in volume flow rate through the nozzle. The volume flow rate increases by the square root of the increase in afterburner temperature. If afterburning were initiated without simultaneously increasing the nozzle throat area A_6, the operating point on the compressor map of figure 4(d) would move up the equivalent rotative speed line toward the stall line by an amount equal to the loss in the effective flow area of the nozzle, $\Delta A_6 = \sqrt{T_6'/T_5'}$, and the compressor could stall.

The second mode of operation results in a complete reorientation of the operating points and lines on the maps. The operating points noted on the compressor map of figure 6(a) are still located on the same engine temperature ratio lines as before, but they have been shifted to the maximum equivalent rotative speed line. Figure 6(b) shows that this shift requires an extension of the performance capability of the turbine, and requires

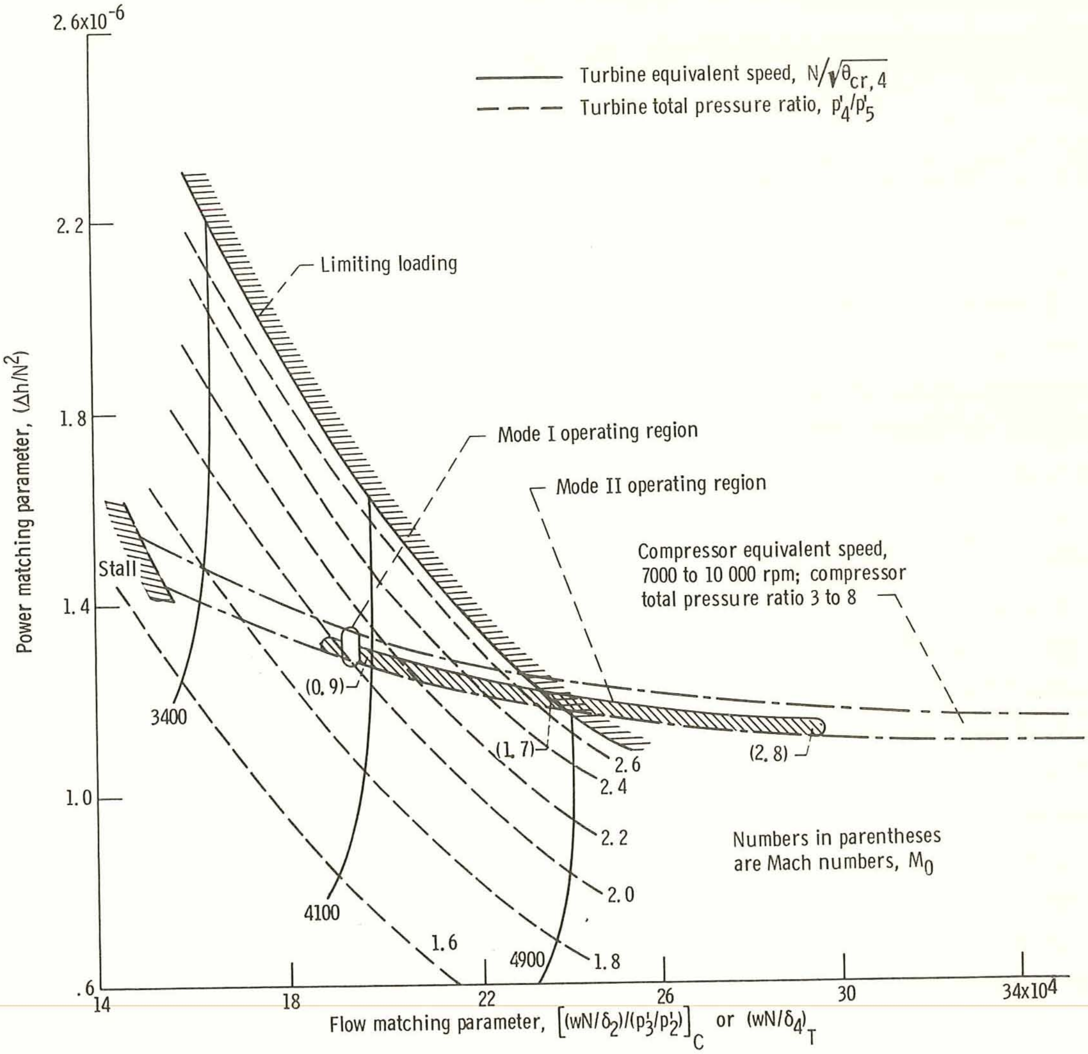


Figure 7. - Compressor-turbine matching maps with example operating modes for a mode I type of turbine.

the turbine to operate over a larger portion of its map. It is also apparent in comparing the engine operating line of figure 6(a) with the nozzle operating lines of figure 4(d) that the nozzle throat area must vary over a wider range to achieve this mode of operation than for mode I operation.

Because the turbine inlet temperature, and hence the engine temperature ratios, remain the same as for mode I operation, N must change proportionally with $\sqrt{\theta_{cr,2}}$ to maintain $N/\sqrt{\theta_{cr,2}}$ constant. (The variation of $\theta_{cr,2}$ with flight altitude and Mach number was shown previously in fig. 4(c).) The equivalent turbine rotative speed, $N/\sqrt{\theta_{cr,4}}$, must also change with $\sqrt{\theta_{cr,2}}$. This variation in $N/\sqrt{\theta_{cr,4}}$ with operating condition is shown in figure 6(b). But turbine pressure ratios must also change from point to point, and the reason for this change is apparent by referring again to the matching map of figure 3. The figure indicates that turbine pressure ratio must increase with increasing turbine equivalent rotative speed to maintain a match with the compressor. As a result, figure 6(b) shows that the operating line approaches the limiting loading condition for the turbine at the supersonic cruise point. Usually, this requires that the turbine designed for a mode II type of operation has more margin to limiting loading, that is, be designed to operate over a wider range of pressure ratios than a turbine designed for a mode I type of operation. This required difference in turbines is apparent in comparing the turbine performance maps of figures 5(b) and 6(b). The difference is also graphically illustrated in figure 7 where the mode II type of operation is shown plotted on the same matching map (same compressor and turbine) as used for the mode I type of operation. The mode II operation reaches a limiting loading condition across the turbine long before the supersonic cruise point is reached.

The mode II type of operation can create other problems too. Since the engine only runs at its maximum rotative speed when flying at its maximum supersonic operating point (maximum value of $\theta_{cr,2}$ on fig. 4(c)) a larger, higher weight-flow, or higher speed, more highly stressed engine may be required to fly the same mission than an engine designed for a mode I type of operation would require. However, the type of mode used depends on the particular application for the engine, including such things as the type of inlet used, the level of noise tolerated, and the level of thrust and efficiency required at each operating point of the engine to meet the objectives of the mission. Occasionally a mixed mode of operation is used, that is, going from take-off to a low supersonic flight condition in a mode II type of operation, and from there to a supersonic cruise condition along a mode I operating line. This tends to minimize the problem of flow mismatch that frequently occurs between the inlet and compressor components of supersonic engines.

Transient Operation

The operating lines that have been described thus far have been drawn through steady-state operating points for the engine, and are referred to as steady-state operating lines. During an engine transient such as an acceleration, a transient operating line is generated which, although not shown on the maps, is located in a uniquely different area of the maps than the steady-state operating lines. The engine is accelerated by increasing the fuel flow to the burner to increase the turbine inlet temperature T_4'. The process can be followed on the compressor maps of figures 4(a) and (d). As turbine inlet temperature is increased, so is the temperature ratio of the engine, θ, which will move the compressor operating point toward stall. This occurs because momentarily before the compressor can accelerate in rotative speed and increase in pressure ratio, the volume flow rate of gas through the turbine and exhaust nozzle has increased. If the throat area of the exhaust nozzle is not increased, or the excess volume flow rate bled overboard, the transient operating line for the compressor will go into stall in the same way analogous to closing the valve at the exit of the compressor, as noted in the discussion of figure 1(a).

The effect of this transient on the turbine operating line can be determined from the matching maps of figure 3. Moving toward the compressor stall line anywhere within the compressor operating band results in a reduction in turbine pressure ratio. The amount of the reduction would be determined primarily by the reduction in turbine equivalent rotative speed, $N/\sqrt{\theta_{cr,4}}$. However, as noted previously, this momentary effect of increasing turbine inlet temperature on turbine pressure ratio and compressor stall margin can be counteracted if the back end of the engine is opened, that is, by increasing A_6, or by increasing the effective flow area downstream of the compressor by bleeding the compressor.

CONCLUDING REMARKS

A graphical method is presented for matching the components and determining the operating characteristics of a turbojet engine. For simplicity, the techniques and relations used are for a single-spool engine. The method would be applicable, however, to matching the components within any given spool of a multispool engine. The subject of matching the spools and developing the operating lines for each spool of a multispool engine was for each spool of a multispool engine was considered beyond the scope of this report. An approach to the problem of matching multiple spools is outlined in reference 4.

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