RESEARCH MEMORANDUM

TWO-SPOOL MATCHING PROCEDURES AND EQUILIBRIUM CHARACTERISTICS OF A TWO-SPOOL TURBOJET ENGINE

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

June 28, 1954

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SUMMARY

Two-spool matching procedures are presented which may be employed to analyze turbojet, turboprop, and stationary power plants. The procedures were applied to analytically obtain the sea-level static equilibrium performance of a simple two-spool turbojet engine in which the compressor and turbine performances were based on experimental results.

For fixed-exhaust-nozzle-area operation of a two-spool turbojet engine, a wide range of thrust can be covered at near minimum specific fuel consumption. At a fixed inner-spool speed, closing the exhaust nozzle moves the operating point toward inner-compressor surge and away from outer-compressor surge; this results in a higher value of turbine-inlet temperature and in lower values of weight flow, outer-spool speed, and over-all compressor pressure ratio. Closing the exhaust nozzle while maintaining a fixed inner-spool speed results in very little thrust change near design speed, a thrust increase at lower speeds, and a slight thrust decrease at higher speeds. The inner spool operates over a much smaller range than the outer spool, suggesting that the inner turbine may be critically designed while the outer turbine should be conservatively designed. Bleeding air from either compressor discharge alleviates surge difficulties in that compressor.

INTRODUCTION

Aircraft engines capable of delivering high thrust and low specific fuel consumption at subsonic flight Mach numbers require high values of compressor pressure ratio which may be attained by using either one-spool or two-spool engines. Several current engines which meet these requirements are of the two-spool variety. Because of its off-design operating characteristics, the two-spool aircraft engine is being considered for other applications requiring good performance over a wide range of engine operation. Reference 1 presents performance calculations for a two-spool turbojet engine of 12:1 design compressor pressure ratio with principal emphasis placed on the results of the analysis rather than on the method of analysis. By using simplified compressor and turbine characteristics, a conclusion was reached 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 outer-compressor and inner-compressor pressure ratios of 3:1 and 4:1, respectively. With the use of realistic compressor characteristics, the off-design operating characteristics of a two-spool turbojet engine are determined.

In order to further evaluate the potential characteristics of two-spool engines, an analytical study of two-spool aircraft engines is now being conducted at the NACA Lewis laboratory. The over-all objective of this program is to investigate problems in the design and operation of aircraft engines containing two-spool compressor and turbine sets. A method of matching the compressors and turbines of two-spool engines is presented herein as the first phase of this analytical program. This method of analysis may be applied to obtain the equilibrium and transient performance of turbojet and turboprop engines in which various amounts of gas and power are extracted from the engine components once the operating characteristics of the engine components are known. The matching process is employed to investigate for sea-level static conditions the equilibrium operation of a simple two-spool turbojet engine in which the compressor and turbine performances are based on experimental results. The results of this analysis show the manner in which the characteristics of compressors and turbines may limit engine operation. 3279

SYMBOLS

The following symbols are used in this report:

A	exhaust-nozzle area, percent design
b	ratio of bleed air flow to compressor-inlet air flow
c_p	specific heat at constant pressure, Btu/(lb)($^{\circ}$R)
F	thrust, lb
f	ratio of fuel flow to air flow at primary-burner inlet
H	stagnation enthalpy, Btu/lb
N	rotative speed, rps
P	total pressure, lb/sq ft

P_a power extracted for auxiliaries, propeller, or acceleration, Btu/sec

p static pressure, lb/sq ft

sfc specific fuel consumption, lb fuel/(hr)(lb thrust)

T total temperature, $^{\circ}R$

W weight flow, lb/sec

η adiabatic efficiency, percent

θ ratio of total temperature to NACA standard sea-level temperature, T/518.4

δ ratio of total pressure to NACA standard sea-level pressure, P/2116

Subscripts:

d design

i inner spool

o outer spool

0 ambient conditions

1 outer-compressor inlet

2 outer-compressor exit, inner-compressor inlet

3 inner-compressor exit, burner inlet

4 burner exit, inner-turbine inlet

5 inner-turbine exit, outer-turbine inlet

6 outer-turbine exit, tail-pipe inlet, afterburner inlet

7 tail-pipe exit, afterburner exit, exhaust-nozzle-inlet, free-wheeling turbine inlet

METHOD OF ANALYSIS

Basis for Analysis

A schematic diagram of a two-spool gas generator is shown in figure 1. The outer compressor and the outer turbine are mounted on a common shaft. Hereafter, these components are called the outer spool. The inner compressor and the inner turbine are mounted on a second shaft which is not coupled mechanically to the shaft of the outer spool. Between this compressor and this turbine is the primary burner. Taken together, these components comprise the inner spool. 3279

In matching compressor and turbine components, three relations are available: The weight flow into the compressor minus the bleed plus the fuel added in the burner equal the weight flow into the turbine. The power required by the compressor, the accessories, and the propeller (in turboprop configurations with the propeller shaft geared to the compressor and turbine shaft) equals the power output of the turbine. The mechanical speeds of the compressor and its driving turbine are the same. By using these three relations, the components of a two-spool gas generator may be matched by first matching the components of the inner spool and then matching the components of the outer spool.

Description of Method

Inner-spool matching. - The components of the inner spool may be matched by a method such as that presented in reference 2. A similar matching procedure is herein described. For simplicity, the three matching relations are expressed in terms of equivalent performance parameters. The continuity, power, and speed relations, respectively, may be expressed as

$$\frac{(1 + f)(1 - b_3)}{(P_3/P_2)(P_4/P_3)} \frac{W_2 N_1}{\delta_2} = \frac{W_4 N_1}{\delta_4} \tag{1}$$

$$\frac{H_3 - H_2}{N_1^2(1 + f)(1 - b_3)} + \frac{P_a}{W_2 N_1^2 (1 + f)(1 - b_3)} = \frac{H_4 - H_5}{N_1^2} \tag{2}$$

$$\frac{T_4}{T_2} = \left(\frac{N_1}{\sqrt{\theta_2}} \middle/ \frac{N_1}{\sqrt{\theta_4}}\right)^2 \tag{3}$$

Inner-spool matching is achieved by graphically satisfying the preceding three equations in the following manner: The performance of the inner compressor is plotted as $(H_3 - H_2)/N_1^2(1 + f)(1 - b_3)$ against the

left side of equation (1) for constant values of $N_1/\sqrt{\theta_2}$ (fig. 2). Inner-turbine performance is plotted as the right side of equation (2) against the right side of equation (1) for constant values of $N_1/\sqrt{\theta_4}$ (fig. 3). Matching of the components is obtained by superposing figures 2 and 3 so as to satisfy equations (1) and (2); the ordinates of figures 2 and 3 are offset by the value of the power-extracted term in equation (2). Equation (3) yields turbine-inlet to compressor-inlet temperature ratios T_4/T_2 for all possible match points. Component
3279 pressure and temperature ratios may be obtained from appropriate component performance maps. Inner-spool performance may be presented as curves of one variable as a function of any other two independent variables. The selection of variables is determined by the method employed to match the outer-spool components.

Outer-spool matching. - The two-spool matching problem becomes one of matching the outer spool with the inner spool. Specifying two independent conditions determines the operating points of all the components. If an operating point is assigned to the inner spool, outer-spool matching is achieved directly. For this approach, it is convenient to express the power and continuity relations, respectively, as

$$\frac{(H_2 - H_1)}{N_O^2} \frac{1}{(1 - b_2)(1 - b_3)(1 + f)} + \frac{P_a}{W_1(1 - b_2)(1 - b_3)(1 + f)N_O^2} = \frac{H_5 - H_6}{N_O^2} \tag{4}$$

$$\log \frac{W_1 N_O}{\delta_2} = \log \left[\frac{(P_5/P_2)}{(1 - b_2)(1 - b_3)(1 + f)}\right] + \log \frac{W_5 N_O}{\delta_5} \tag{5}$$

Outer-compressor performance is plotted as $(H_2 - H_1)/N_O^2(1-b_2)(1-b_3)(1+f)$ against the left side of equation (5) for constant values of $W_2\sqrt{\theta_2}/\delta_2$ and $N_O/\sqrt{\theta_1}$ (fig. 4). The performance of the outer turbine is plotted as $(H_5 - H_6)/N_O^2$ against $\log W_5N_O/\delta_5$ for constant values of $W_5\sqrt{\theta_5}/\delta_5$ and $N_O/\sqrt{\theta_5}$ (fig. 5).

In order to match the inner and outer spool, it is convenient to plot inner-spool performance as $W_2\sqrt{\theta_2}/\delta_2$ against $W_5\sqrt{\theta_5}/\delta_5$ for constant values of $N_1/\sqrt{\theta_2}$ and P_5/P_2 (fig. 6). Inner-spool operation is, of course, limited by the equivalent flow that can be passed by the outer turbine. For each assigned point of operation on figure 6, the value of $\log \left[\frac{P_5/P_2}{(1 - b_2)(1 - b_3)(1 + f)}\right]$ is calculated, and the values of $W_2\sqrt{\theta_2}/\delta_2$ and $W_5\sqrt{\theta_5}/\delta_5$ are noted. Figures 4 and 5 are superposed so as to satisfy equations (4) and (5); the ordinates of figures 4 and 5 are offset by the value of the extracted power term in equation 4 and the abscissas are offset by the value of the calculated P_5/P_2 term in equation (5). The operating points of the outer compressor and the outer turbine are fixed at the intersection of the appropriate lines of constant $W_2\sqrt{\theta_2}/\delta_2$ and $W_5\sqrt{\theta_5}/\delta_5$. In using this procedure, it has been found convenient to assign several values of $W_5\sqrt{\theta_5}/\delta_5$ for each selected value of $W_2\sqrt{\theta_2}/\delta_2$. Choosing pairs of values for $W_2\sqrt{\theta_2}/\delta_2$ and $W_5\sqrt{\theta_5}/\delta_5$ in this way dictates the values to be used in plotting lines of constant $W_2\sqrt{\theta_2}/\delta_2$ and $W_5\sqrt{\theta_5}/\delta_5$ on figures 4 and 5.

An alternative procedure for matching the outer spool with the inner spool may be employed if the outer-compressor operating point is assigned rather than that of the inner spool. Equation (4) is employed to express the power relation. Instead of the continuity relation, the speed relation is employed. It is expressed as

$$\frac{T_5}{T_2} = \left(\frac{N_O}{\sqrt{\theta_1}} \bigg/ \frac{N_O}{\sqrt{\theta_5}}\right)^2 \bigg/ \frac{T_2}{T_1} \tag{6}$$

Outer-compressor performance is plotted as $(H_2 - H_1)/N_O{}^2$ against $W_2\sqrt{\theta_2}/\delta_2$ for constant values of $N_O/\sqrt{\theta_1}$, as in figure 7(a). Inner-spool performance is plotted as $W_2\sqrt{\theta_2}/\delta_2$ against $W_5\sqrt{\theta_5}/\delta_5$ for constant values of $N_I/\sqrt{\theta_2}$ and T_5/T_2, as in figure 7(b). The performance of the outer turbine is plotted as $(H_5 - H_6)/N_O{}^2$ against $W_5\sqrt{\theta_5}/\delta_5$ for constant values of $N_O/\sqrt{\theta_5}$ (fig. 7(c)). An operating point is assigned on the outer-compressor map (fig. 7(a)). Values of $W_2\sqrt{\theta_2}/\delta_2$, $N_O/\sqrt{\theta_1}$, and $(H_2 - H_1)/N_O{}^2$ are read. Values of $(H_5 - H_6)/N_O{}^2$ and T_2/T_1 are calculated from equations (4) and (7), respectively:

$$\frac{T_2}{T_1} = 1 + \frac{H_2 - H_1}{N_O{}^2}\left(\frac{N_O}{\sqrt{\theta_1}}\right)^2 \frac{1}{518.4c_{p,1}} \tag{7}$$

A value of $W_5\sqrt{\theta_5}/\delta_5$ less or equal to the maximum value that can be passed by the outer turbine is assumed. Because assigning the outer-compressor operating point determines the operating points of all the other components, assuming a value of $W_5\sqrt{\theta_5}/\delta_5$ is an overspecification and will lead to a contradiction if the wrong value is assumed. For the assumed value of $W_5\sqrt{\theta_5}/\delta_5$ and the known values of $W_2\sqrt{\theta_2}/\delta_2$ and $(H_5 - H_6)/N_0^2$, values of T_5/T_2 and $N_0/\sqrt{\theta_5}$ are read from figures 7(b) and (c), respectively. By using this value of $N_0/\sqrt{\theta_5}$ and the known values of $N_0/\sqrt{\theta_1}$ and T_2/T_1, a value of T_5/T_2 is calculated from equation (6). If this second value of T_5/T_2 does not equal the initial value of T_5/T_2 read from figure 7(b), a new value of $W_5\sqrt{\theta_5}/\delta_5$ is assumed and the process repeated until the two values of T_5/T_2 agree. In using this procedure for outer-spool matching, it has been found convenient to assign outer-spool operating points along lines of constant outer-spool speed and to first calculate the match points for the higher values of $W_2\sqrt{\theta_2}/\delta_2$. As lower values of $W_2\sqrt{\theta_2}/\delta_2$ are selected, higher values of $W_5\sqrt{\theta_5}/\delta_5$ will result until the choking value is reached. From this point on, all lower selected values of $W_2\sqrt{\theta_2}/\delta_2$ will be accompanied by the choking value of $W_5\sqrt{\theta_5}/\delta_5$.

Pumping characteristics. - In order to obtain engine performance for various operating conditions, it is convenient to plot the two-spool gas-generator pumping characteristics as shown in figure 8. The matching procedure discussed previously yields values of $N_0/\sqrt{\theta_1}$ and $N_i/\sqrt{\theta_1}$. The remaining pumping characteristics are calculated from various component parameters obtained from appropriate component performance maps.

Matching gas generator with other engine components. - Other engine components are matched with the two-spool gas generator in the same manner as with the one-spool gas generator. Specifying a flight condition yields values of T_1, θ_1, and P_0/p_0. The characteristics of the inlet give a value of P_1/P_0. The performance of the gas generator is completely determined by specifying two independent engine parameters, such as outer-spool mechanical speed N_0 and inner-turbine-inlet temperature T_4. The performance of the tail pipe or afterburner gives values of T_7/T_6 and P_7/P_6. For engine configurations with an exhaust nozzle at station 7, the exhaust-nozzle area is determined from the known values of equivalent weight flow $W_7\sqrt{\theta_7}/\delta_7$ and exhaust-nozzle pressure ratio P_7/p_0. For turboprop configurations with the propeller geared to a free-wheeling turbine at station 7, operation of the free-wheeling turbine is fixed by the equivalent weight flow $W_7\sqrt{\theta_7}/\delta_7$ and the free-wheeling turbine power, which is determined by the specified flight condition, the propeller shaft speed, and the propeller characteristics.

Applications for matching procedures. - The matching procedures discussed in the previous sections may be employed to obtain the equilibrium engine performance of various two-spool configurations. The two-spool gas generator may be preceded by an inlet and followed by an exhaust nozzle to form a simple turbojet. A variation of this configuration is achieved by having an afterburner between the gas-generator discharge and the exhaust nozzle. Turboprop engines in which the propeller is geared to the outer-spool shaft or driven by a free-wheeling turbine may also be analyzed. The two-spool matching procedures may, of course, be applied to stationary power plants employing a two-spool gas generator.

The two-spool matching procedures may also be applied to study 3279
acceleration problems. For equilibrium operation of a two-spool configuration, two independent quantities determine the operation of all the two-spool components. For operation of a two-spool configuration during acceleration, the power balance for each of the spools no longer holds, so that four independent quantities determine the operation of all the two-spool components. Two-spool matching during acceleration may be achieved by specifying the excess power of each spool and the operating point of one of the components such as the outer compressor. The operation of the other components is obtained by following the matching procedures previously discussed. In relating turbine and compressor power, of course, the specified excess power for acceleration must be accounted for.

Illustrative Example

The two-spool matching procedures were employed to analytically obtain the equilibrium performance of a simple two-spool turbojet engine. The compressor and turbine component performance maps are presented in figure 9 in terms of the conventional rating parameters; these maps are based on compressor and turbine data determined experimentally at the Lewis laboratory. The design-point conditions are as follows:

Over-all compressor pressure ratio	10.4
Outer-compressor equivalent weight flow, lb/sec	48
Outer-compressor pressure ratio	2.6
Outer-compressor efficiency, percent	82
Inner-compressor pressure ratio	4.0
Inner-compressor efficiency, percent	83.7
Inner-turbine-inlet temperature, °R	2074
Inner-turbine equivalent specific work, Btu/lb	24.1
Inner-turbine efficiency, percent	84
Outer-turbine equivalent specific work, Btu/lb	13.9
Outer-turbine efficiency, percent	88.5

In matching the components, constant values of fuel-air ratio and burner pressure ratio P_4/P_3 were used. Engine performance for static sea-level conditions was calculated with the assumption of zero bleed and isentropic flow in the inlet and downstream of the outer turbine through a simple convergent nozzle. Lines of constant outer-spool speed, inner-spool speed, inner-turbine-inlet temperature, and exhaust-nozzle area were determined and plotted on the component and engine performance maps. The line representing an exhaust-nozzle pressure ratio of 1, hereinafter referred to as the zero thrust line, was determined and plotted on both component and engine performance maps.

In order to determine the effect of compressor-discharge bleed, calculations were made for two cases of bleed. For the first case, 10 percent of the engine air flow was bled from the discharge of the outer compressor; the design-exhaust-nozzle-area equilibrium operating line was determined so that it could be plotted on the compressor component maps. Similar calculations were made for a second case in which 10 percent of the engine air flow was bled from the discharge of the inner compressor.

RESULTS AND DISCUSSION

The results obtained by applying the two-spool matching procedures to a hypothetical two-spool turbojet engine without an afterburner are presented in the engine and component performance plots of figures 10 to 17.

Engine performance at sea-level static conditions. - The sea-level static equilibrium engine performance for zero bleed is presented in figure 10 as a plot of equivalent specific fuel consumption against equivalent thrust for lines of constant outer-spool speed, inner-spool speed, turbine-inlet temperature, and exhaust-nozzle area. The compressor surge lines do not seriously limit the engine performance; that is, a wide range of thrust at low specific fuel consumption is obtainable without the engine being limited by surging of the inner or outer compressor. Moreover, a wide range of thrust at near minimum specific fuel consumption can be covered at constant-exhaust-nozzle-area operation. When operating at design outer-spool speed, closing the exhaust nozzle from 114 to 87 percent of the design value increases the thrust by 57 percent and the specific fuel consumption by 33 percent. At fixed design inner-spool speed, however, closing the exhaust nozzle over the same range results in practically no change in thrust and a 22-percent increase in specific fuel consumption. Over most of the range shown in figure 10, opening the exhaust nozzle above its design value at a constant value of outer-spool speed or at a constant value of inner-spool speed gives lower values of specific fuel consumption. For actual two-spool engines, specific fuel consumption might well increase as exhaust-nozzle area is increased above its design value because of component performance characteristics and inlet and tail-pipe pressure losses different from those for the illustrative example of this report.

The sea-level static engine performance for constant-exhaust-nozzle-area operation and zero bleed is presented in figure 11. Thrust, weight flow, outer-spool speed, specific fuel consumption, turbine-inlet temperature, and over-all compressor pressure ratio are plotted against inner-spool speed for constant values of exhaust-nozzle area. All values are plotted as percent design. For constant-exhaust-nozzle-area operation, as inner-spool speed increases, thrust, weight flow, outer-spool speed, turbine-inlet temperature, and over-all compressor pressure ratio increase. Specific fuel consumption decreases, reaches a minimum, and then increases. At a fixed inner-spool speed, closing the exhaust nozzle increases the turbine-inlet temperature and decreases the weight flow, the outer-spool speed, and the over-all pressure ratio. As pointed out previously, at design inner-spool speed, closing the nozzle has very little effect on engine thrust. At lower speeds, closing the exhaust nozzle increases the thrust; while at inner-spool speeds higher than design, closing the exhaust nozzle decreases the thrust slightly. 3279

Component performance. - The component performance plots (figs. 12 to 15) are similar to those in figure 9. As a result of the matching calculations for zero bleed, the lines of constant outer-spool speed, inner-spool speed, turbine-inlet temperature, and exhaust-nozzle area are shown on the performance maps of the outer compressor (fig. 12), the inner compressor (fig. 13), the inner turbine (fig. 14), and the outer turbine (fig. 15). Also shown on each of the component performance maps are the minimum and maximum outer-spool speed lines, 62 and 112 percent design, respectively, that were used in the example; the surge lines of both compressors; a turbine-inlet temperature line of 2500° R; and the zero thrust line. The zero-thrust line is, of course, an absolute limit in that it is associated with an infinite exhaust-nozzle area. The surge lines determined from component testing may differ from those obtained from two-spool engine operation. The surge lines used herein correspond to those obtained from component testing.

The outer-compressor performance plots in figure 12 show that closing the exhaust nozzle moves the equilibrium operating line away from outer-compressor surge and to a region of higher turbine-inlet temperature. For a one-spool engine, closing the exhaust nozzle moves the equilibrium operating line in the direction of surge and higher turbine-inlet temperatures.

The performance of the inner compressor as part of a hypothetical two-spool engine is presented in figure 13. Whereas the outer-compressor equivalent speed $N_O/\sqrt{\theta_1}$ varied from 62 to 112 percent design, the corresponding inner-compressor equivalent speed $N_i/\sqrt{\theta_2}$ varied from only 82 to 108 percent design. The portion of the inner-compressor map that is covered by the selected exhaust-nozzle-area range of 87 to 114 percent design is small. Closing the exhaust-nozzle area moves the equilibrium operating line toward the inner-compressor surge line and, as noted previously in this section, to a region of higher turbine-inlet temperatures.

The inner-turbine map in figure 14 shows that, as part of a two-spool engine, the inner turbine operates over a very small range and that design specific work is exceeded by only 3 percent. This means that the inner turbine could be designed close to its aerodynamic limits without danger of limiting loading being encountered during off-design operation.

In figure 15 it is shown that the outer turbine operates over about the same equivalent speed range as the outer compressor and that, during some off-design operating conditions, design specific work is exceeded by as much as 49 percent. This means that, when engine off-design operation is planned with exhaust-nozzle areas above the design value, the outer turbine should be conservatively designed in order to avoid limiting-blade-loading operation.

The over-all compressor performance map of the hypothetical two-spool engine is presented in figure 16. Over-all compressor pressure ratio is plotted against inlet equivalent weight flow for lines of constant outer-spool speed, inner-spool speed, turbine-inlet temperature, and exhaust-nozzle area. At a fixed outer-spool speed, the turbine-inlet temperature may be increased until limiting turbine-inlet temperature, inner-compressor surge, or minimum exhaust-nozzle area is reached. Turbine-inlet temperature may be decreased until outer-compressor surge or maximum exhaust-nozzle area is reached.

Effect of compressor-discharge bleed. - The displacement of the design-exhaust-nozzle-area equilibrium operating line on the compressor component maps resulting from compressor-discharge bleed is shown in figure 17. Design-exhaust-nozzle-area equilibrium operating lines for no bleed, 10-percent bleed at the outer-compressor discharge, and 10-percent bleed at the inner-compressor discharge are shown on the outer-compressor performance map in figure 17(a) and on the inner-compressor performance map in figure 17(b). Bleeding from the outer-compressor discharge shifted the operating line away from the outer-compressor surge line (fig. 17(a)) and had no effect on the operating line of the inner-compressor map (fig. 17(b)). If enough air is bled from the outer-compressor discharge, the operating line will shift toward the inner-compressor surge line. Bleeding from the inner-compressor discharge shifted the operating line away from both the outer-compressor surge line (fig. 17(a)) and the inner-compressor surge line (fig. 17(b)).

CONCLUDING REMARKS

The two-spool matching procedures presented herein permit the calculation of transient and equilibrium engine performance from component data. Turbojet, turboprop, and stationary power plants using a two-spool gas generator may be analyzed.

By employing the two-spool matching procedures to analytically obtain the sea-level static equilibrium performance of a simple two-spool turbojet engine, the following characteristics were noted: A wide range of thrust at low specific-fuel-consumption values is obtained without the engine being limited by surging of either compressor. For fixed-exhaust-nozzle-area operation, a wide range of thrust can be covered at near minimum specific fuel consumption. For this type of operation, as inner-spool speed increases, thrust, weight flow, outer-spool speed, turbine-inlet temperature, and over-all compressor pressure ratio increase. At a fixed inner-spool speed, closing the exhaust nozzle moves the operating point toward inner-compressor surge and away from outer-compressor surge; this results in a higher value of turbine-inlet temperature and in lower values of weight flow, outer-spool speed, and over-all pressure ratio. Closing the exhaust nozzle while maintaining a fixed inner-spool speed results in very little thrust change near design speed, a thrust increase at lower speeds, and a slight thrust decrease at higher speeds. The inner spool operates over a much smaller range than the outer spool, suggesting that the inner turbine may be designed close to its aerodynamic limits while the outer turbine should be conservatively designed. Bleeding air from either compressor discharge alleviates surge difficulties in that compressor.

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Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 16, 1954

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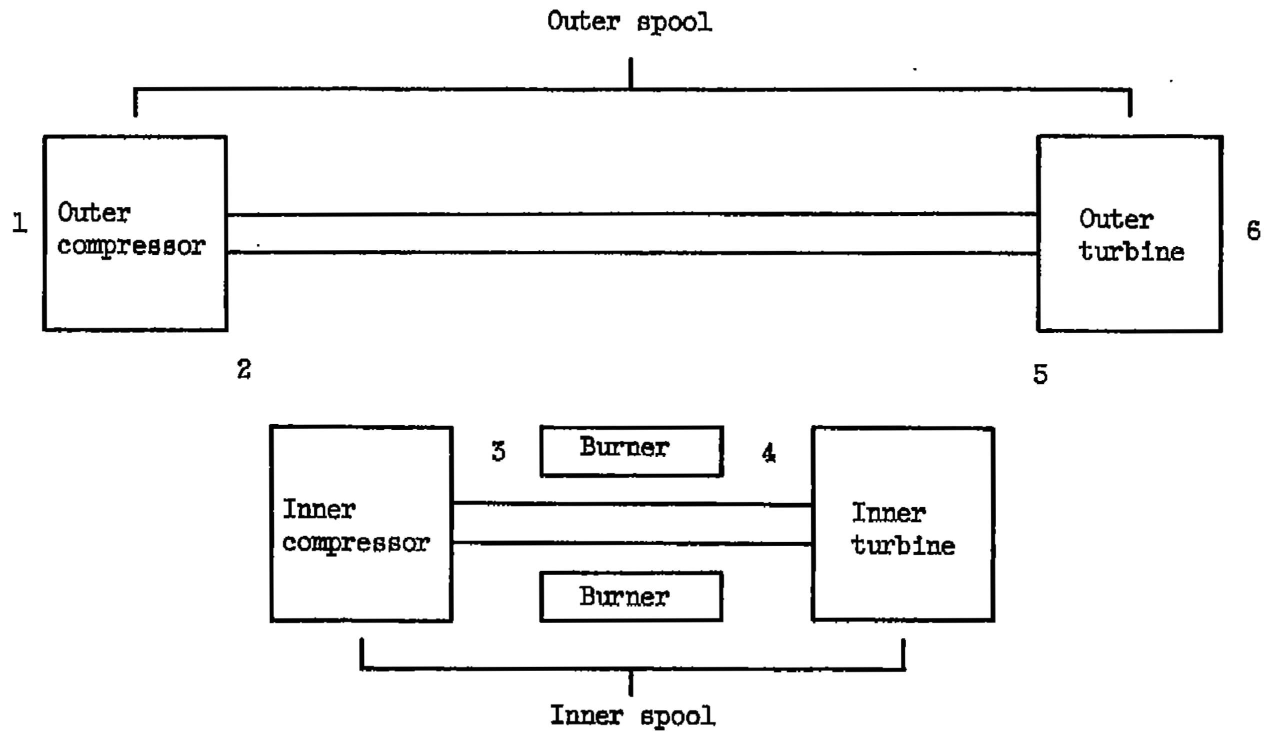

Figure 1. - Schematic diagram of two-spool gas generator.

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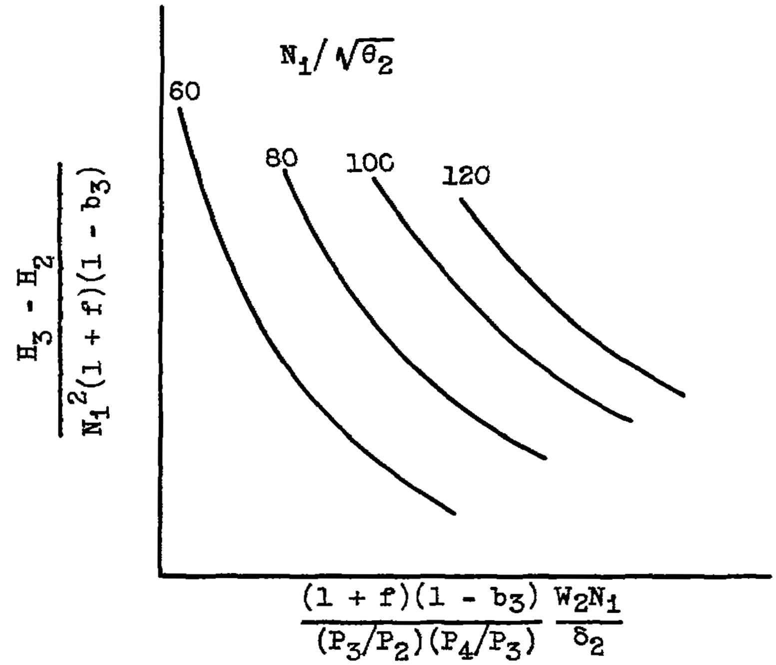

Figure 2. - Inner-compressor matching map.

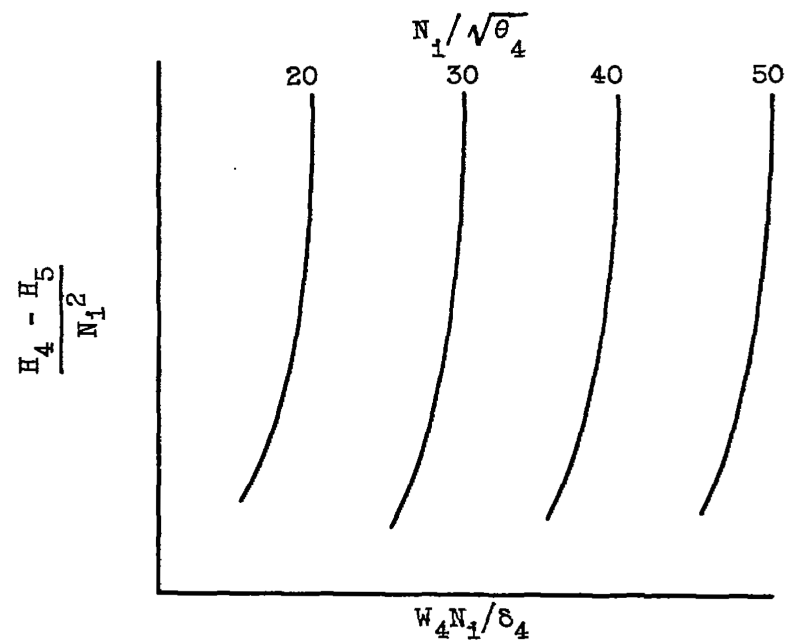

Figure 3. - Inner-turbine matching map.

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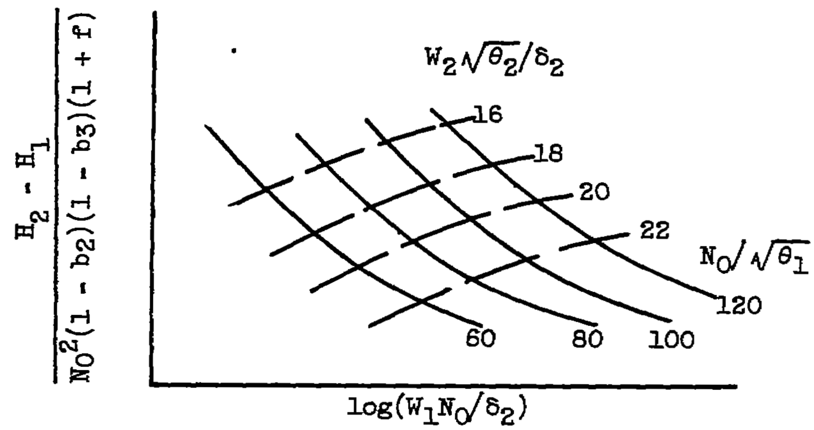


Figure 4. - Outer-compressor matching map.

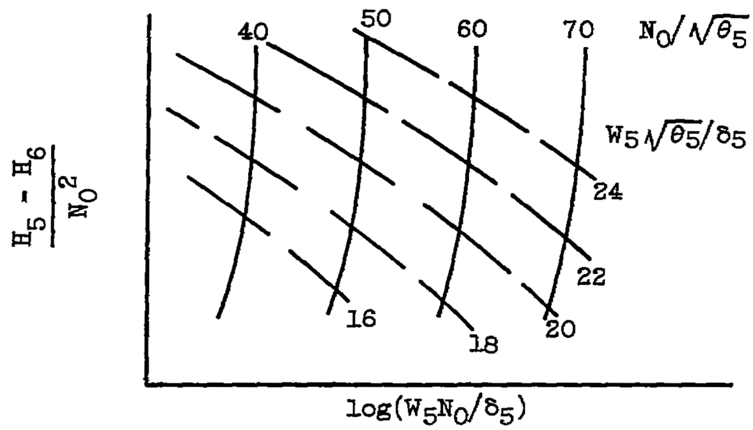


Figure 5. - Outer-turbine matching map.

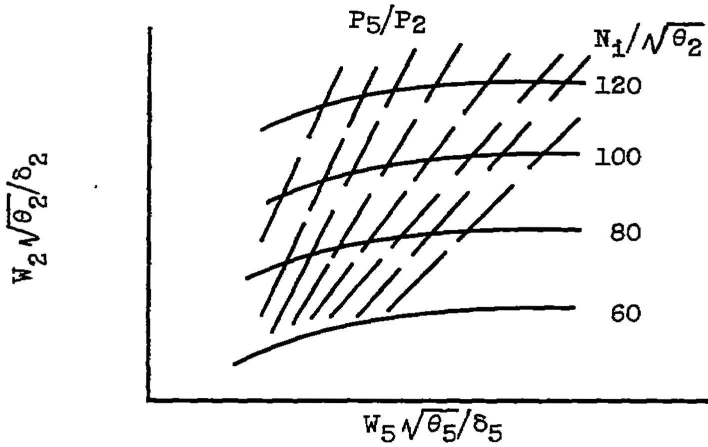
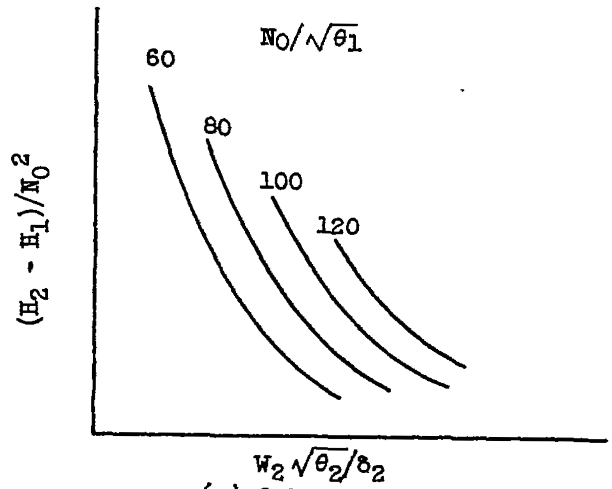
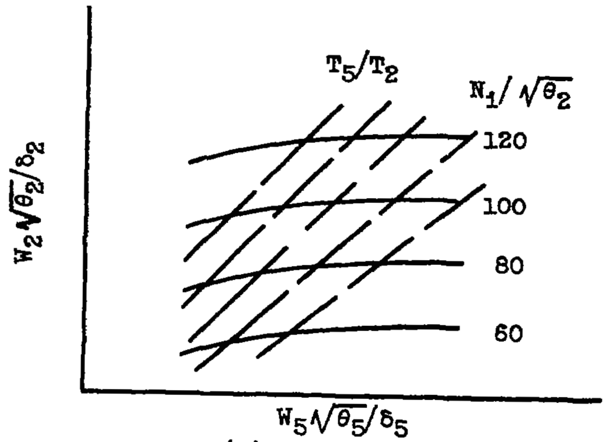


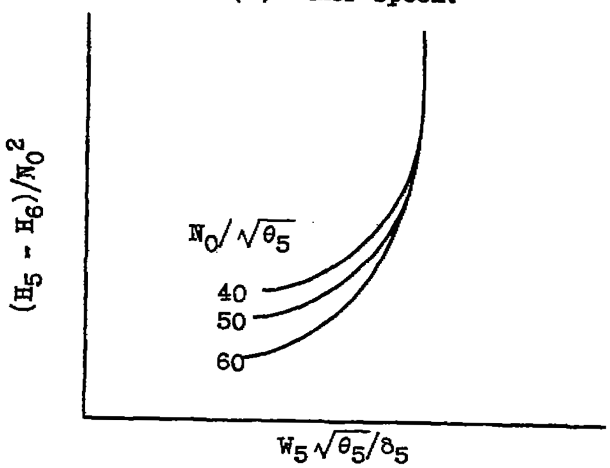
Figure 6. - Inner-spool matching map.



(a) Outer compressor.



(b) Inner spool.



(c) Outer turbine.

Figure 7. - Matching maps.

3279

CY-3

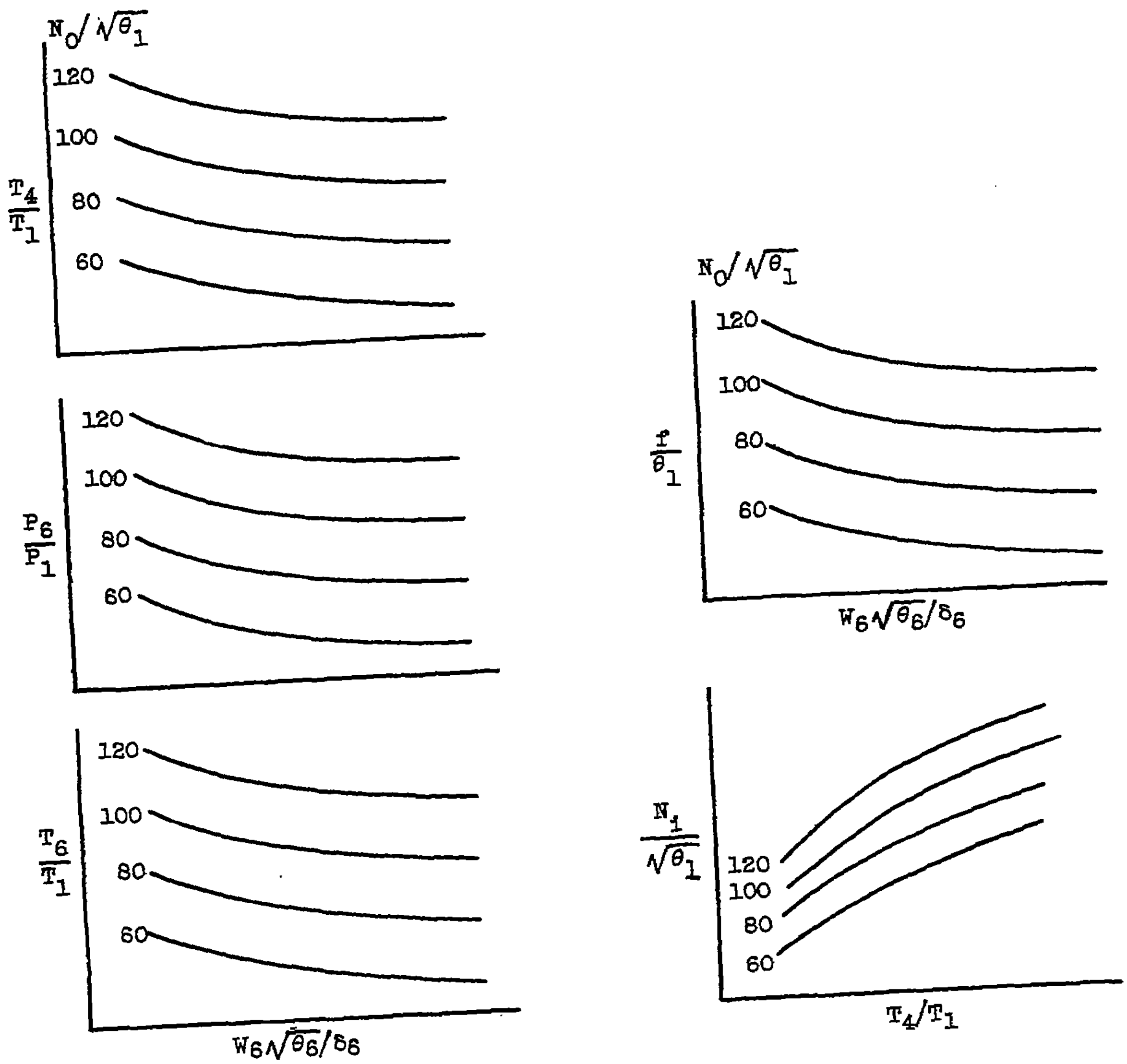
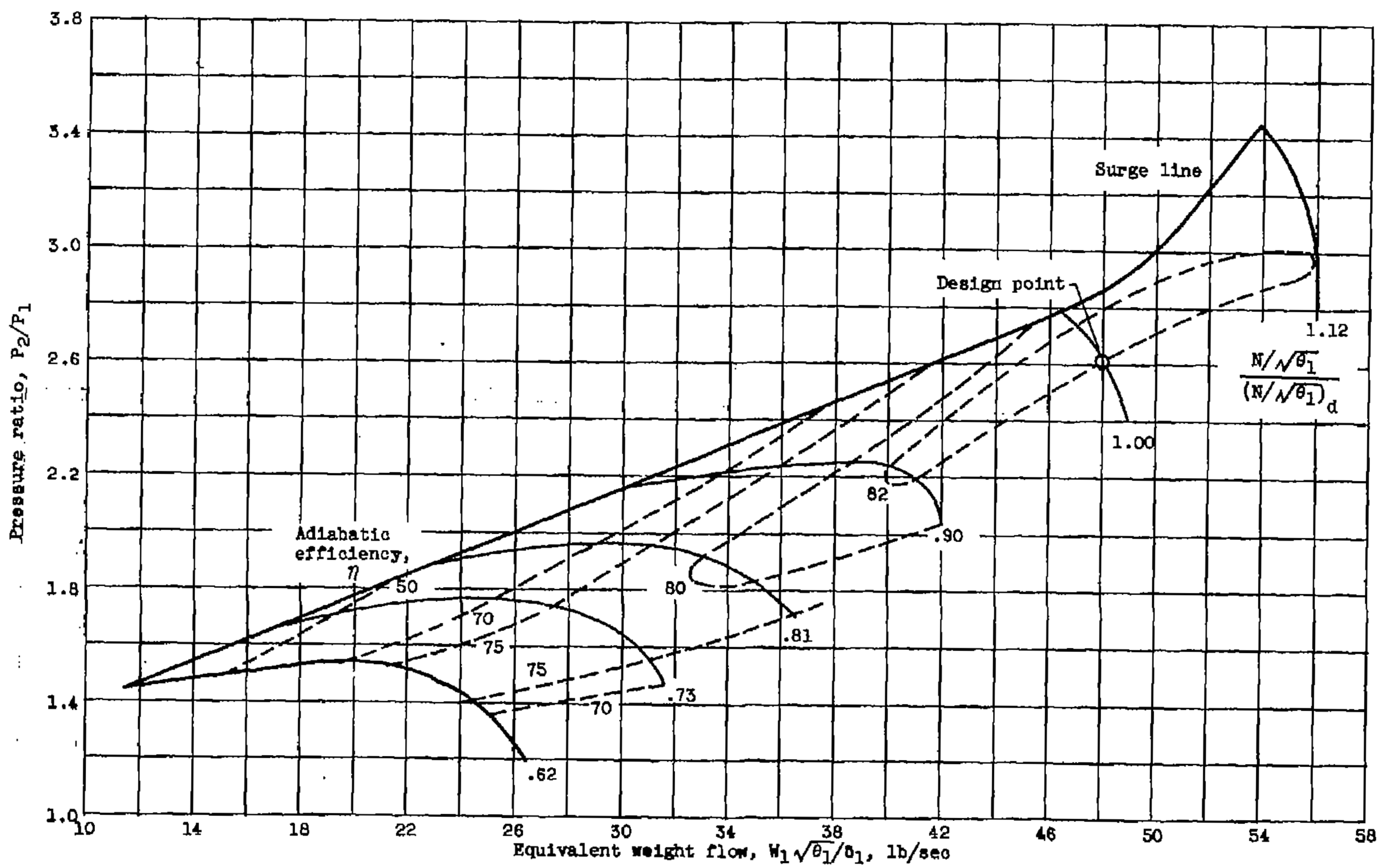


Figure 8. - Two-spool gas-generator pumping characteristics.

[redacted]



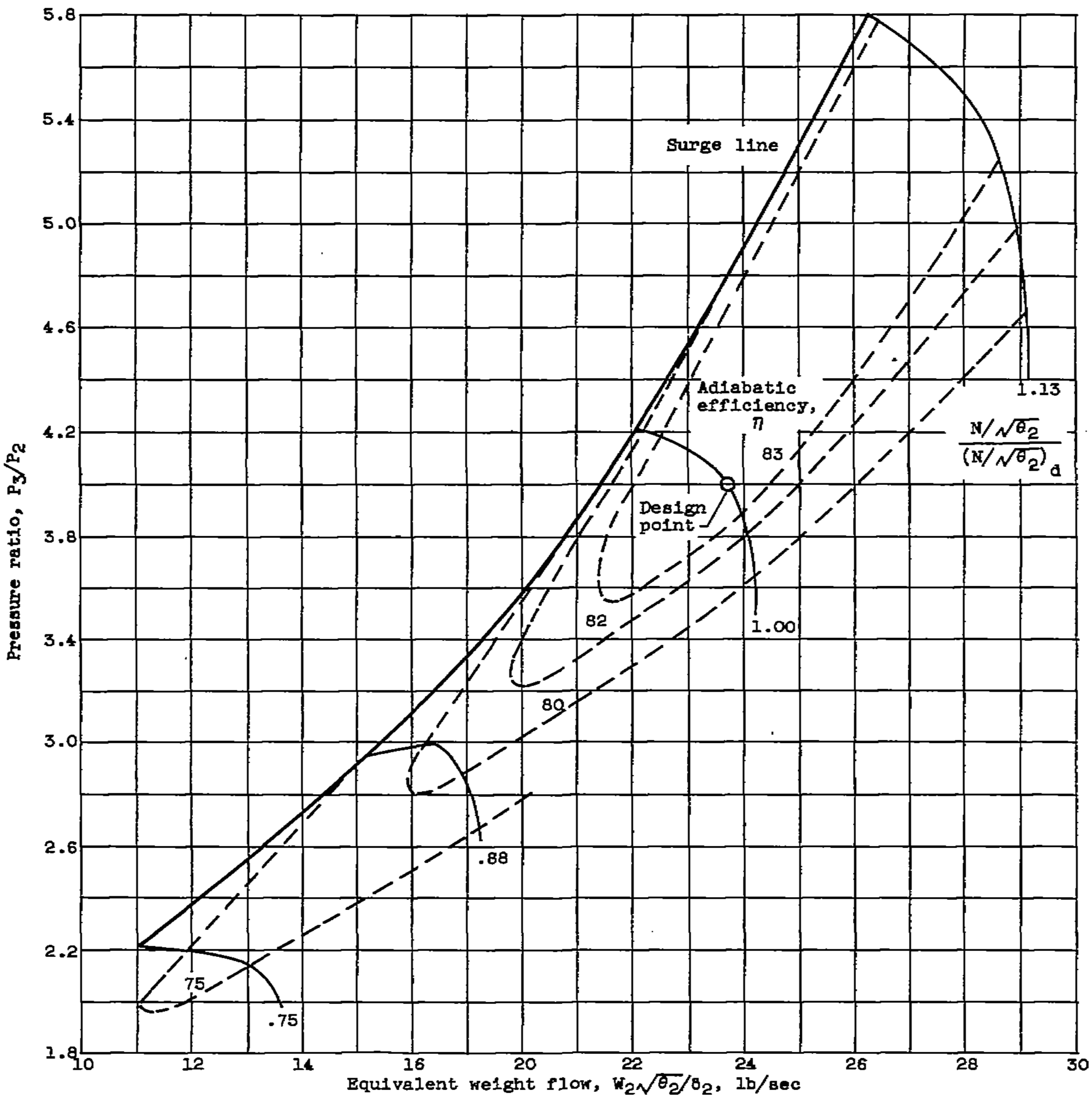
(a) Outer compressor.

Figure 9. - Component performance maps.

[redacted]

3279

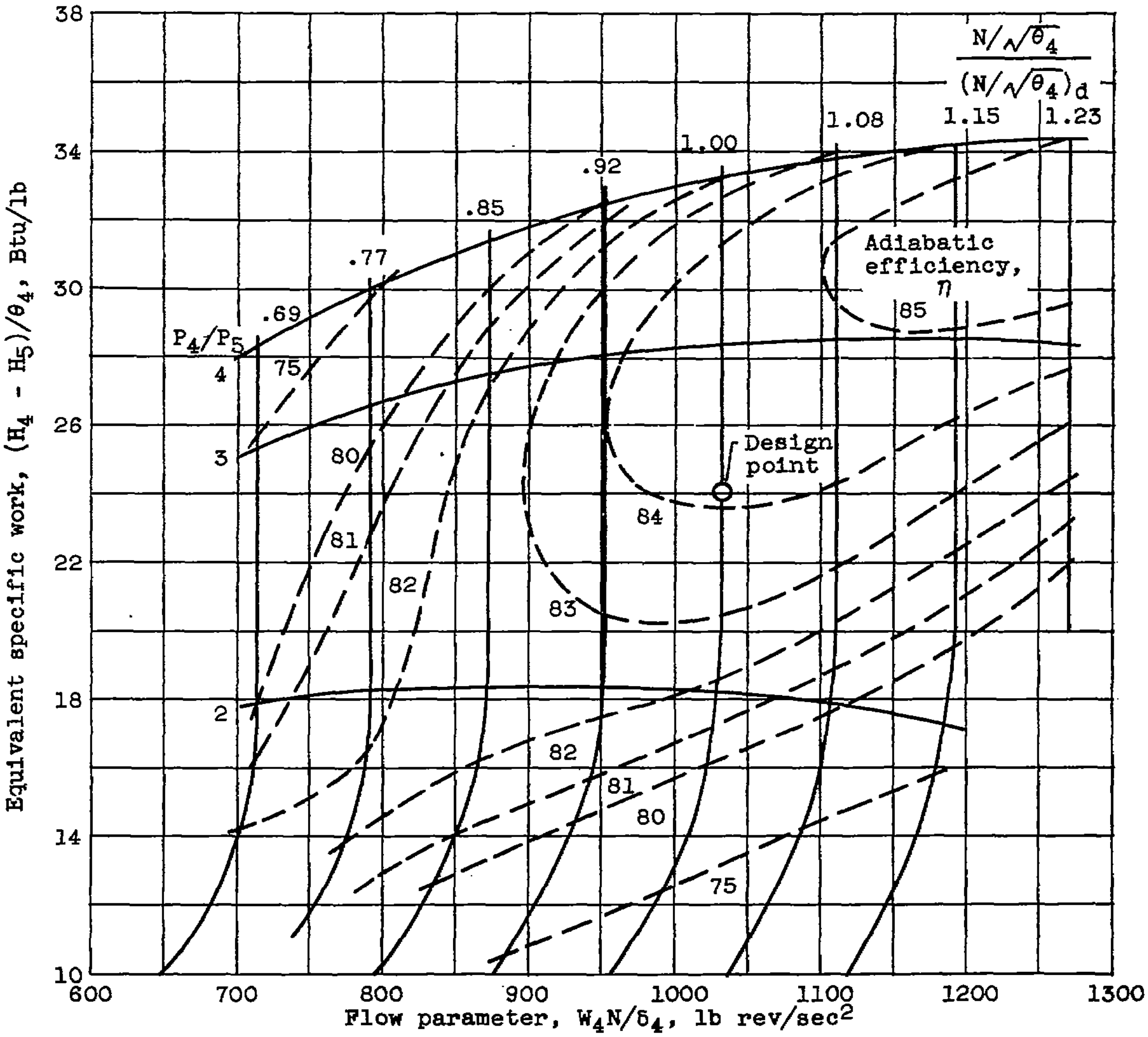
CY-3 back



(b) Inner compressor.

Figure 9. - Continued. Component performance maps.

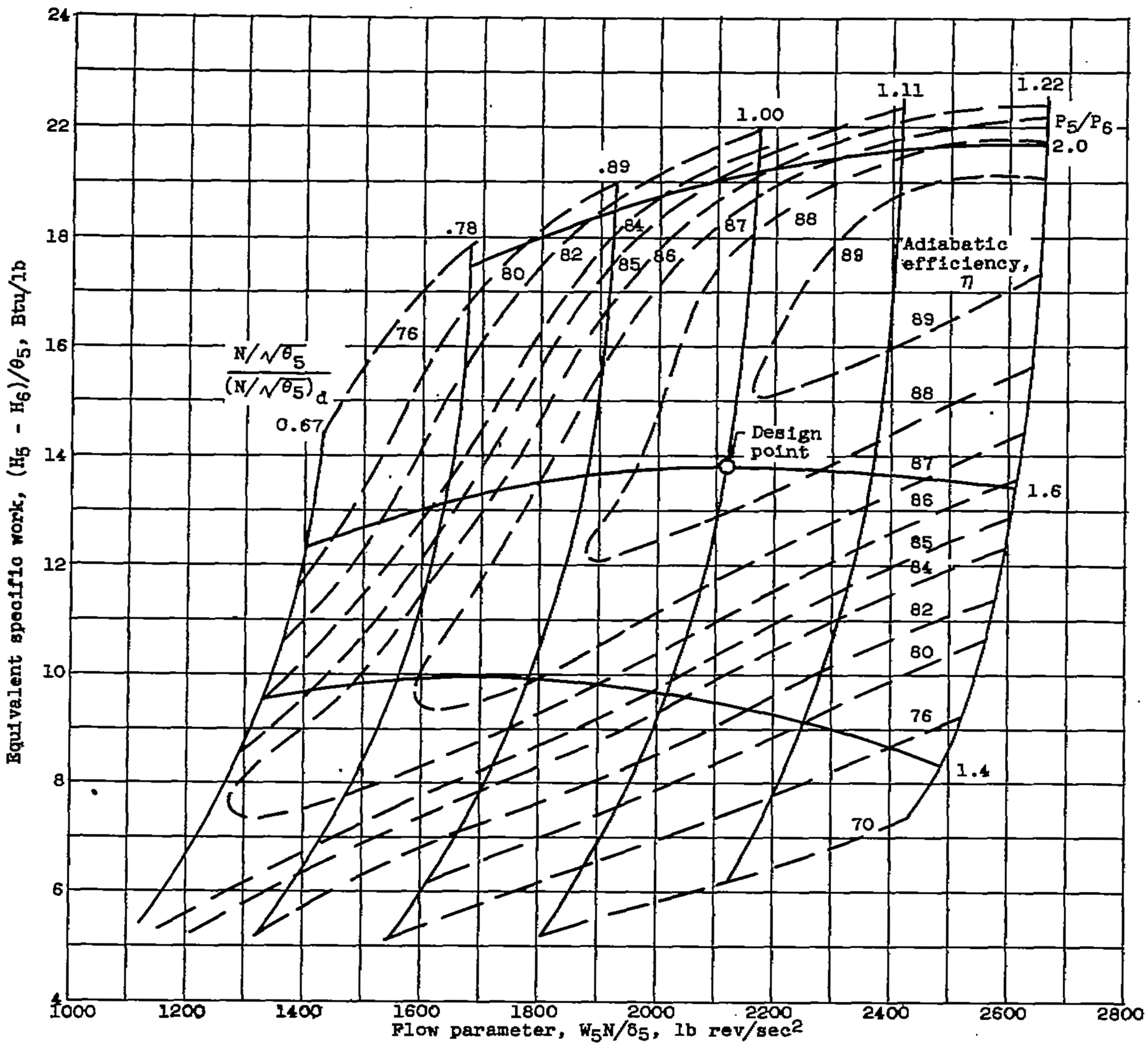
5279



(c) Inner turbine.

Figure 9. - Continued. Component performance maps.

3279



(d) Outer turbine.

Figure 9. - Concluded. Component performance maps.

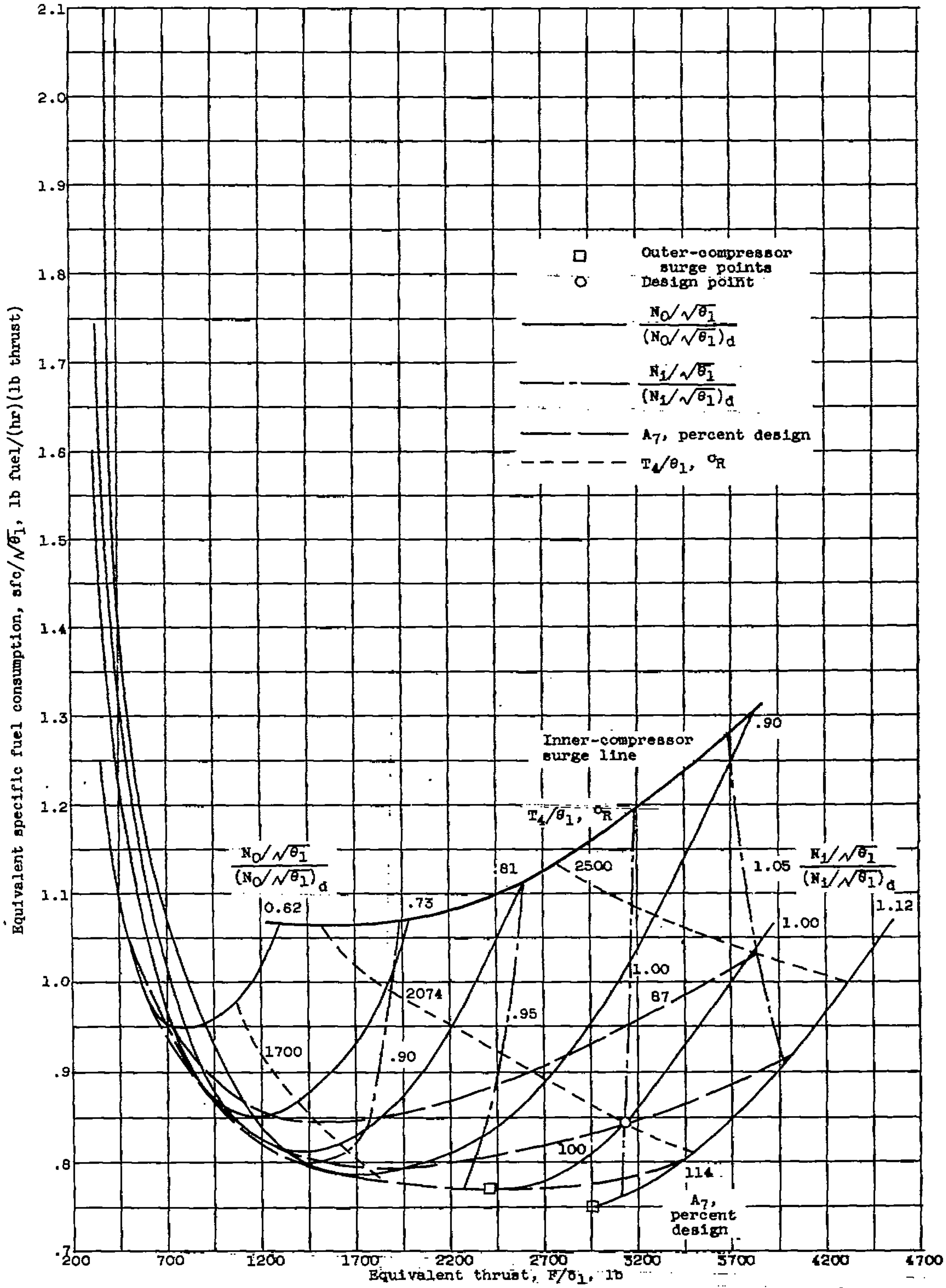
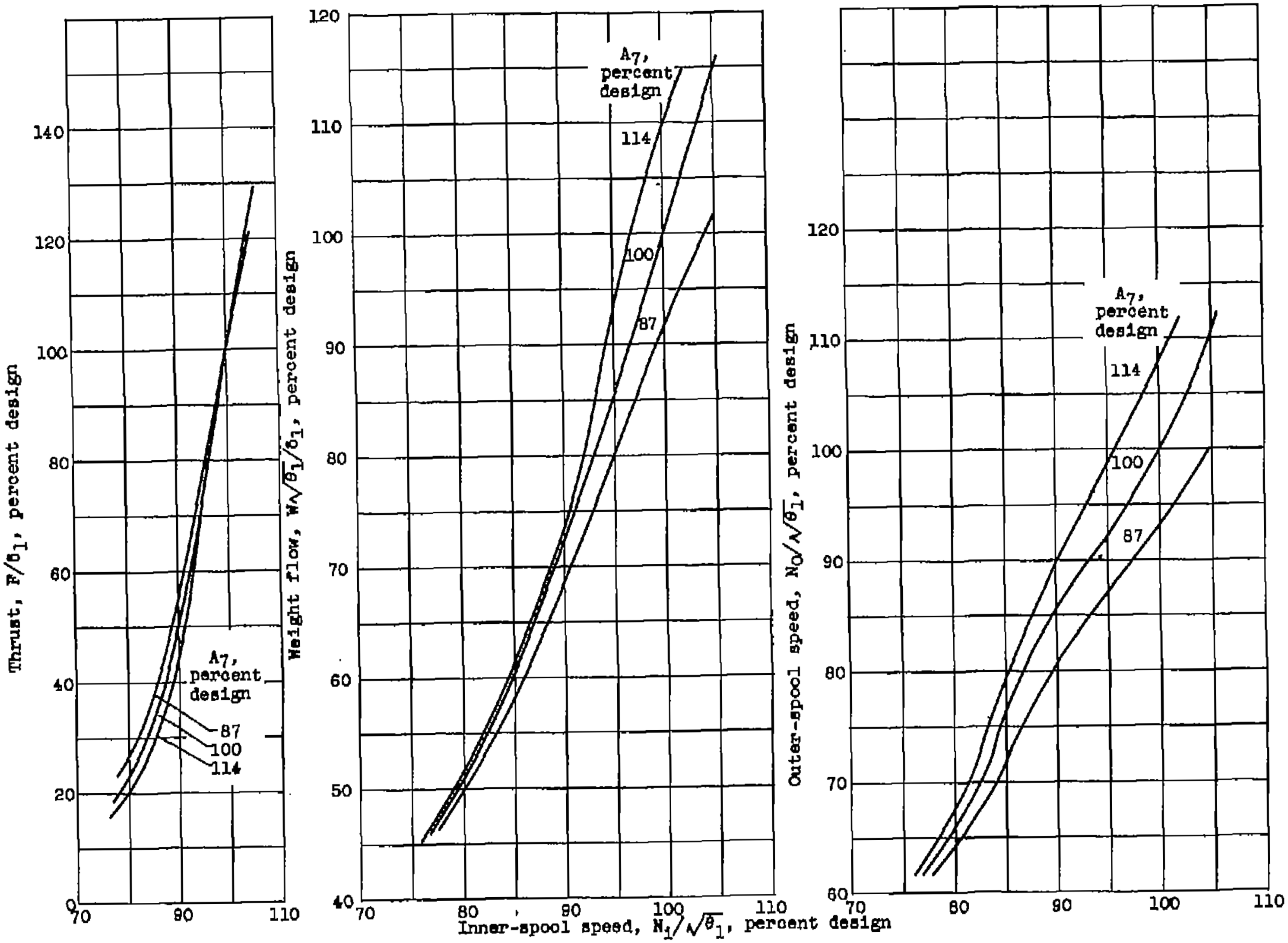


Figure 10. - Sea-level static performance of hypothetical two-spool turbojet engine.

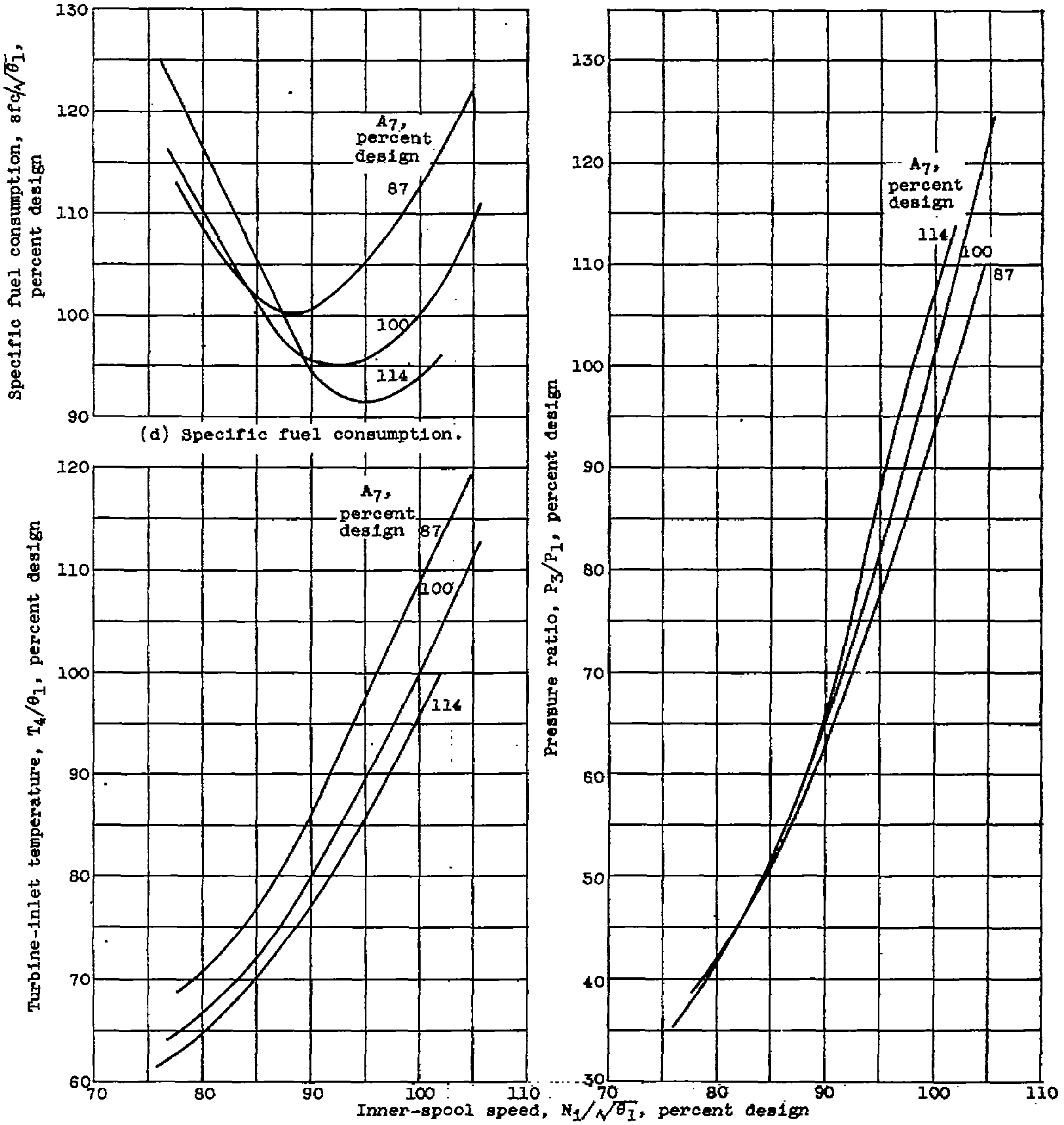
[redacted]



(a) Thrust. (b) Weight flow. (c) Outer-spool speed.

Figure 11. - Sea-level static engine performance for constant-exhaust-nozzle-area operation.

[redacted]



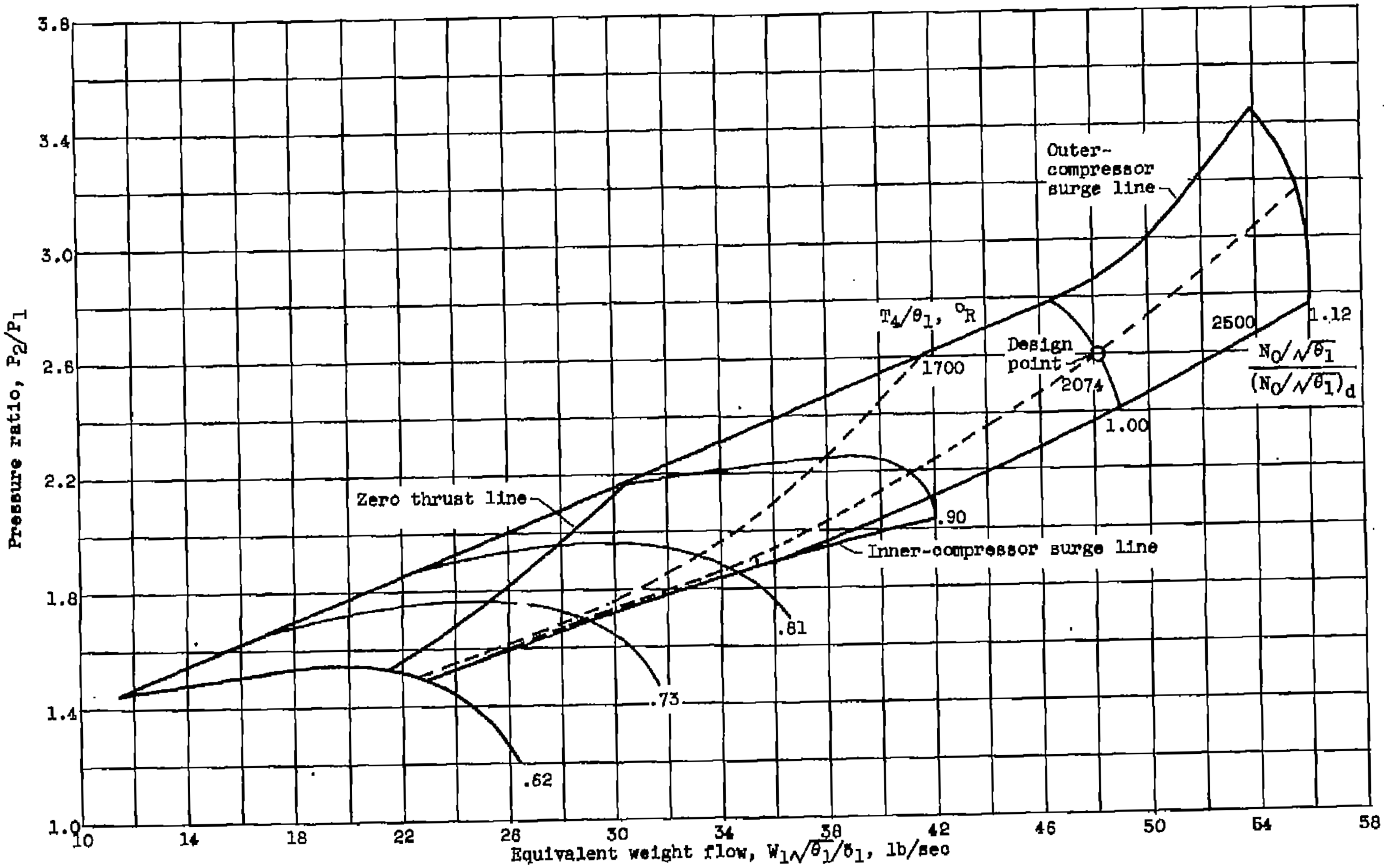
(d) Specific fuel consumption.

(e) Turbine-inlet temperature.

(f) Pressure ratio.

Figure 11. - Concluded. Sea-level static engine performance for constant-exhaust-nozzle-area operation.

[redacted]

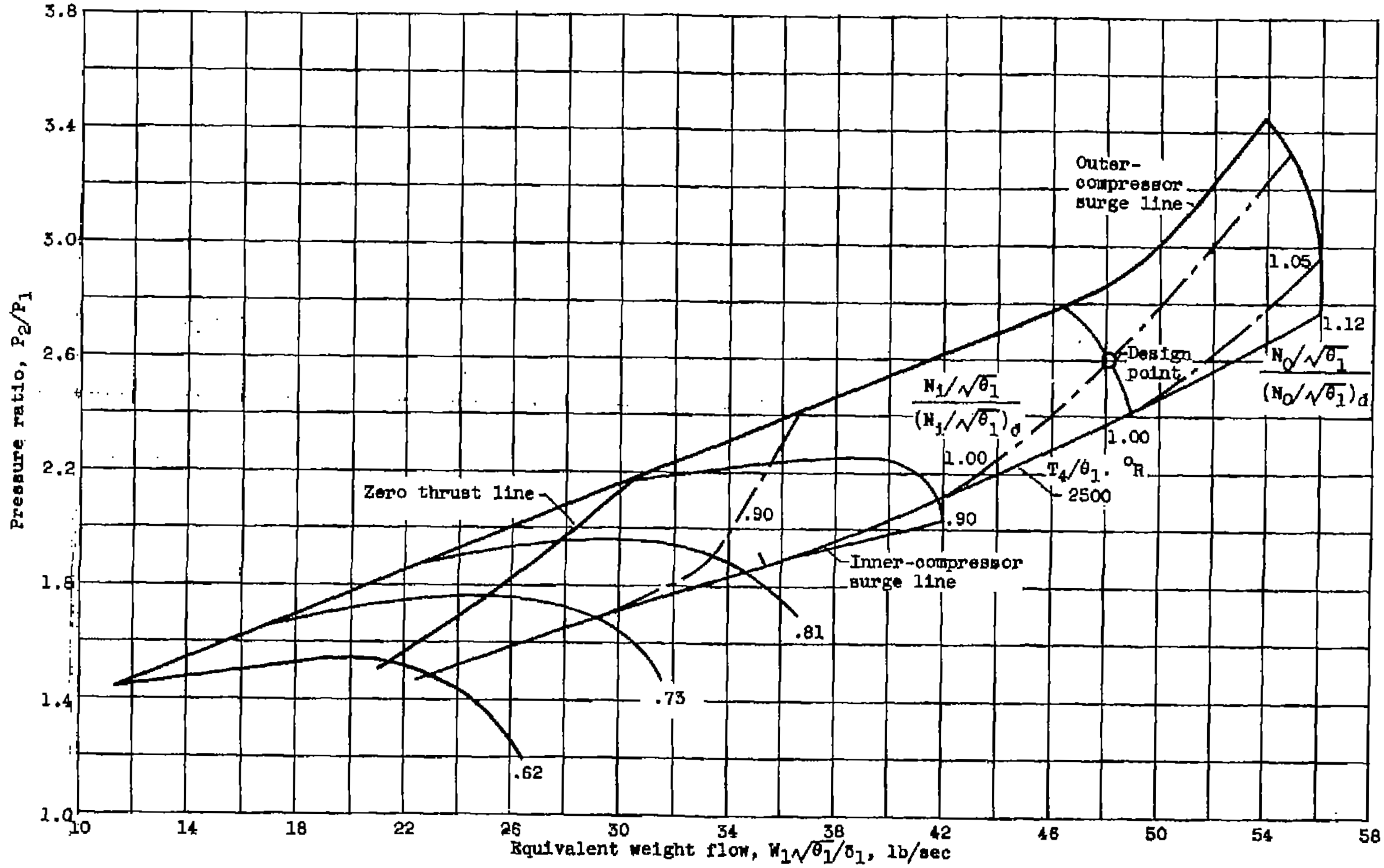


[redacted]

(a) Constant-outer-spool-speed lines and constant-turbine-inlet-temperature lines.

Figure 12. - Performance of outer compressor.

[redacted]

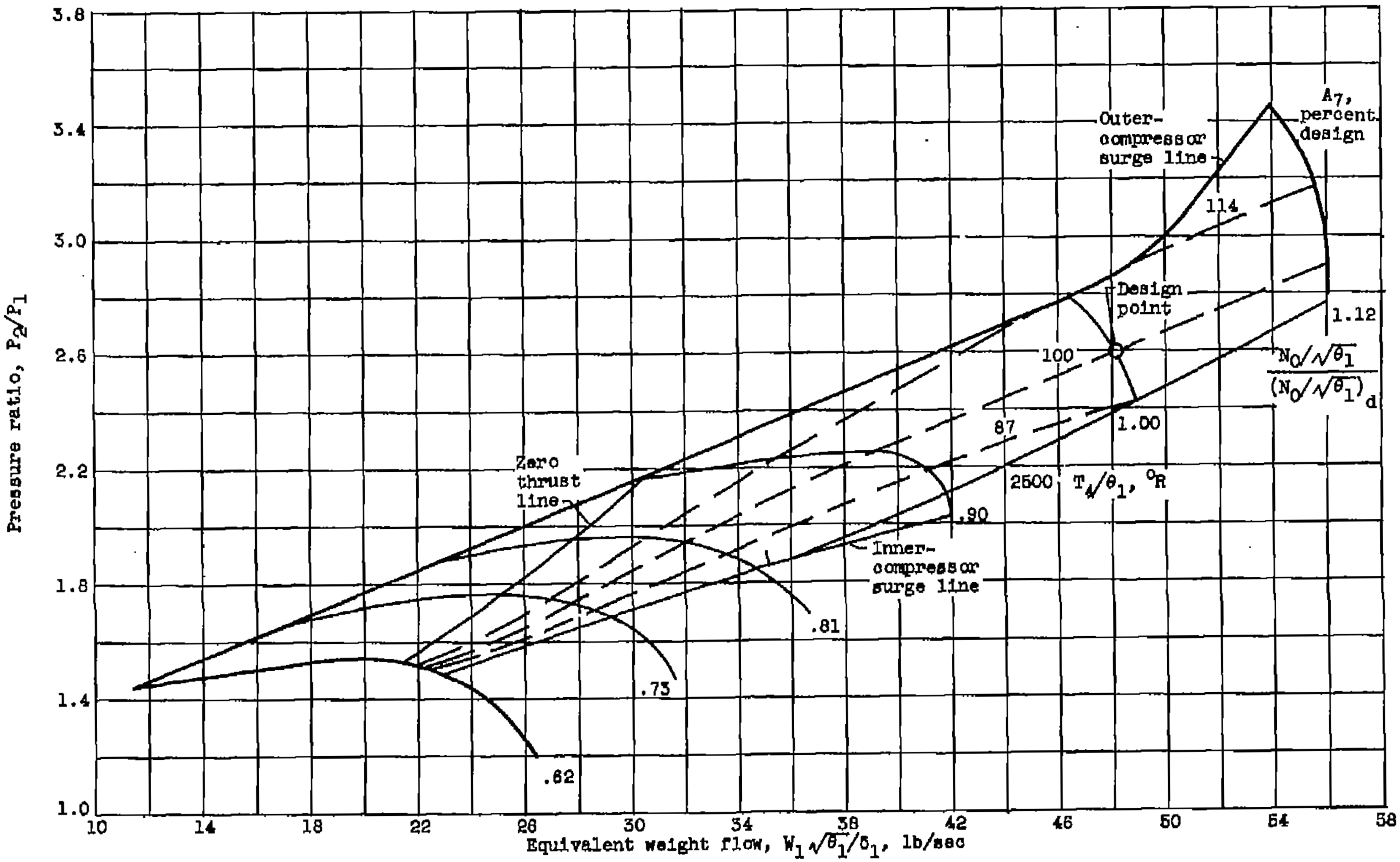


(b) Constant-inner-spool-speed lines.

Figure 12. - Continued. Performance of outer compressor.

[redacted]

[redacted]

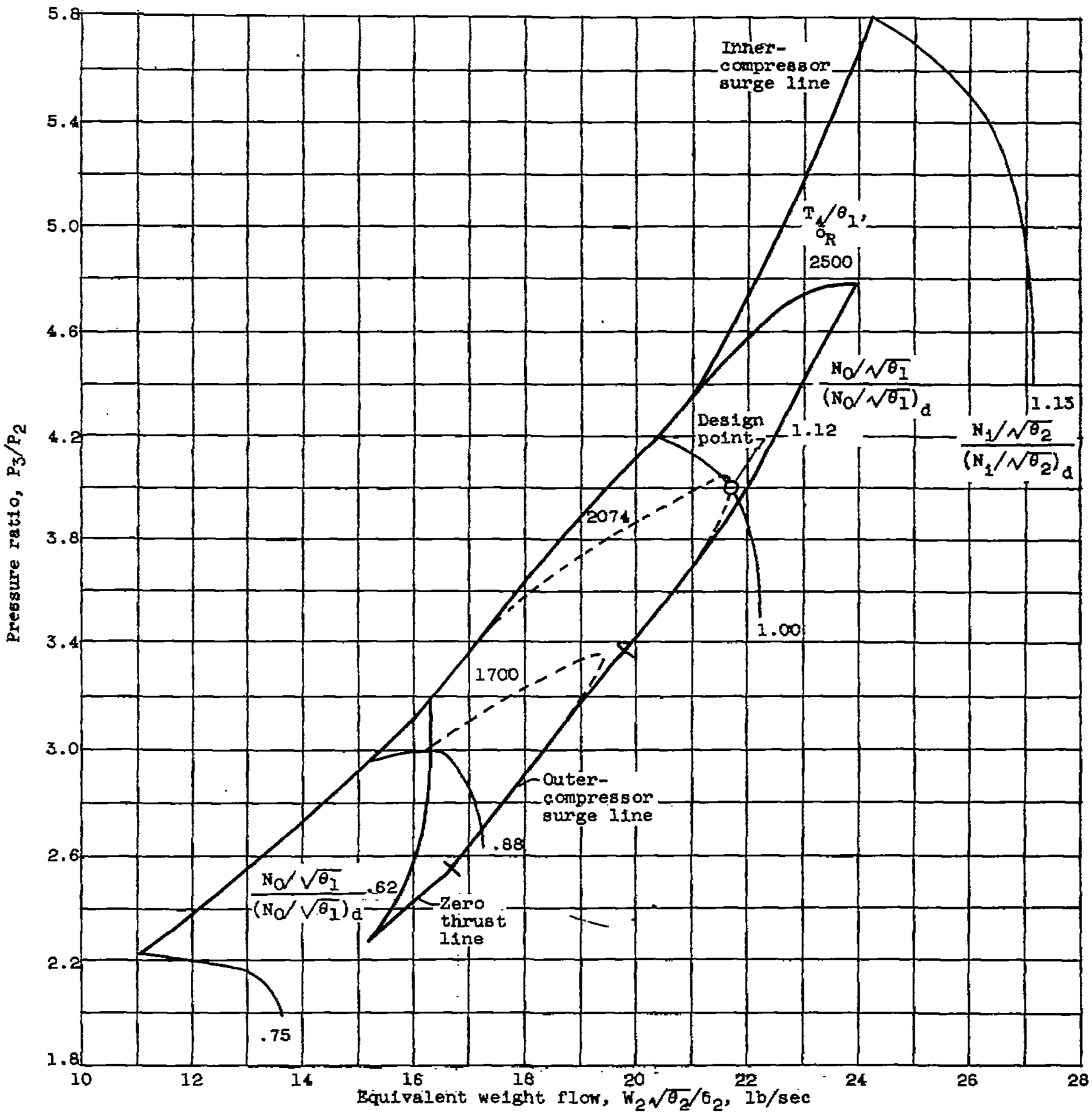


(c) Constant-exhaust-nozzle-area lines.

Figure 12. - Concluded. Performance of outer compressor.

[redacted]

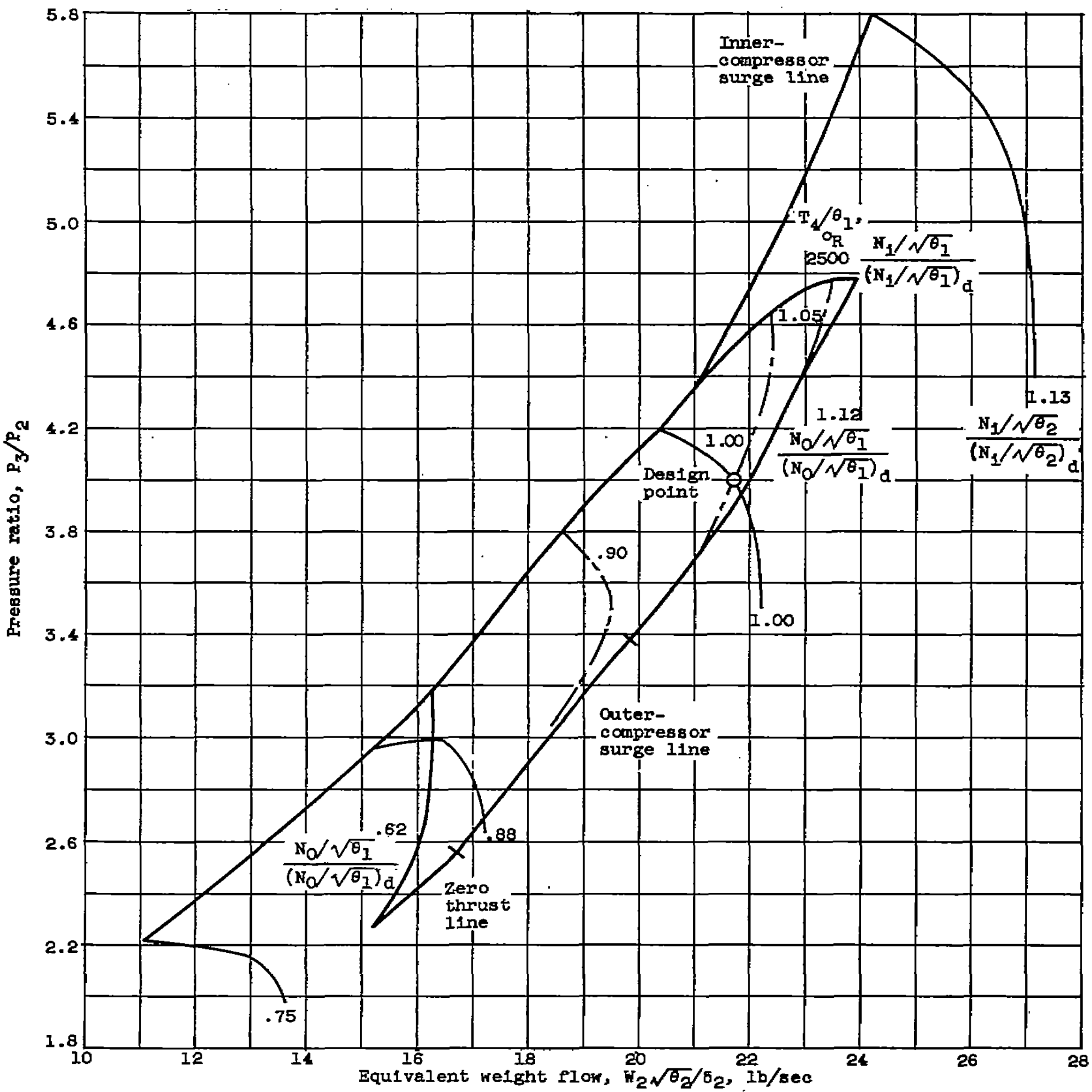
3279



(a) Constant-outer-spool-speed lines and constant-turbine-inlet-temperature lines.

Figure 13. - Performance of inner compressor.

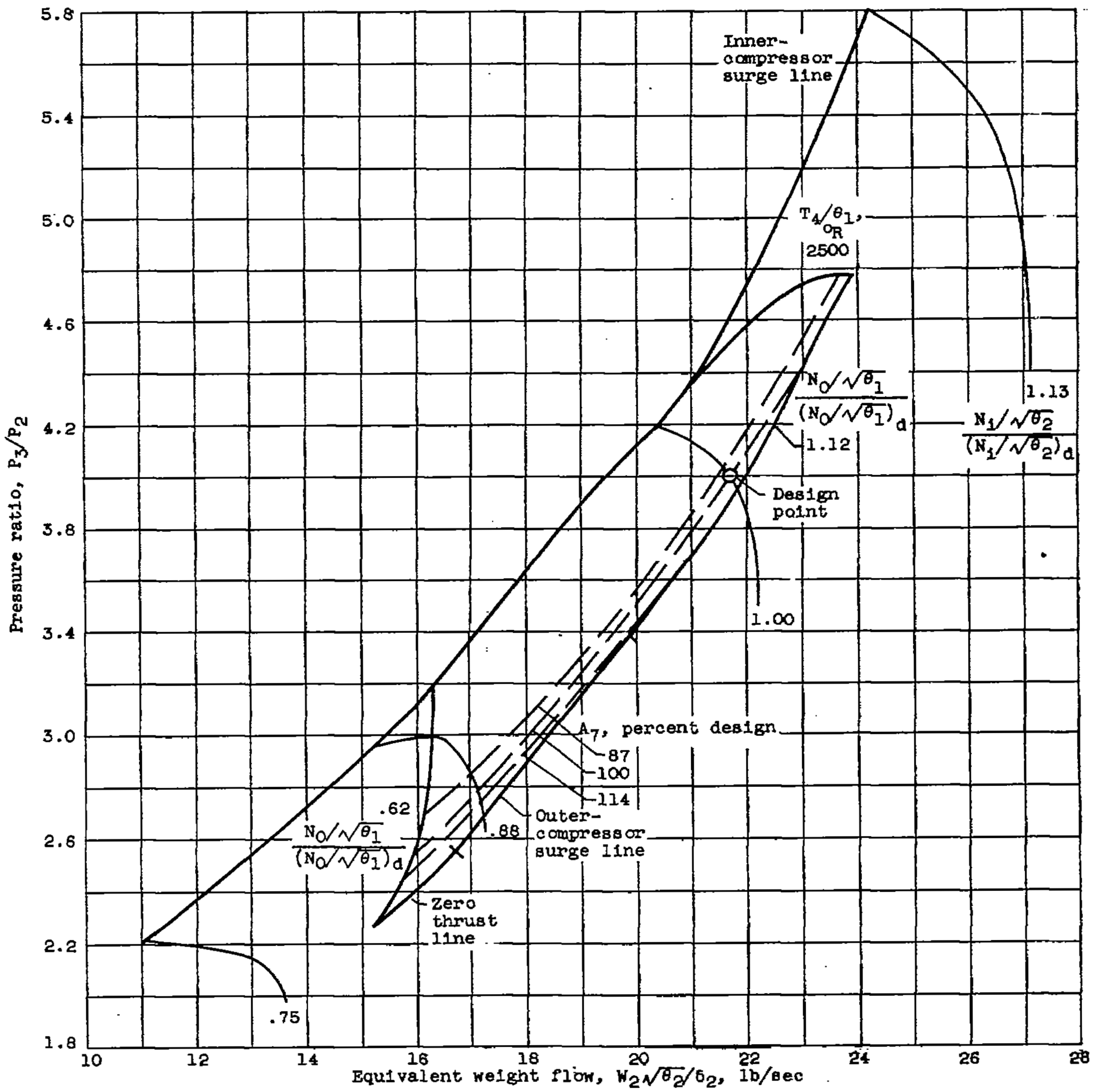
3279



(b) Constant-inner-spool-speed lines.

Figure 13. - Continued. Performance of inner compressor.

3279



(c) Constant-exhaust-nozzle-area lines.

Figure 13. - Concluded. Performance of inner compressor.

3279

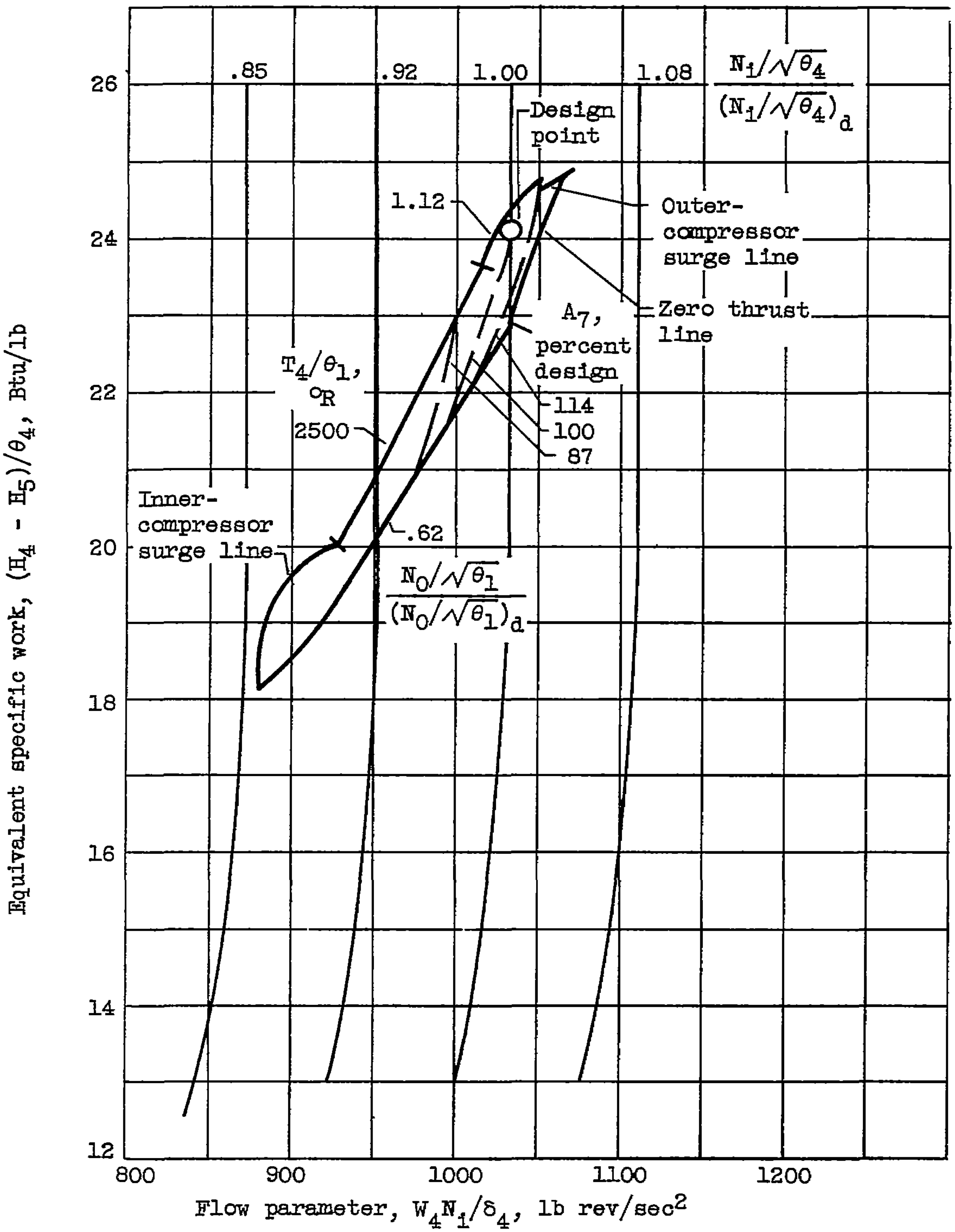
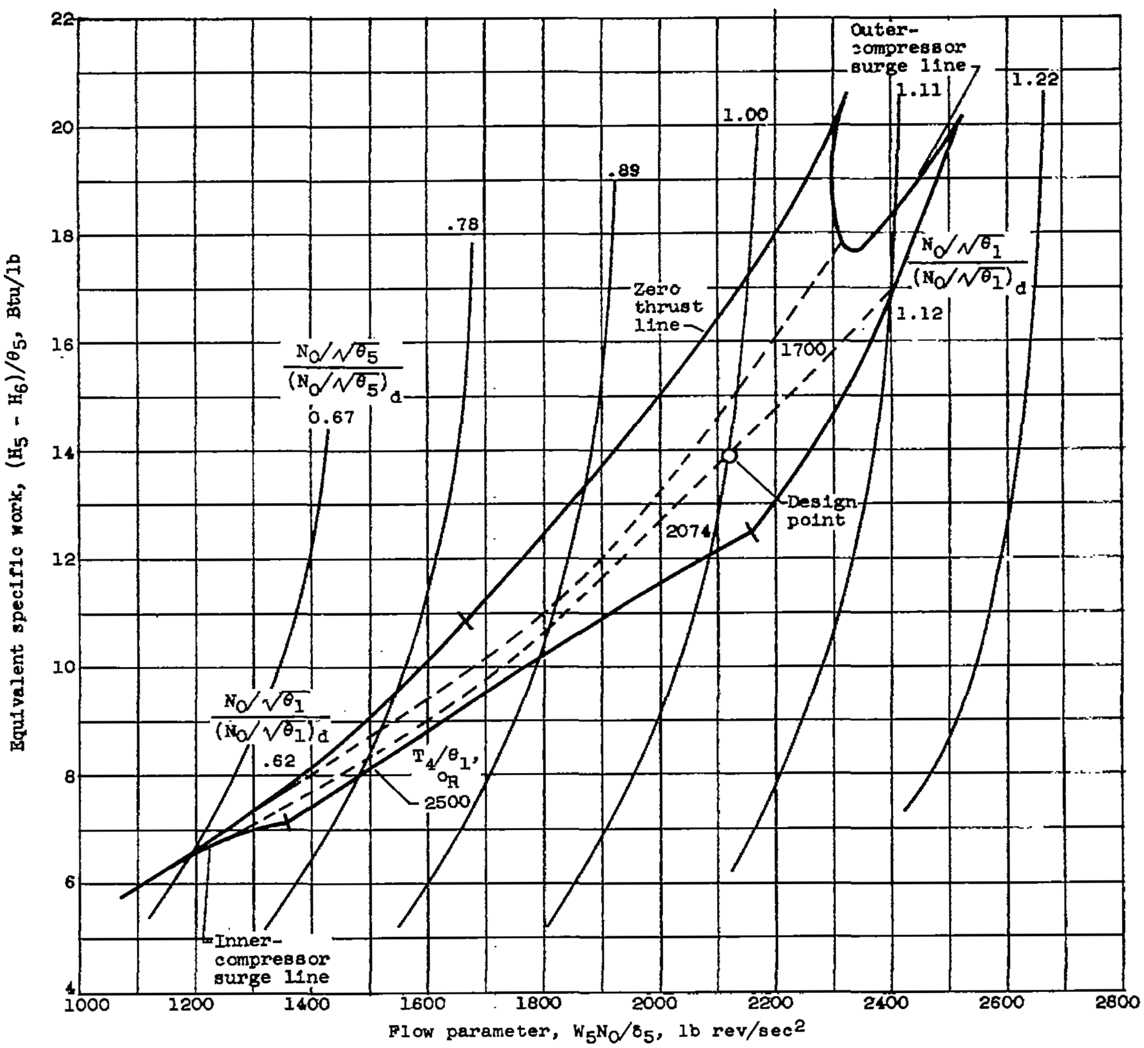


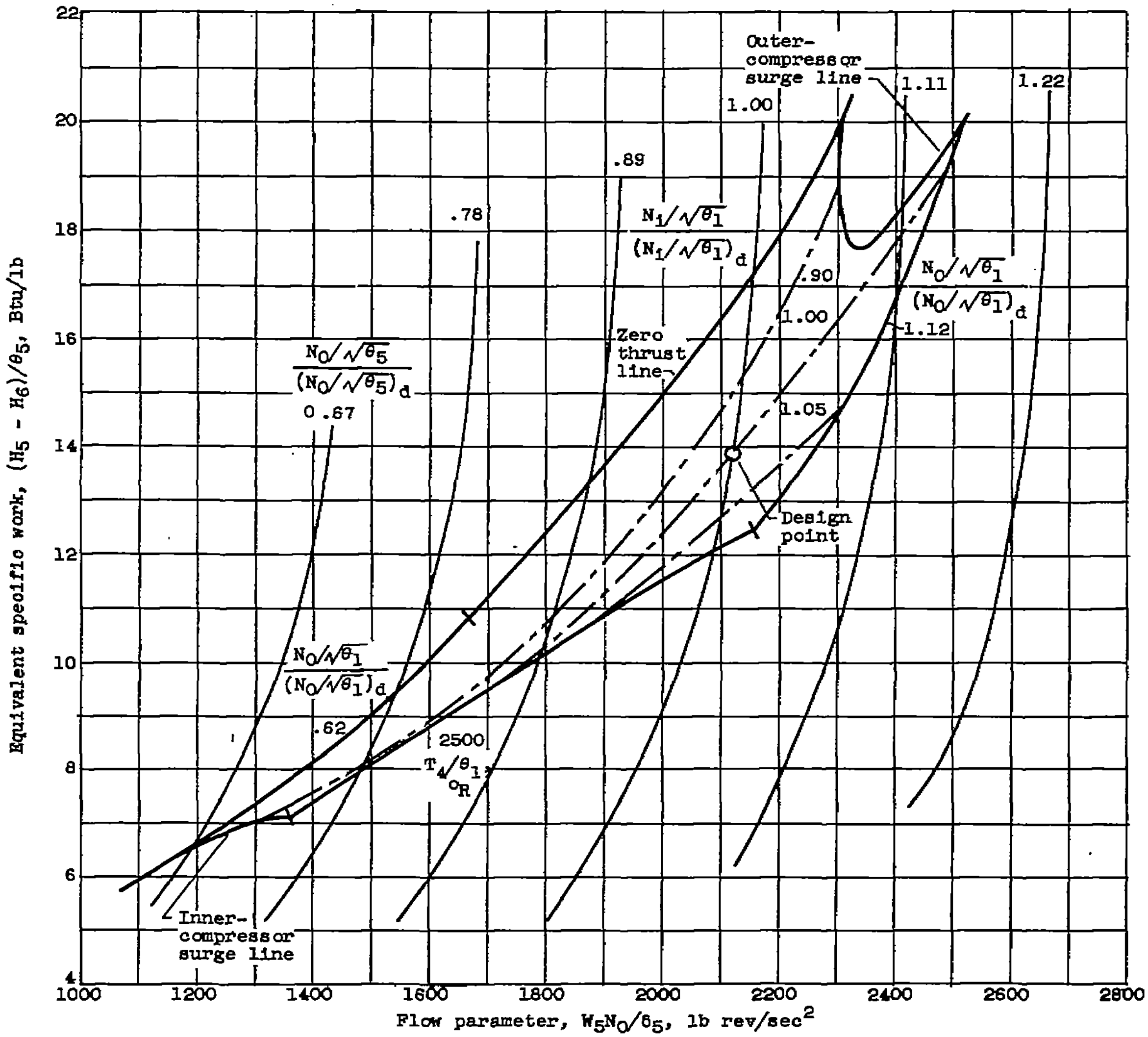
Figure 14. - Performance of inner turbine.



(a) Constant-outer-spool-speed lines and constant-turbine-inlet-temperature lines.

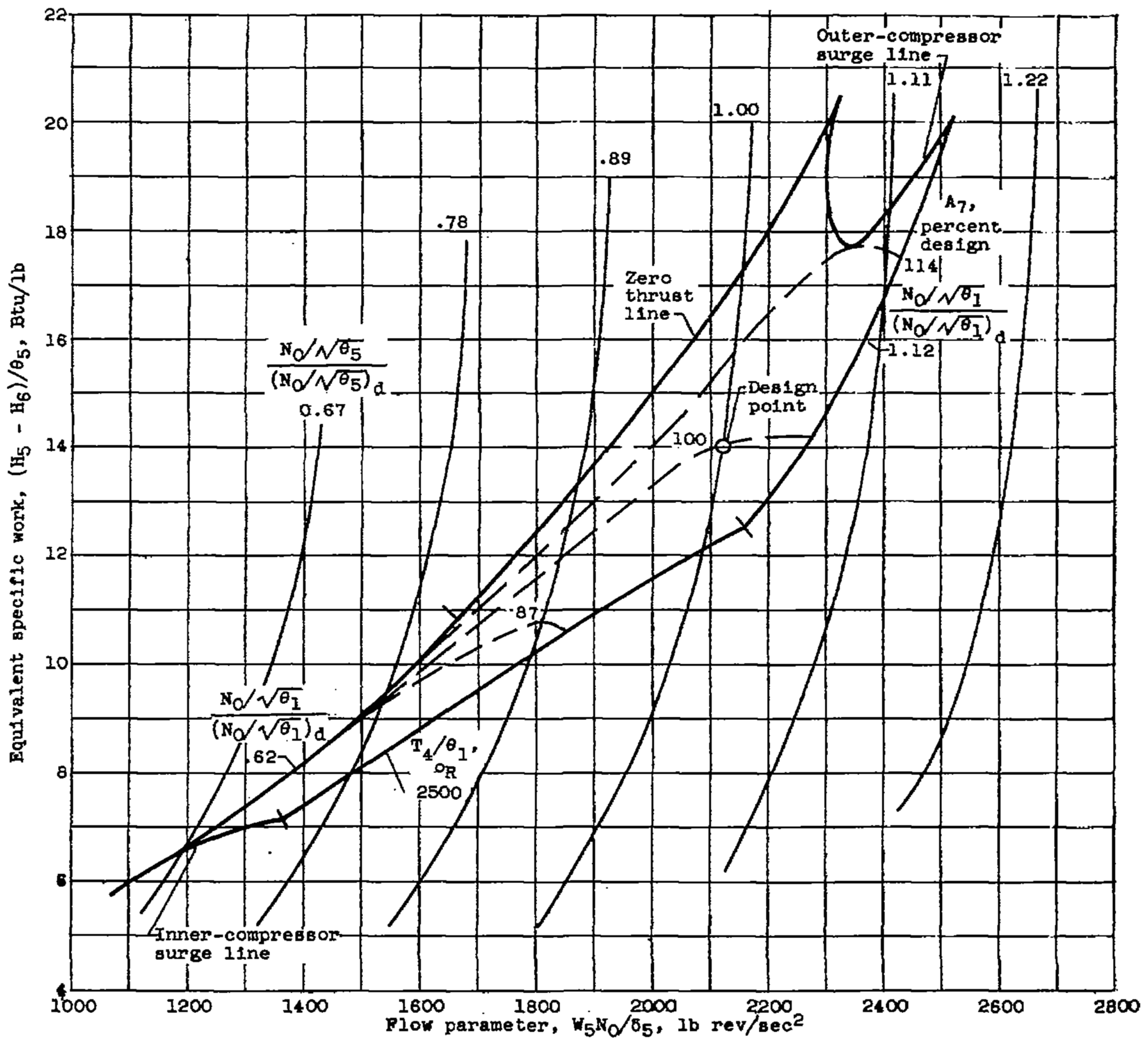
Figure 15. - Performance of outer turbine.

3279



(b) Constant-inner-spool-speed lines.

Figure 15. - Continued. Performance of outer turbine.



(c) Constant-exhaust-nozzle-area lines.

Figure 15. - Concluded. Performance of outer turbine.

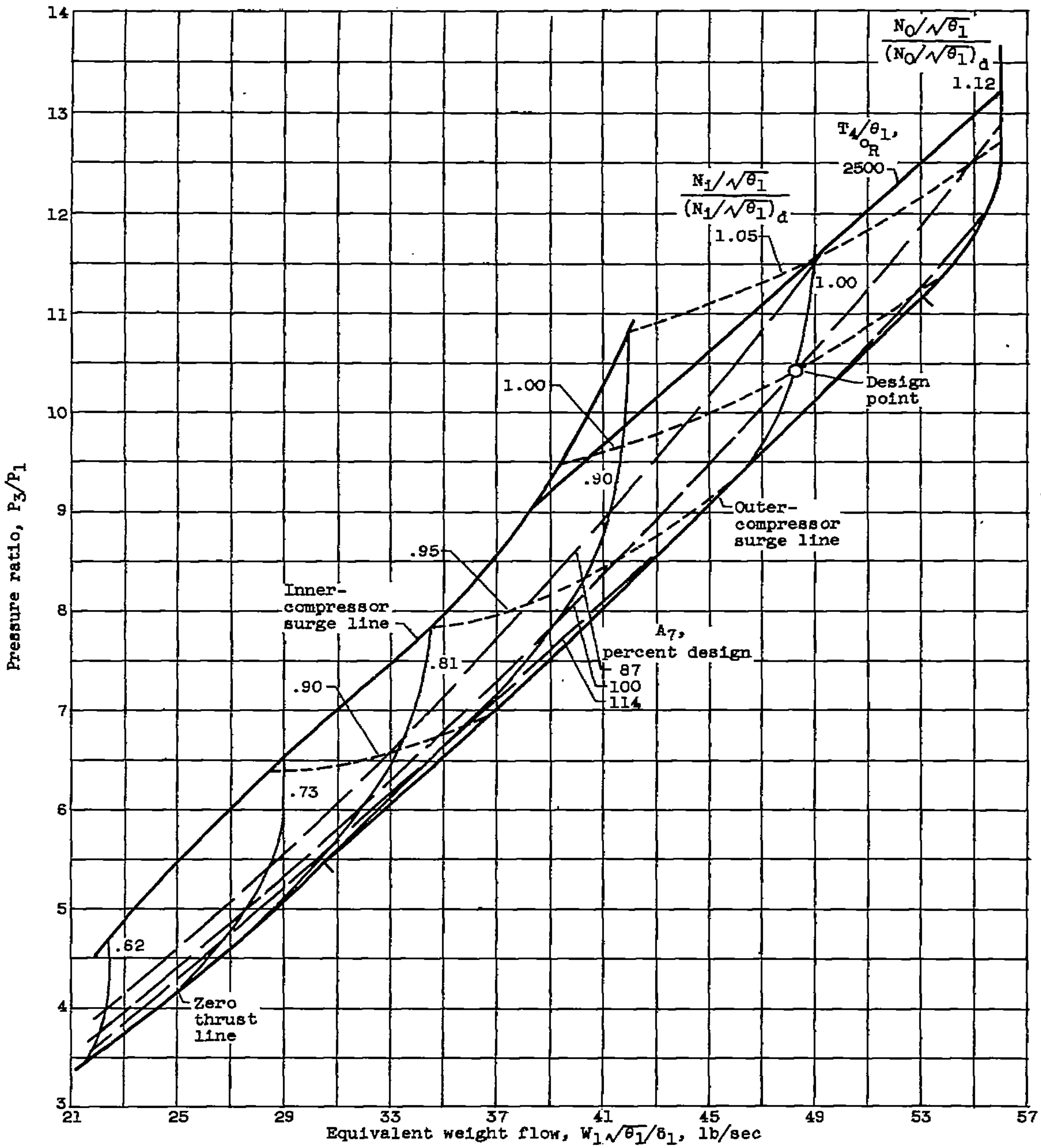
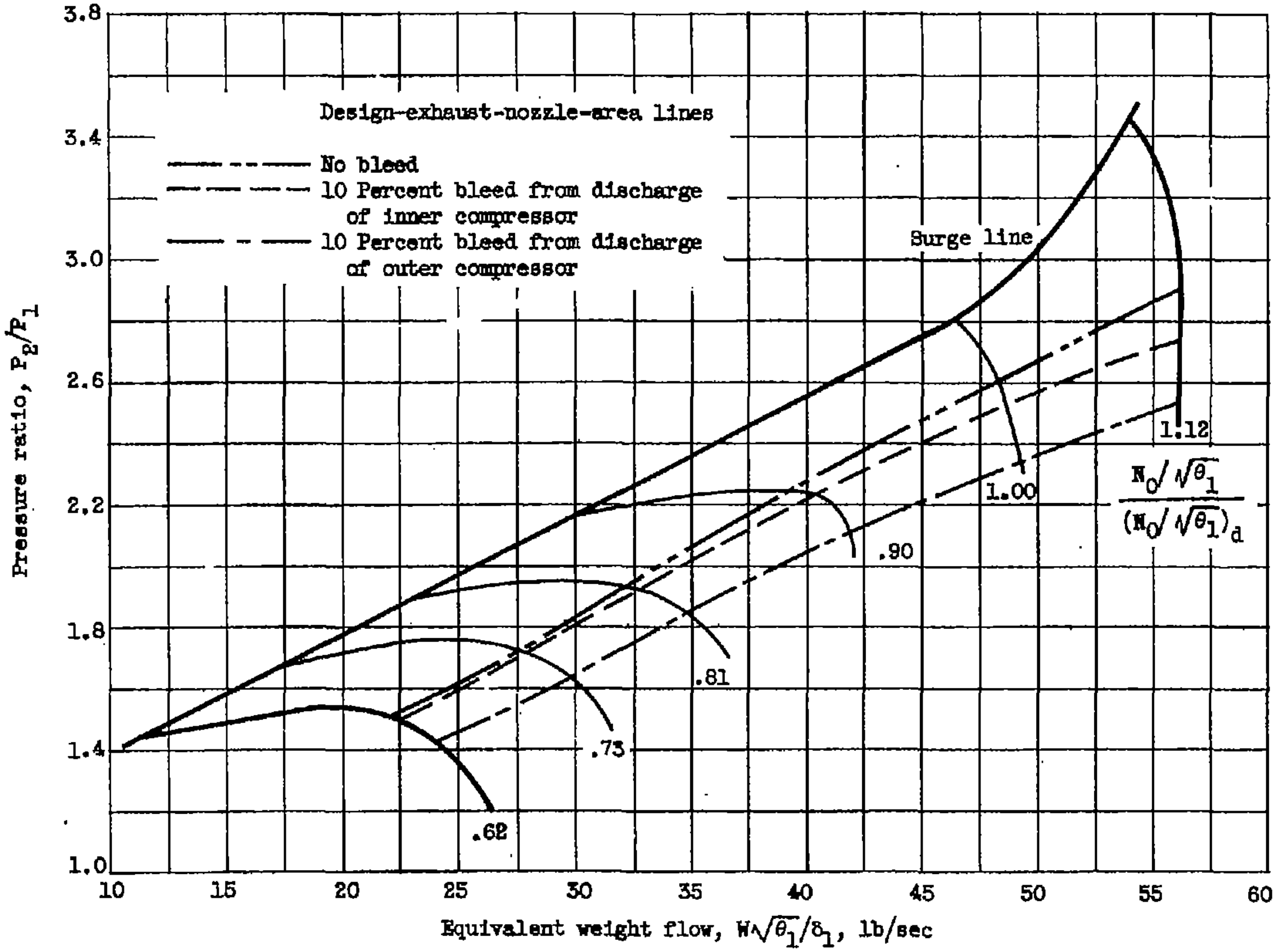
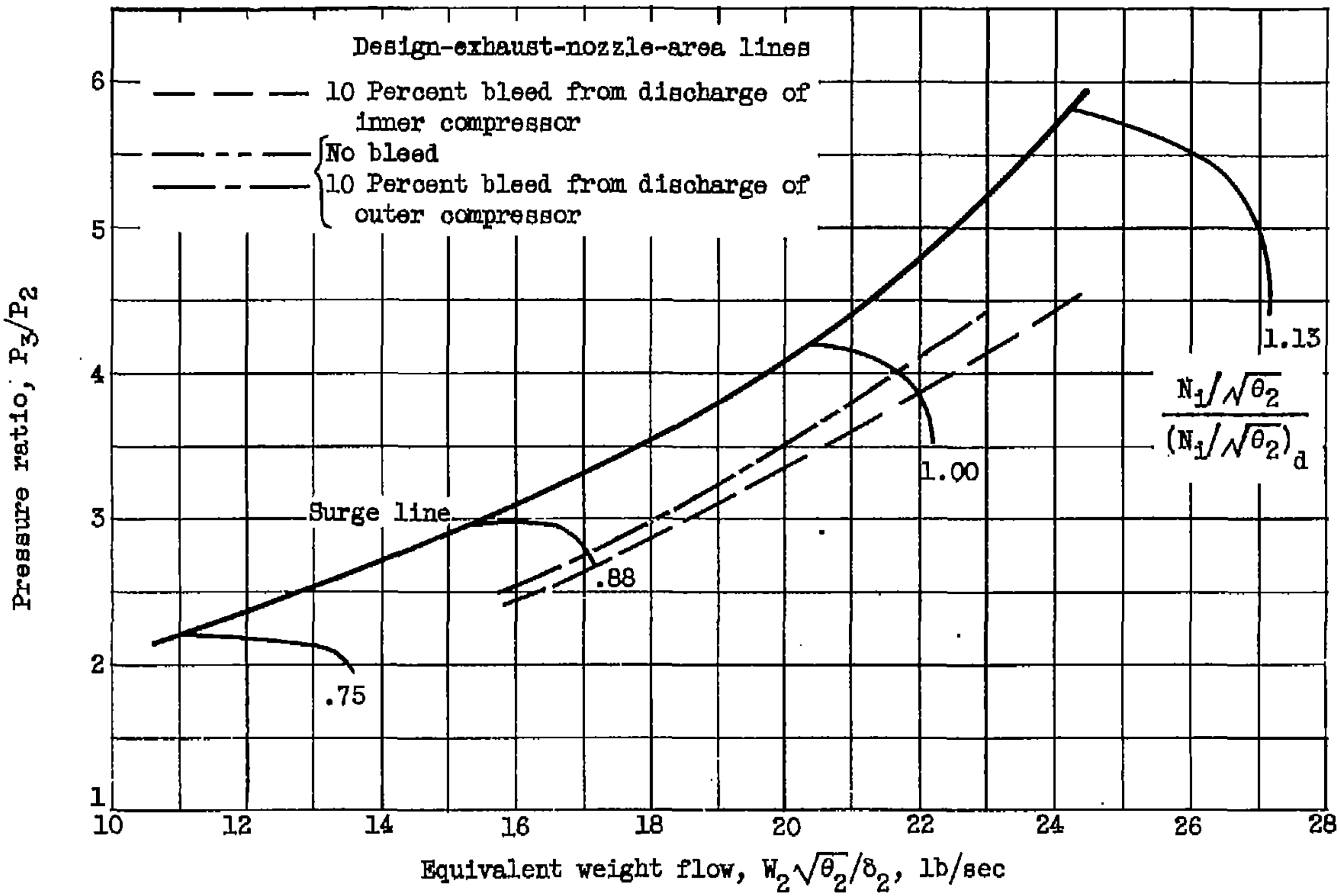


Figure 16. - Over-all compressor performance map.



(a) Outer-compressor performance map.

Figure 17. - Effect of compressor-discharge bleed on design-exhaust-nozzle-area equilibrium operating line.



(b) Inner-compressor performance map.

Figure 17. - Concluded. Effect of compressor-discharge bleed on design-exhaust-nozzle-area equilibrium operating line.