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STUDY OF VARIABLE TURBINE GEOMETRY FOR SMALL GAS TURBINE ENGINES

By

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April 1967

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

CONTRACT DA 44-177-AMC-425(T)

ALLISON DIVISION
GENERAL MOTORS
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Appropriate technical personnel have reviewed this report and concur with the conclusions contained herein.

The findings and recommendations outlined herein will be taken into consideration in the planning of future programs for turbines and turbine engines.

Task 1M125901A01409

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EDR 4965

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ABSTRACT

An analytical investigation of the transient and steady-state performance of a series of gas turbine engines utilizing variable geometry in the turbine has been completed. Shaft-power engines with and without regeneration and incorporating either free- or single-shaft configurations were investigated at compressor pressure ratios of 10 and 16. In addition, free-shaft, simple-cycle, high bypass, fan engines were evaluated using the 10- and 16-pressure-ratio gas generators for the high pressure system. Extensive use was made of the IBM 7094 II digital computer to analyze both the turbine and overall engine performance.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure		Page

Figure		Page

LIST OF TABLES

SYMBOLS

a	speed of sound
A	area
BPR	bypass ratio
BT	type of blade leading edge: blunt, normal, sharp
C_d	nozzle area coefficient
C_v	nozzle velocity coefficient
F_n	net thrust
H	normal velocity head correction factor for incidence
M	Mach number
N	r.p.m.
P	pressure
R	pressure ratio
s.f.c.	specific fuel consumption
T	temperature
TIT	turbine inlet temperature
U	rotor wheel speed
V	velocity
W	mass flow
Y	turbine loss coefficient
β	turbine blade inlet angle
η	efficiency
γ	ratio of specific heats
θ	temperature ratio
δ	pressure ratio
Yt	zero incidence loss coefficient

SUBSCRIPTS

a	air
g	gas generator
p	power turbine
c	compressor
d	design
e	expansion
amb	ambient
r	regenerator
b	burner
L	leakage
f	fuel
th	thermal
1	engine inlet
M	maximum
t	turbine

SYMBOLS AND LINES ON ENGINE PARAMETER CURVES

⊙	50-percent power
△	single-point calculation
———	constant area
— — —	variable power turbine area
— - — -	variable gasifier turbine area
— - - —	both power turbine and gasifier turbine area variable

INTRODUCTION

This report contains the analytical results and describes the work accomplished to evaluate the performance characteristics of variable turbine geometry in a number of gas turbine engine configurations. The effort included the evaluation of 18 engines incorporating combinations of the following features:

- Turboshaft - turboprop - turbofan
- Regenerative and simple cycle
- Free and single shaft

Two cycle design points were considered. One was a 10.0:1-compressor-pressure-ratio engine running at 2500°F. turbine inlet temperature and the other a 16.0:1-compressor-pressure-ratio engine at 3000°F. turbine inlet temperature.

Sufficient steady-state and transient performance was computed from 100 percent down to 30 percent of rated power to determine the characteristics of variable turbine performance in the various configurations. Primary emphasis was placed on performance at the sea level static operating condition. Additional calculations were made at sea level 250 knots for the turboprop engine. The use of variable geometry to increase the 6000-foot 95°F. ambient temperature power was also explored.

The performance calculations for this study were limited to 100-percent free-turbine r.p.m. on the free-shaft engines and 100-percent r.p.m. on the single-shaft configurations.

There are numerous combinations of gasifier and free-shaft speed which could be investigated on the free-shaft engine, however, the optimum characteristic of free-shaft speed versus gasifier speed will be different for various turbine control modes. In addition, the deviation between the optimum speed and constant speed in terms of specific fuel consumption versus percent power is not significant. For these reasons, all free-shaft engines were investigated at a constant free-shaft speed.

For the single-shaft engine there are an infinite number of compressor pressure ratio, turbine inlet temperature, and speed combinations available as function of load (output shaft torque) and turbine area.

Therefore, to provide a common basis for comparison to the free-shaft configurations, the performance of the single-shaft engine was based on a constant 100-percent output shaft speed.

All engine configurations used a three-stage compressor (two axial followed by a centrifugal) and four axial turbine stages. The turbofan used the same flow path as the free-shaft turboshaft/turboprop engines with a 4.0 bypass ratio, a 1.51-pressure ratio fan ahead of the compressor. The fan was driven by the free turbine. The turbines were common for all the configurations at each compressor pressure ratio.

Mechanical design definition of the various engine configurations was limited to determination of the moment of inertia of the respective rotor systems. These data were required for use in the transient performance analysis.

DEVELOPMENT OF THE PROBLEM

INTRODUCTION

There are three parameters that are of major importance in establishing the throttled power characteristics of a gas turbine engine:

- Airflow
- Turbine inlet temperature
- Compressor pressure ratio

Power level is determined primarily by airflow and turbine inlet temperature and, to a lesser extent, by compressor pressure ratio. Cycle efficiency and, hence, specific fuel consumption are established by the combination of turbine inlet temperature and pressure ratio (in this preliminary development of the problem, the effects of component efficiency and losses were ignored since these are of a second-order nature). Thus, a given combination of airflow, turbine inlet temperature, and compressor pressure ratio produces a unique combination of power output and fuel consumption. This situation holds true regardless of engine configuration.

However, the engine configuration and/or control method can impose a restriction on the possible combinations of airflow, temperature, and pressure ratio that occur during throttled power operation. In a fixed geometry engine, throttling is accompanied by a decrease in turbine inlet temperature and compressor pressure ratio. This causes the cycle efficiency to decrease and produces the familiar characteristic of a rising specific fuel consumption as power is reduced.

The use of variable turbine geometry offers the potential of altering the flow-temperature-pressure ratio matching characteristics of the engine in a manner such that the engine operates closer to the optimum compressor pressure ratio and/or turbine inlet temperature for maximum cycle efficiency (minimum specific fuel consumption) at throttled power settings. Additionally, the engine rematching that is possible with variable turbine geometry appears to provide a means for reducing engine acceleration time from low power settings.

Insight into the throttling characteristics of the shaft-power gas turbine engine can be gained by examination of the thermal efficiency equations for the Brayton cycle. Two cases are of interest: the simple cycle and the regenerative cycle. Equations 1 and 2 describe the thermal efficiency relationships for each. The equations are equally applicable for single- or free-shaft configurations. Figure 1 depicts the thermal efficiency as a function of pressure ratio and turbine temperature with component efficiencies as noted. The effect of changing the component efficiencies can be seen on Figure 2 for a representative temperature ratio and pressure ratio. The change in thermal efficiency with turbine efficiency is of particular interest. When incorporating variable geometry in an engine, care must be exercised to maintain the turbine efficiency at a reasonable level to prevent an excessive loss in thermal efficiency.

$$\eta_{th} = \frac{\left[\eta_c \, \eta_t \, (T_M/T_1) - R_c^{\frac{\gamma-1}{\gamma}}\right]\left(R_c^{\frac{\gamma-1}{\gamma}} - 1\right)}{\left[\eta_c \, (T_M/T_1 - 1) - \left(R_c^{\frac{\gamma-1}{\gamma}} - 1\right)\right] R_c^{\frac{\gamma-1}{\gamma}}} \tag{1}$$

$$\eta_{th} = \frac{\left(R_c^{\frac{\gamma-1}{\gamma}} - 1\right)\left[\eta_c \, \eta_t \left(T_M/T_1\right) - \eta_c\left(R_c^{\frac{\gamma-1}{\gamma}} - 1\right) - 1\right]}{T_M/T_1 \left\{\left[1 + \eta_c\left(R_c^{\frac{\gamma-1}{\gamma}} - 1\right)\right] - \eta_R\left[1 + (1-\eta_t)\,\eta_c\left(R_c^{\frac{\gamma-1}{\gamma}} - 1\right)\right]\right\} - \left\{\left(1-\eta_R\right)\left[1 + \left(R_c^{\frac{\gamma-1}{\gamma}} - 1\right)\right]\left[1+\eta_c\left(R_c^{\frac{\gamma-1}{\gamma}} - 1\right)\right]\right\}} \tag{2}$$

For the simple-cycle case, the importance of maintaining both turbine inlet temperature and compressor-pressure ratio at their maximum value is clearly evident from the curves of Figure 1. Any decrease in either of these parameters will cause a reduction in thermal efficiency. Thus, the ideal method of throttling an engine would be to reduce flow while maintaining temperature ratio and pressure ratio at their maximum values. It will be shown later that such operation is possible providing enough variable geometry is incorporated in the turbine.

There are other throttling methods that would produce somewhat lesser gains in thermal efficiency. One alternative is to hold temperature and reduce pressure ratio, while another is to hold pressure ratio and reduce temperature. In either of these cases, the flow will vary with the geometry change. In summary, it can be stated that there is a potential gain in thermal efficiency with variable geometry providing either turbine inlet temperature or compressor pressure ratio can be maintained at a higher level than that associated with fixed geometry operation.

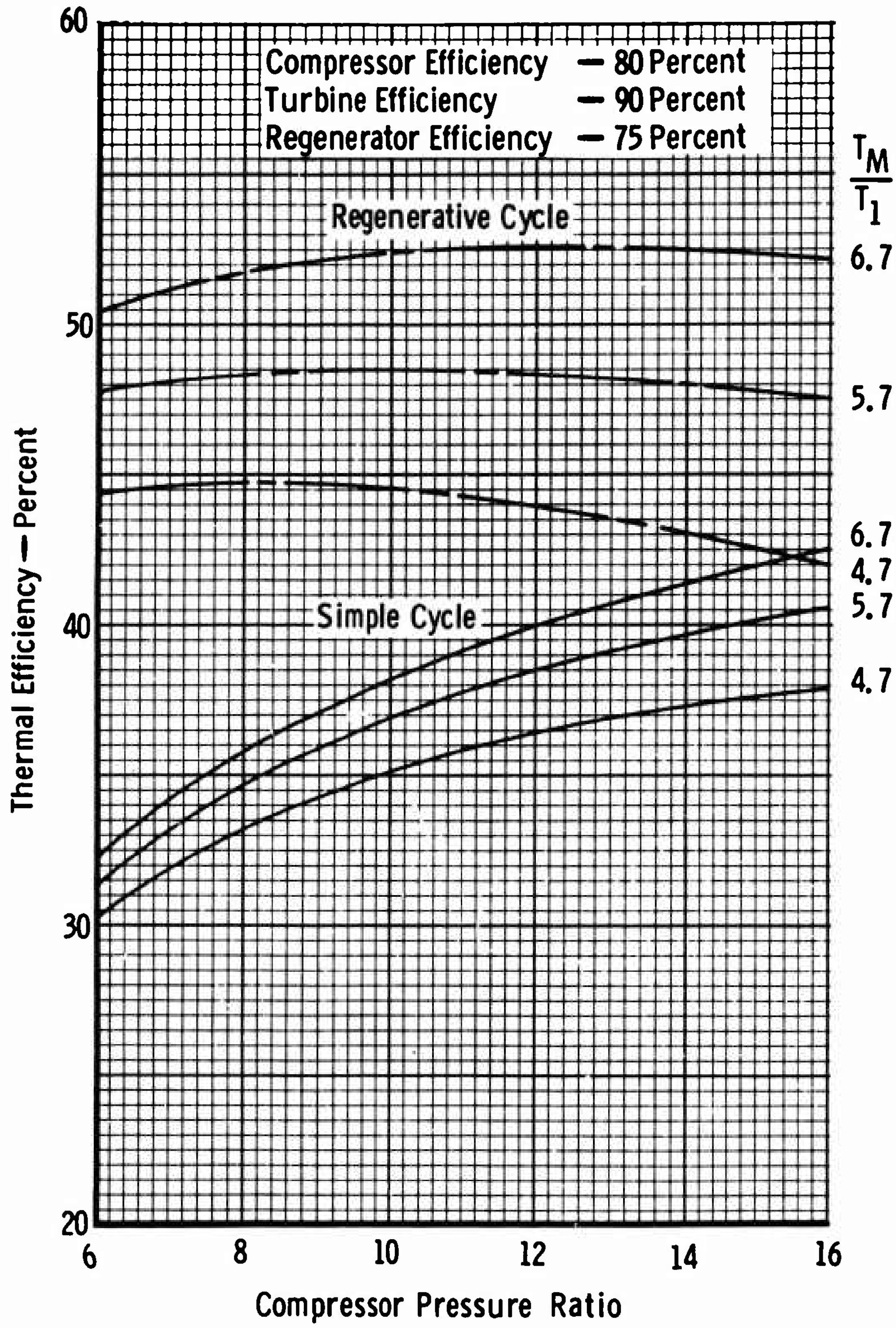

Figure 1. Thermal Efficiency as a Function of Compressor Pressure Ratio.

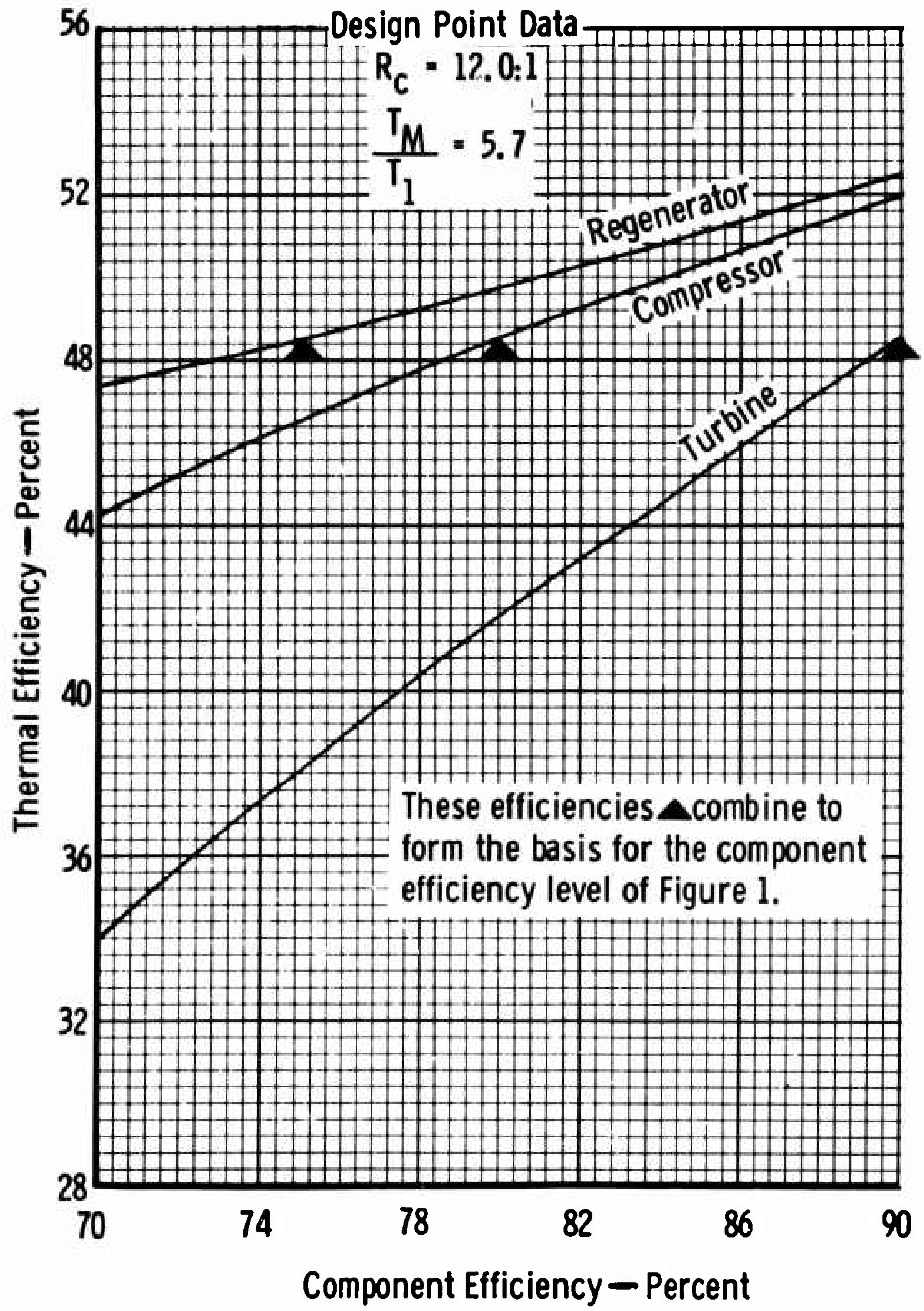

Figure 2. Thermal Efficiency as a Function of Component Efficiency.

Figure 1 also shows that the regenerative cycle exhibits efficiency characteristics and levels that are markedly different from those of the simple cycle. Thermal efficiency can either increase or decrease with pressure ratio, but, in general, it remains relatively constant over a broad range of pressure ratios. On the other hand, temperature ratio has a much larger effect for the regenerative-cycle than for the simple-cycle engine. The thermal efficiency characteristics of the regenerative cycle will change shape and level with changes in regenerator effectiveness. Higher effectiveness levels will show maximum thermal efficiency at lower pressure ratios whereas lower effectiveness levels will move the thermal efficiency characteristic toward that of the simple cycle.

It can be concluded from Figure 1 that throttling at maximum temperature is desirable in the regenerative cycle and at both maximum temperature and pressure ratio in the simple cycle.

Figure 3 is a typical compressor map for a 16.0:1-compressor-pressure-ratio engine showing several possible operating lines. The five possible modes of operation are shown by heavy lines superimpsoed on Figure 3. For the case of single-shaft engine operation, it is possible to operate over a wide range on the map. The case investigated here, however, is only concerned with operation at 100-percent r.p.m. This is denoted by the vertical line extending down from the design point along the 100-percent speed line. Fixed area operation is defined by the lowest of the three lines extending to the left of the design point. With this type operation, the flow, pressure ratio, and turbine temperature are all being simultaneously reduced during throttling. The dashed line immediately above the fixed area line denotes operation at constant turbine inlet temperature. The two horizontal broken lines define operation at constant pressure ratio and varying temperature and are also applicable to the case of constant pressure ratio and constant temperature. The circled points on the respective operating lines define the 50-percent power operating condition.

A relative measure of the acceleration times for the various control modes can be made by examination of the 50-percent power points with respect to compressor speed, i.e., the lower the speed at 50-percent power for a given control mode, the higher the acceleration time.

The ability to operate in the various modes shown on Figure 3 can be determined from an analysis of the flow capacity of the turbines with variable geometry. A first-order procedure has been developed whereby the area variation required to effect specific desired operational characteristics can be examined.

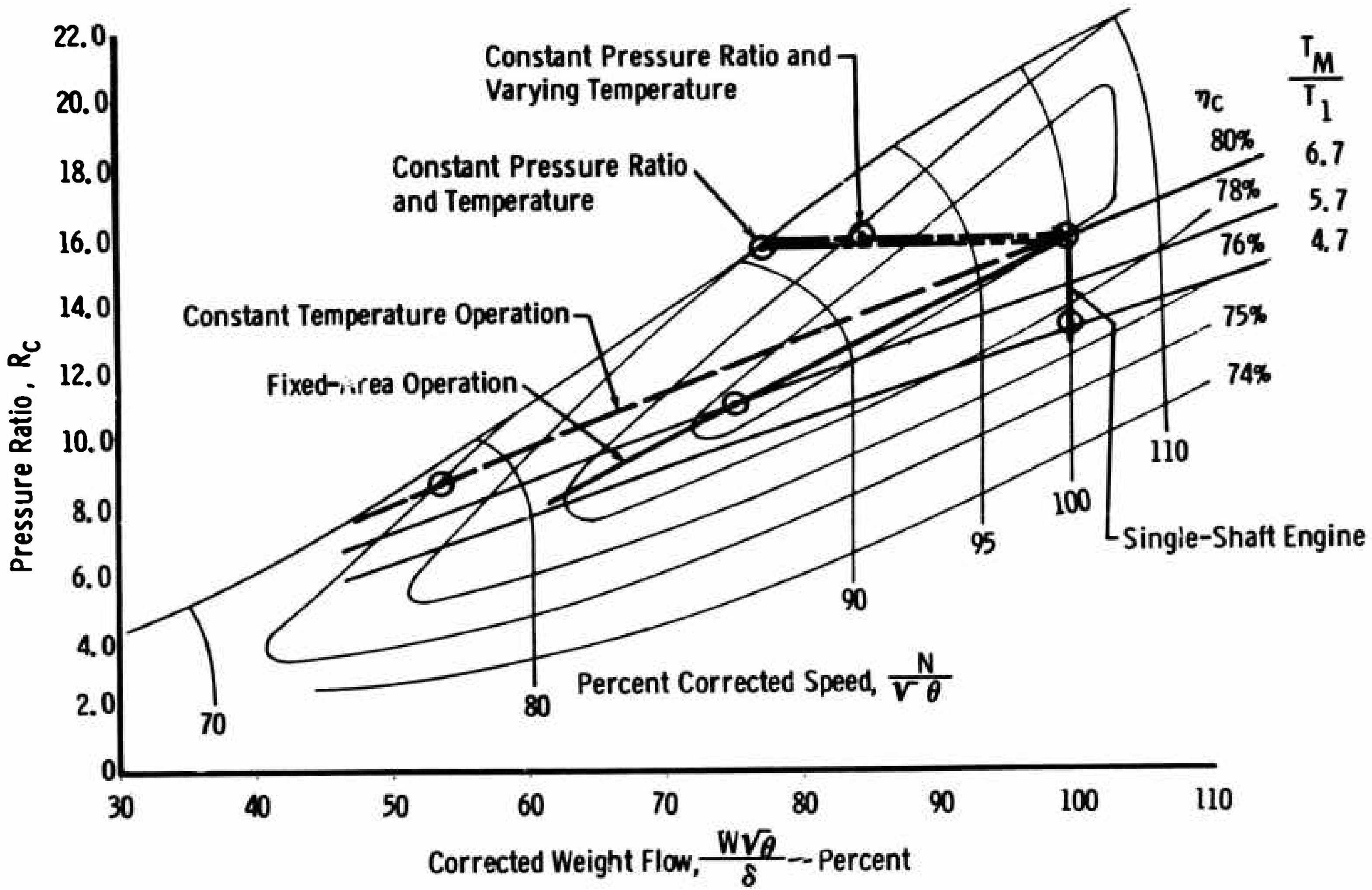

Figure 3. A Characteristic Compressor Map.

Under the assumption that the turbine (or turbines in a free-shaft engine) is choked, Equation 3

$$\frac{W\sqrt{T}}{PA} = \text{Constant} = K \tag{3}$$

defines the relationship of flow, temperature, pressure, and area at the inlet to the turbine or turbines. Equation 3 can be rearranged as follows:

$$\frac{P}{\sqrt{T}} \propto \frac{W}{A} \tag{4}$$

By performing cycle calculations, it is possible to determine the characteristic of W/A for the turbine as a function of pressure ratio and turbine temperature using the relationship of Equation 4.

The various modes of operation can then be defined in terms of turbine nozzle area requirements, as shown in Figure 4.

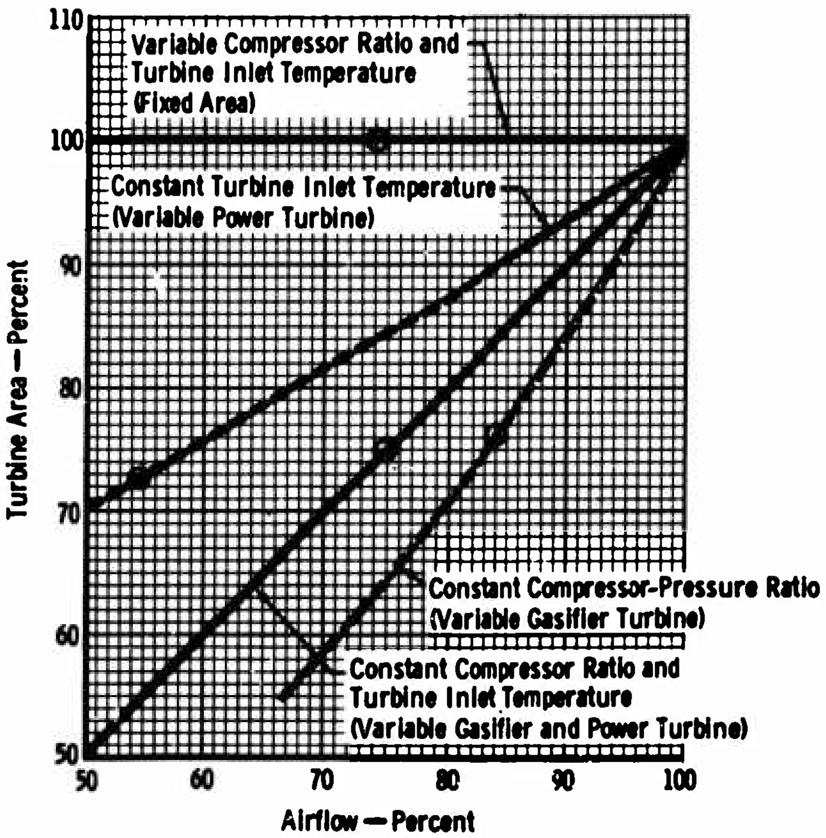

Figure 4. Percent Turbine Area as a Function of Percent Airflow.

Identification of the 50-percent power point on Figure 4 shows the turbine area requirement to range from 72 to 76 percent at this power setting. The flow variation is a result of the effect of pressure ratio and turbine temperature on power output. Note the area requirement in this ideal case is always less than the design value.

The foregoing analysis dealt with the free-shaft engine and required the examination of two areas in the turbine: one the gasifier and one the free turbine. For the single-shaft engine, some simplifications are possible as a result of selecting operation at 100-percent r. p. m. Because 100-percent r. p. m. operation results in a flow of 100 percent, a plot can be made of percent area (which is proportional to $W\sqrt{T}/P$) as a function of turbine temperature and pressure ratio, as shown on Figure 5. Fixed geometry is represented on these coordinates as a vertical line. Operation at constant temperature requires increased nozzle area and results in decreased pressure ratio as shown by the horizontal line at the top of Figure 5. Constant pressure ratio operation requires decreased nozzle area and results in decreased temperature as shown on Figure 5.

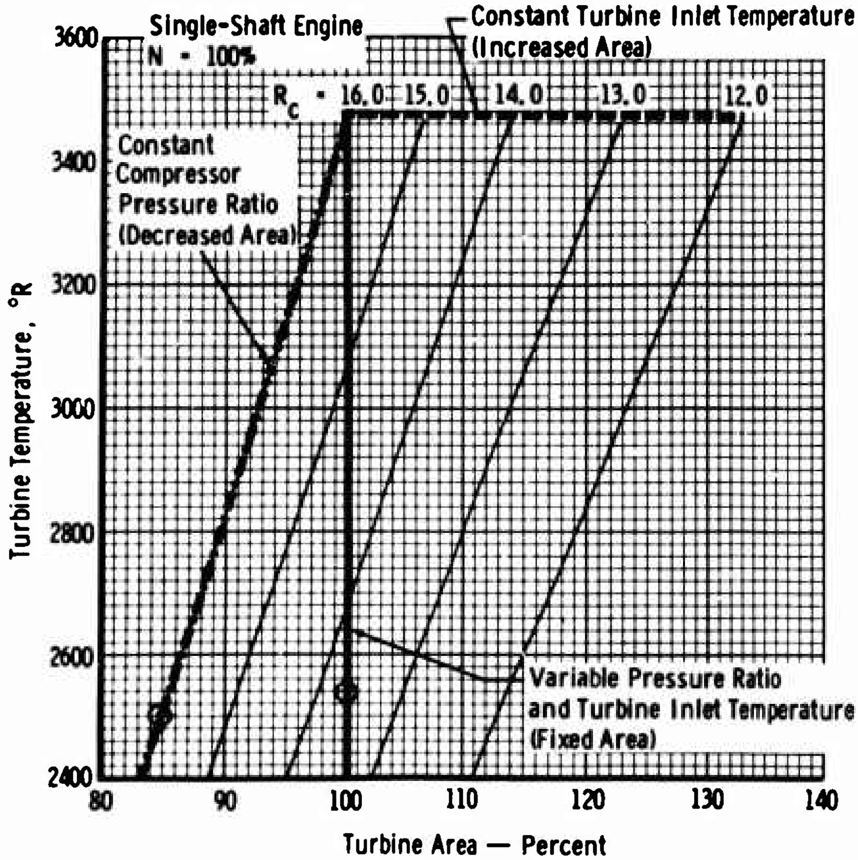

Figure 5. Turbine Flow Characteristic for a Single-Shaft Engine.

The turbofan engine is not as readily amenable to a thermal efficiency analysis as are the shaft-power engines. This stems from the fact that both propulsive efficiency and thermal efficiency must be considered in the evaluation of the fan cycle along with the number of variables to be considered. Prior studies of fan-type engines have shown the advantages of high overall pressure ratio and high bypass ratio to minimize specific fuel consumption.* These same data show, however, that high turbine temperature is not beneficial in reducing specific fuel consumption. To evaluate the turbofans for this study, use was made of the variable turbine geometry to operate the engine at maximum pressure ratio and bypass ratio. Data were developed on both of the fan configurations to determine the potential performance gain with variable turbine geometry.

DESIGN POINT ANALYSIS

This study considered regenerative and simple-cycle turboprop and turboshaft configurations and simple-cycle turbine fan engines. Each of these was examined for two thermodynamic design points in terms of compressor pressure ratio and turbine inlet temperature. The above resulted in a total of 18 engine configurations. A simple two-letter, three-digit code was devised for identification of the various engines. This will be used throughout the report. Table I lists the coding procedure.

The two thermodynamic design conditions are:

- 10-Pressure Ratio at 2500°F. Turbine Temperature
- 16-Pressure Ratio at 3000°F. Turbine Temperature

The two fan engine configurations were derived from the shaft-power engines by incorporating a 1.52-pressure-ratio fan to supercharge the compressor and to provide a 4.0-bypass ratio. In the fan engine configuration, the high pressure compressor is operating at less than 100-percent corrected r.p.m. Thus, the core pressure ratio at the design point for the two fan engines is 8.6 and 13.7. The resultant overall pressure ratios are then 13.0 and 20.7, respectively. These fan designs use the same turbines as the shaft engines.

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*S. Moise, Parametric and Preliminary Design Studies of Cruise-Fan Propulsion Systems, Pratt and Whitney Aircraft, Division of United Aircraft Corporation. USAAVLABS Technical Report 65-21, Contract DA 44-177-AMC-167 (T). May 1965. pp. 8 and 9.

TABLE I

CODE FOR ENGINE IDENTIFICATION

Code	Type of Engine* (1st letter)	Type of Cycle (2nd letter)	Shaft Configuration (1st number)	Compressor Pressure** (2nd-3rd number)
TR110	T-Turboshaft	R-Regenerative	1-Single Shaft	10
TR116	T-Turboshaft	R-Regenerative	1-Single Shaft	16
TR210	T-Turboshaft	R-Regenerative	2-Free Shaft	10
TR216	T-Turboshaft	R-Regenerative	2-Free Shaft	16
TS110	T-Turboshaft	S-Simple	1-Single Shaft	10
TS116	T-Turboshaft	S-Simple	1-Single Shaft	16
TS210	T-Turboshaft	S-Simple	2-Free Shaft	10
TS216	T-Turboshaft	S-Simple	2-Free Shaft	16
FS210	F-Turbofan	S-Simple	2-Free Shaft	10
FS216	F-Turbofan	S-Simple	2-Free Shaft	16

*For the design point and steady-state analysis, the turboshaft and turboprop are considered to be the same; thus, 10 design points are listed. For the turboprop analysis, a P will be substituted for the T in the first eight configurations to denote the turboprop.

**This also identifies the turbine temperature since the 10 R_c was run only at 2500°F. and the 16 at 3000°F.

The following design point efficiencies were assumed to determine the sea level static, standard day performance with fixed turbine geometry:

- Compressor Efficiency — 80 percent
- Burner Efficiency — 99 percent
- Regenerator Effectiveness — 75 percent
- Gas Generator or Single-Shaft Turbine Efficiency — 87 percent
- Power or Fan Turbine Efficiency — 90 percent
- Fan Efficiency — 85 percent

The airflow size was selected at 10 lb/sec. The following values were assumed for the extraneous losses in the cycle:

- Turbine Cooling Bleed — 4.0 at 2500°F.
    - Percent of Inlet Flow — 12.0 at 3000°F.

● Pressure Drop		
● All Cycles	Burner	2.0 percent
● Turboprop and Turboshaft Cycles	Exhaust	3.0 percent
● Regenerative Cycles	Regenerator Cold Side	1.0 percent
	Regenerator Hot Side	6.0 percent
● Fan Cycle	Fan Nozzle	1.0 percent
● Overboard Leakage		
● Simple Cycle		
10 Pressure Ratio		1.0 percent
16 Pressure Ratio		1.5 percent
● Regenerative Cycle		
10 Pressure Ratio		1.5 percent
16 Pressure Ratio		2.5 percent

Table II lists the sea level static, standard day horsepower, thrust, and specific fuel consumption of the various engine configurations. The only difference between the turboprop and turboshaft engines is the sizing of the exhaust nozzle. These data provide the base line from which the characteristics of variable turbine geometry are explored.

The component efficiencies during throttled operation were defined by the compressor map and the results of the turbine analysis. Turbine cooling air and leakage were held constant during throttling. The heat exchanger effectiveness and pressure drop were varied as a function of the Reynolds number into either side of the heat exchanger.

TURBINE ANALYSIS

The results of the design point cycle calculation provided data for turbine design. The turbine requirements are summarized on Table III. Analysis of these data determined that four turbine stages would be required on all the engine configurations and that with gearing, where required, the same turbines would be applicable to the free- or single-shaft engines. In the free-shaft turboshaft power engines or the fan configuration, two stages would drive the high-pressure system and two the low.

After establishing the turbine design point, calculations were made to determine the off-design characteristics of the turbine.

The turbine performance analysis procedure employed in the Allison computer program is a modification of the procedure developed by Ainley and Mathieson. This procedure is a constant-stage, mean-line calculation and is based on overall blade row loss data.

TABLE II

ENGINE DESIGN POINT SUMMARY
59°F. — SEA LEVEL ALTITUDE

Engine	Shaft Horsepower	Thrust	Specific Fuel Consumption
TR110	2180	50	0.344
TR116	2680	54	0.343
TR210	2220	50	0.339
TR216	2760	55	0.336
TS110	2340	72	0.452
TS116	2880	74	0.411
TS210	2400	70	0.441
TS216	2970	71	0.398
PR110	2090	165	0.354
PR116	2580	180	0.352
PR210	2140	165	0.348
PR216	2660	180	0.344
PS110	2190	235	0.482
PS116	2730	240	0.433
PS210	2280	234	0.466
PS216	2840	239	0.418
FS210	—	2350	0.540
FS216	—	2500	0.563

The analysis procedure is conveniently divided into two areas for discussion purposes. The first area delineates the procedure to obtain the basic performance characteristics of each blade row for a given turbine geometry. The second area delineates the development of the performance analysis procedure which uses the basic loss data.

The procedure to obtain the basic loss data or performance characteristics of the individual blade rows consists of the following two parts:

- Obtaining the blade row loss coefficients as a function of incidence and exit Mach number
- Obtaining the blade row discharge angles as a function of downstream exit Mach number

TABLE III

TURBINE DESIGN POINT SUMMARY

Engine	Number of Stages	Turbine Corrected Flow, $W\sqrt{\theta}/\delta$ (lb./sec.)	Expansion Ratio, P_{in}/P_{out}	Total Corrected Work, $\Delta h/B$ (BTU/lb.)	Average Corrected Work per Stage, $\Delta h/B$ (BTU/lb.)	Calculated Efficiency (Percent)
TS110	4	2.39	9.33	56.9	14.2	90.6
TS116	4	1.49	14.9	65.9	16.5	90.8
TS210 Gasifier	2	2.39	2.51	26.3	13.2	87.6
Power	2	5.55	3.72	36.9	18.5	89.9
TS216 Gasifier	2	1.49	3.04	31.2	15.6	87.1
Power	2	4.25	4.9	43.4	21.7	90.2

Blade row loss coefficient, as employed in the performance analysis procedure, is defined as

$$Yt = \frac{\text{inlet total pressure minus exit total pressure}}{\text{exit total pressure minus exit static pressure}} = \frac{P_1 - P_2}{P_2 - P_{s2}} \tag{5}$$

Zero incidence loss coefficient data have been accumulated as a function of the blade row inlet and exit gas angles for rotating rig performance of approximately 60 different turbines. These data represent a total loss coefficient, including the profile and secondary end losses. If the assumption of symmetrical stage velocity triangles is made, the stage efficiency can be approximated by the following expression:

$$\eta \text{ stage} = \frac{1}{\left(1 - \frac{Va}{U}\right)\frac{Yt \sec^2 \beta_2}{\frac{Va}{U} - 2 \tan \beta_2}} \tag{6}$$

The zero incidence data that would be employed in the performance analysis procedure are valid for blade hub-to-tip radius ratios from 0.55 to 0.87 and for blading section geometry which reflects aerodynamic design consistent with conventional and accepted industry practice.

The zero incidence blade row loss coefficient is modified for positive and negative incidence in two respects. The first modification charges the loss for velocity head normal to the blade inlet angle. This assumption is independent of directional sense and the blade leading edge geometry. Examination of blading cascade data shows a greater loss for positive incidence than that for negative incidence. This is readily explained by the extremely adverse surface pressure gradients that result at negative incidence. Therefore, the second modification alters the normal velocity head loss by the characteristic "H" of Figure 6. The off-design loss coefficient of an individual blade row is calculated as follows:

Compute:

$$i = \alpha_1 - \beta_1 \tag{7}$$

and obtain from Figure 6

$$H = f(i, BT)$$

M_1^0 = Inlet Mach Number Component Parallel to Inlet Blade Angle

Yt = Zero Incidence Loss Coefficient

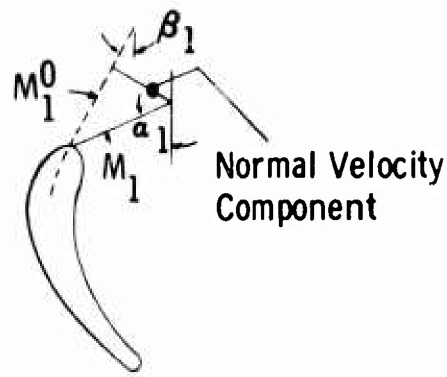
P_1 = Inlet Total Pressure

β_1 = Inlet Blade Angle

α_1 = Inlet Gas Angle

M_1 = Inlet Mach Number

BT = Type of Blade Leading Edge { Blunt / Normal / Sharp



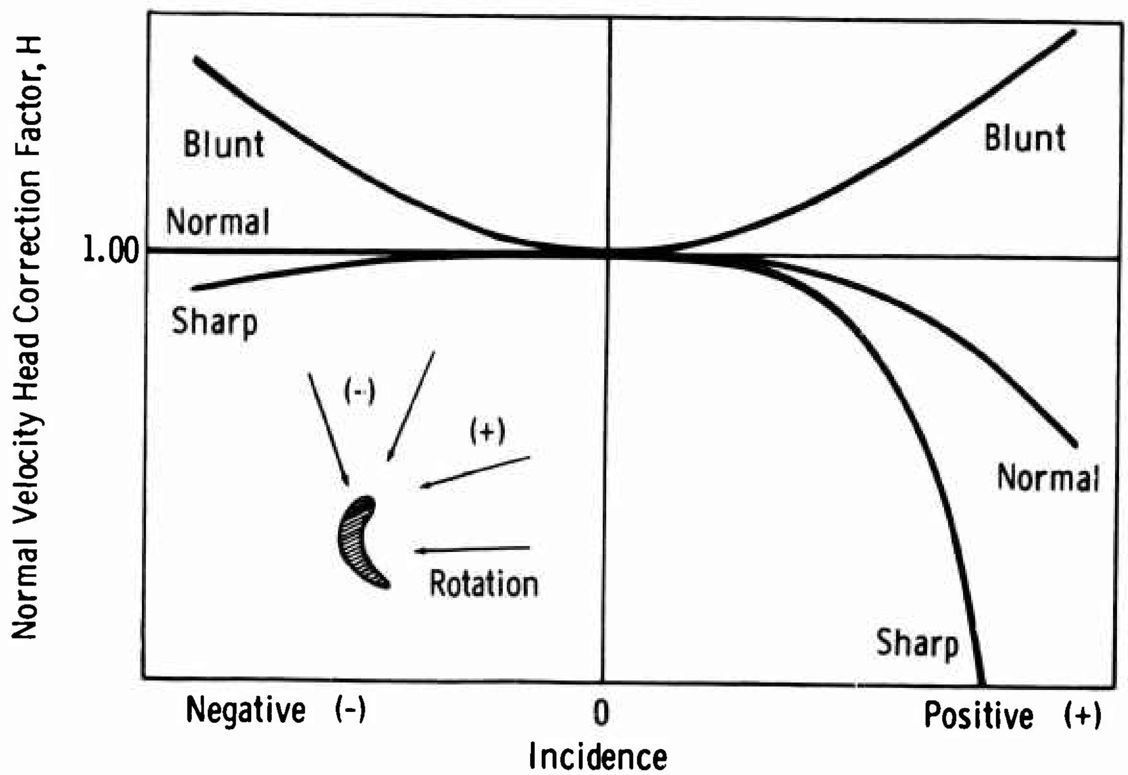


Figure 6. Normal Velocity Head Correction Factor and Incidence Angle Relation.

Define M_1^0 as the component of M_1 parallel to the inlet blade angle. Hence,

$$M_1^0 = M_1 \cos i \tag{8}$$

Define P_1^0 as the blade inlet total pressure associated with vector M_1^0. Then,

$$P_1 \left(1 + \frac{\gamma-1}{2} M_1^2\right)^{\frac{-\gamma}{\gamma-1}} = P_1^0 \left[1 + \left(\frac{\gamma-1}{2}\right)(H)(M_1^0)^2\right]^{\frac{-\gamma}{\gamma-1}}$$

$$= P_1^0 \left[1 + \left(\frac{\gamma-1}{2}\right)(H)(M_1)^2 (\cos i)^2\right]^{\frac{-\gamma}{\gamma-1}}$$

and

$$P_1^0 = P_1 \left[\frac{1 + \left(\frac{\gamma-1}{2}\right)(H)(M_1^0)^2 (\cos i)^2}{1 + \left(\frac{\gamma-1}{2}\right)(M_1)^2}\right]^{\frac{\gamma}{\gamma-1}} \tag{9}$$

Substituting Equation (9) into Equation (5) yields, upon rearrangement of terms, the blade loss coefficient at off-design,

$$Yt = \frac{\frac{P_1}{P_2}\left[\frac{1 + \left(\frac{\gamma-1}{2}\right)(M_1)^2 (H) (\cos i)^2}{1 + \left(\frac{\gamma-1}{2}\right)(M_1)^2}\right]^{\frac{\gamma}{\gamma-1}}}{(P_2 - P_{s_2})} \tag{10}$$

The data necessary to the performance analysis procedure are as follows:

- Flow path diameters at each blade row inlet and exit
- Blade row inlet angles
- Total blade row loss coefficients as a function of incidence and exit Mach number
- Blade row exit gas angles as a function of downstream Mach number

The calculation is initiated by selection of an inlet total temperature and pressure plus an associated mass flow rate and rotational speed. The following discussion of the procedure assumes that the inlet total temperature and pressure and the rotational speed will be held constant. The performance will then be calculated along a constant corrected speed line characteristic starting in the unchoked region of operation and concluding the calculation at limiting loading.

An inlet gas angle is specified for the first stator to obtain the stator incidence. The stator loss coefficient is obtained as a function of downstream Mach number. It is now possible to calculate the stator downstream absolute flow conditions by iterating on continuity since the stator inlet flow, total temperature, and pressure are known in addition to the stator loss characteristics, exit gas angle characteristics, and exit annulus area.

The rotor inlet relative conditions are obtained by combining the stator absolute flow vectors with the rotor wheel speed. The difference between the relative inlet gas angle and rotor inlet blade angle is the incidence from which the loss characteristics of the rotor blade may be obtained. The relative conditions out of the rotor are calculated in the same manner as the absolute conditions out of the preceding stator. The rotor exit relative properties are combined with the rotor wheel speed to obtain the absolute flow conditions at the stage exit. This procedure is repeated until the last rotor exit conditions are determined. Knowing the individual stage inlet and exit properties and the overall conditions, it is possible to calculate the individual stage and overall turbine efficiencies at one point on the speed line in the unchoked region. Additional points on the speed line are obtained by increasing the mass flow rate and then repeating the preceding procedure.

The problem of choking in one of the blade rows is soon evident as the flow rate is continually increased. This problem is handled by checking each blade row for choking before attempting to calculate the downstream state conditions. The incidence on the blade row is known, therefore, the loss coefficient of the row is known as a function of the downstream Mach number. Also, for each loss coefficient there is a maximum rotor inlet corrected flow and downstream Mach number. If the selected corrected through-flow is greater than the maximum for the blade row under investigation, the inlet mass flow rate must be reduced. Choking is said to occur when the selected through-flow is within ± 1/2 percent of the maximum value.

The turbine inlet corrected flow rate will remain constant once the blade row which chokes first is determined. Additional points on the speed line are obtained by holding flow conditions upstream of the choke point constant and incrementing the velocity, or Mach number, out of the choked blade row. The new downstream Mach number and the incidence of the choked blade row determine a new blade row loss coefficient. The continuity equation is now applied to determine the new flow conditions immediately downstream of the choked row. The unchoked turbine performance procedure is now repeated on succeeding downstream blade rows to the turbine exit or to the blade row downstream which chokes next. If a blade row downstream chokes, the last incremented Mach number must be reduced until the corrected through-flow of the newly choked row is within ± 1/2 percent of its maximum. The last rotor exit axial Mach number is always checked for limiting loading. If limiting loading is not reached, the Mach number out of the choked blade row furthest downstream is again increased and the calculation is repeated until limiting loading is reached.

With the aforementioned analysis procedure, data were calculated for a two-stage turbine with variations in turbine corrected speed, first stator area, and second stator area. The variations in all three parameters included a minimum of 60 percent and maximum of 120 percent. The results of these calculations were the turbine efficiency, turbine corrected flow $(W\sqrt{T})/P$, work, and expansion ratio. These data were then plotted to determine the characteristic performance of the turbine with area variation as a function of expansion ratio and corrected speed. It was learned that the second stator area had only a secondary effect on controlling the turbine flow parameter and generally a detrimental effect on efficiency. Thus, to effect a change in turbine flow for the turbines investigated herein, only the first nozzle area is changed. The culmination of the analysis of all these turbine data was the development of turbine flow factor, $(W\sqrt{T})/P$, and efficiency as a function of the turbine expansion ratio. The independent variable was turbine corrected speed. These data are shown in Figures 7 through 10 for both the single- and free-shaft engines.

Figures 7 and 8 are for the free-shaft engine; 9 and 10 are for the single-shaft engine. Figure 7 provides efficiency data for the gasifier turbine. The power turbine has the same characteristic of efficiency as a function of corrected speed and expansion ratio but a different design point value. A factor is, therefore, provided on Figure 7 to be applied to the gasifier efficiency data for determining the power turbine efficiency.

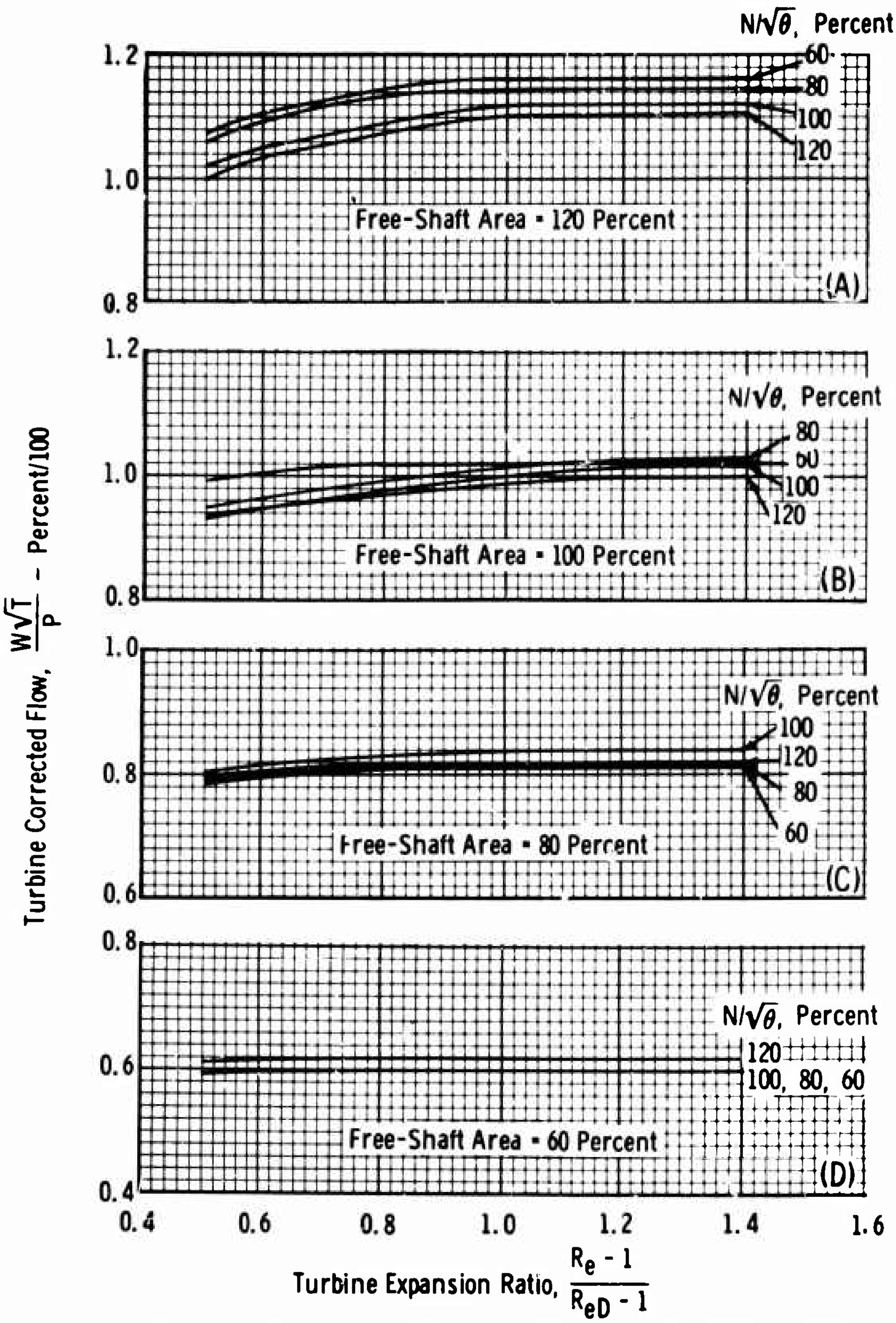


Figure 7. Turbine Corrected Flow as a Function of Turbine Expansion Ratio for Free-Shaft Engine.

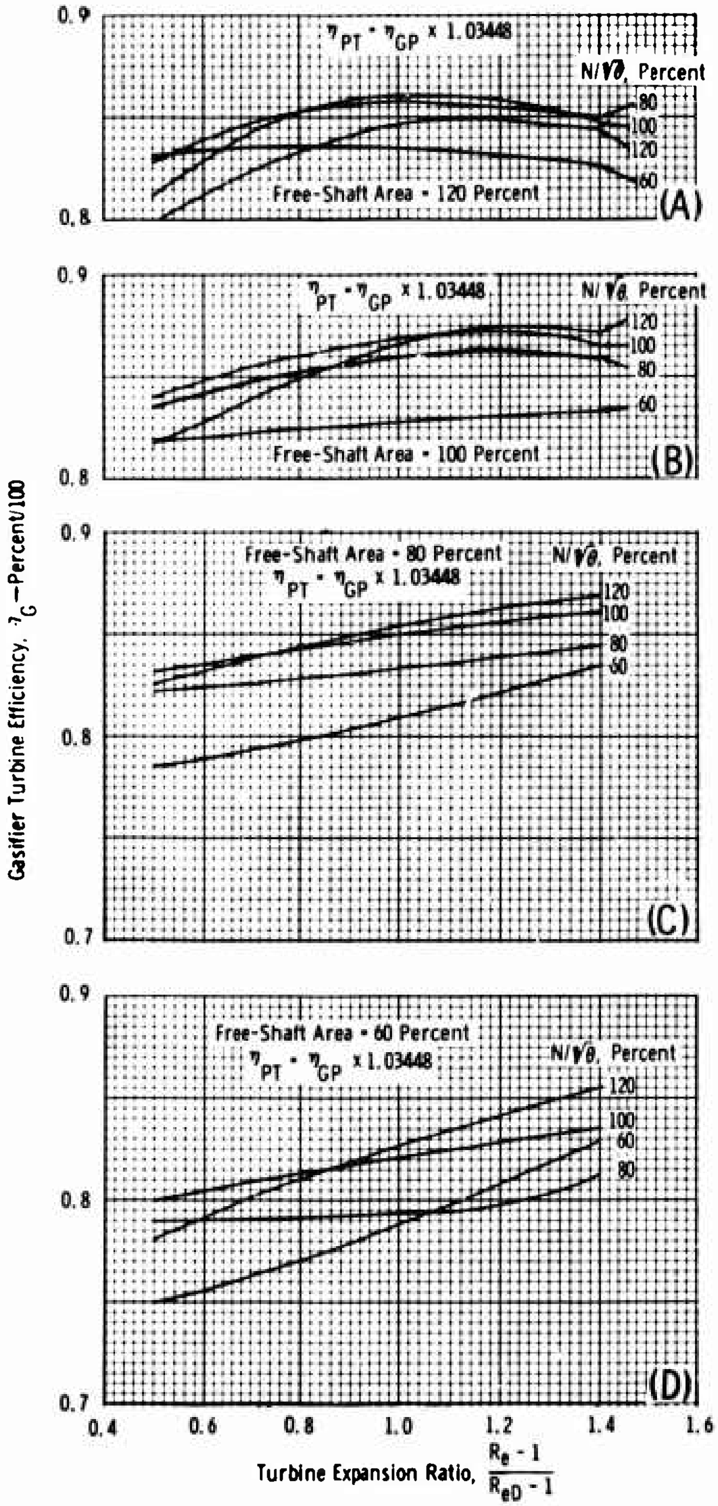


Figure 8. Turbine Efficiency as a Function of Turbine Expansion Ratio for Free-Shaft Engine.

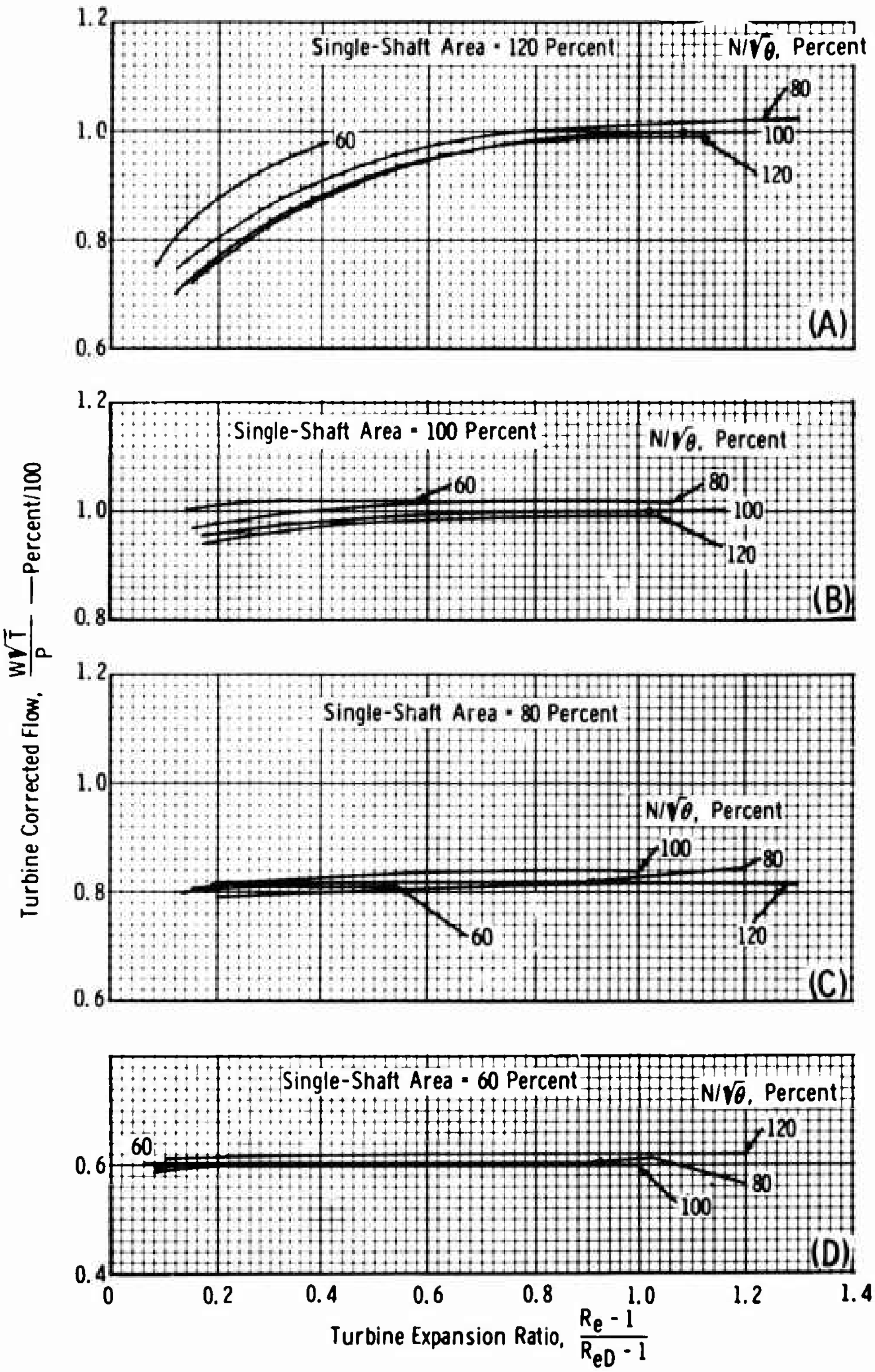


Figure 9. Turbine Corrected Flow as a Function of Turbine Expansion Ratio for Single-Shaft Engine.

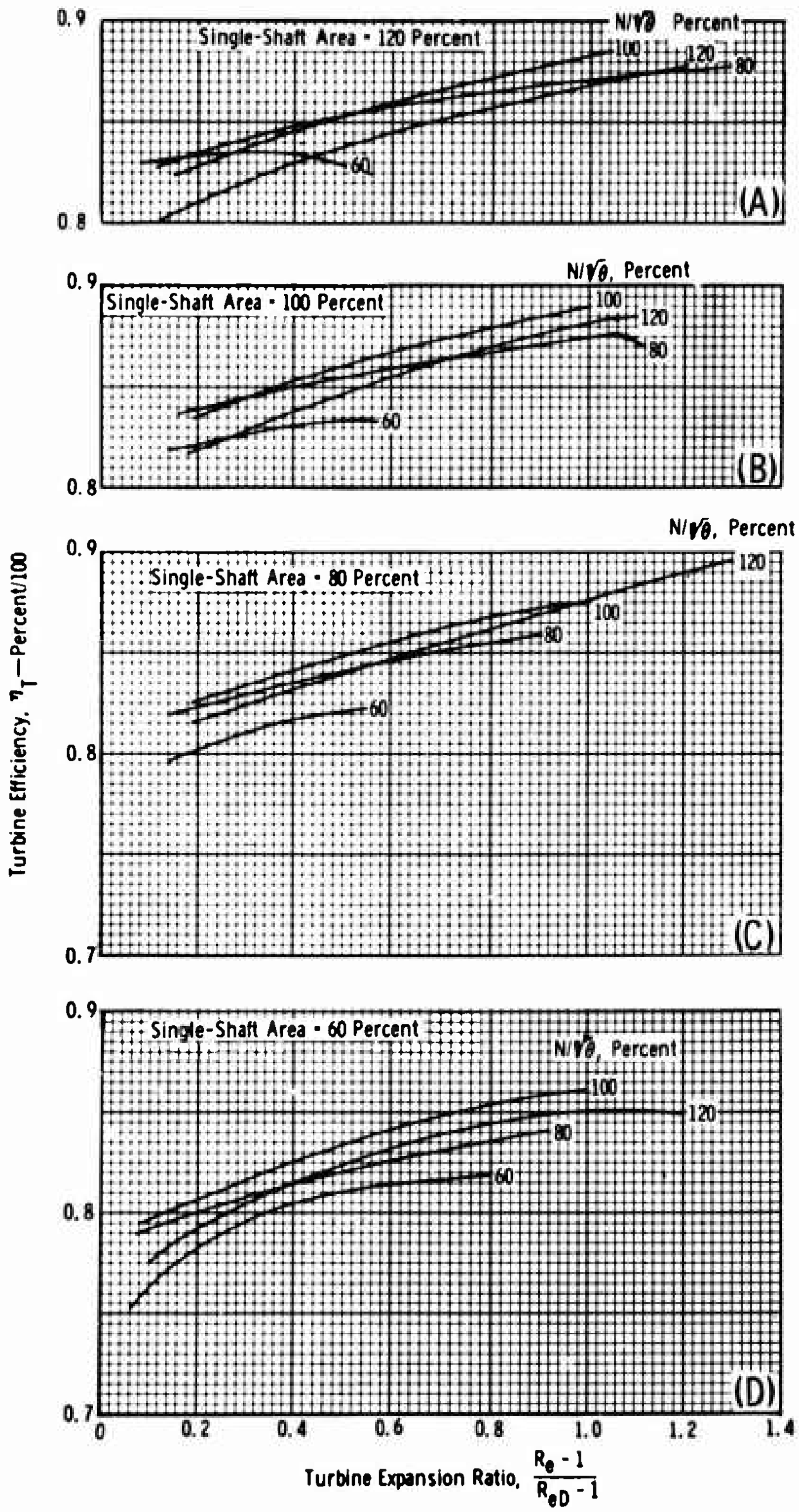


Figure 10. Turbine Efficiency as a Function of Expansion Ratio for Single-Shaft Engine.

MECHANICAL CONFIGURATION

For the purpose of this study, the mechanical design of the various engines was limited to a first order definition of the rotor systems for each configuration. This information was required to compute the moment of inertia to be used in the transient performance calculations. Figures 11 through 14 show the various rotor configurations. Both compressors consisted of a two-stage axial followed by a single centrifugal stage. All engines incorporated four turbine stages with commonality of the turbines between the free-shaft, single-shaft, and the fan turbofan/turboprop engines. The fan-engine configurations utilized the same rotor systems as the shaft-power engines except for the addition of a forward-mounted fan to supercharge the shaft-engine compressor. Detailed mechanical analysis of the rotor systems was not a consideration in this study.

Table IV summarizes the weight and inertia data of the rotor systems.

TABLE IV

ESTIMATED WEIGHT AND INERTIA OF ROTOR SYSTEMS

Engine	Shaft Power		Fan	
R_c/TIT, °F.	10/2500	16/3000	10/2500	16/3000
Weight, lb.	50.8	46.1	67.6	62.9
Polar Moment of Inertia, lb.-in.^{2}				
Gasifier	268.6	208.4	268.6	208.4
Power	173.7	165.5	173.7	165.5
Fan	—	—	368.0	368.0

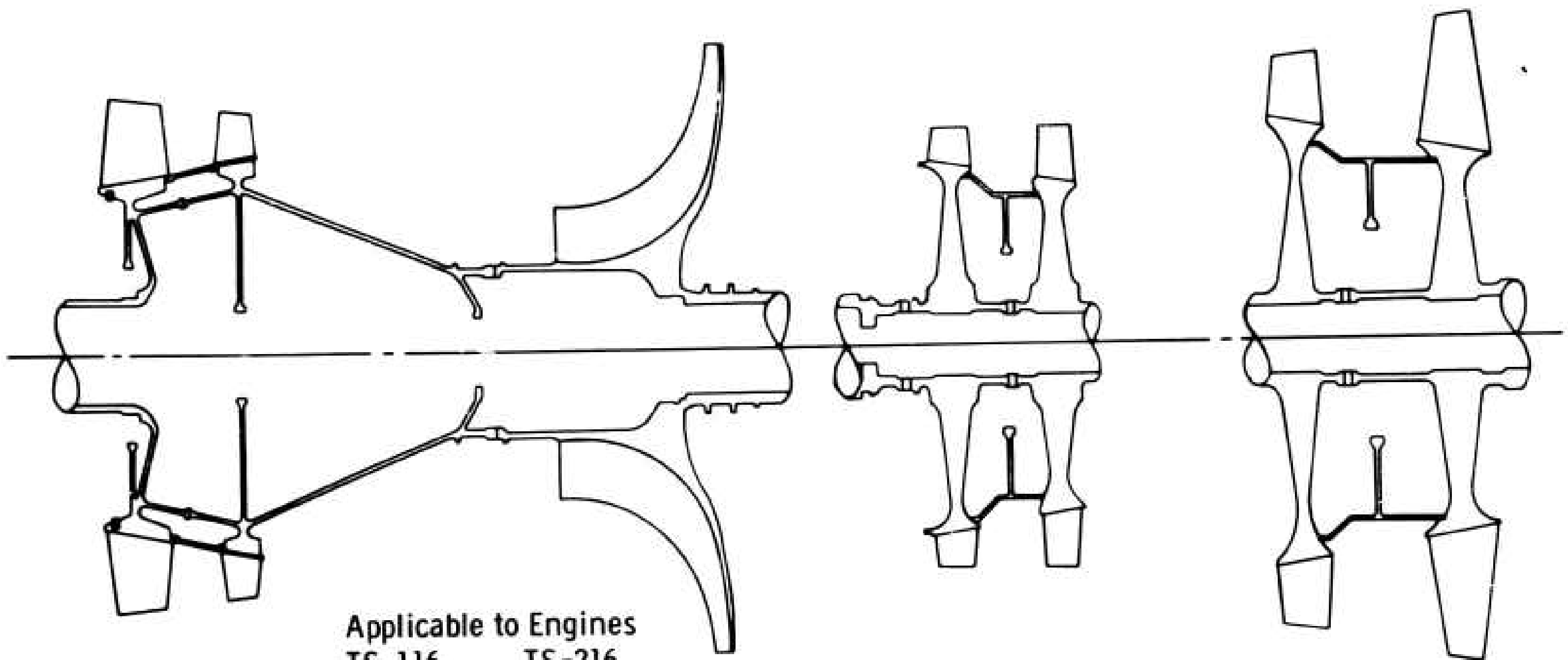


Figure 11. Rotor System for 16.0:1-Pressure-Ratio Shaft-Power Engine.

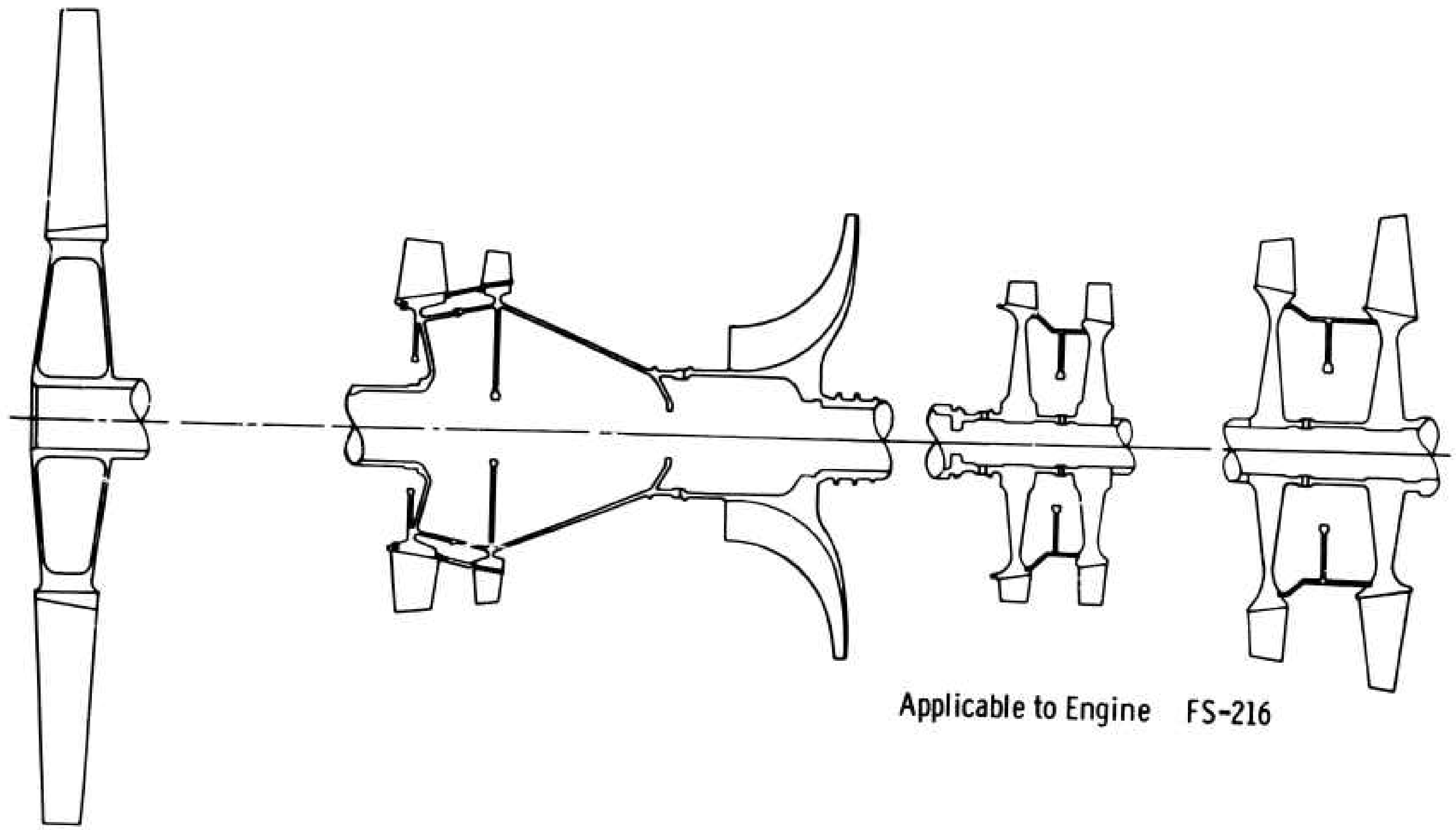


Figure 12. Rotor System for 16.0:1-Pressure-Ratio Fan Engine.

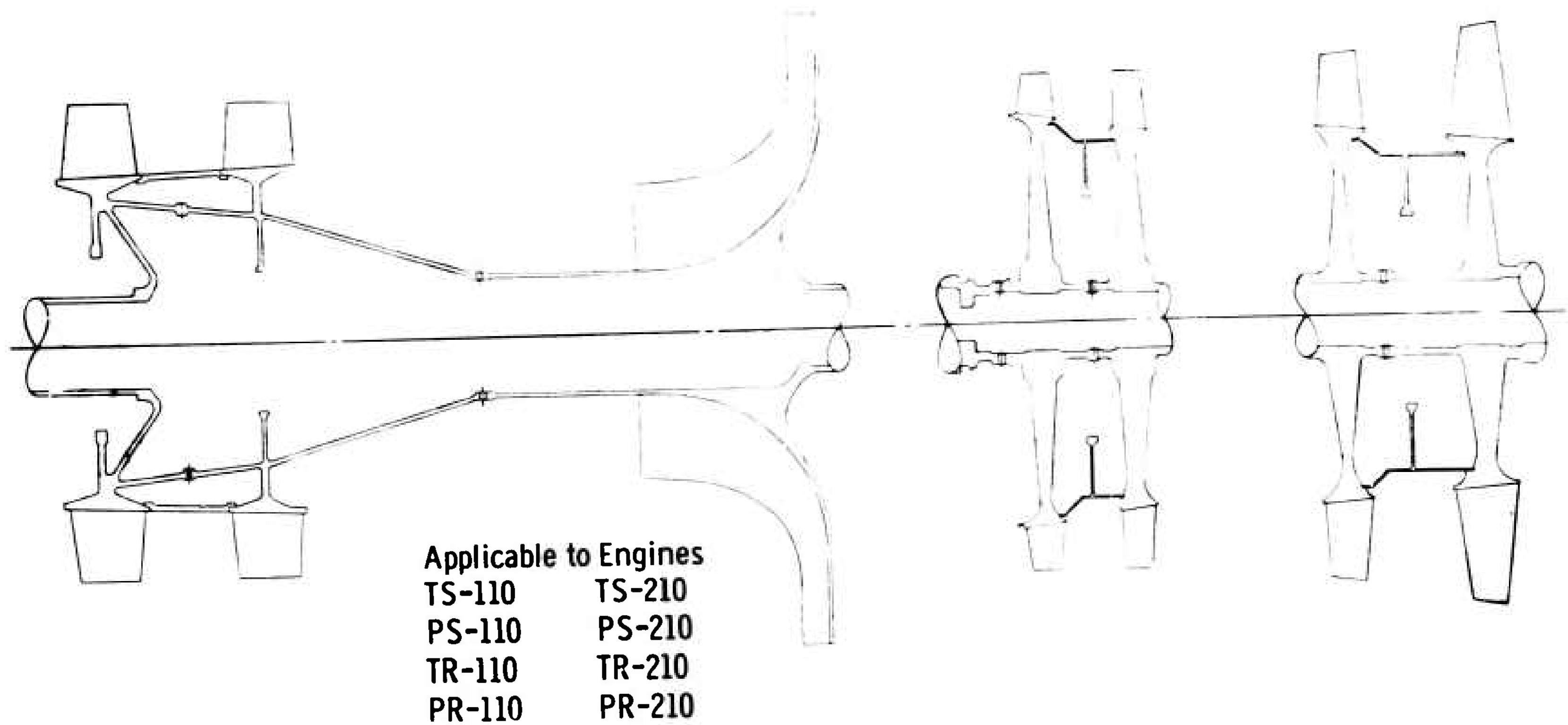


Figure 13. Rotor System for 10.0:1-Pressure-Ratio Shaft-Power Engine.

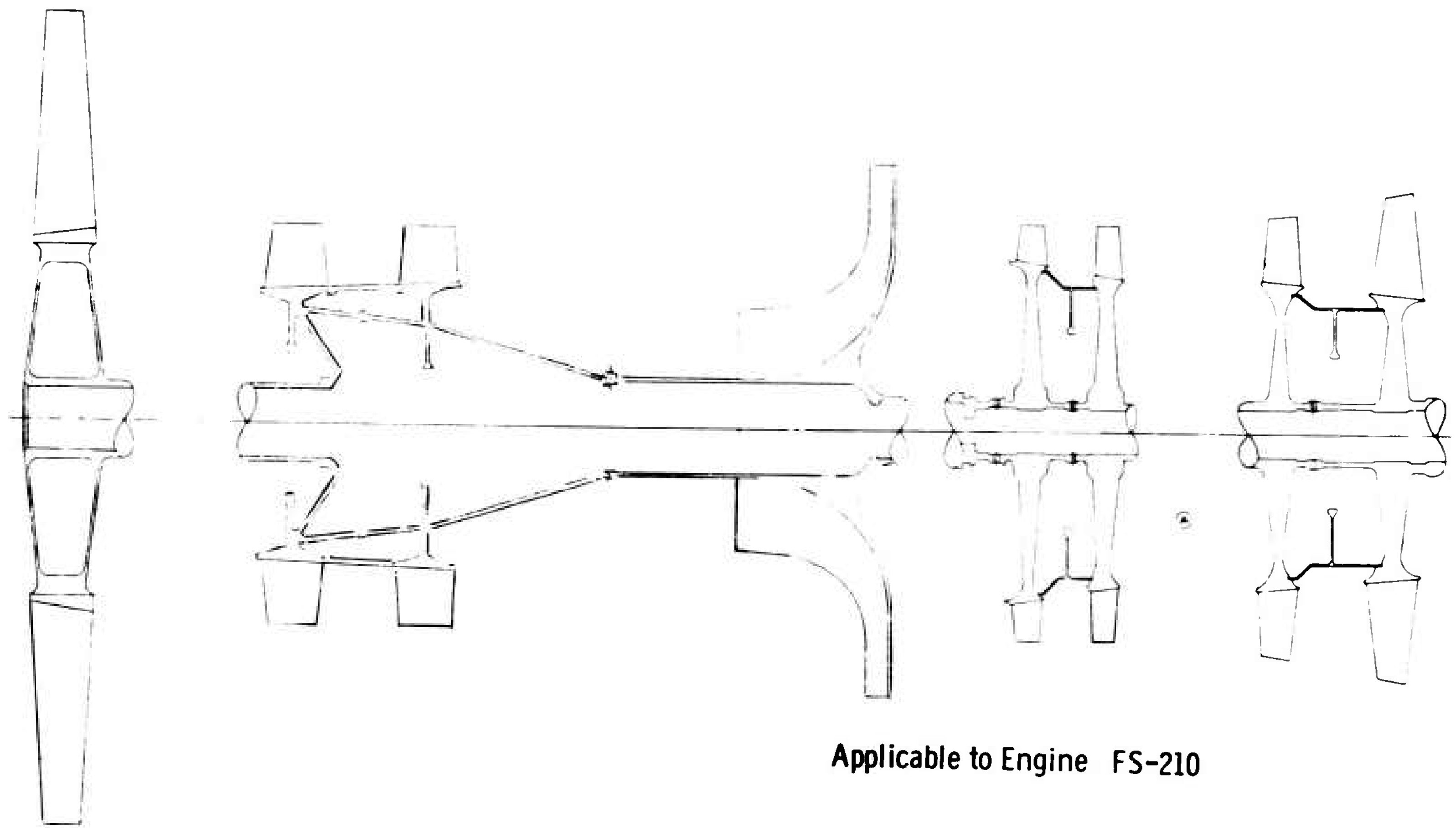


Figure 14. Rotor System for 10.0:1-Pressure-Ratio Fan Engine.

RESULTS

Graphic and tabular results are included in this report. The graphical data describe the operating lines on the compressor map and depict the engine variables as functions of percent power for various modes of operation. The tabular data provide convenient comparisons between the engine types and summarize the data for each of the engines at 50-percent power. Table V is an index to the curves and a key to the data which are presented. The symbols identify the extent of the calculations made for each engine. Most of the data were computed at sea level static on a standard temperature day. Altitude, air speed, and ambient temperature effects were evaluated for specific cases.

For the fixed area case, the steady-state performance was computed from 100-percent down to 30-percent power for all engine configurations. For other turbine nozzle area configurations, the amount of data computed was determined by the particular requirement. In some cases, data were computed over the complete power range. In other cases, where no advantage from the use of variable geometry was evident, spot-check data were computed at selected power settings. No data were computed for those cases where the results from one engine could be carried over to another. Several ground rules were established for the computation of the data.

- On the free-shaft engine, the free-turbine r.p.m. was maintained at 100 percent. On the single-shaft engine, only 100-percent r.p.m. was explored.
- The turbine inlet temperature was defined as the temperature into the first turbine stator or burner outlet. A portion of the turbine cooling air extracted from the compressor discharge was readmitted to the cycle prior to the first turbine rotor. A heat balance was done at this point. Thus, the first rotor inlet temperature was reduced and the mass flow through the turbine was increased to effect a proper assessment of the turbine cooling air. The turbine inlet temperature data plotted, therefore, are the first rotor inlet temperatures and are lower in magnitude than the 2500°F. and 3000°F. burner outlet temperatures.
- The engine pressure ratio was not allowed to exceed the design value.
- In cases where the operating line and surge line intersected, calculations were made at the surge pressure ratio or along the surge line to determine the maximum performance available.

Tables VI, VII, and VIII summarize the data at 50-percent power for the various engines in terms of percent change in specific fuel consumption from the fixed area case.

TABLE V

INDEX TO CURVES AND DATA

Engine Configuration	Figure Number	Table Reference	Fixed Area		Variable Gasifier		Variable Power		Both Variable or Single Shaft	
			Steady State	Transient	Steady State	Transient	Steady State	Transient	Steady State	Transient
TS110	15 - 17	VII	2	4	1	1	1	1	2	4
TS116	18 - 20	VII	2	4	1	1	1	1	2	4
TS210	21 - 24	VI	2	5	2	4	4	4	2	4
TS216	25 - 28	VI	2	5	2	4	3	4	2	4
TR110	29 - 31	VII	2	4	1	1	1	1	3	4
TR116	32 - 34	VII	2	4	1	1	1	1	3	4
TR210	35 - 38	VI	2	4	4	4	2	4	2	4
TR216	39 - 42	VI	2	4	3	4	2	4	2	4
FS210	43 - 47	VIII	2	5	2	4	4	4	4	4
FS216	48 - 52	VIII	2	5	2	4	4	4	3	4

Code:
1 Not applicable
2 Complete data 30- to 100-percent power
3 Spot-check points
4 Data not required based on other results
5 Necessary data computed

TABLE VI

SUMMARY OF SPECIFIC FUEL CONSUMPTION AT 50-PERCENT POWER—FREE-SHAFT TURBOSHAFT

Cycle	Regenerative		Simple	
R_c/TIT, °F.	10/2500 (TR210)	16/3000 (TR216)	10/2500 (TS210)	16/3000 (TS216)
Fixed Area s.f.c.	0.370	0.363	0.520	0.465
Variable Gasifier s.f.c.	—	0.400	0.490	0.455
Percent*	—	+10.2	-5.7	-2.2
Variable Power s.f.c.	0.335	0.332	—	0.497
Percent*	-9.5	-8.5	—	+6.9
Both Variable s.f.c.	0.342	0.345	0.494	0.455
Percent*	-7.5	-5.0	-5.0	-2.2

*Percent change from fixed area specific fuel consumption.

TABLE VII

SUMMARY OF SPECIFIC FUEL CONSUMPTION AT 50-PERCENT POWER—SINGLE-SHAFT TURBOSHAFT

Cycle	Regenerative		Simple	
R_c/TIT, °F.	10/2500 (TR110)	16/3000 (TR116)	10/2500 (TS110)	16/3000 (TS116)
Fixed Area s.f.c.	0.465	0.466	0.546	0.496
Variable Area s.f.c.	0.453	0.461	0.515	0.472
Percent*	-2.6	-1.1	-5.5	-4.9

*Percent change from fixed area specific fuel consumption.

TABLE VIII

SUMMARY OF SPECIFIC FUEL CONSUMPTION AT 50-PERCENT POWER—FREE-SHAFT TURBOFAN

Cycle	FS210	FS216
R_c/TIT, °F.	10/2500	16/3000
Fixed Area s. f. c.	0. 703	0. 714
Variable Gasifier s. f. c.	0. 681	0. 702
Percent*	-2. 2	-1. 6

*Percent change from fixed area specific fuel consumption.

DISCUSSION OF RESULTS

STEADY-STATE PERFORMANCE

The following discussion of the steady-state performance is arranged according to the five general types investigated.

1. TS110 - Turboshaft - Simple Cycle - Single Shaft - 10.0:1 R_c
   TS116 - Turboshaft - Simple Cycle - Single Shaft - 16.0:1 R_c

Calculations on the single-shaft engine were limited to operation at 100-percent shaft r.p.m. This resulted in operation at 100-percent flow because of the vertical speed line characteristic on the compressor map. Thus, in all cases, throttling was accomplished by varying only pressure ratio and turbine temperature. Figures 15 through 17 define the steady-state performance for the 10.0:1-compressor-pressure-ratio engine.

For the fixed geometry case, throttling was effected by a simultaneous reduction in both pressure ratio and turbine temperature. In the variable geometry case, the turbine nozzle area was reduced while maintaining the design pressure ratio; thus, throttling occurred from temperature only. Another mode of operation would be to increase the nozzle area to maintain turbine temperature while throttling pressure ratio. However, this mode of operation is not practical because of the insufficient decrease in horsepower with pressure ratio and the extreme area requirement. Figure 15 is the compressor map for the 10.0:1-compressor-pressure-ratio engine with the operating line or point superimposed for the two modes of operation. Figures 16A and B show the change in turbine temperature and pressure ratio associated with this operation. The resulting specific fuel consumption is shown on Figure 16C.

The area required to effect this operation and the change in turbine efficiency can be seen on Figures 17A and B. The improvement in specific fuel consumption at 50-percent power is equal to 5.5 percent. At 50-percent power, the turbine nozzle area must be reduced to 82 percent of the design value. The difference in turbine efficiency between the fixed geometry and variable geometry case is not significant.

Figures 18 through 20 define the steady-state performance and operating characteristics for the 16.0:1-compressor-pressure-ratio engine. In general, the results on this engine are the same as on the 10.0:1-compressor-pressure-ratio engine. The improvement in specific fuel consumption at 50-percent power is 4.7 percent compared to the 5.5 percent of the 10.0:1-compressor-pressure-ratio engine.

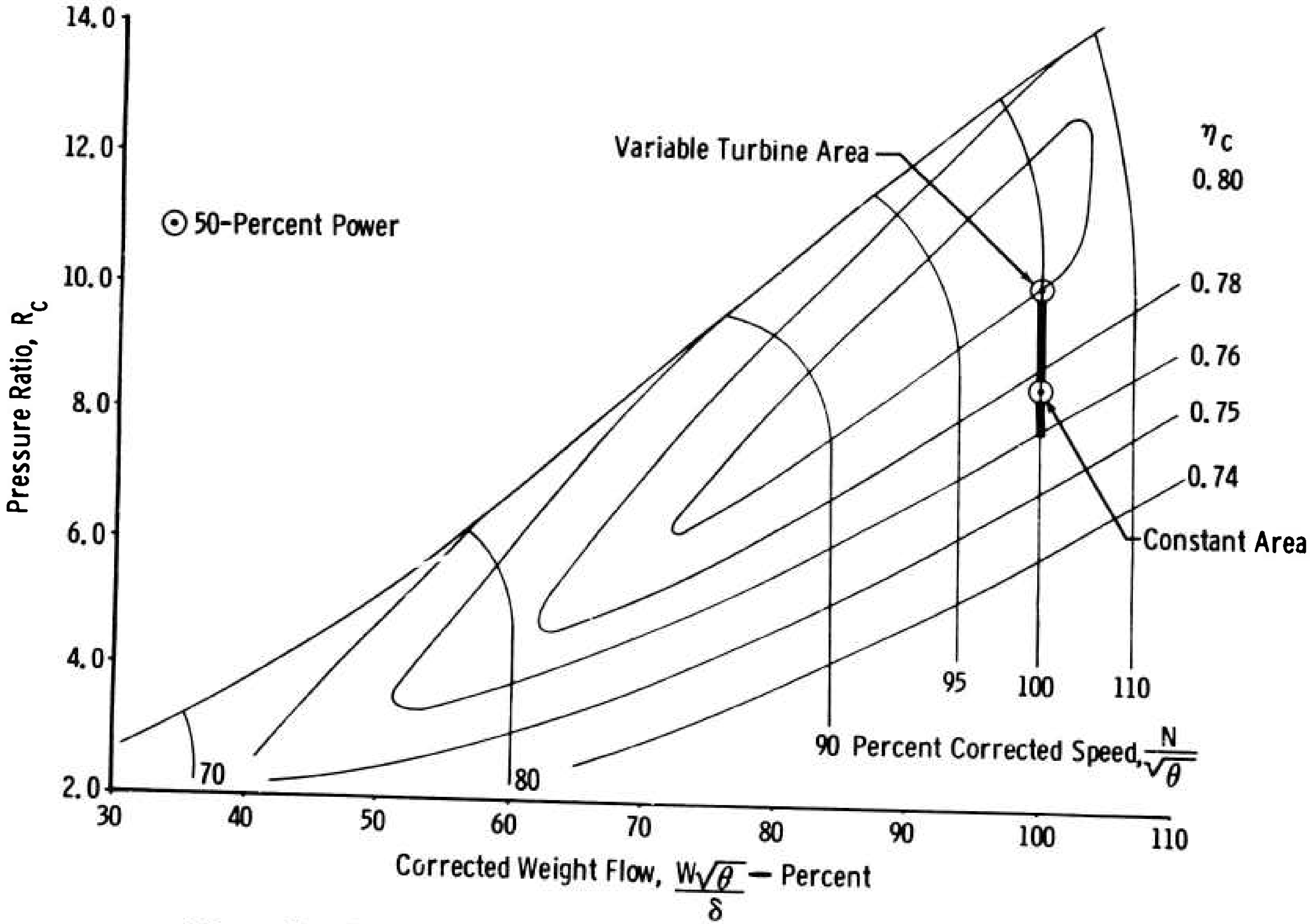


Figure 15. Engine TS110—Operating Lines on the Compressor Map.

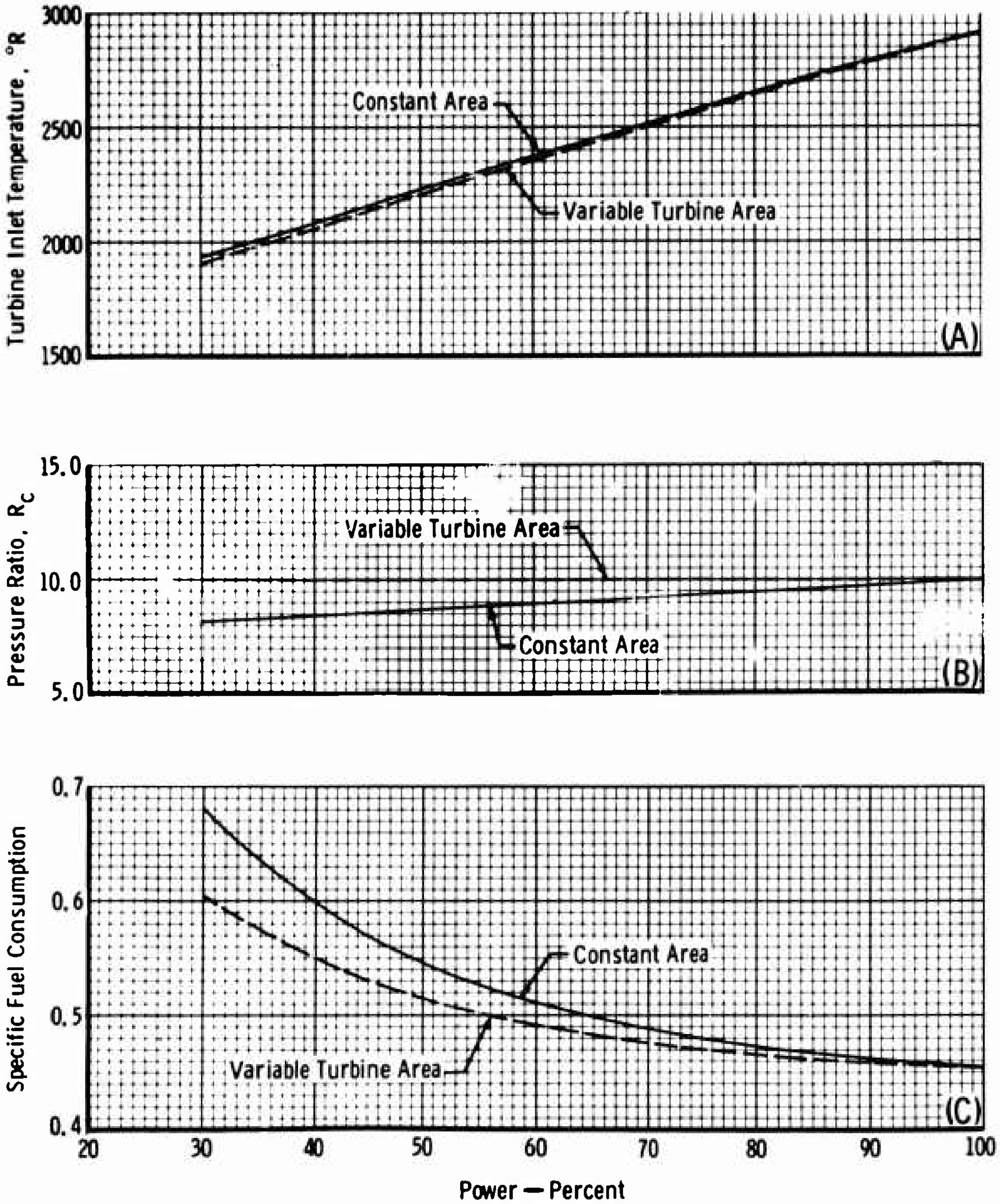


Figure 16. Engine TS110—Turbine Inlet Temperature, Pressure Ratio, and Specific Fuel Consumption as Functions of Percent Power.

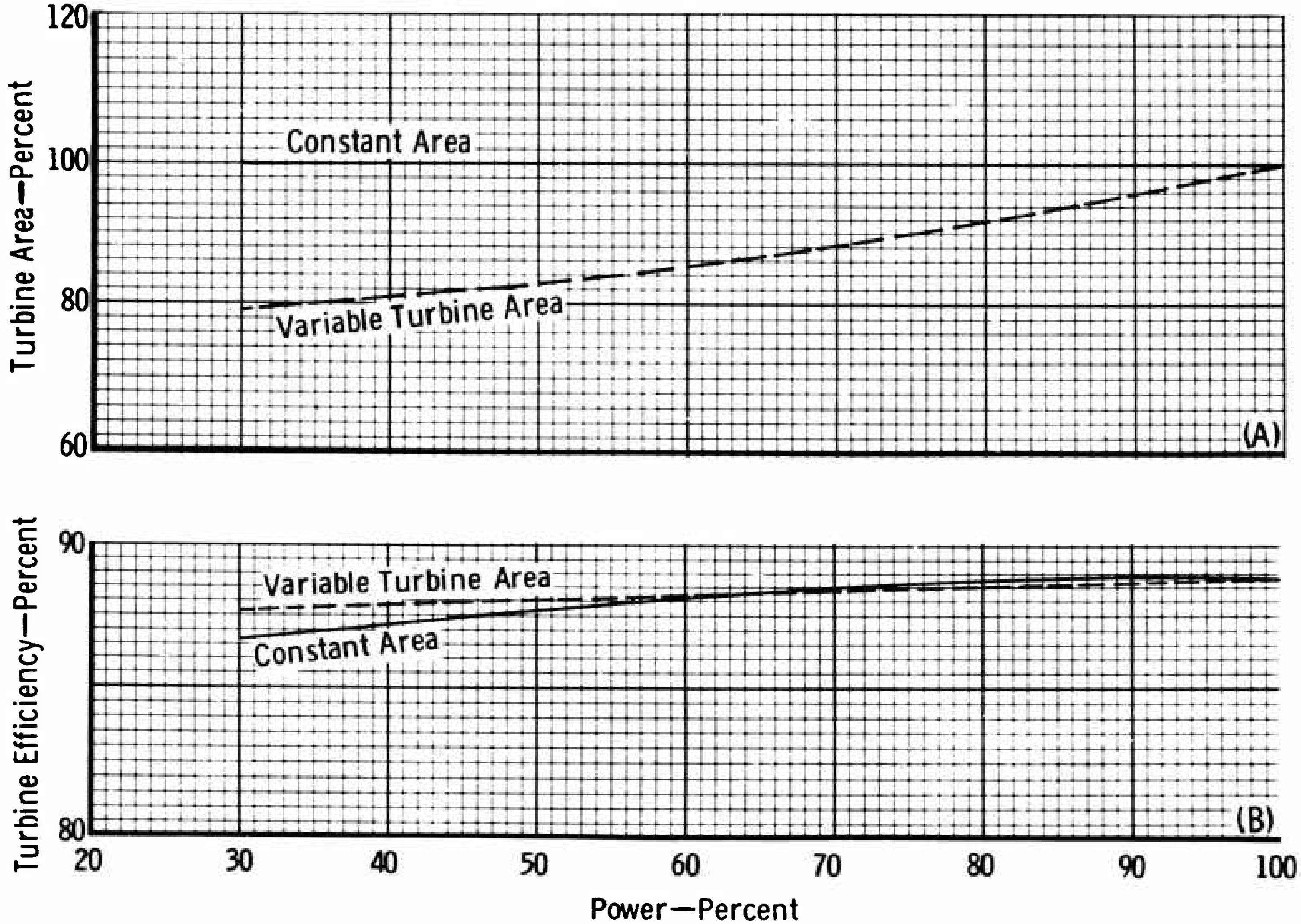


Figure 17. Engine TS110—Percent Turbine Area and Turbine Efficiency as Functions of Percent Power.

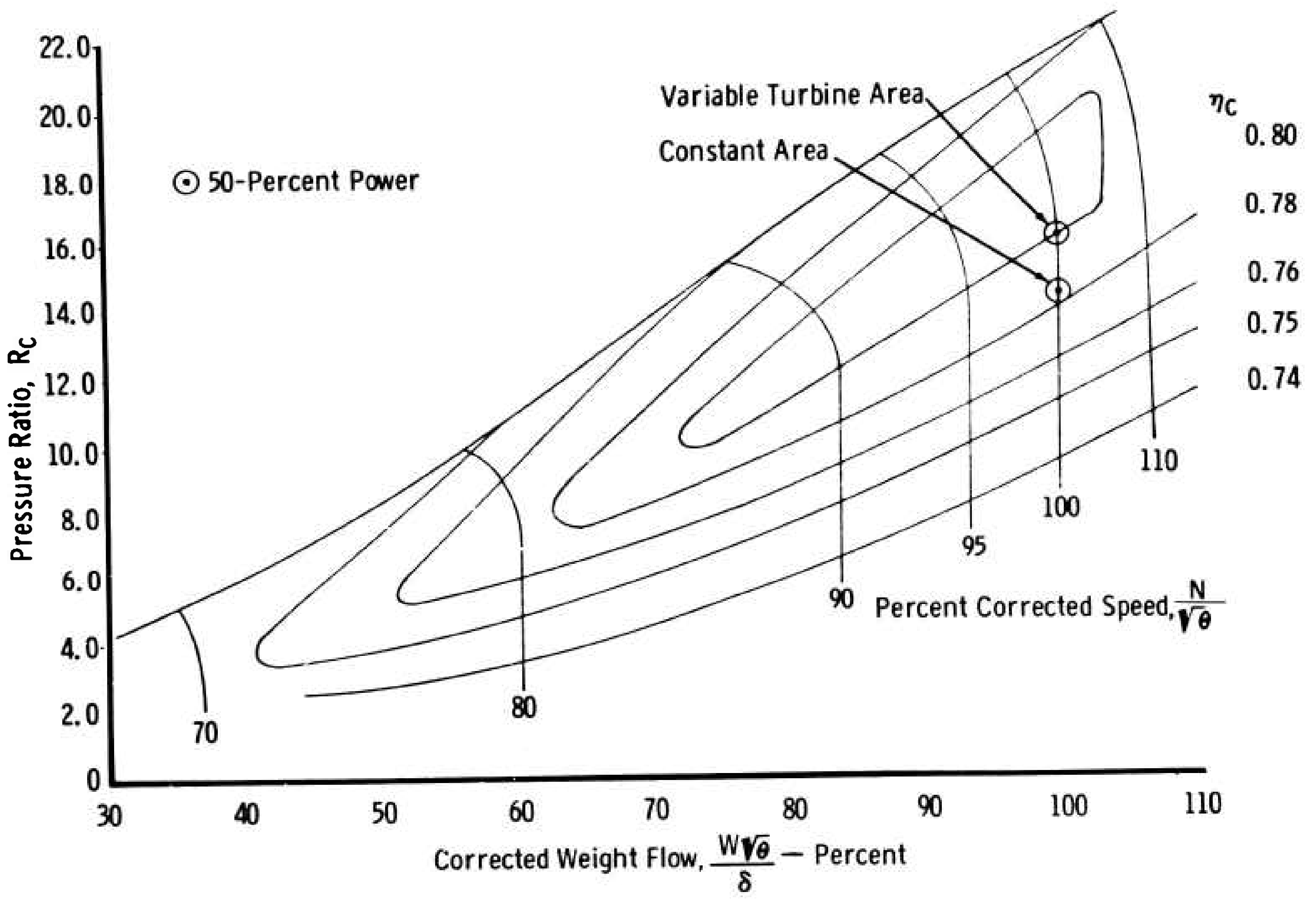


Figure 18. Engine TS116—Operating Lines on the Compressor Map.

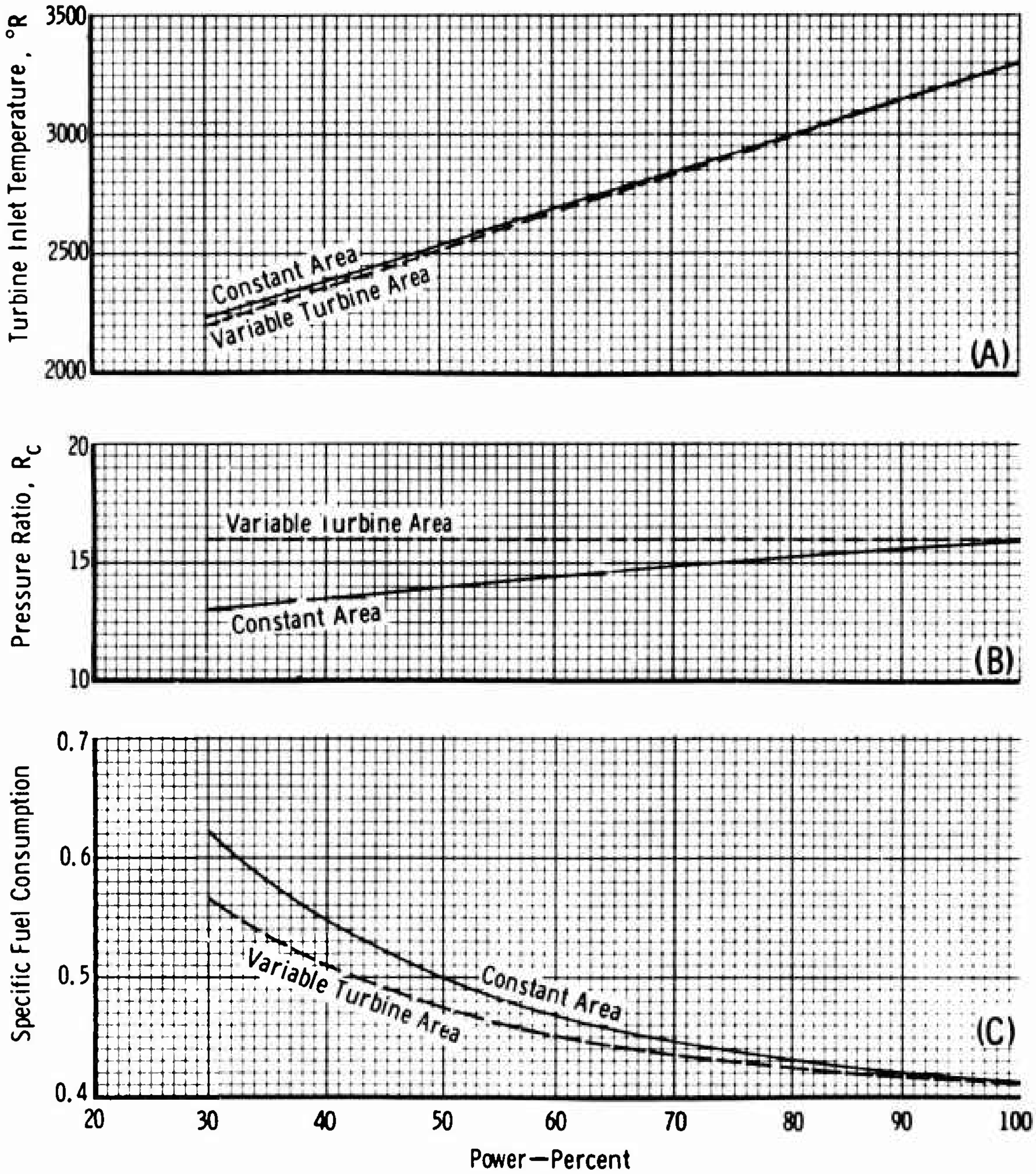


Figure 19. Engine TS116—Turbine Inlet Temperature, Pressure Ratio, and Specific Fuel Consumption as Functions of Percent Power.

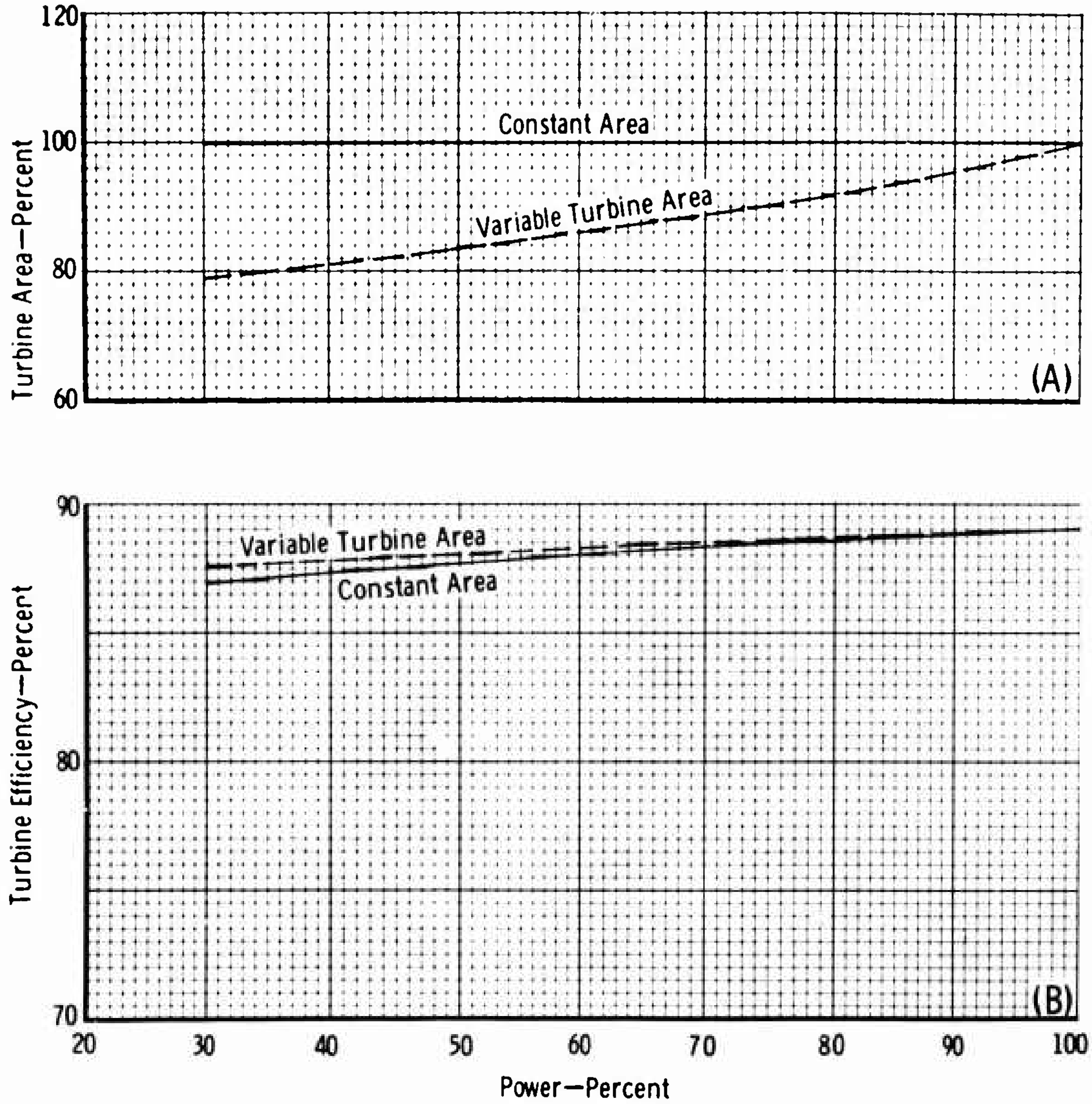


Figure 20. Engine TS116—Percent Turbine Area and Turbine Efficiency as Functions of Percent Power.

2. TS210 - Turboshaft - Simple Cycle - Free Shaft - 10.0:1 R_c
TS216 - Turboshaft - Simple Cycle - Free Shaft - 16.0:1 R_c

The free-shaft engine configurations were run at 100-percent free-turbine speed and variable gasifier speed to effect throttling. Data were calculated for the following modes of operation:

- Fixed-area turbine
- Variable gasifier turbine nozzle
- Variable power turbine nozzle
- Both nozzles variable

Results of the calculations and the operational characteristics of the 10.0:1-compressor-pressure-ratio engine are presented in Figures 21 through 24. These data include operation at fixed area, variable gasifier area, and both nozzles variable.

Figure 21 is the compressor map for the 10.0:1-compressor-pressure-ratio engine showing operating lines for the three modes of operation. The turbine temperature and pressure ratio requirements for these modes of operation are shown in Figures 22A and B.

For the case where both turbine nozzles or just the gasifier is varied to hold pressure ratio, the operating line intersects the surge line. At this point, operation was assumed along the surge line. This approach enabled operation at the limiting available pressure ratio. Although this is not practical in a given engine design, it is of interest to this study to define the maximum performance potential with variable geometry. The resulting specific fuel consumption for these modes of operation is shown in Figure 22C. At 50-percent power, the reduction in specific fuel consumption from the fixed geometry case is 5.7 percent for the variable gasifier turbine and 5.0 percent with both nozzles variable. The difference in specific fuel consumption is attributable to the loss in component efficiencies associated with varying both nozzles to maintain constant pressure and temperature during throttling. The component efficiency values are presented in Figure 21 for the compressor and in Figure 23A and B for the turbines. Figure 24A and B show the area requirements for accomplishing this operation.

For the 16.0:1-compressor-pressure-ratio engine, full operating lines were determined for three cases—fixed area, variable gasifier turbine, and variable gasifier and power turbines. Variable power turbine (constant temperature) calculations were limited to spot-point data after it

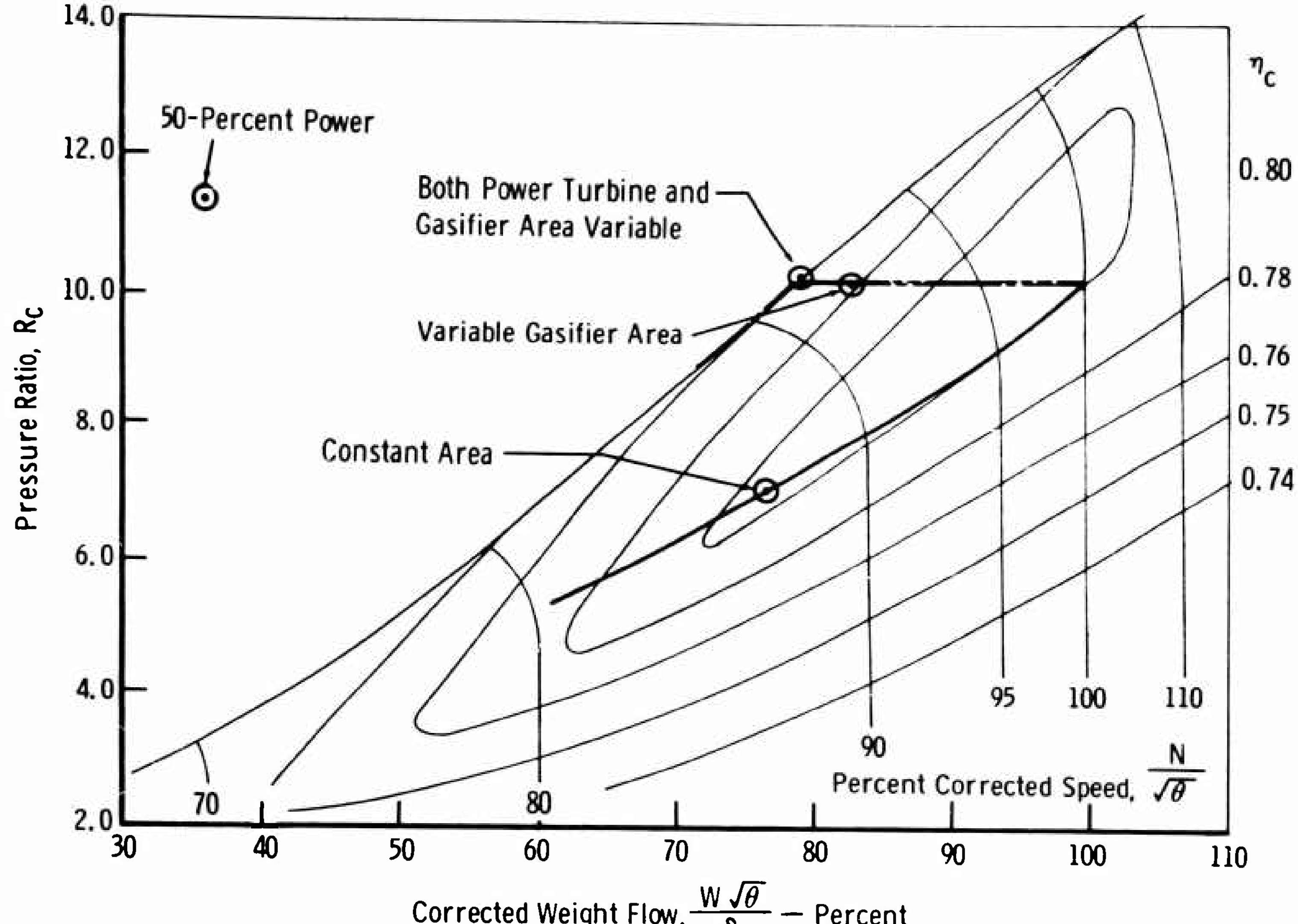


Figure 21. Engine TS210—Operating Lines on the Compressor Map.

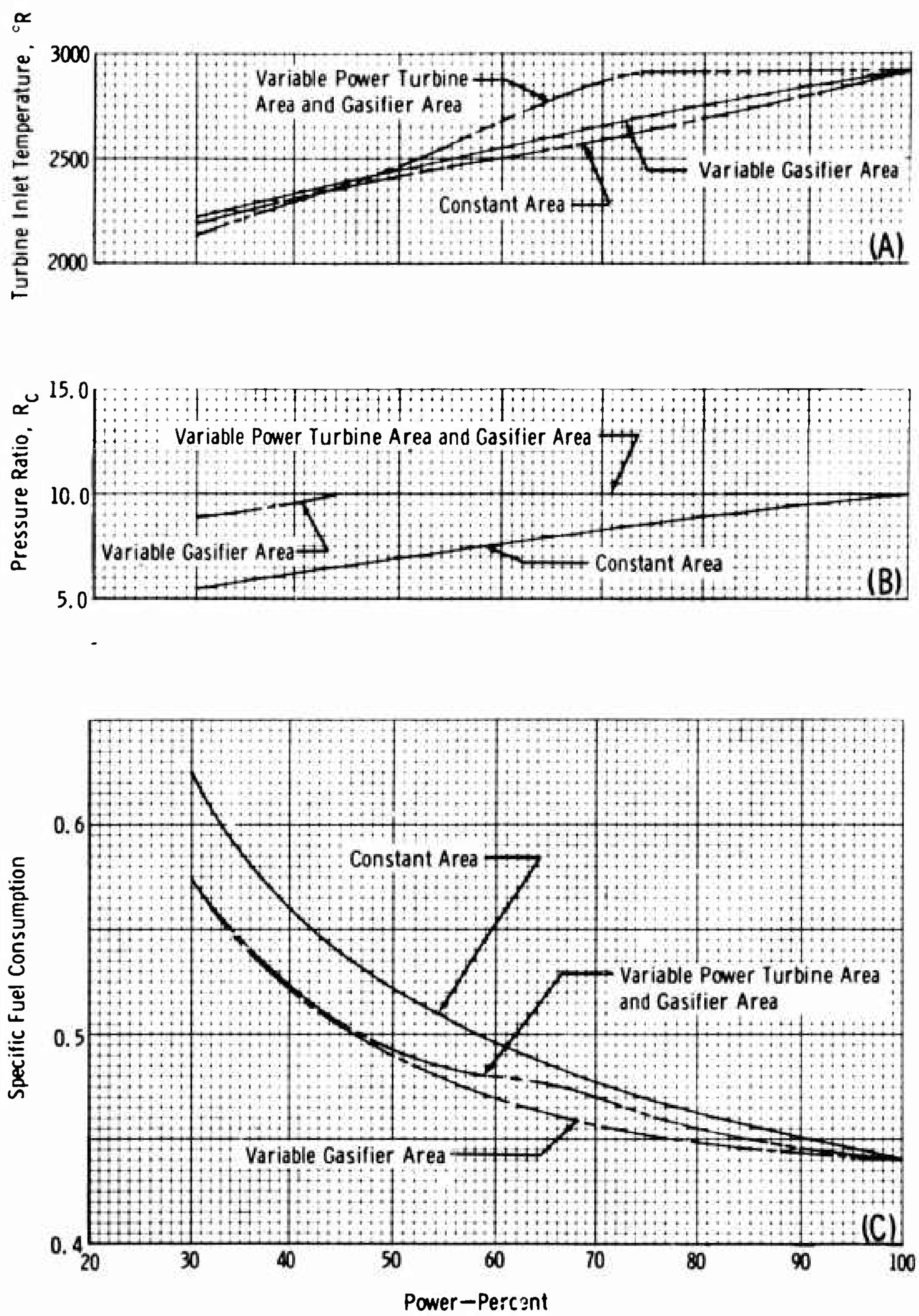


Figure 22. Engine TS210—Turbine Inlet Temperature, Pressure Ratio, and Specific Fuel Consumption as Functions of Percent Power.

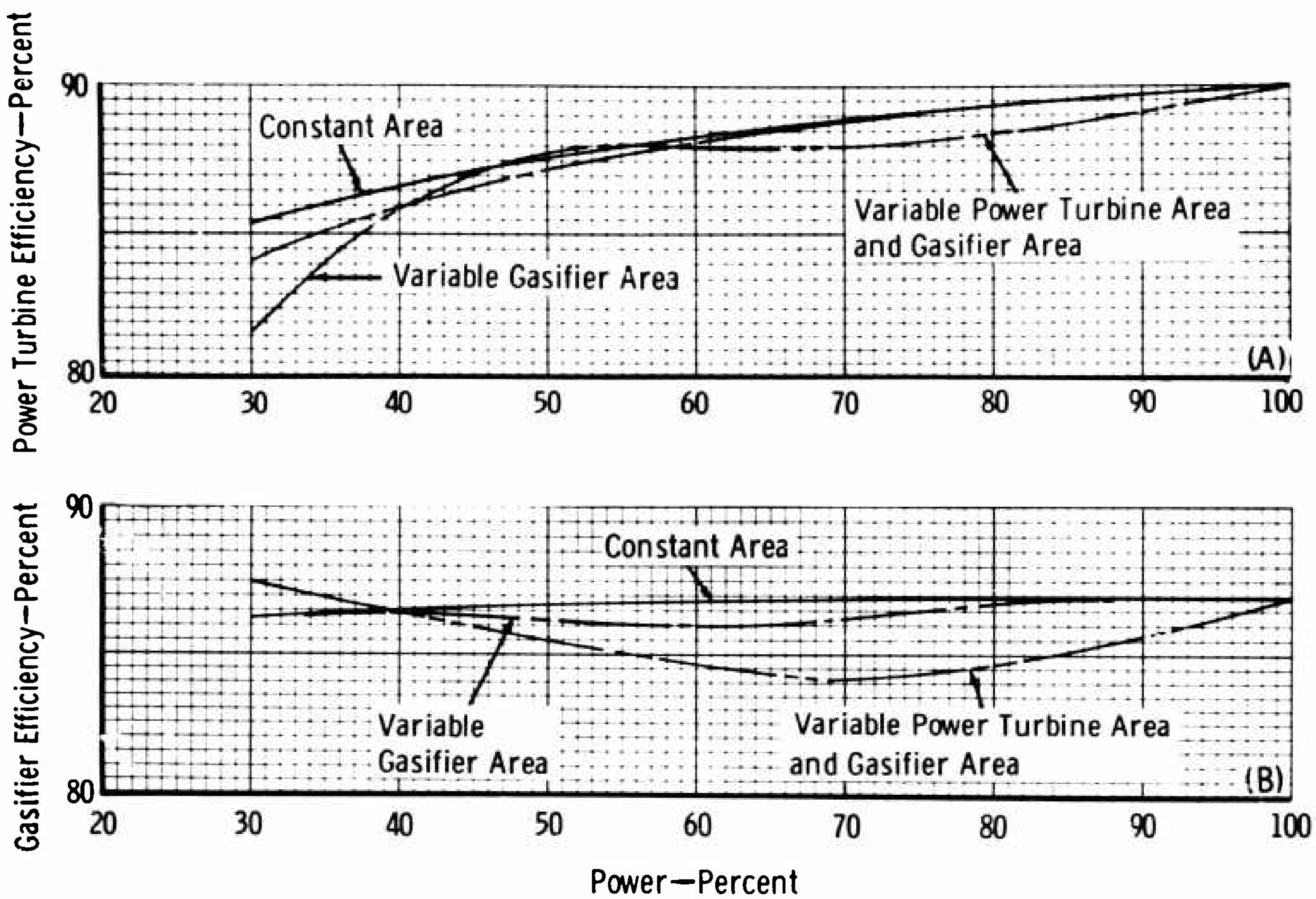


Figure 23. Engine TS210—Power Turbine and Gasifier Efficiencies as Functions of Percent Power.

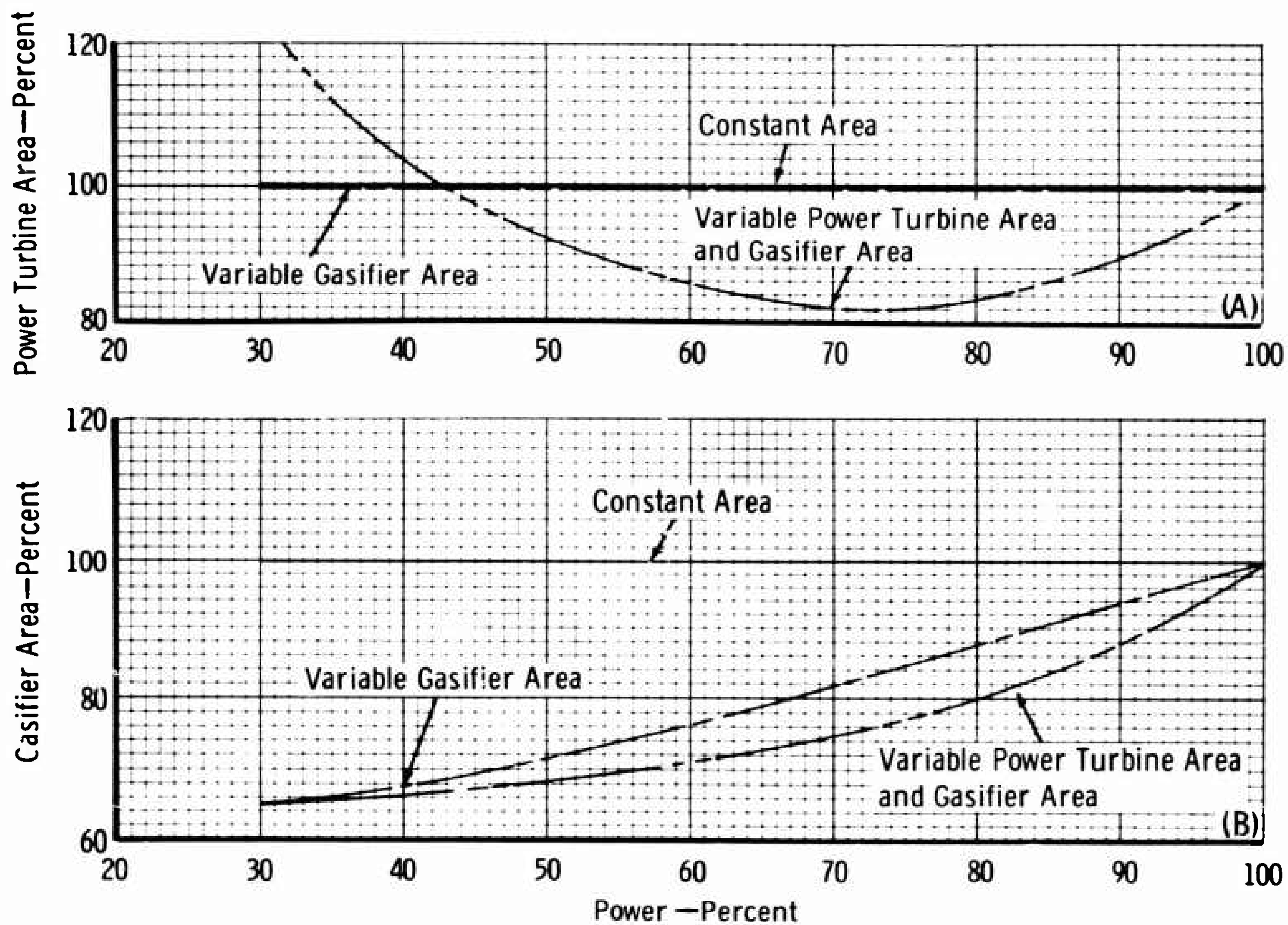


Figure 24. Engine TS210—Percent Power Turbine and Gasifier Areas as Functions of Percent Power.

was determined that the resulting specific fuel consumption would be higher than for the fixed area case. The reason for the poor performance is the extreme throttling required of the compressor, resulting in low pressure ratio and low component efficiency. The data can be seen as a single point at 50-percent power on Figures 25 through 28.

As in the case of the 10.0:1-compressor-pressure-ratio engine, the maximum pressure ratio-temperature operation (both nozzles variable) did not produce the maximum performance gain.

Since the variable power and gasifier turbine combination provides flexibility to operate at numerous combinations of pressure ratio, temperature, and flow, one additional mode of operation was explored. Movement on the compressor map was limited to obtain maximum compressor efficiency. The turbine temperature was then varied from this point by changing both the gasifier and power turbine nozzle areas. This resulted in a requirement for a power turbine area greater than the 120-percent limit shown in Figure 28A. In addition, no improvement in performance was evident. This is a result of the decrease in turbine temperature.

Figure 25 shows the compressor map with operating lines for this configuration. Figures 26A and B show how turbine temperature and pressure ratio were varied. The results in terms of specific fuel consumption are shown on Figure 26C. The improvement in fuel consumption compared to the fixed area engine was the same for variable gasifier and for both nozzles variable, amounting to 2.2 percent. Operation at constant temperature resulted in a fuel consumption increase of 6.9 percent over the fixed area case.

3. <u>TR110 - Turboshaft - Regenerative Cycle - Single Shaft - 10.0:1 R_c</u>
   <u>TR116 - Turboshaft - Regenerative Cycle - Single Shaft - 16.0:1 R_c</u>

The single-shaft regenerative engines were run at 100-percent speed in the same manner as the single-shaft simple-cycle engines; i.e., throttling was accomplished by varying temperature and/or pressure ratio at 100-percent flow. Figures 29 through 31 show the performance for the 10.0:1-compressor-pressure-ratio engine. Figure 29 is the compressor map for this engine. The turbine temperature and pressure ratio are shown in Figures 30A and B where the solid line denotes constant area operation and the four triangular symbols represent spot-point calculations at various power settings with variable geometry. The resulting specific fuel consumption is shown in Figure 30C. The specific fuel consumption difference

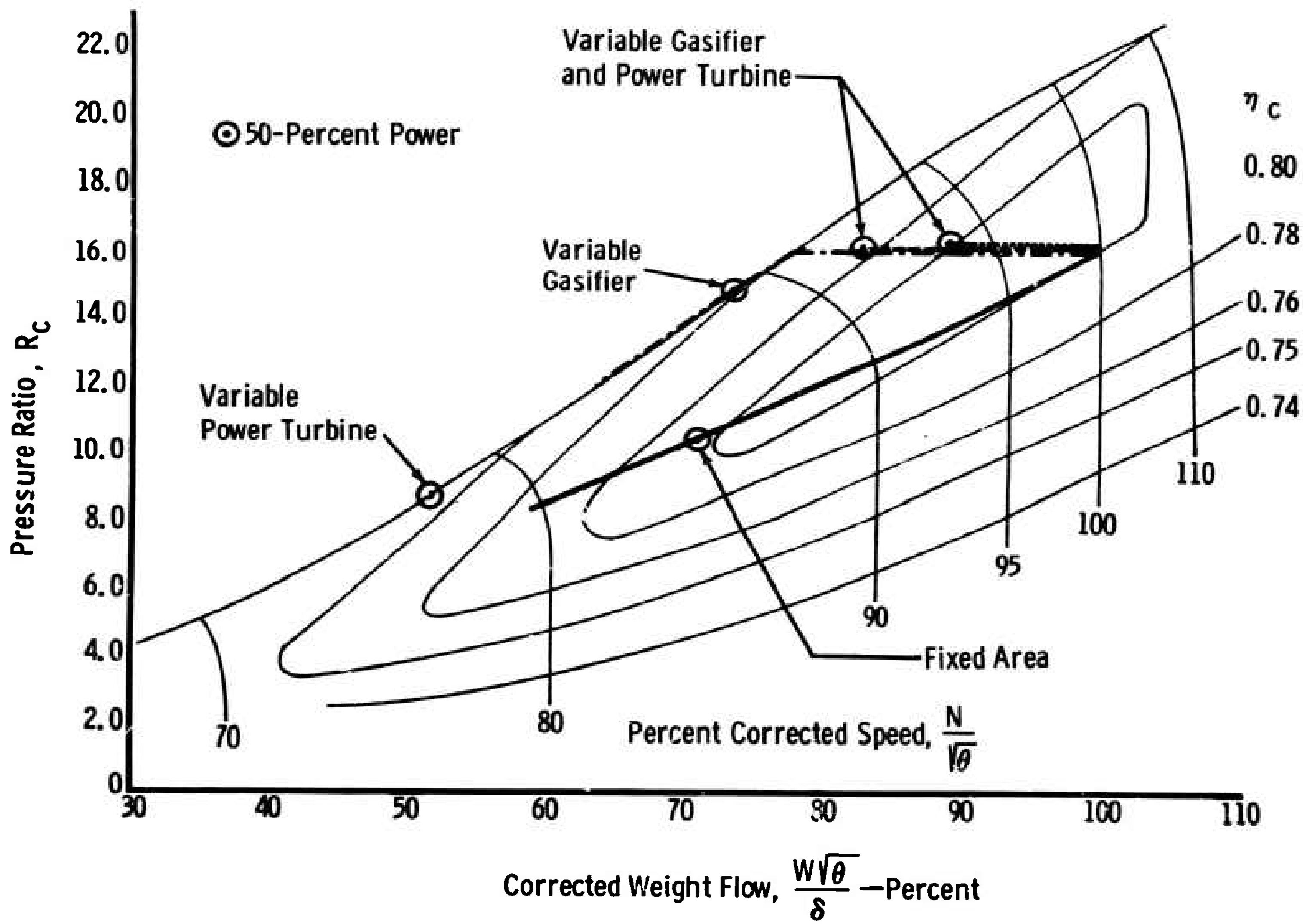


Figure 25. Engine TS216—Operating Lines on the Compressor Map.

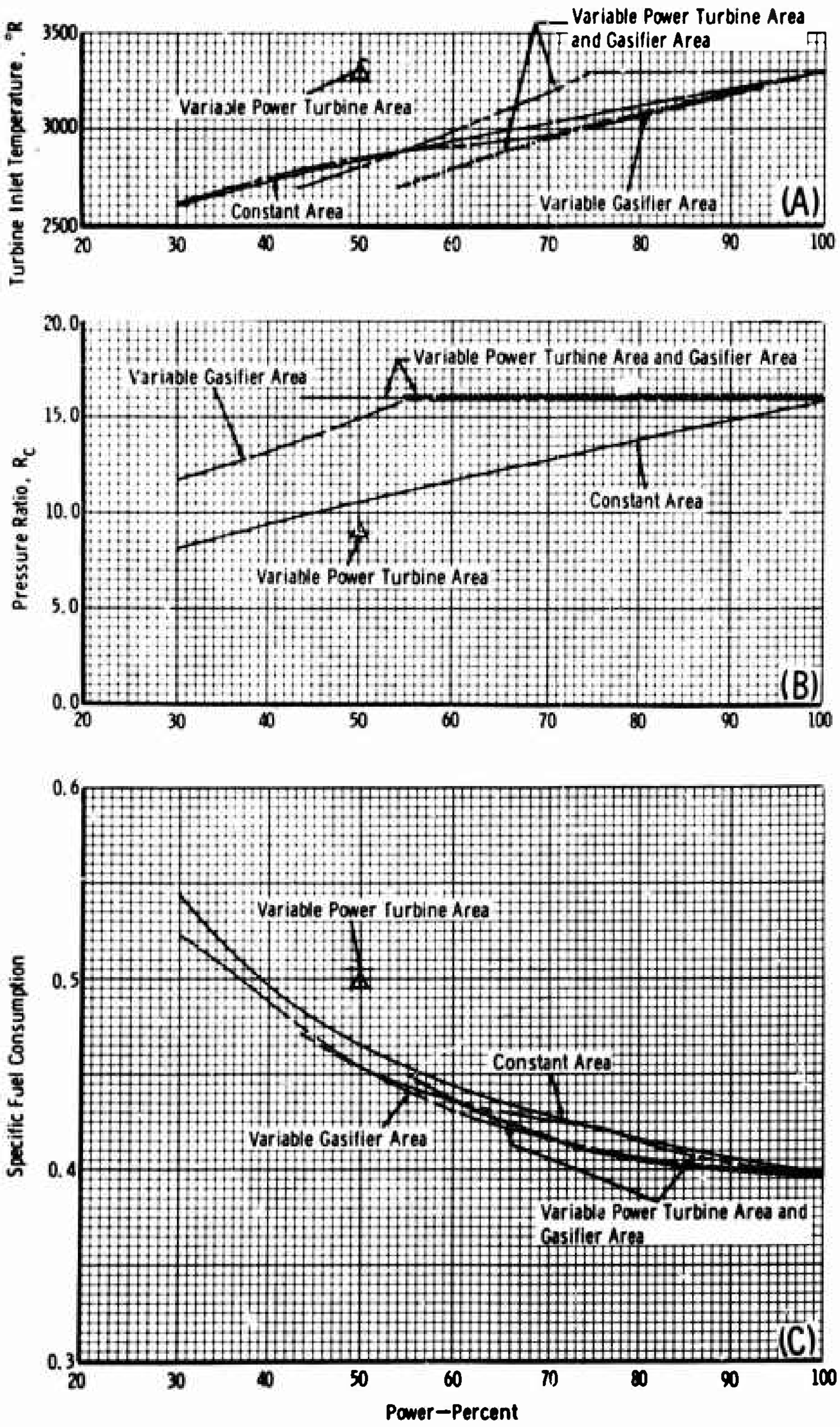


Figure 26. Engine TS216—Turbine Inlet Temperature, Pressure Ratio, and Specific Fuel Consumption as Functions of Percent Power.

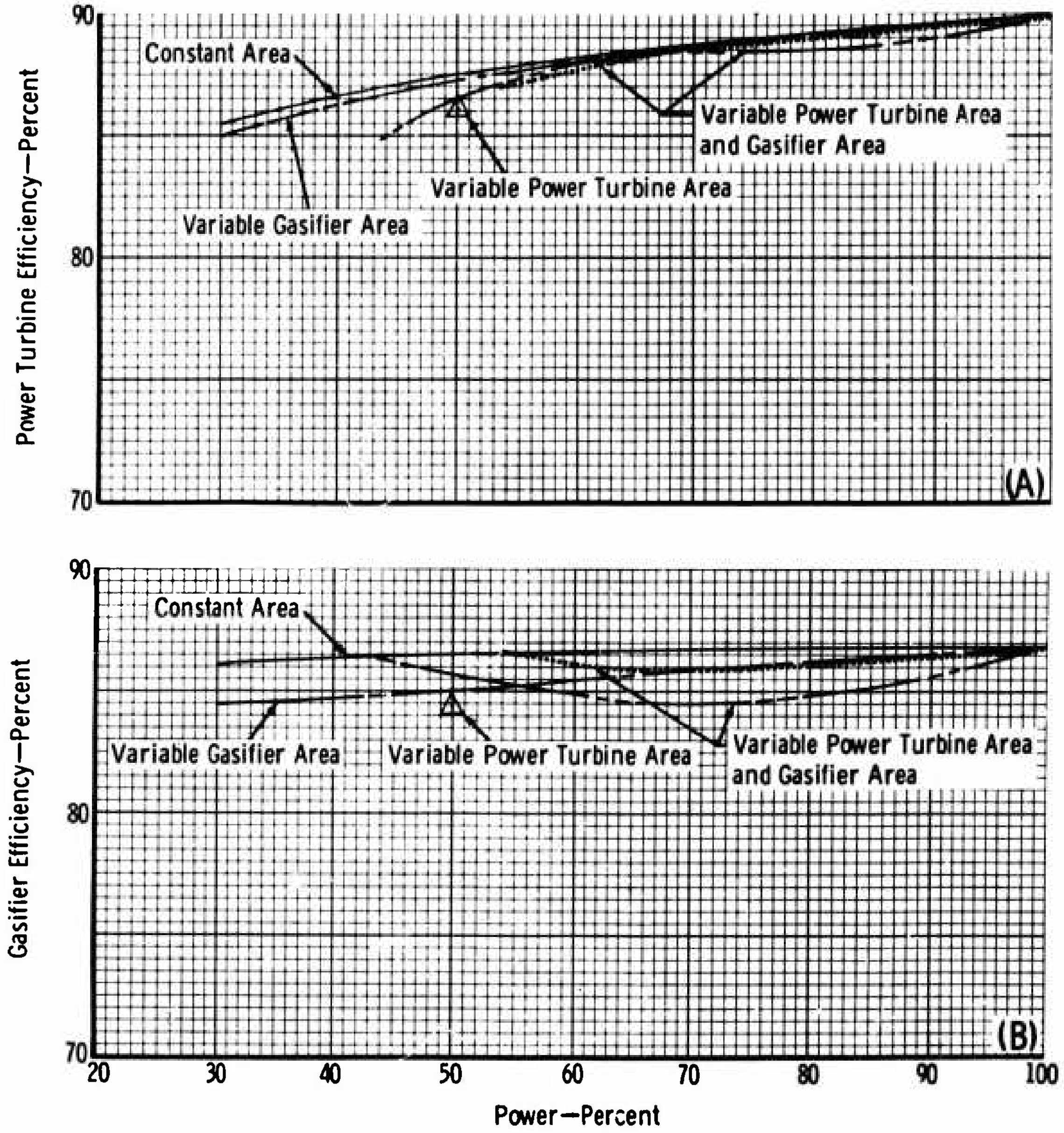


Figure 27. Engine TS216—Power Turbine and Gasifier Efficiencies as Functions of Percent Power.

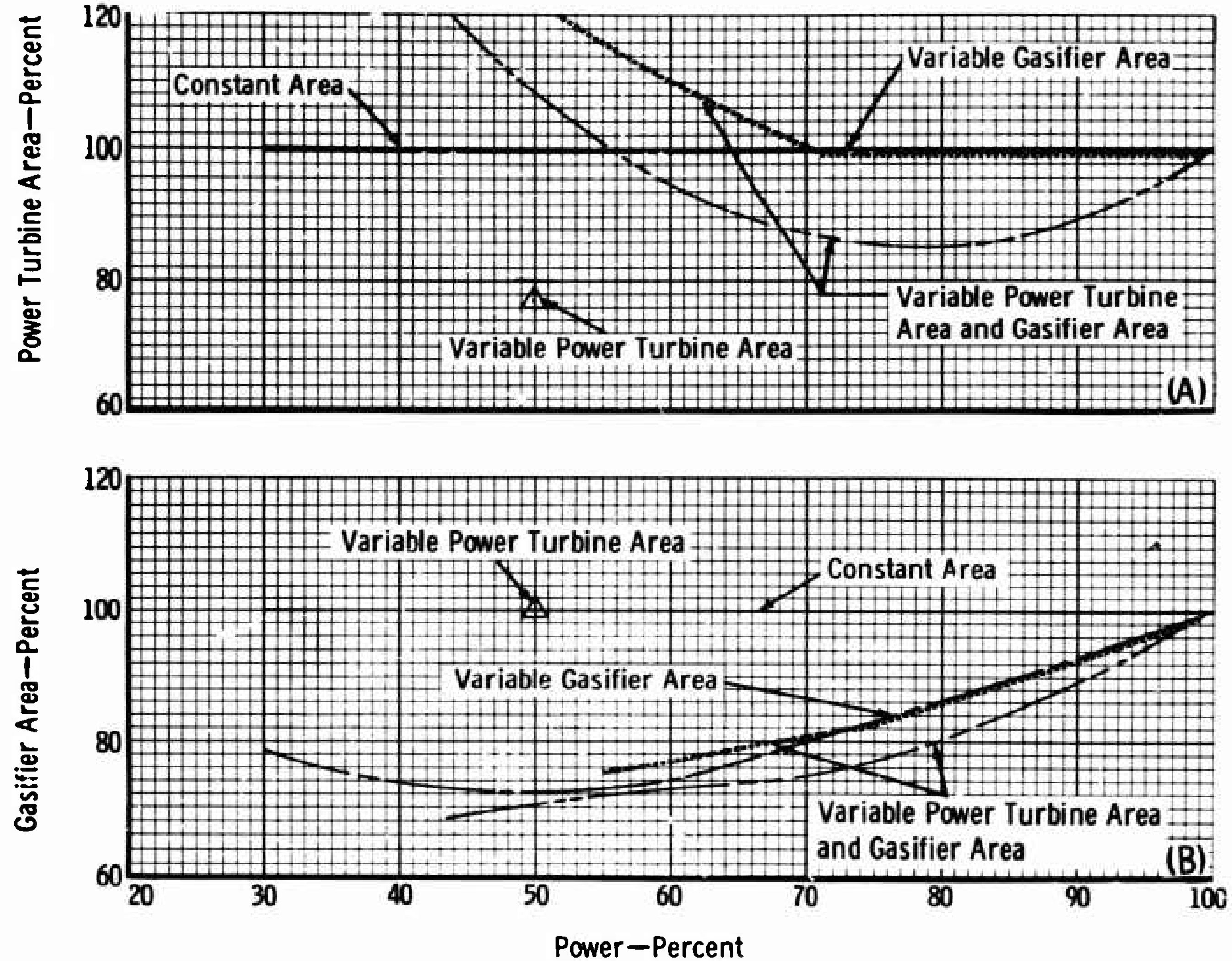


Figure 28. Engine TS216—Percent Power Turbine and Gasifier Areas as Functions of Percent Area.

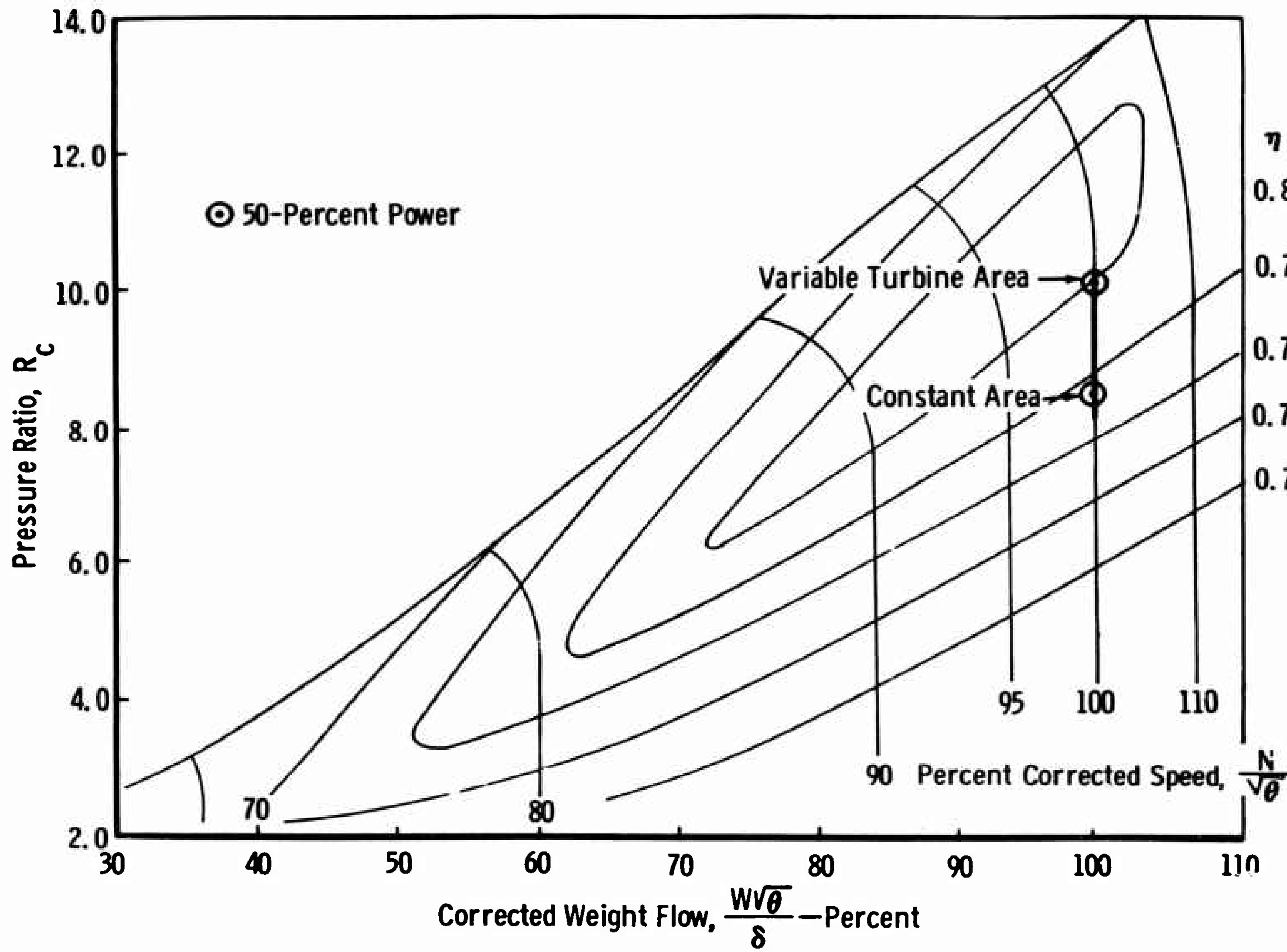


Figure 29. Engine TR110—Operating Lines on the Compressor Map.

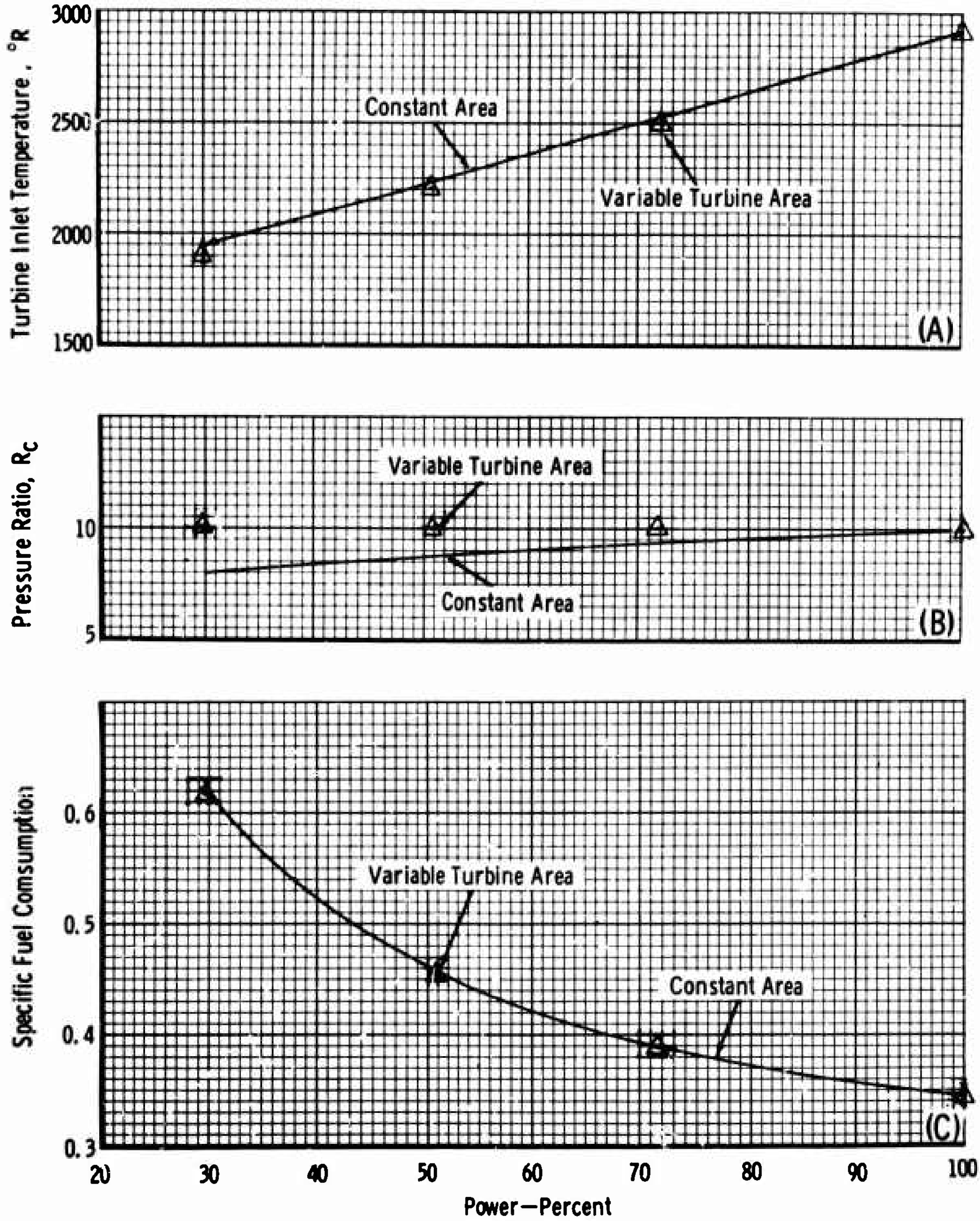


Figure 30. Engine TR110—Turbine Inlet Temperature, Pressure Ratio, and Specific Fuel Consumption as Functions of Percent Power.

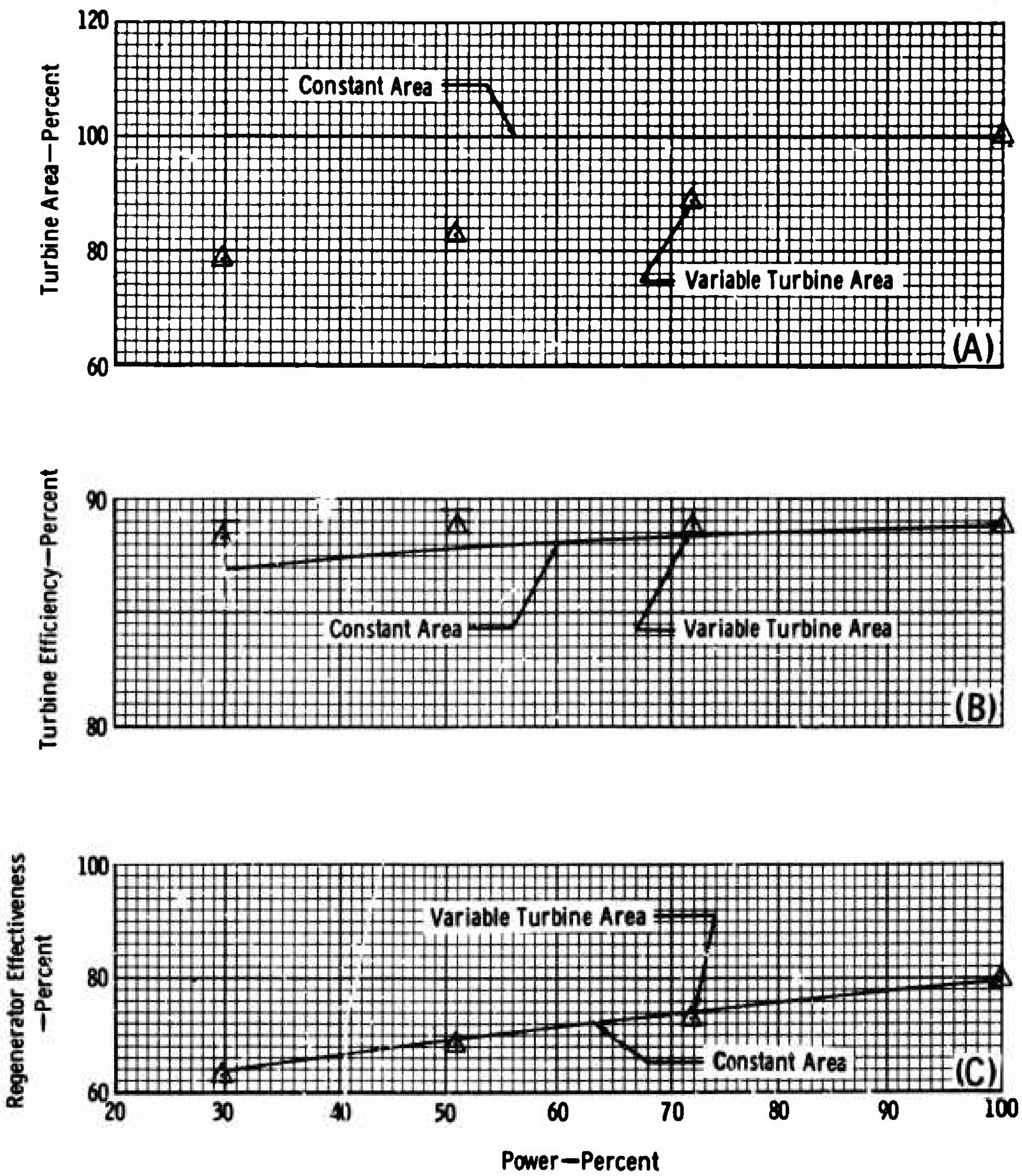


Figure 31. Engine TR110—Percent Turbine Area, Turbine Efficiency, and Regenerator Effectiveness as Functions of Percent Power.

between fixed and variable geometry is not significant. This is a result of the thermal efficiency and, therefore, of the specific fuel consumption's being essentially independent of pressure ratio and primarily dependent on temperature in the regenerative cycle. As was the case in the simple-cycle engine, throttling at constant temperature is not practical in the simple-cycle engine at constant speed because of the minimal reduction in output power with decreased pressure ratio. Figure 31A shows that the area required to hold pressure ratio at 30-percent power is 78 percent of the design value. Figure 31B shows the turbine efficiency to be slightly higher with variable geometry. This is the reason for the slight gain in specific fuel consumption with this mode of operation. The regenerator effectiveness plotted in Figure 31C is essentially the same for the two modes of operation.

Comparable data on the 16.0:1-compressor-pressure-ratio engine are shown in Figures 32 through 34. As was the case with the 10.0:1-compressor-pressure-ratio engine, no significant improvement in performance could be obtained with the incorporation of variable geometry. In general, the differences in specific fuel consumption and the component efficiencies are within 1 percent of those values determined for the 10.0:1-compressor-pressure-ratio engine.

The limitation of constant speed operation seriously detracted from the performance gains available with variable geometry on the single-shaft regenerative engine. Previous studies have shown that variable r.p.m. operation of this type engine can provide significant gains in specific fuel consumption by operating at constant temperature during throttling. Variable turbine geometry is, however, not necessarily a requirement to realize these gains. Control of the load may in some cases be used to maintain turbine temperature during throttling while varying speed.

4. TR210 - Turboshaft - Regenerative Cycle - Free Shaft - 10.0:1 R_c
TR216 - Turboshaft - Regenerative Cycle - Free Shaft - 16.0:1 R_c

The performance for the regenerative free-shaft engines is shown in Figures 35 through 38 for the 10.0:1-compressor-pressure ratio engine. These data are the result of performance calculations with a variable gasifier nozzle in combination with a variable power turbine nozzle, constant area performance, and performance with a variable power turbine only.

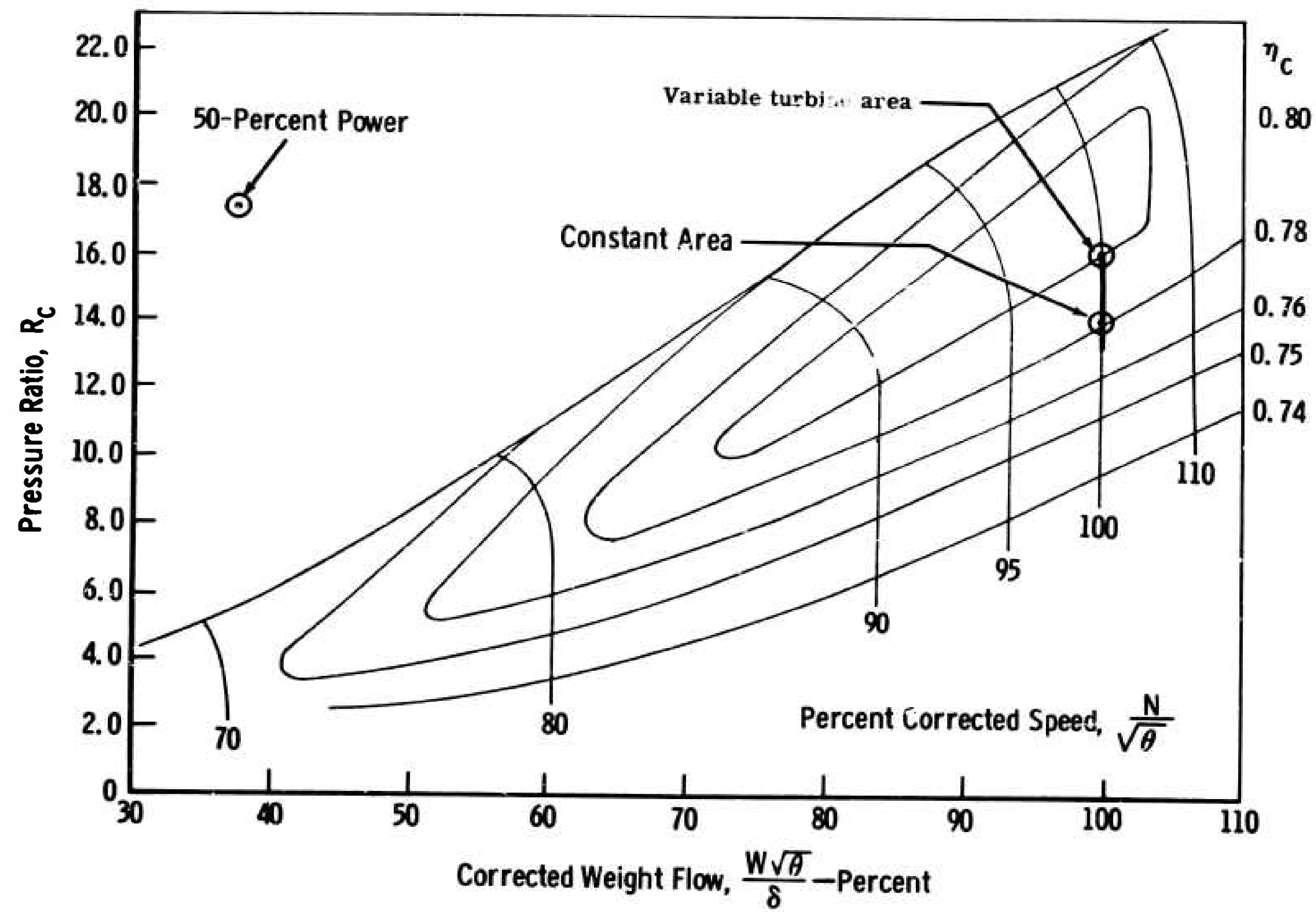


Figure 32. Engine TR116—Operating Lines on the Compressor Map.

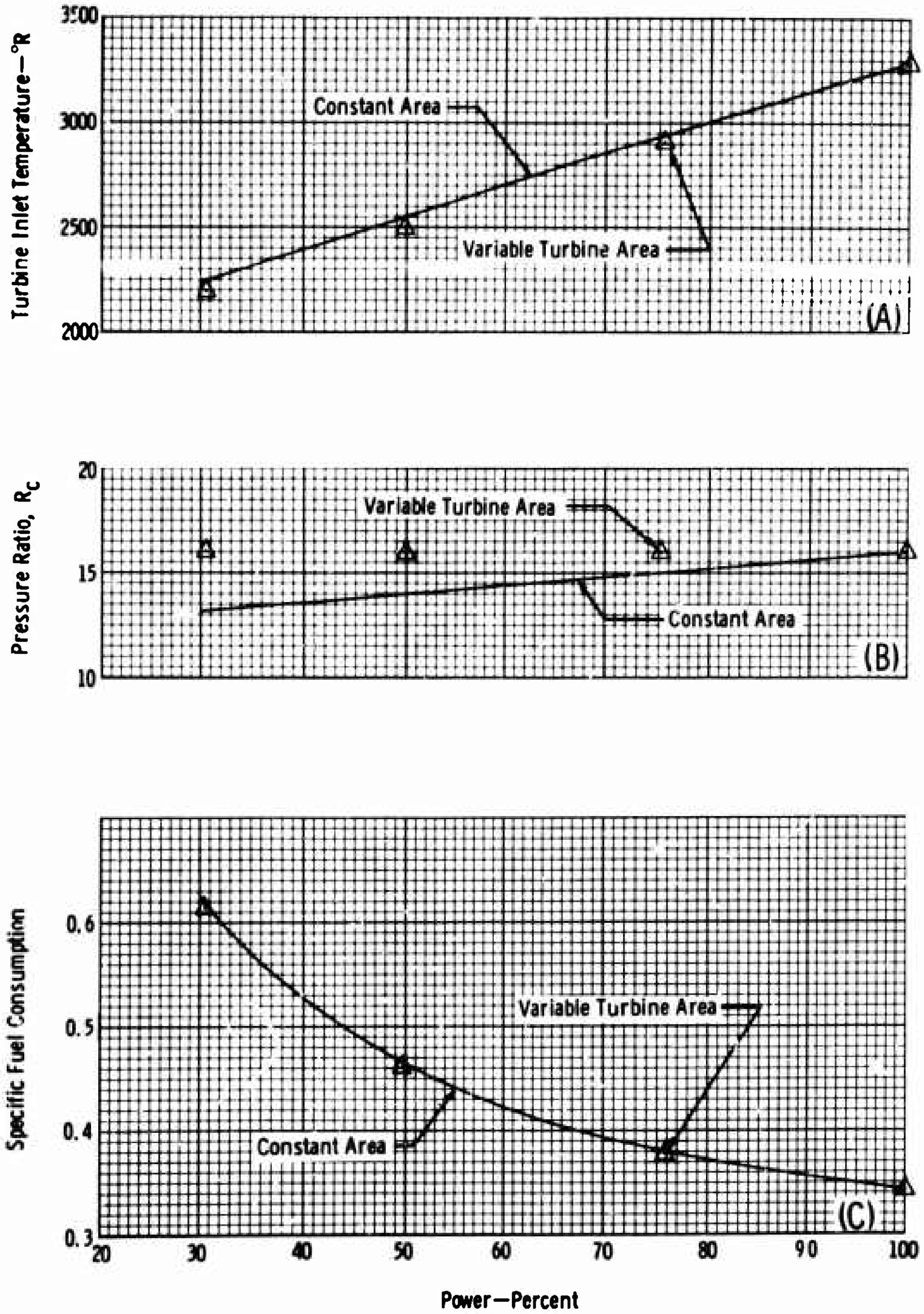


Figure 33. Engine TR116—Turbine Inlet Temperature, Pressure Ratio, and Specific Fuel Consumption as Functions of Percent Power.

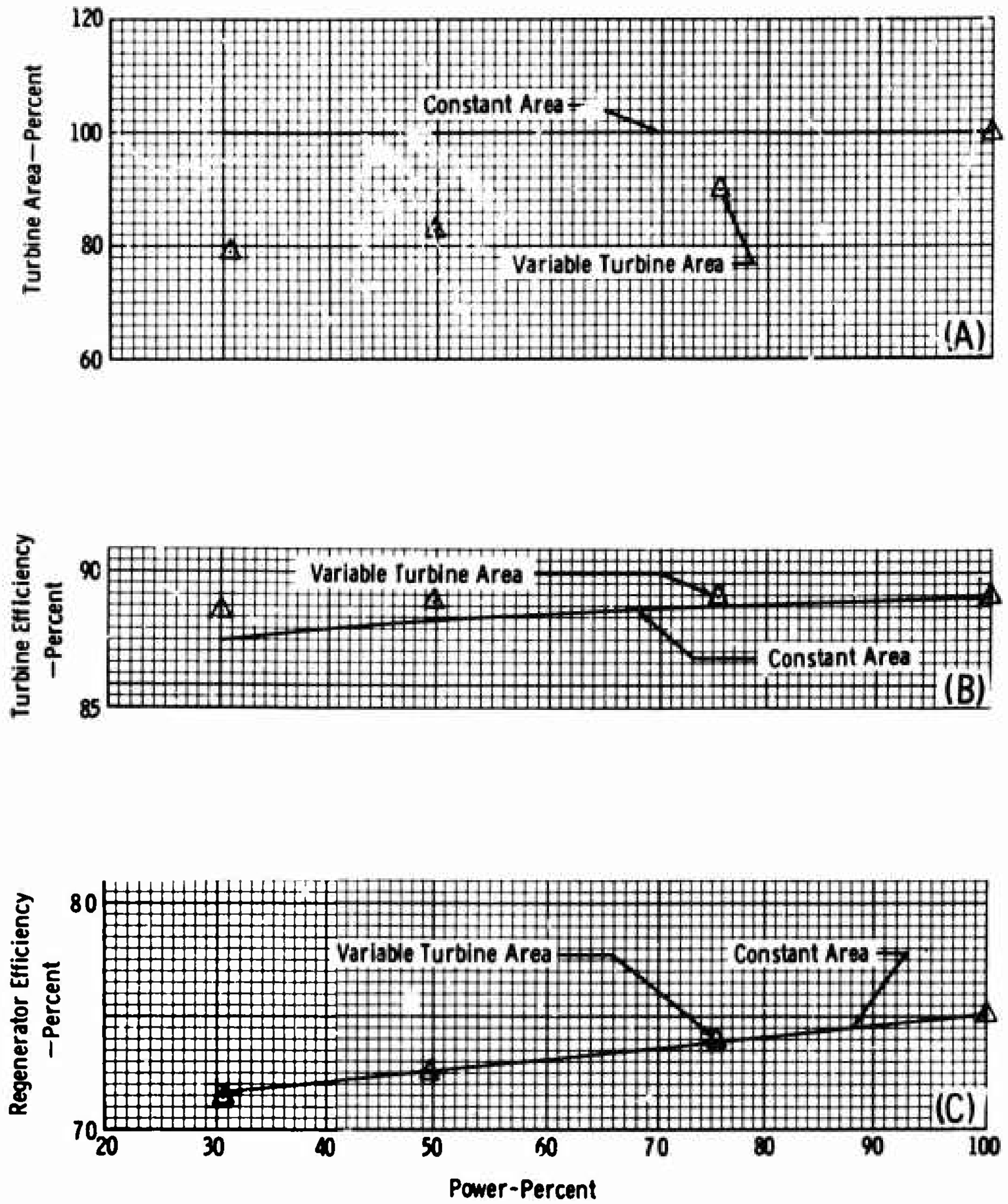


Figure 34. Engine TR116—Percent Turbine Area, Turbine Efficiency, and Regenerator Effectiveness as Functions of Percent Power.

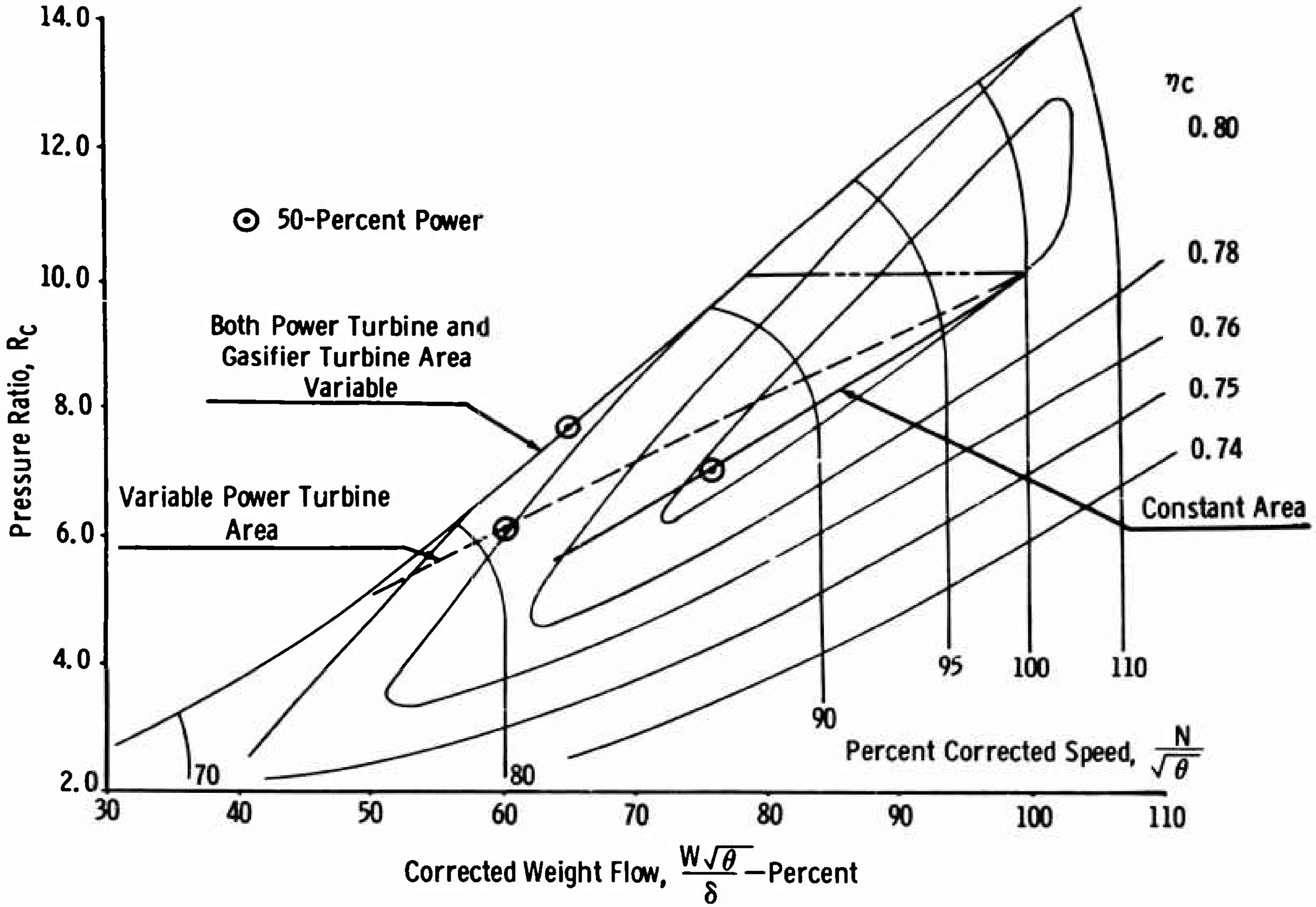


Figure 35. Engine TR210—Operating Lines on the Compressor Map.

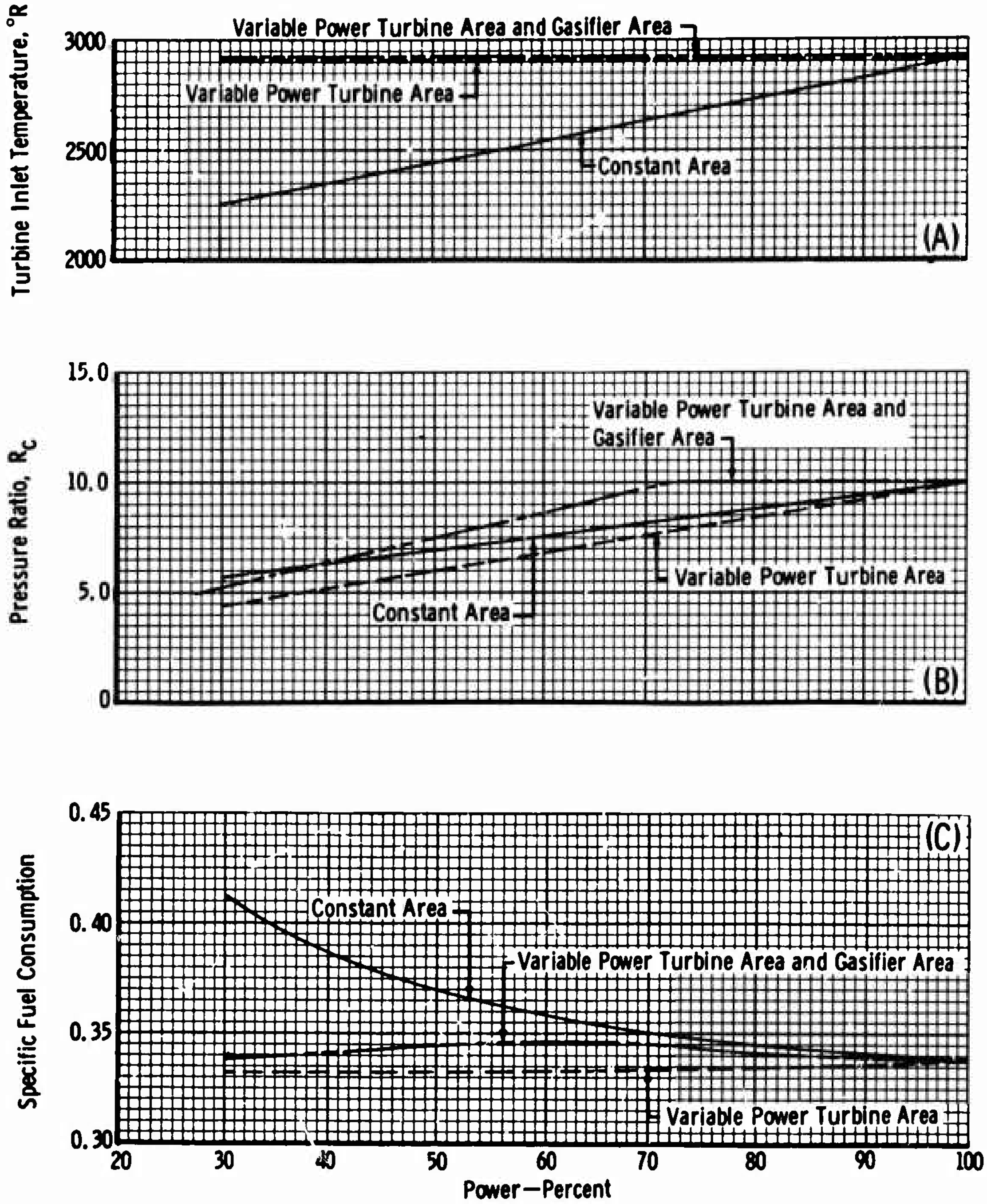


Figure 36. Engine TR210—Turbine Inlet Temperature, Pressure Ratio, and Specific Fuel Consumption as Functions of Percent Power.

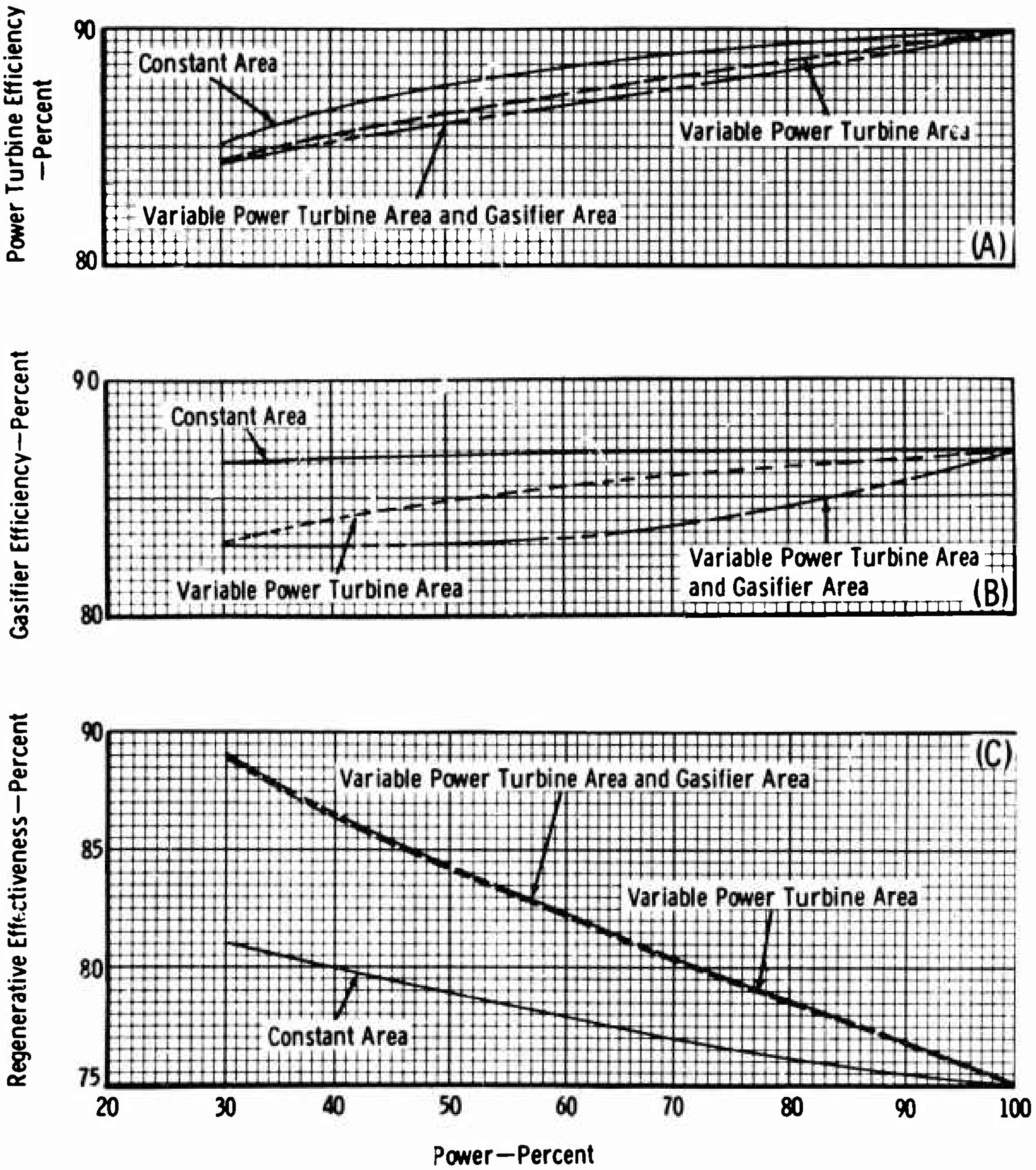


Figure 37. Engine TR210—Power Turbine and Gasifier Efficiency, and Regenerator Effectiveness as Functions of Percent Power.

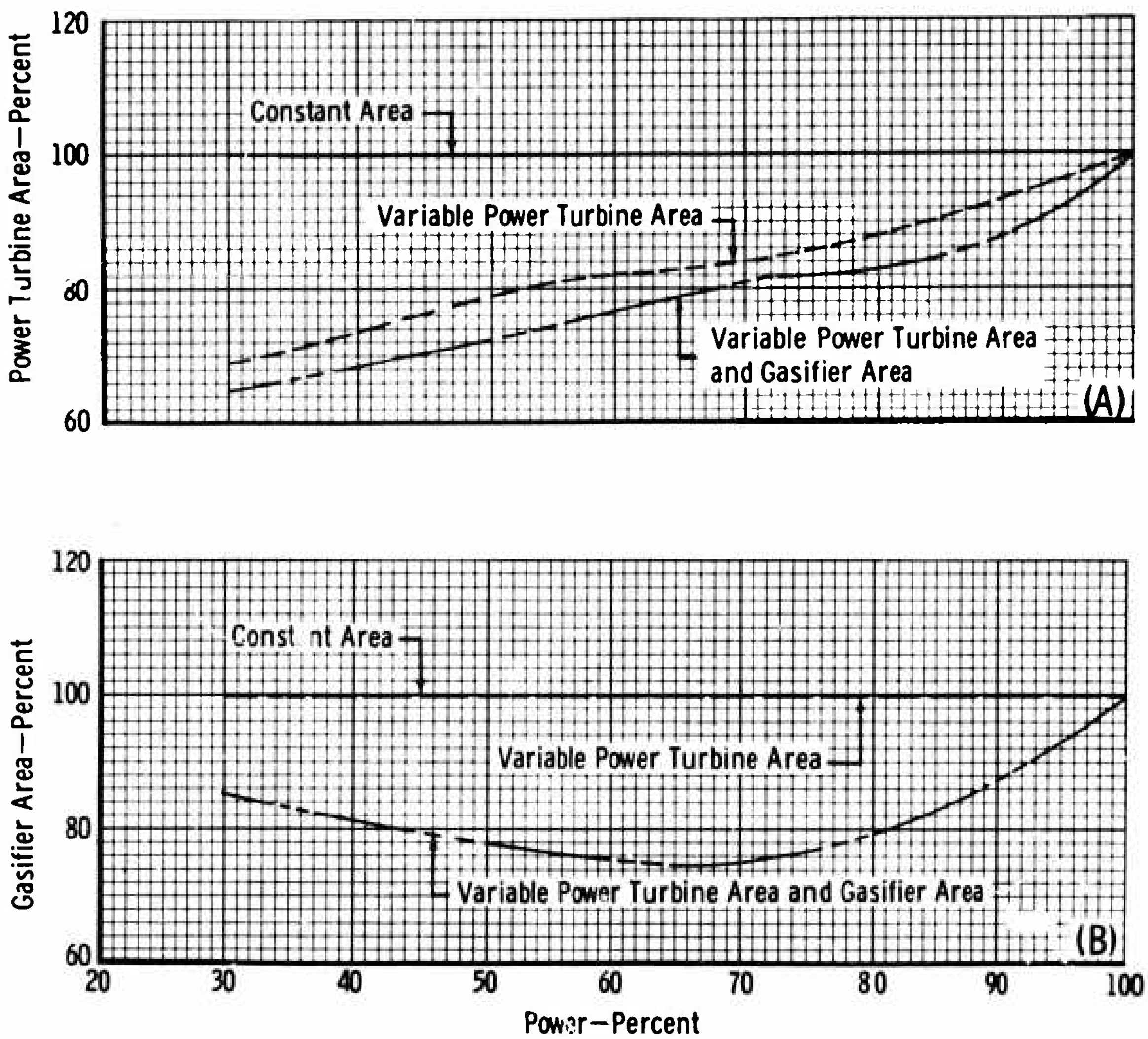


Figure 38. TR210—Percent Power Turbine and Percent Gasifier Areas as Functions of Percent Power.

As was the case in the simple-cycle, free-shaft engines, variable gasifier and power turbine geometry were used in combination to operate at maximum pressure ratio and temperature, simultaneously. Power was throttled by reducing flow only until the surge line was encountered. At this point, operation was defined along the surge line at constant turbine temperature. Figure 35 depicts the compressor map for the 10.0:1-compressor-pressure-ratio engine with the operating lines and 50-percent power points superimposed.

The corresponding value of temperature and pressure ratio for these operating lines is shown on Figures 36A and B. Operation along the lines shown on the compressor map produces the specific fuel consumption versus power characteristic of Figure 36C. The specific fuel consumption is essentially constant and equal to the rated value, with the variable power turbine being used to hold constant turbine temperature throughout the operating range. The improvement in specific fuel consumption at 50-percent power is equal to 9.5 percent over the fixed area case. This is the maximum specific fuel consumption improvement found in all of the engines investigated.

Figures 37A and B show the turbine efficiencies to be less with this mode of operation than for the fixed area engine. Figure 37C, however, shows the regenerator effectiveness to be markedly increased at 50-percent power, overriding the effect of reduced component efficiency on specific fuel consumption. This increase in effectiveness is the result of throttling by reducing the flow. The flow through the heat exchanger at a given percent power is significantly less with the constant temperature operation than with the fixed area case. This results in an increased effectiveness of the heat exchanger. A secondary factor contributing to the desirable specific fuel consumption characteristic for constant temperature operation is the more nearly optimum combination of turbine temperature and pressure ratio.

By using variable gasifier and power turbine geometry in this engine, a specific fuel consumption reduction of 7-1/2 percent, compared with 9-1/2 percent using variable power turbine geometry alone, is obtained. The greater loss in turbine efficiency with this mode of operation, plus a less desirable combination of pressure ratio and turbine inlet temperature, results in a lower gain in thermal efficiency. Figures 38A and B define the changes in power and gasifier nozzle area to operate these modes.

Figures 39 through 42 show comparable data on the 16.0:1-compressor-pressure-ratio engine. However, the gain in specific fuel consumption was not as significant as with that on the 10.0:1-compressor-pressure-ratio. The comparable numbers are 8-1/2 percent for the 16.0:1-compressor-pressure-ratio variable power turbine case compared with 9-1/2 percent for the 10.1:1-compressor-pressure-ratio engine, and 5 percent for the 16.0:1-compressor-pressure-ratio case with both nozzles varying compared to 7-1/2 percent for the 10.0:1-compressor-pressure-ratio engine.

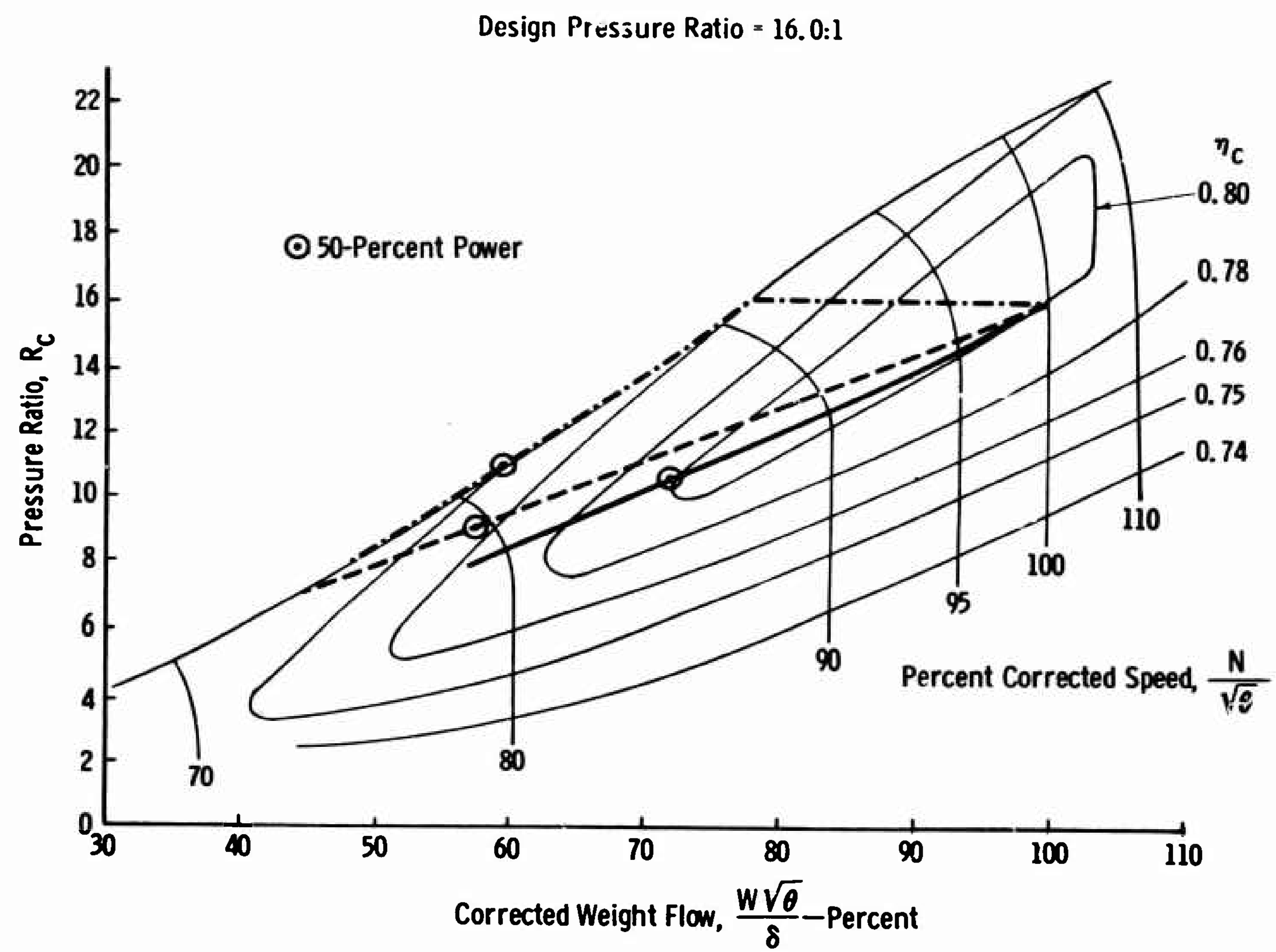


Figure 39. Engine TR216—Operating Lines on the Compressor Map.

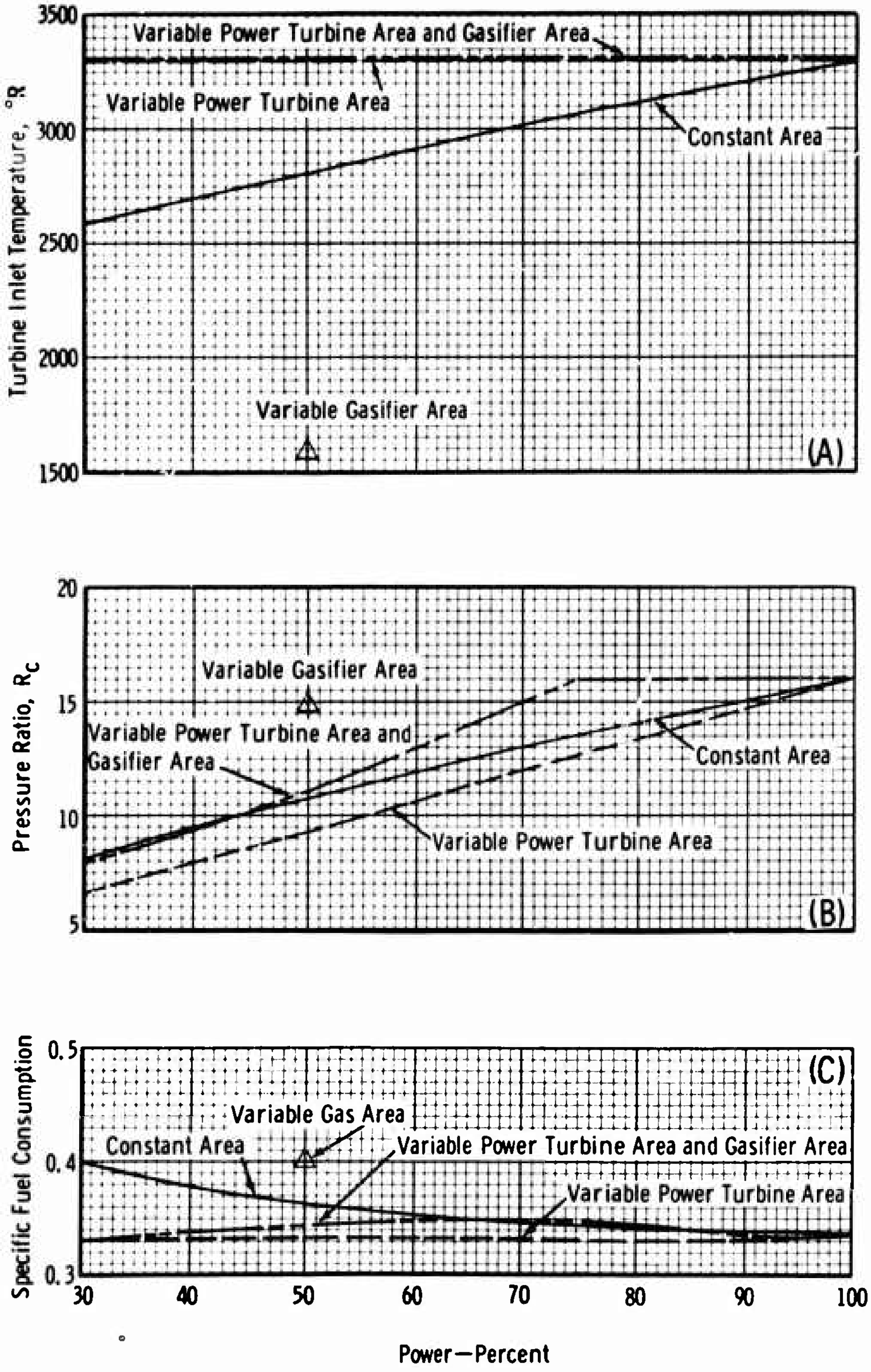


Figure 40. Engine TR216—Turbine Inlet Temperature, Pressure Ratio, and Specific Fuel Consumption as Functions of Percent Power.

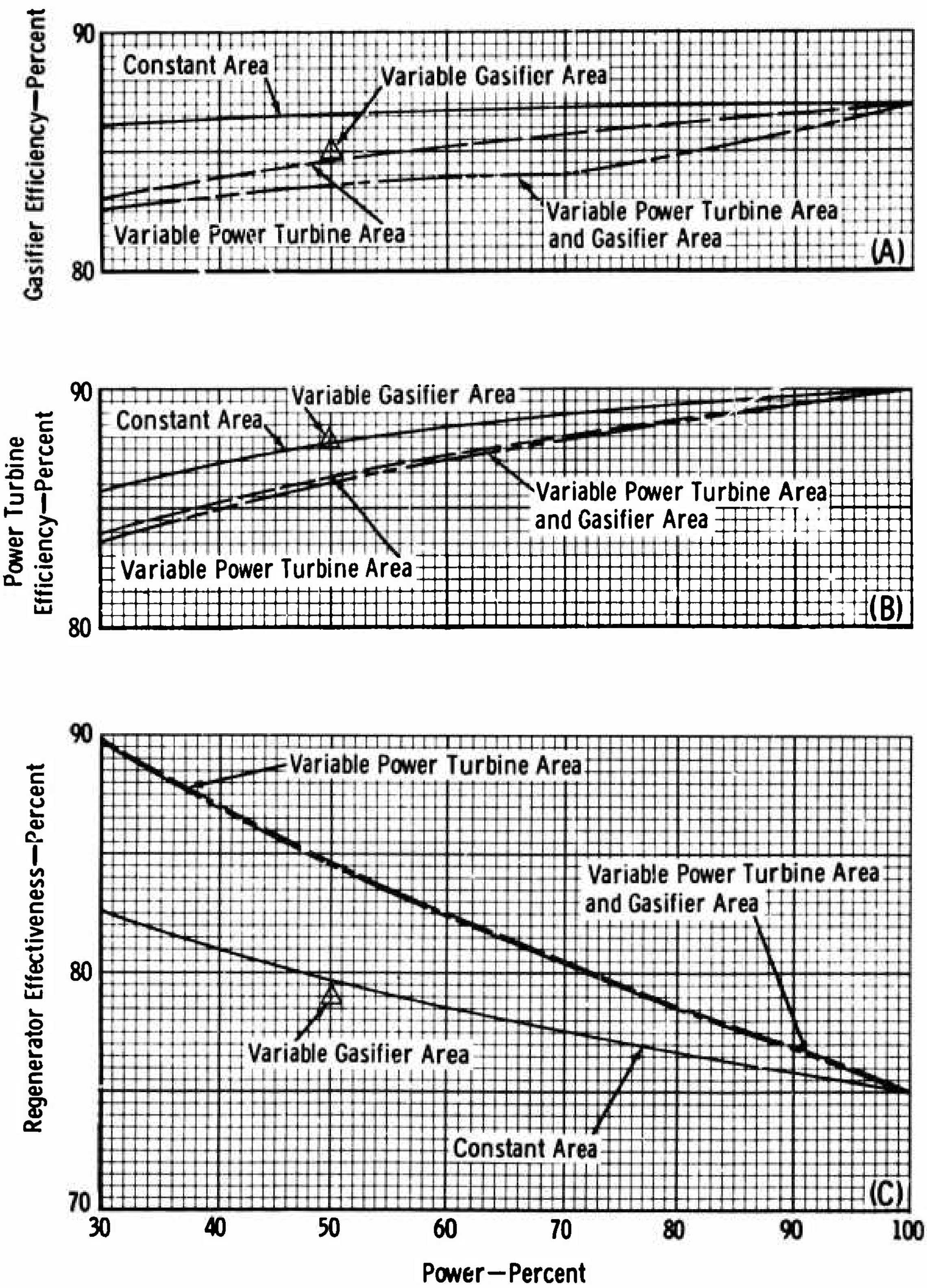


Figure 41. Engine TR216—Power Turbine and Gasifier Efficiencies and Regenerator Effectiveness as Functions of Percent Power.

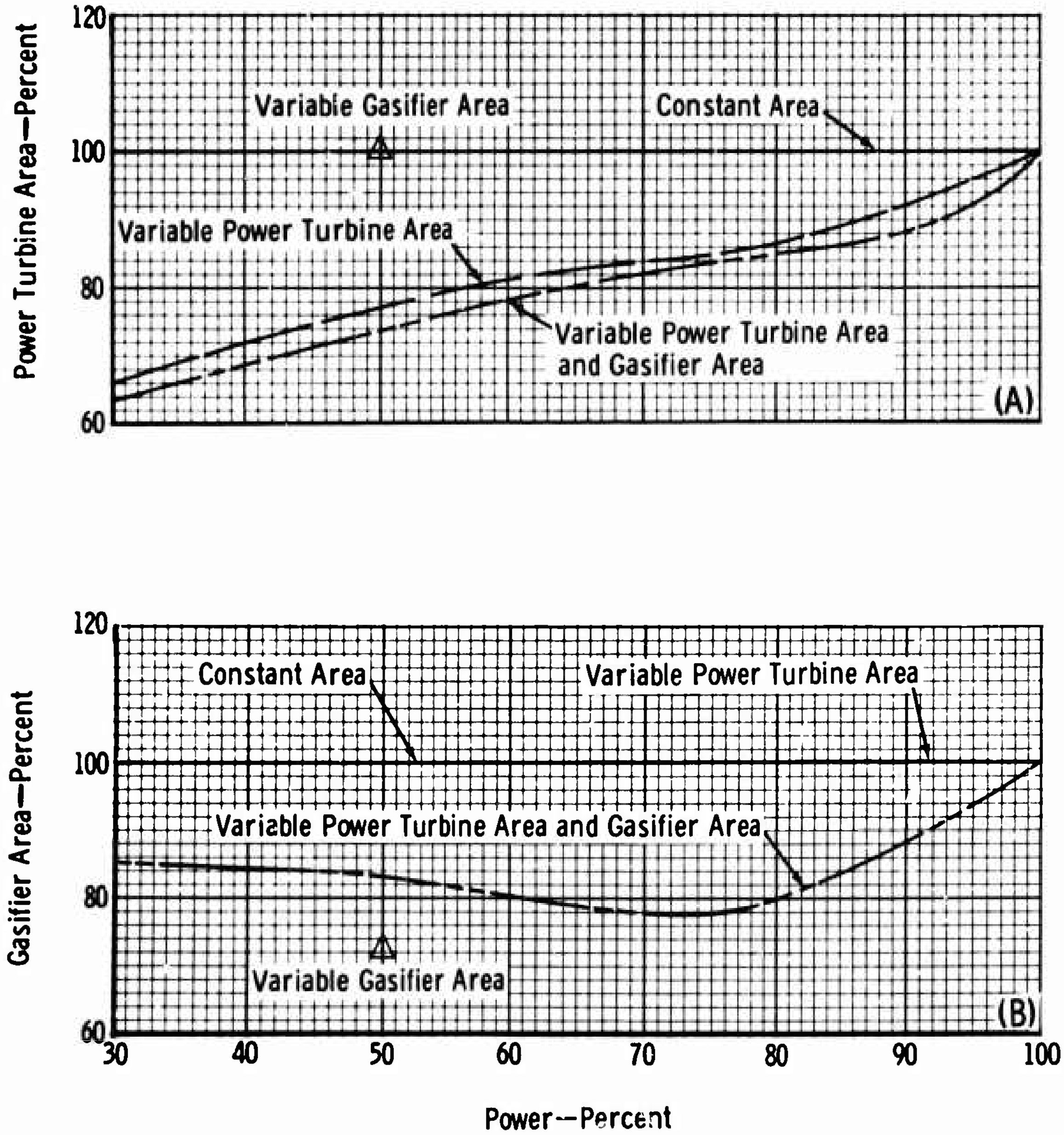


Figure 42. Engine TR216—Percent Power Turbine and Gasifier Areas as Functions of Percent Power.

One additional mode of operation was explored on the 16.0:1-compressor-pressure-ratio engine. This is identified by a triangular symbol on Figures 40 through 42. For this case, the engine pressure ratio was held constant and the turbine temperature was throttled by changing the gasifier nozzle area. The resulting specific fuel consumption at 50-percent power was 8-1/2 percent higher with this mode of operation than with fixed geometry. This indicates the importance of maintaining maximum temperature in the regenerative cycle.

5. FS210 - Turbofan - Simple Cycle - Free Shaft - 10.0:1 R_c
FS216 - Turbofan - Simple Cycle - Free Shaft - 16.0:1 R_c

The fan engines are free-shaft, simple-cycle configurations utilizing a forward mounted 1.52:1-compressor-pressure-ratio fan providing a 4.0-bypass ratio at the sea level static design point. The high-pressure systems for the fan engine and the fan turbine are exactly the same as those of the shaft engines. The fan engines are unmixed and incorporate a fixed primary and fan jet nozzle.

Supercharging the shaft engines with the fan resulted in the high-pressure system operating at a reduced corrected speed. This, in turn, resulted in a reduced high-pressure pressure ratio. The 10.1:1-compressor-pressure-ratio engine operates at an 8.6:1-high-pressure pressure ratio, and the 16.0:1-compressor-pressure-ratio engine operates at a 13.7:1-high-pressure ratio in the fan engine. Incorporation of the fan results in a 13.0:1 and 20.7:1 overall pressure ratio for the 10.0:1- and 16.0:1-pressure-ratio-shaft engines, respectively.

One problem encountered in the fan engine analysis was the inability to select numerous operating conditions in terms of temperature, flow, and pressure ratio. It was not possible to run the fan engine at reduced power levels while maintaining a constant overall pressure ratio due to the turbine inlet temperature exceeding its design value. This was due to the requirement to match continuity on both of the fixed jet nozzle areas, reducing the flexibility of operation available with variable turbine geometry. If both jet nozzles had been variable, the continuity and power matching of the high- and low-pressure rotating components could have been altered, allowing more flexibility.

Previous fan-type engine studies have shown that to attain minimum specific fuel consumption it is desirable to maintain the pressure and bypass ratios at as high a level as possible. These same studies have shown that high-temperature operation increases fuel consumption on this type engine. Investigation showed that fan engines could not be operated at a constant overall pressure ratio without exceeding the limiting turbine inlet temperature. Therefore, data were calculated by using a variable gasifier area to maintain constant high-pressure pressure ratio; on the 16.0:1-compressor-pressure-ratio engine, calculations were also made using both nozzles variable to increase the overall pressure ratio.

Fan data were calculated at sea level 250 knots. Conventional fixed area operation was first defined over the range of thrust from 30 to 75 percent of the sea level static, standard day value. The 250-knot thrust at 100-percent r.p.m. is equal to 75 percent of the sea level static value.

Figures 43 through 47 define the performance for the 10.0:1-compressor-pressure-ratio engine (FS210). Figures 43 and 44 show the fan and high-pressure compressor maps, respectively. Two operating lines are shown. As evaluated for the shaft power engine, operation along the surge line was computed with variable geometry to evaluate the maximum performance gains available. One line is for the constant area case and the other for the variable gasifier area. The circled points identify operation at 50-percent sea level static power. Figures 45A and B define the turbine temperature and bypass ratio resulting from both modes of operation. The specific fuel consumption is defined in Figure 45C. An increasing reduction in specific fuel consumption can be seen down to about 50-percent power where the difference remains constant at approximately 3.0 percent. Figures 46A and B define the individual pressure ratio of the high-pressure system and the fan. The turbine efficiencies are shown in Figures 47A and B and are essentially the same for either mode of operation. The area change in the gasifier nozzle required to effect constant high-pressure pressure-ratio operation is presented in Figure 47C and is within the limits available in the turbine.

Data were run on the 16.0:1-compressor-pressure-ratio fan engine (FS216) similar to the data described for the 10.0:1-compressor-pressure-ratio fan and similar results were obtained. Noting the small performance gain on the 10.0:1- and 16.0:1-compressor-pressure-ratio engines using variable gasifier geometry, one additional mode of operation was explored. Both nozzles were varied in an effort to increase the overall pressure ratio. Results of this calculation are denoted by a triangular symbol for a single point at 52 percent of sea level static, standard day thrust on Figures 48 through 52, defining the performance for this engine.

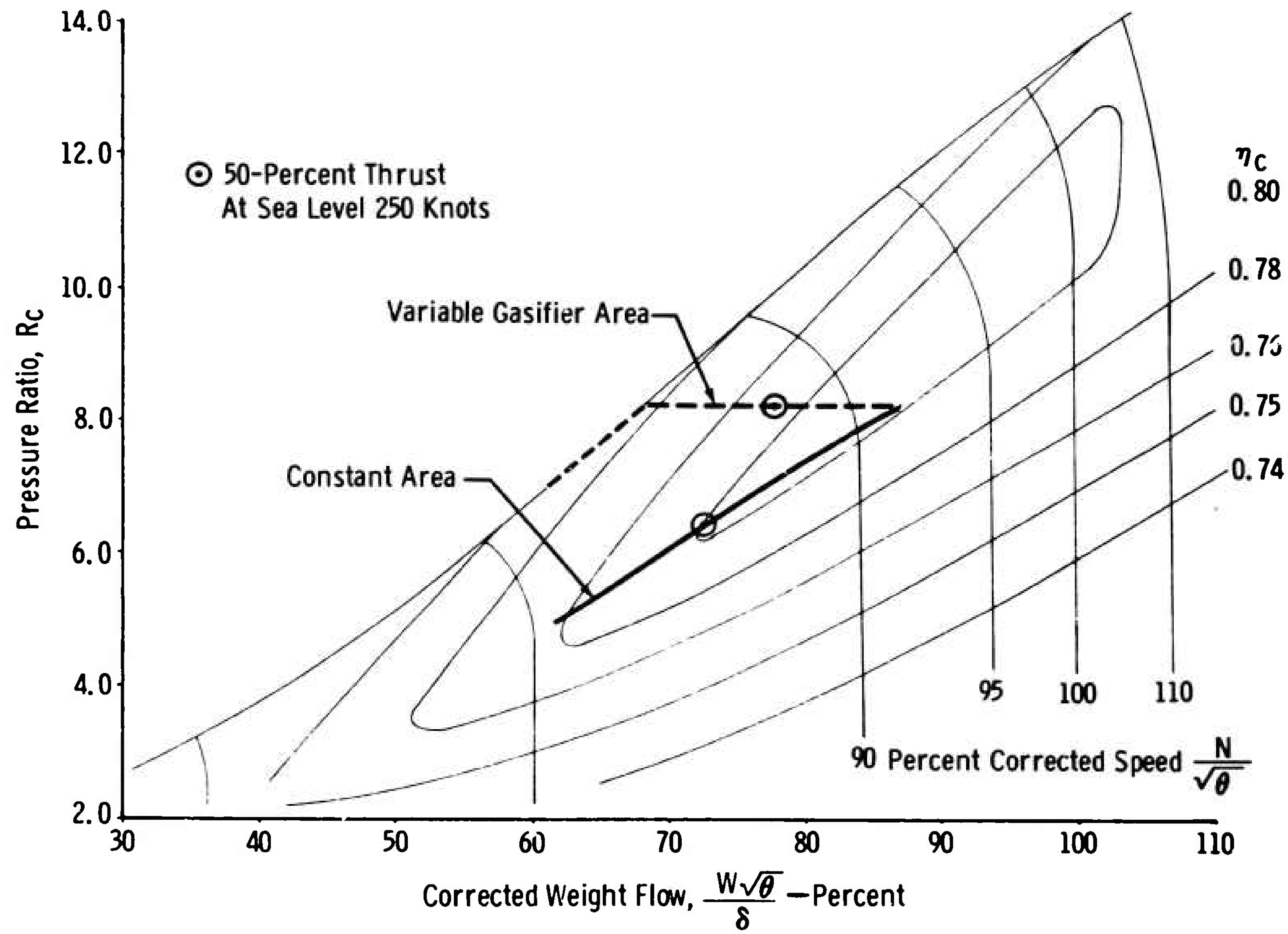


Figure 43. Engine FS210—Operating Lines on the Compressor Map.

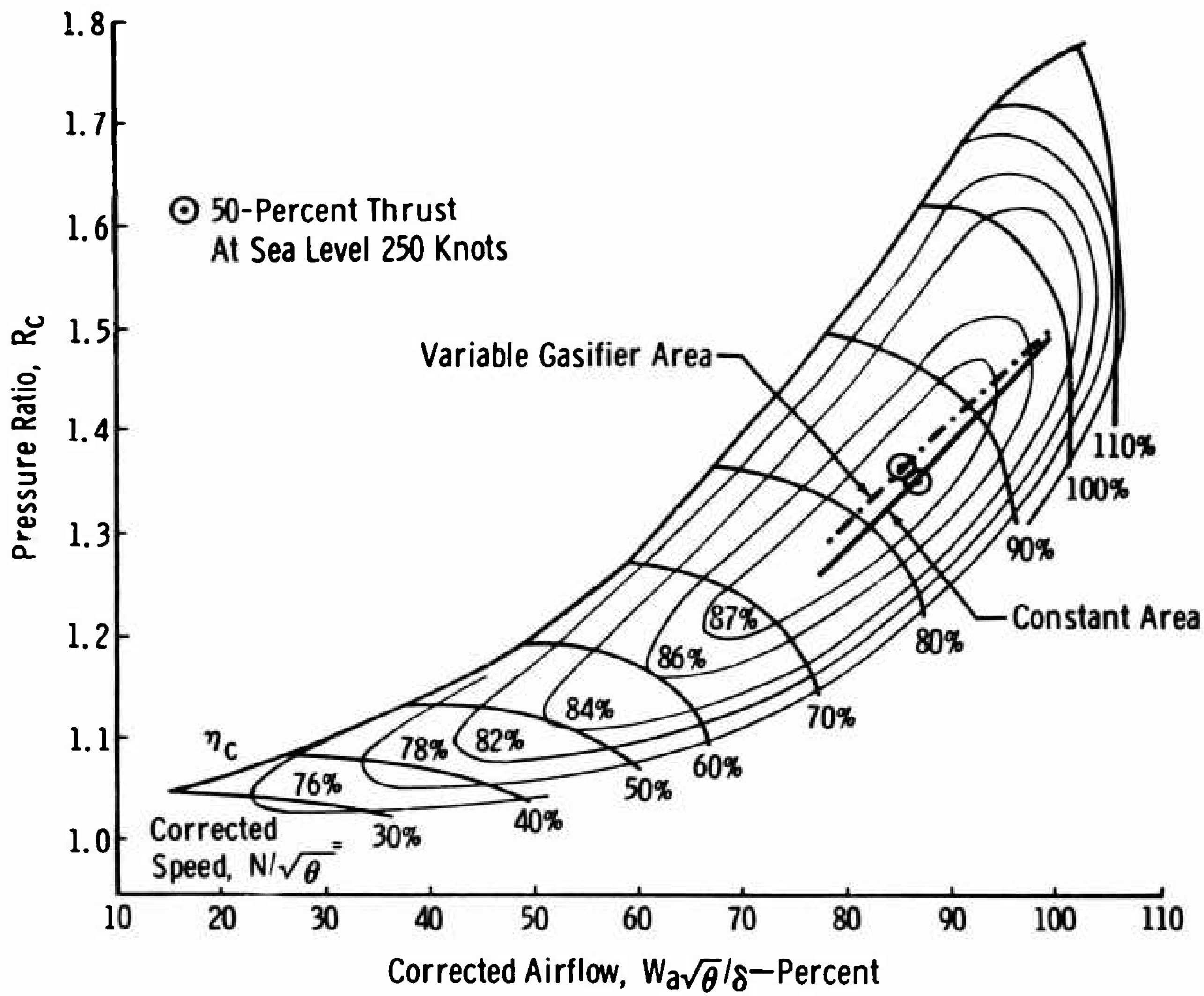


Figure 44. Engine FS210—Operating Lines on the Fan Map.

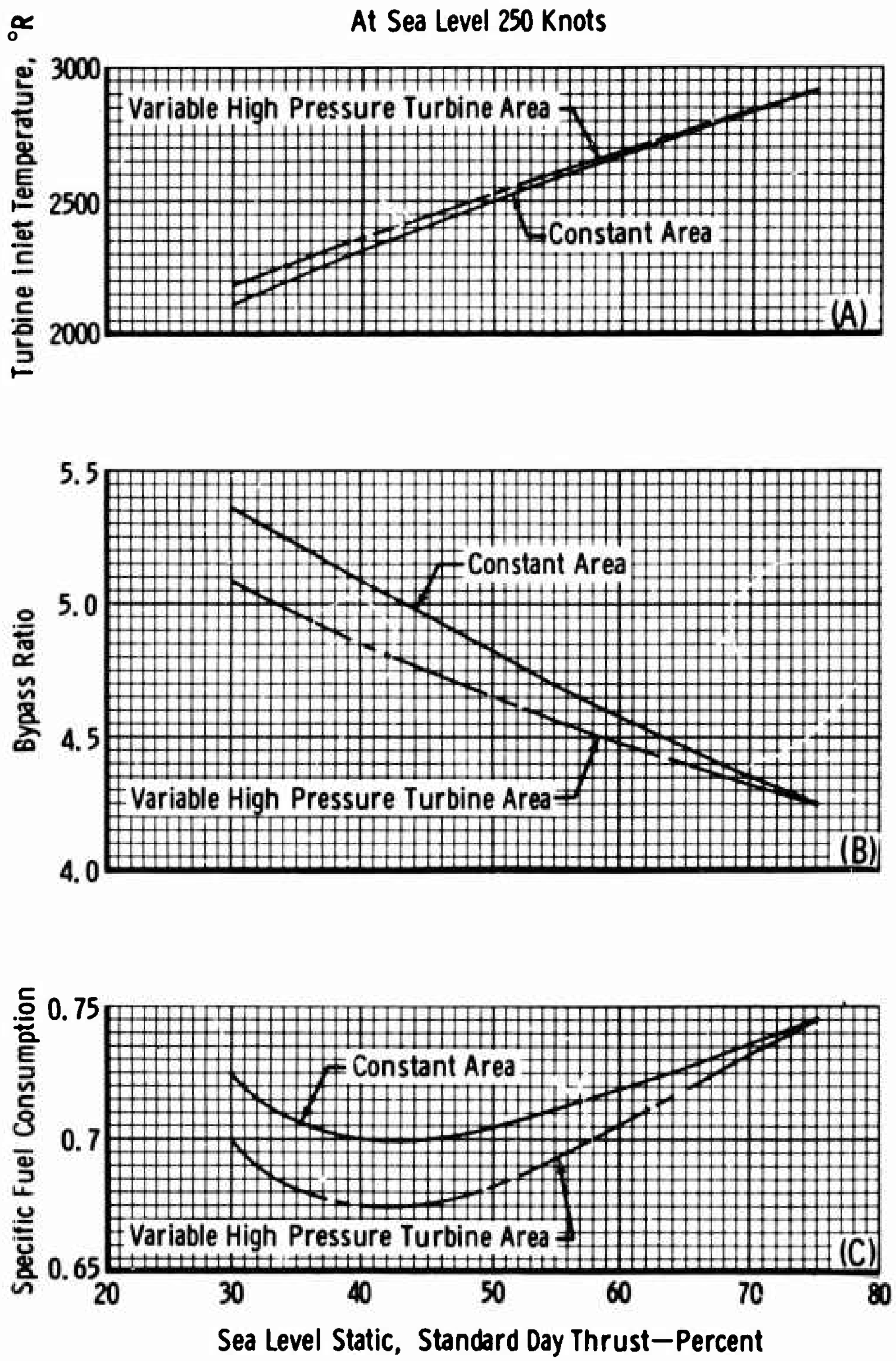


Figure 45. Engine FS210—Turbine Inlet Temperature, Bypass Ratio, and Specific Fuel Consumption as Functions of Percent Sea Level Static, Standard Day Thrust.

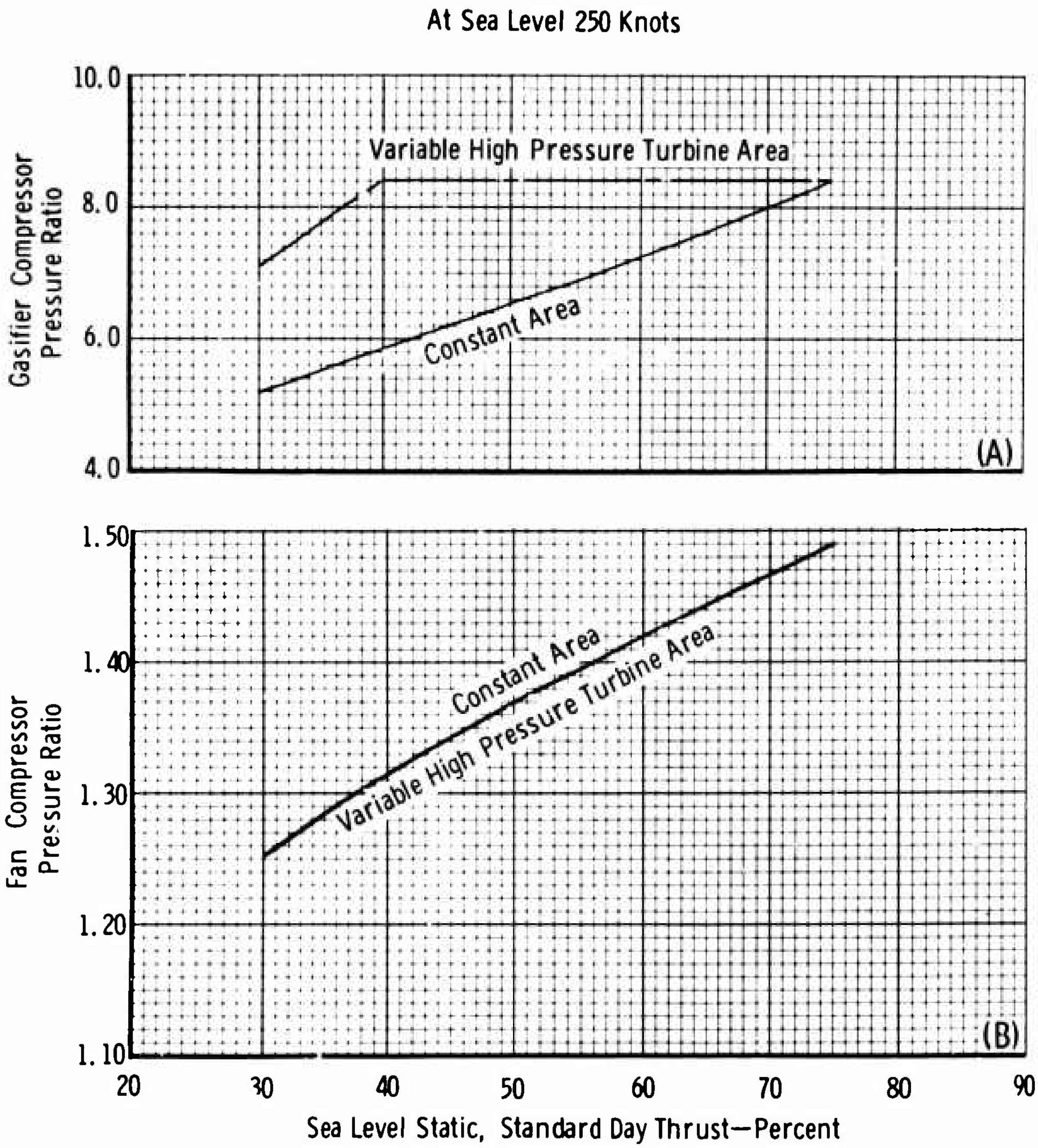


Figure 46. Engine FS210—Pressure Ratio of the Fan and of the Compressor as Functions of Percent Seal Level Static, Standard Day Thrust.

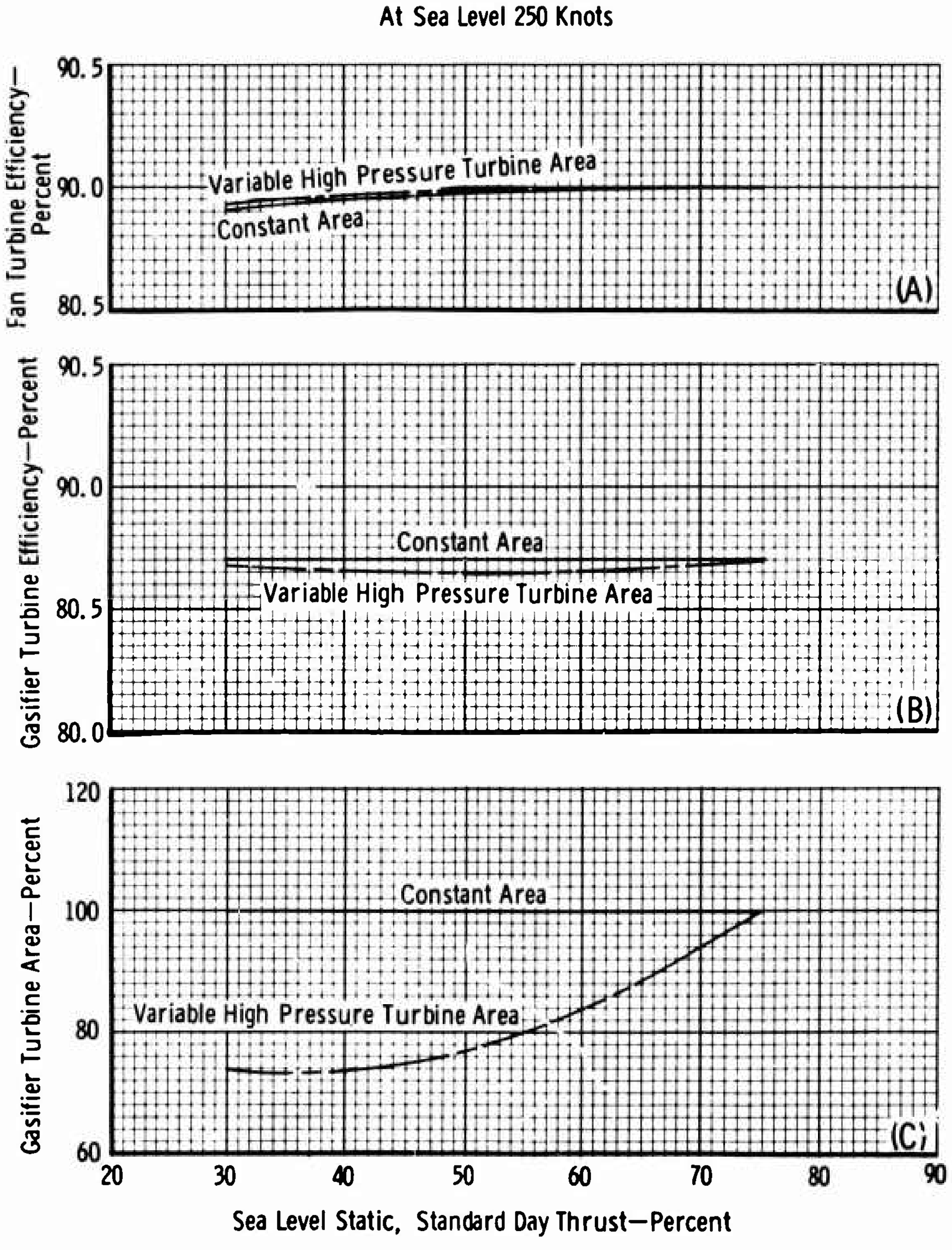


Figure 47. Engine FS210—Percent Gasifier Area, and Fan and Gasifier Turbine Efficiencies as Functions of Sea Level Static, Standard Day Thrust.

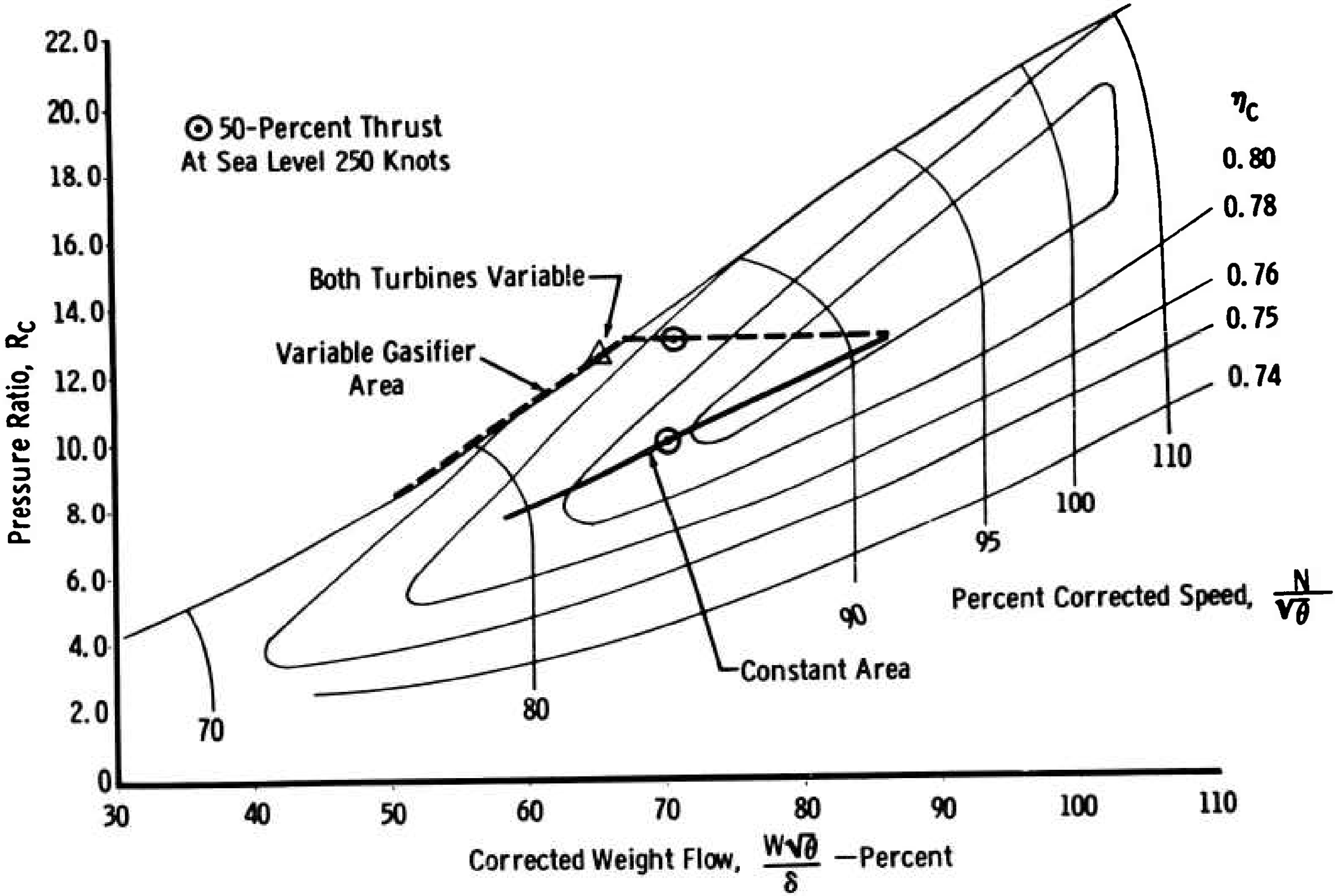


Figure 48. Engine FS216—Operating Lines on the Compressor Map.

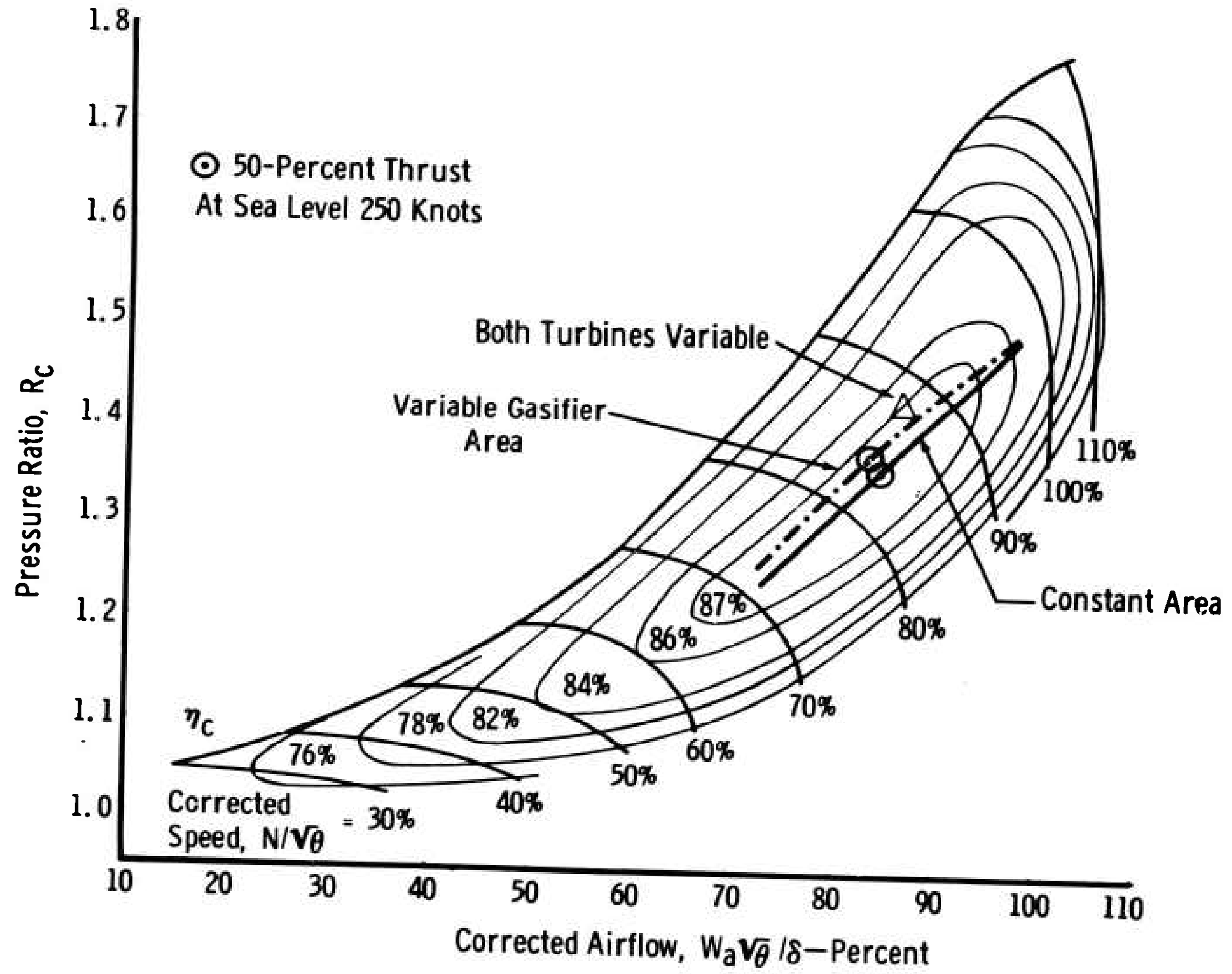


Figure 49. Engine FS216—Operating Lines on the Fan Map.

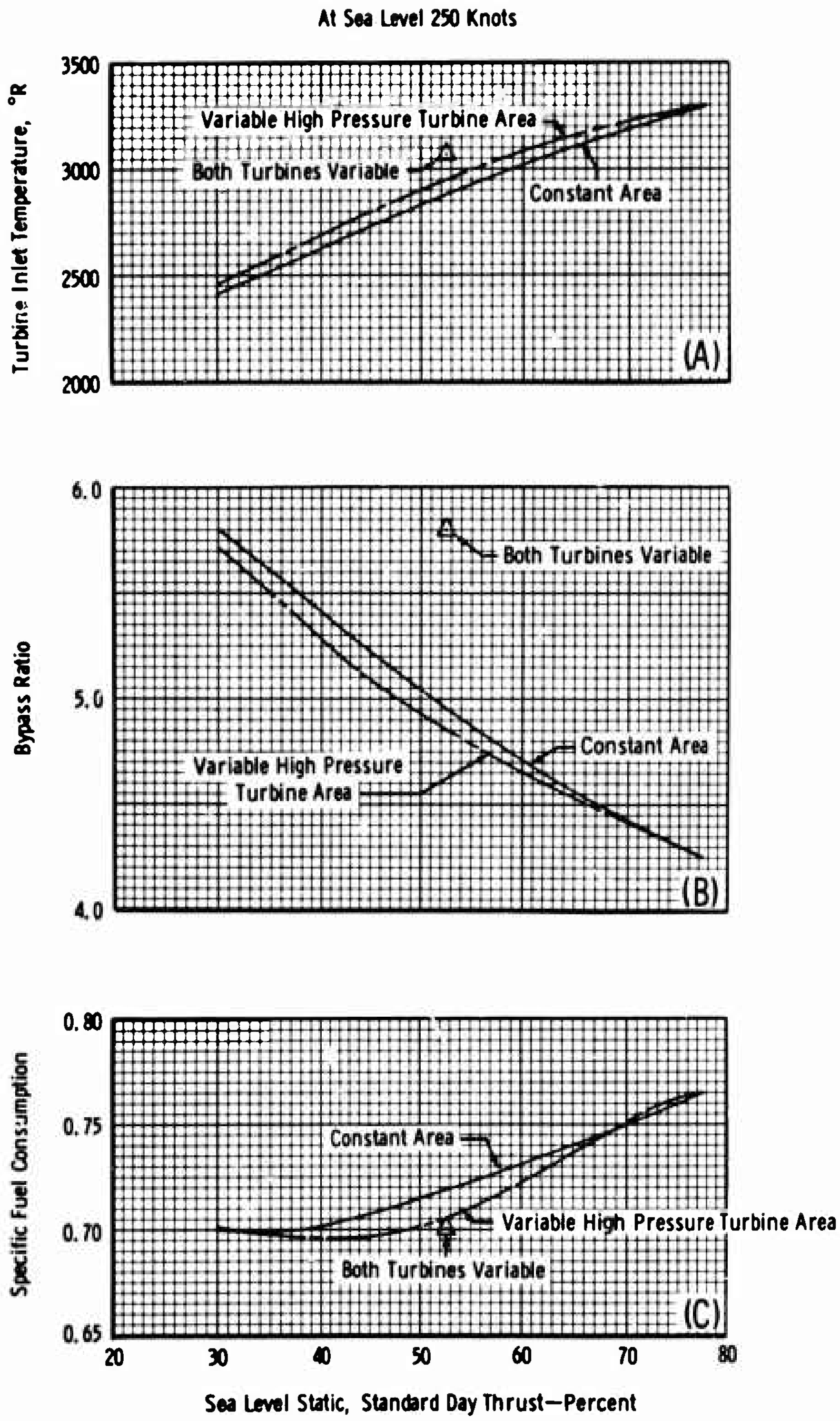


Figure 50. Engine FS216—Turbine Inlet Temperature, Bypass Ratio, and Specific Fuel Consumption as Functions of Percent Sea Level Static, Standard Day Thrust.

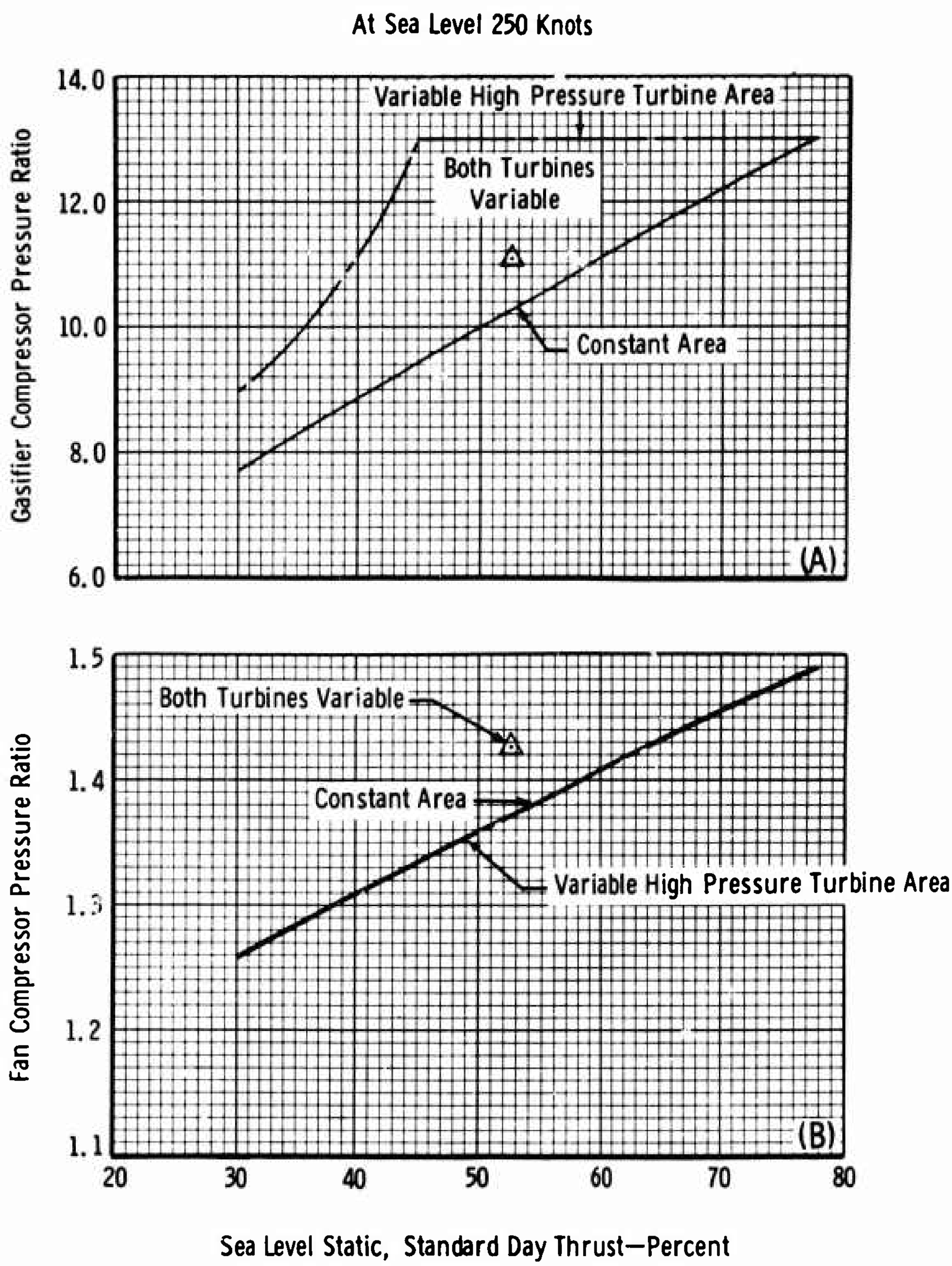


Figure 51. Engine FS216—Pressure Ratio of the Fan and of the Compressor as Functions of Percent Sea Level Static, Standard Day Thrust.

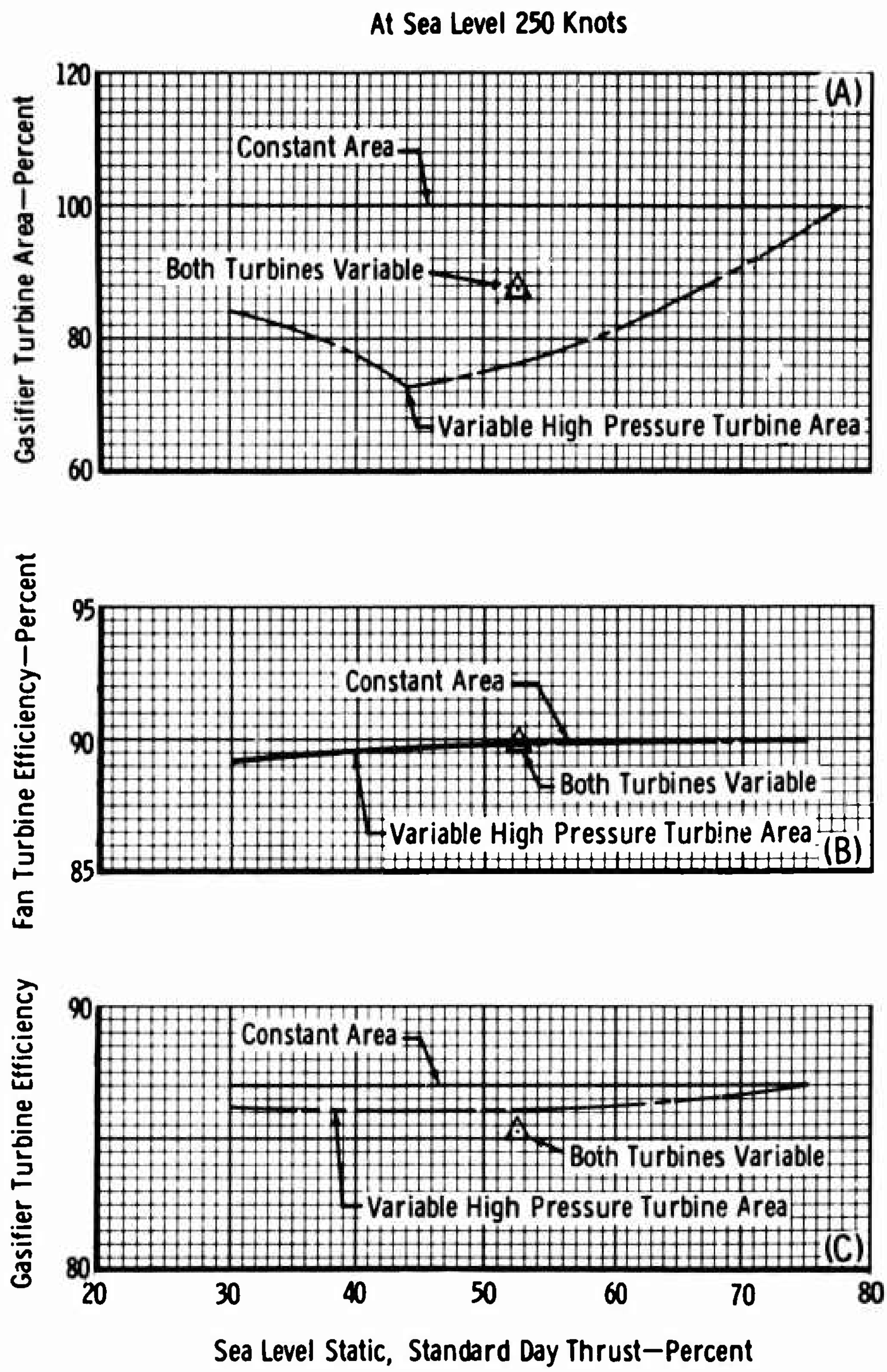


Figure 52. Engine FS216—Percent Gasifier Area and Fan and Gasifier Turbine Efficiencies as Functions of Sea Level Static, Standard Day Thrust.

When both nozzles were varied, 50-percent thrust occurred at a point on the compressor surge line. Thus, no significant gain in overall pressure ratio was accomplished. This mode of operation also required increased turbine temperature, as shown in Figure 50A, and, therefore, resulted in a minimal change in fuel consumption, as shown in Figure 50C. The power turbine nozzle area required is essentially the same as that of the gasifier, which is plotted in Figure 52A.

EFFECT OF AMBIENT TEMPERATURE

Characteristically, the free-shaft engine running at 100-percent gasifier r. p. m. operates above its design turbine temperature at ambient temperatures in excess of the design values. To avoid this overtemperature operation, it is common practice on this type of engine to reduce the r. p. m. during hot day operation. This causes a reduction in the inlet mass flow due to the reduction in r. p. m. and to the lower inlet air density, and thus places a twofold penalty on horsepower.

A part of this study was to determine whether the degradation in hot day power could be restored with the use of variable turbine geometry. Calculations were performed on Engine TS216 to compare fixed area, variable gasifier area, and variable power turbine area at the 6000-foot, 90°F. day operating condition. Table IX summarizes the results of these calculations. In the fixed area case, the gasifier r. p. m. was throttled to 96 percent of its design value to limit temperature to the design value of 3300°R. The horsepower was defined for this case and used as a base line to evaluate the effect of variable geometry. The second column in Table IX indicates that with variable gasifier geometry the r. p. m. can be restored to 99. 7 percent and the operation at design pressure ratio and turbine temperature is possible. This requires a reduction in the gasifier nozzle area of 12 percent and results in an 8-percent increase in shaft horsepower.

Variable power turbine geometry is defined in the third column in Table IX. Here the pressure ratio is 14. 7:1, but the turbine temperature is held at the design value of 3300°R. This mode of operation requires a 5-percent increase in power turbine nozzle area resulting in a 9-percent increase in power output

These data are representative of the benefits available from power turbine geometry on any of the free-shaft engines. If either a variable gasifier or variable power turbine is available in a specific engine designed for sea level static, standard day conditions, it will provide an effective means of augmenting hot day power.

TABLE IX

6000-FOOT ALTITUDE - 95°F. DAY PERFORMANCE ENGINE TS216

	Fixed Area	Variable Gasifier	Variable Power
Gasifier r.p.m., Percent	96	99.7	100
Pressure Ratio	13.8:1	16.0:1	14.7:1
Turbine Temperature, °R.	3300	3300	3300
Airflow, Percent	86.5	92	93.2
Turbine Nozzle Area, Percent			
Gasifier	100	88	100
Power	100	100	105
Percent of Fixed Area Shaft Horsepower	100	108	109

EFFECT OF AIR SPEED

This study is based primarily on the evaluation of the turboprop and turboshaft engines with variable turbine geometry at sea level static conditions. It is also of interest, however, to determine whether a flight condition has a major effect on the change in performance with variable geometry. Data were generated on Engine PR210 at sea level 250 knots with and without variable geometry for comparison to the sea level static case. These data are plotted in Figures 53 through 56.

The engine characteristics at the sea level 250-knot condition are shown to be similar to those at sea level static. The primary effect of operating at 250 knots is to increase the power output as a result of the ram pressure ratio. A comparison of the data at the two flight conditions indicates that at a given power setting the percent change in specific fuel consumption between the sea level 250 knots and the sea level static operation is essentially the same. Although the magnitude of the various parameters throughout the engine is different when comparing sea level 250 knots and sea level static data, the magnitude of change between the fixed area and the variable area case is essentially the same. Therefore, it is possible to determine the sea level 250-knot performance with fixed versus variable geometry based on calculations at sea level static.

The variable geometry turbofan engines were evaluated primarily at sea level 250 knots; however, to determine the effects of higher flight conditions on performance, additional data were generated at sea level 400 knots for Engine FS216. These data are plotted in Figures 57 through 60.

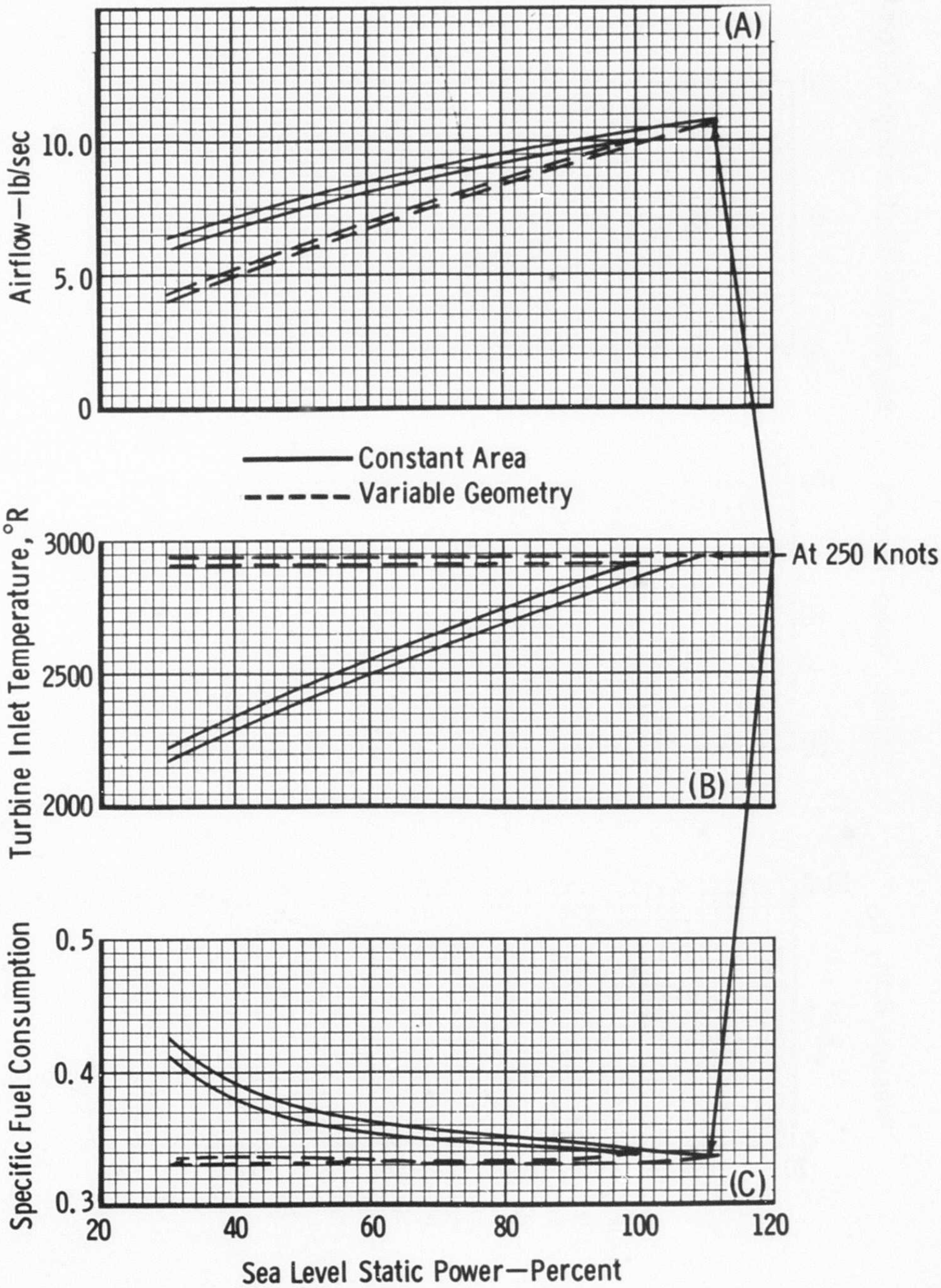


Figure 53. Engine PS210—Comparison of Sea Level Static and Sea Level 250 Knots.

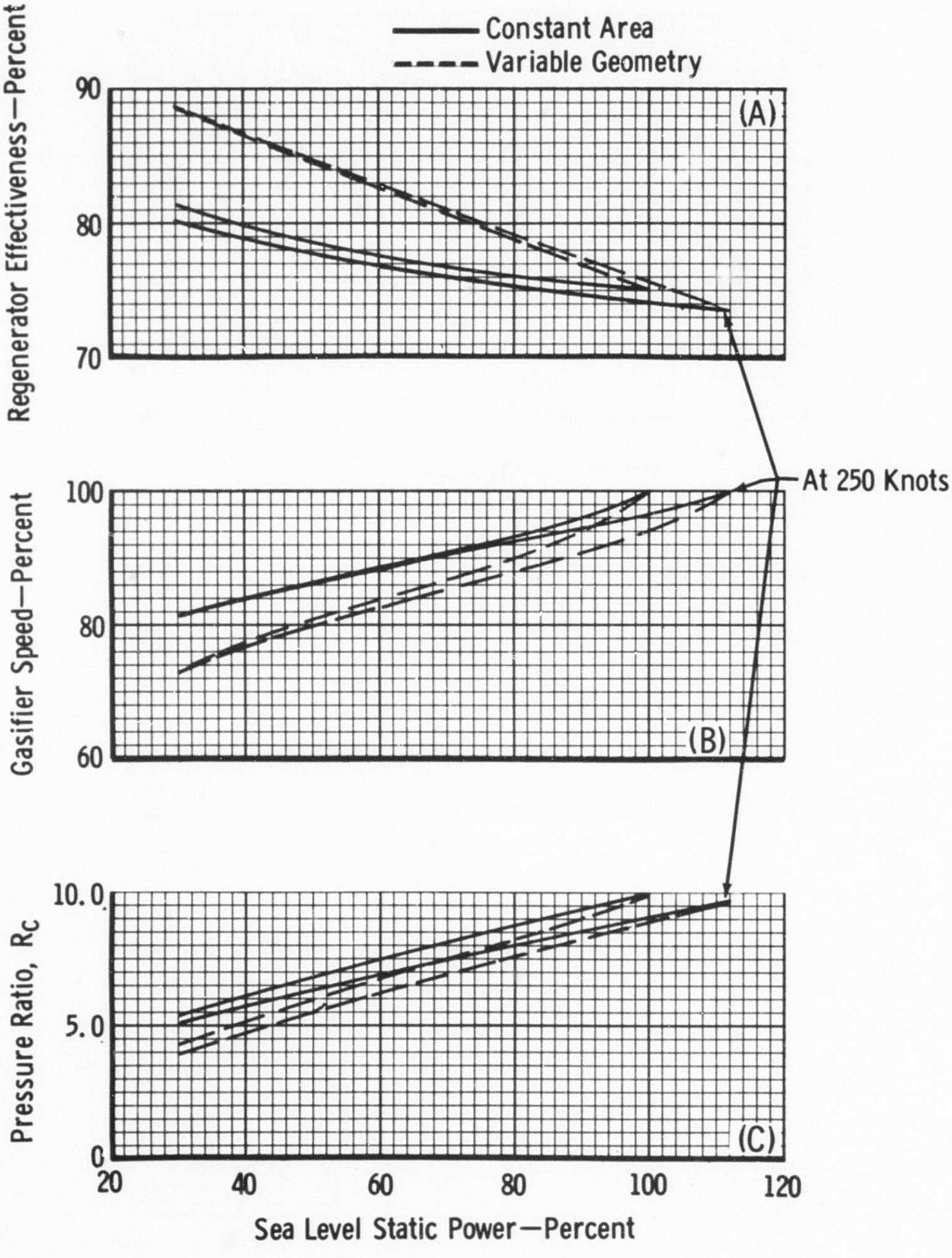


Figure 54. Engine PS210—Comparison of Sea Level Static and Sea Level 250 Knots.

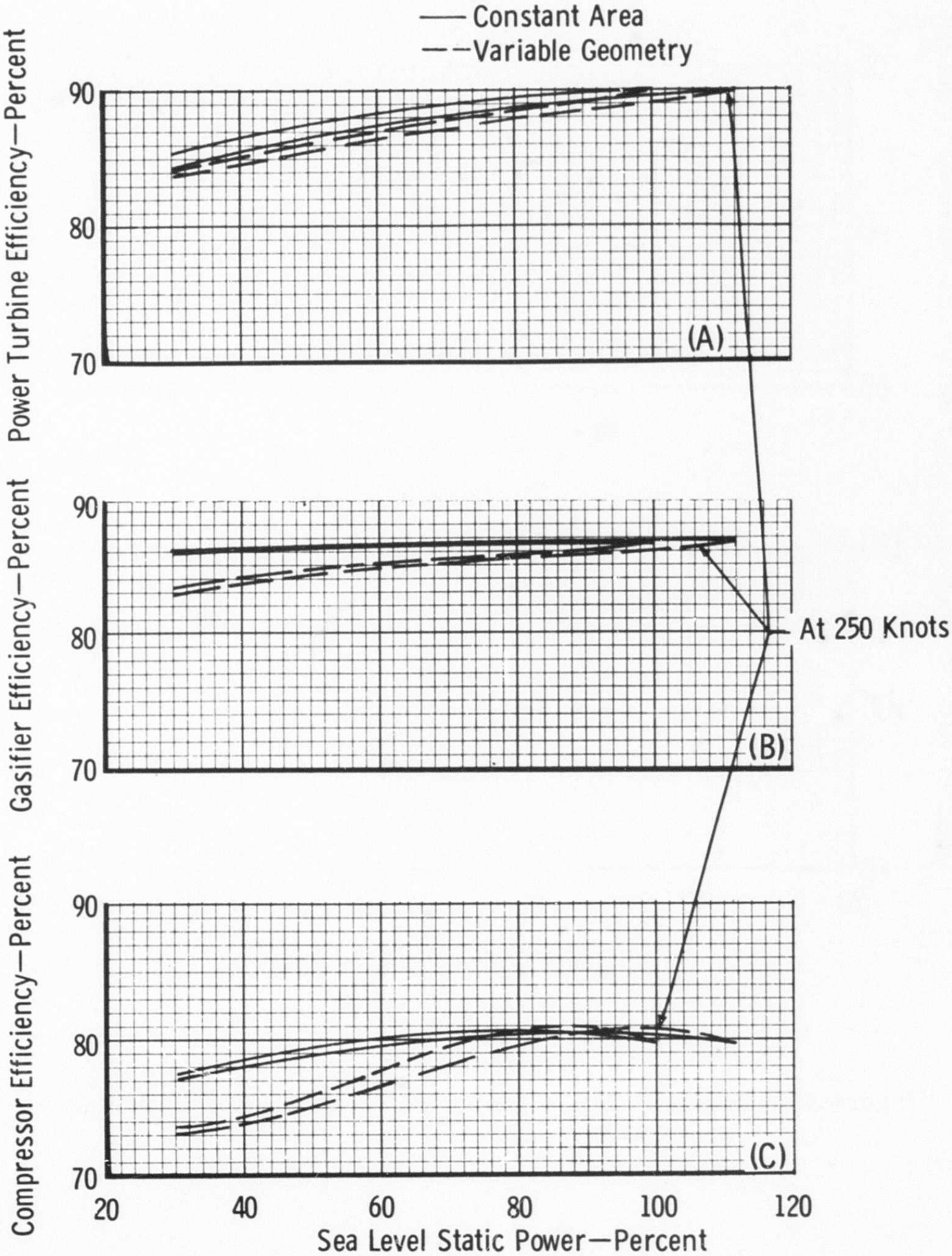


Figure 55. Engine PS210—Comparison of Sea Level Static and Sea Level 250 Knots.

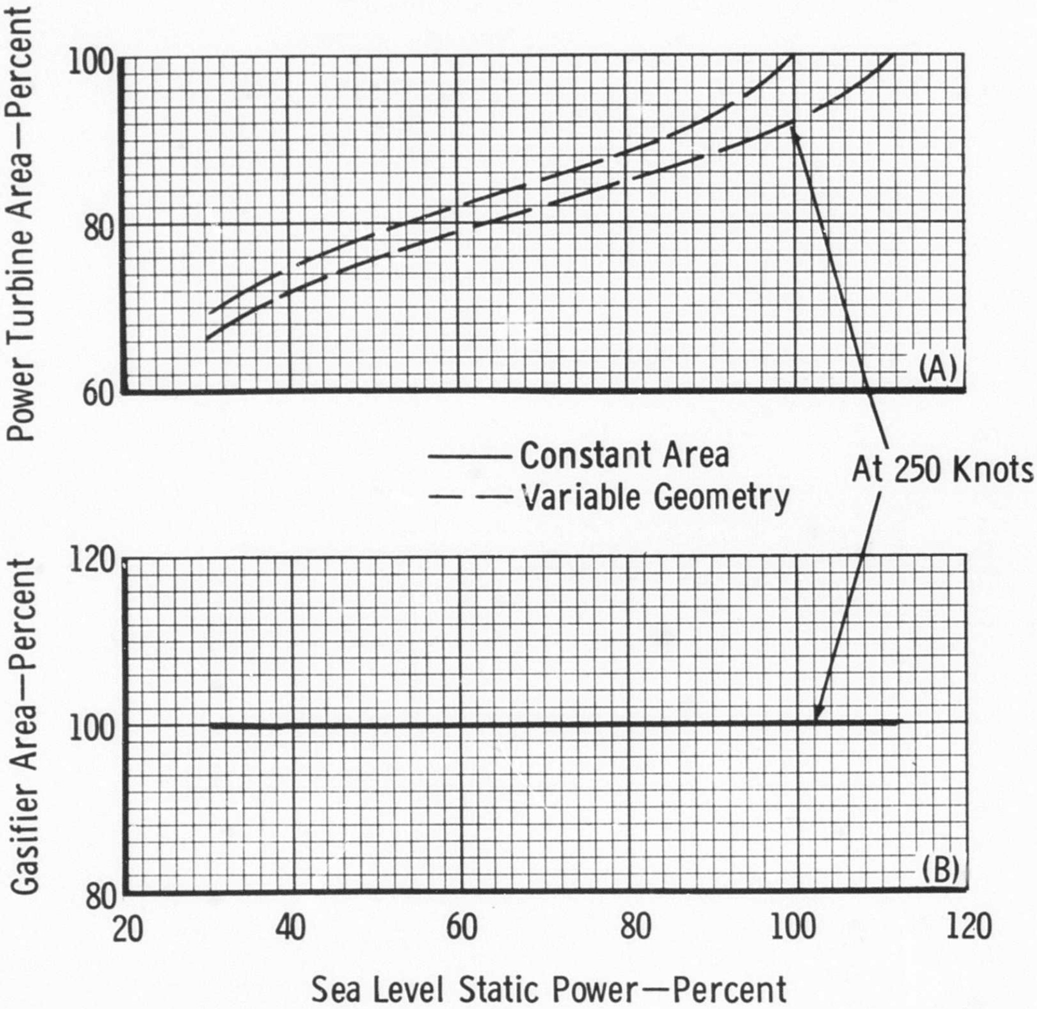


Figure 56. Engine PS210—Comparison of Sea Level Static and Sea Level 250 Knots.

The performance characteristics at sea level 400-knot conditions were similar to the sea level 250-knot conditions. However, there was a substantial reduction in net thrust and an increase in specific fuel consumption. This is a result of the increased ram drag at 400 knots. Here again the absolute levels of the various engine parameters are different when comparing the two flight conditions. However, the percent change between the fixed and variable area control modes is nearly the same. Therefore, the same conclusions for variable geometry can be drawn at sea level 400 knots as were made at sea level 250 knots.

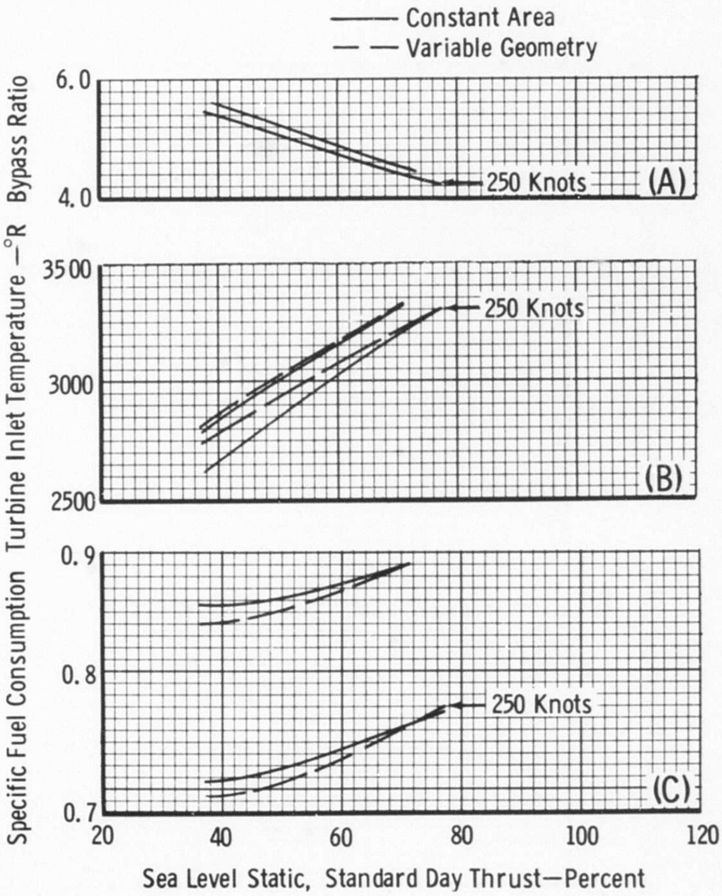


Figure 57. Engine FS216—Comparison of Sea Level 250 Knots and Sea Level 400 Knots.

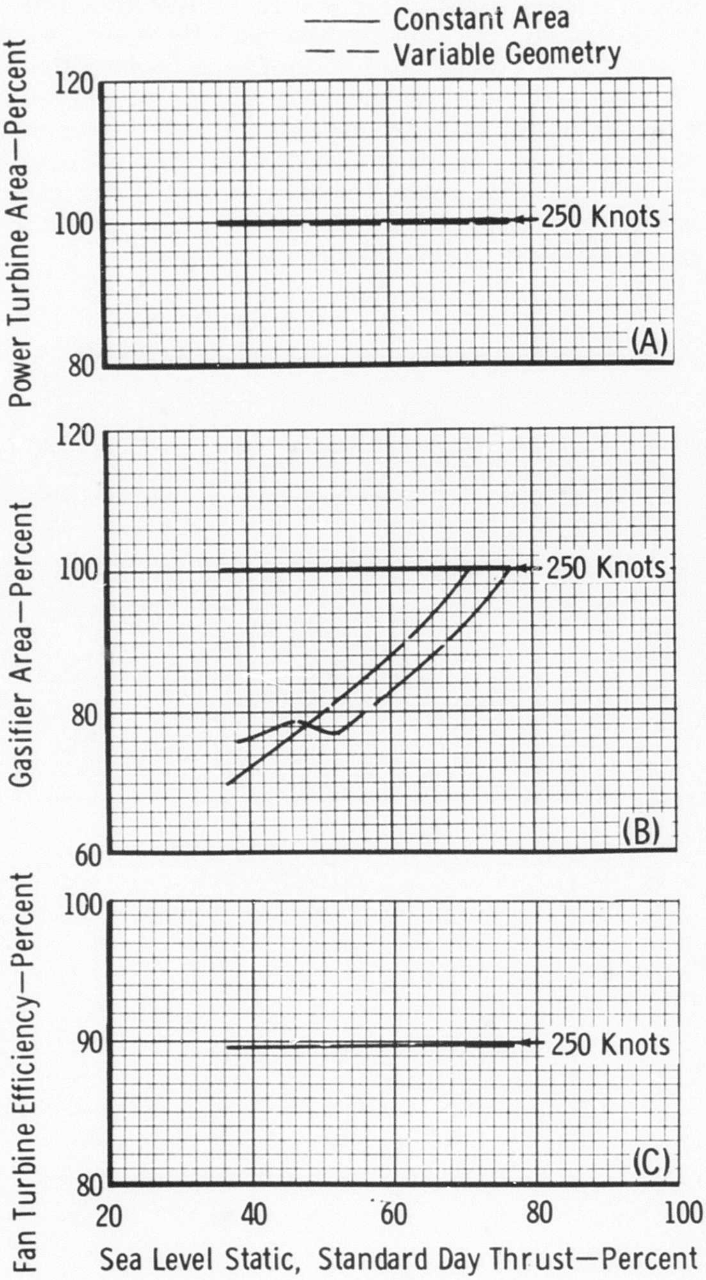


Figure 58. Engine FS216—Comparison of Sea Level 250 Knots and Sea Level 400 Knots.

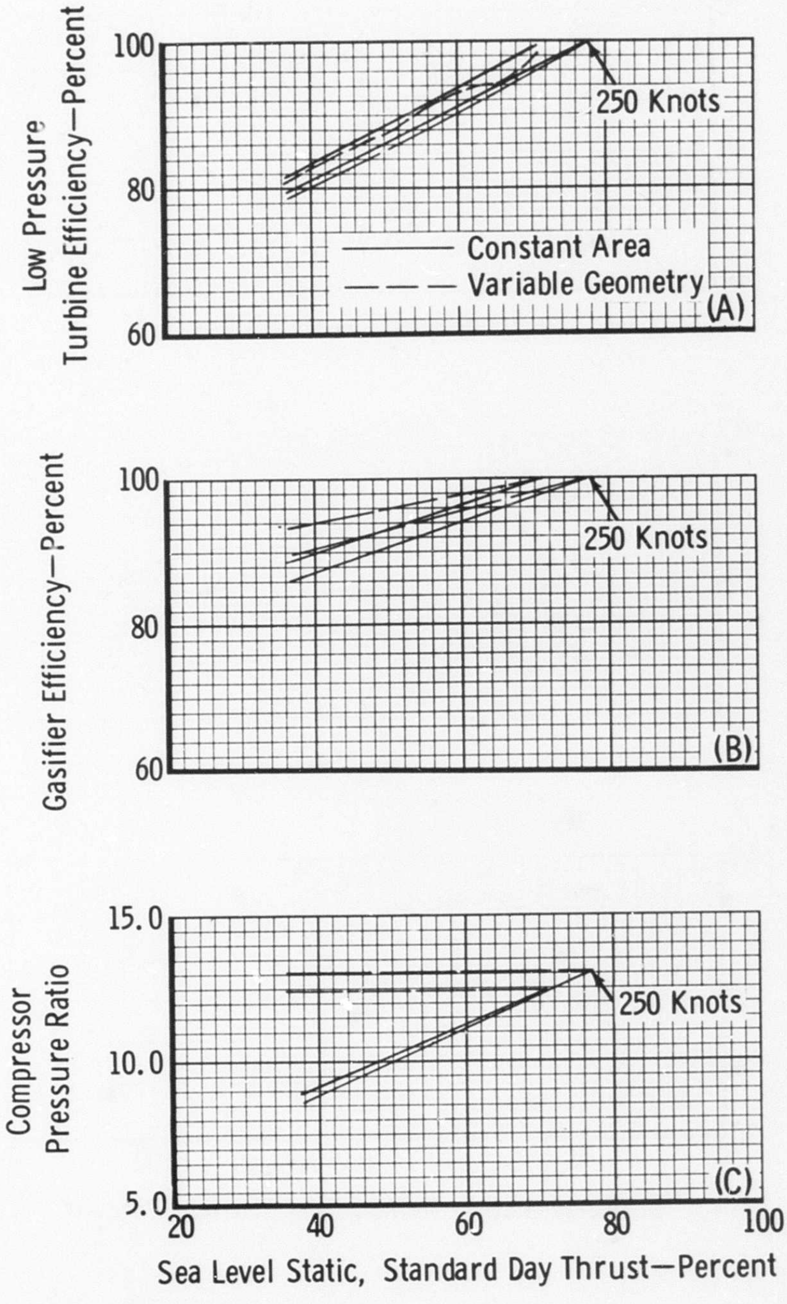


Figure 59. **Engine FS216—Comparison of Sea Level 250 Knots and Sea Level 400 Knots.**

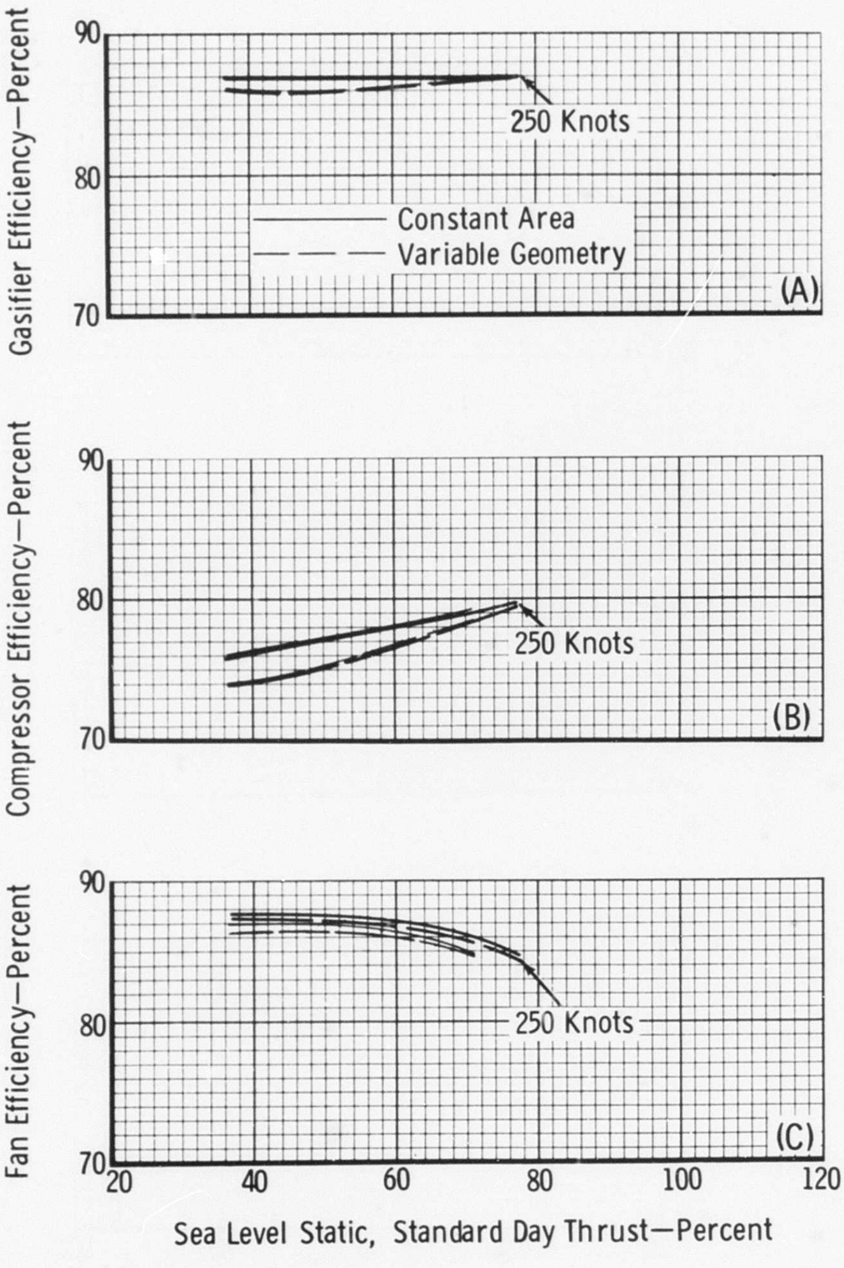


Figure 60. Engine FS216—Comparison of Sea Level 250 Knots and Sea Level 400 Knots.

ACCELERATION DATA

Table X lists the acceleration times from 30- to 100-percent power for the free-shaft and fan engines investigated. The acceleration times are based on the rotor system moments of inertia of Table IV.

TABLE X

SUMMARY OF ACCELERATION DATA

FREE SHAFT AND TURBOFAN				
	Time to Accelerate from 30- to 100-Percent Power in Seconds			
	Fixed Area	Variable Gasifier	Variable Power	Both Variable
PS & TS210	1.63	1.20	—	1.00
PS & TS216	1.48	1.28	—	1.00
PR & TR210	1.56	—	1.84	1.84
PR & TR216	1.55	—	1.75	1.69
FS210	1.61	1.45	—	—
FS216	1.59	1.50	—	—

The accelerations were calculated using a transient fuel input determined by a turbine inlet temperature versus gasifier speed schedule, permitting surge-free operation under wave-off conditions. This schedule, shown in Figure 61, is defined in terms of the allowable ΔT above the steady-state turbine inlet temperature with design turbine area. In the variable geometry engines, the mode of operation is to return the turbine area to its design value at the start of acceleration, providing the necessary surge margin to accommodate the acceleration. The return of the turbine area to its design value and the addition of transient fuel is a simultaneous operation. Proper scheduling of the turbine geometry actuator and the transient fuel input will allow the engine to maintain a constant speed and pressure ratio at the start of the acceleration.

For the regenerative engines, the heat exchanger was assumed to have no effect on the acceleration since the heat exchanger response time is long compared to the acceleration time.

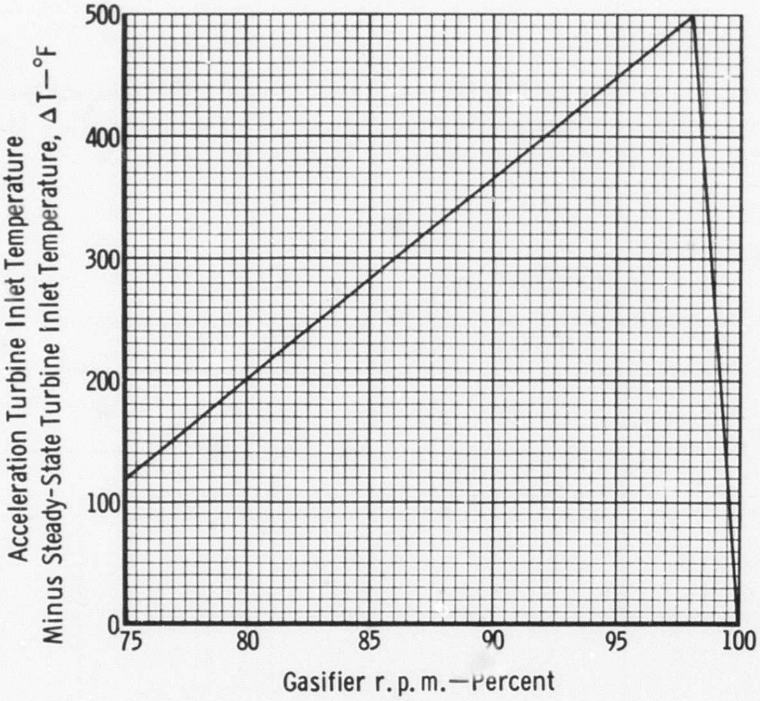


Figure 61. Acceleration Turbine Temperature as a Function of Percent Gasifier R. P. M.

Figure 62 shows the acceleration time as a function of gasifier speed for the four shaft configurations. The 30-percent power points are identified for the various control modes of the engines investigated. The 16.0:1-compressor-pressure-ratio engines demonstrated slightly better acceleration times than the 10.0:1-compressor-pressure-ratio engines of similar control modes. This is due to the higher moments of inertia for the 10.0:1-compressor-pressure-ratio rotor system. The acceleration of the free-shaft engine was not influenced by fuel control response time. However, with variable geometry, these engines were limited to a minimum of one second acceleration because of the variable geometry actuator response time.

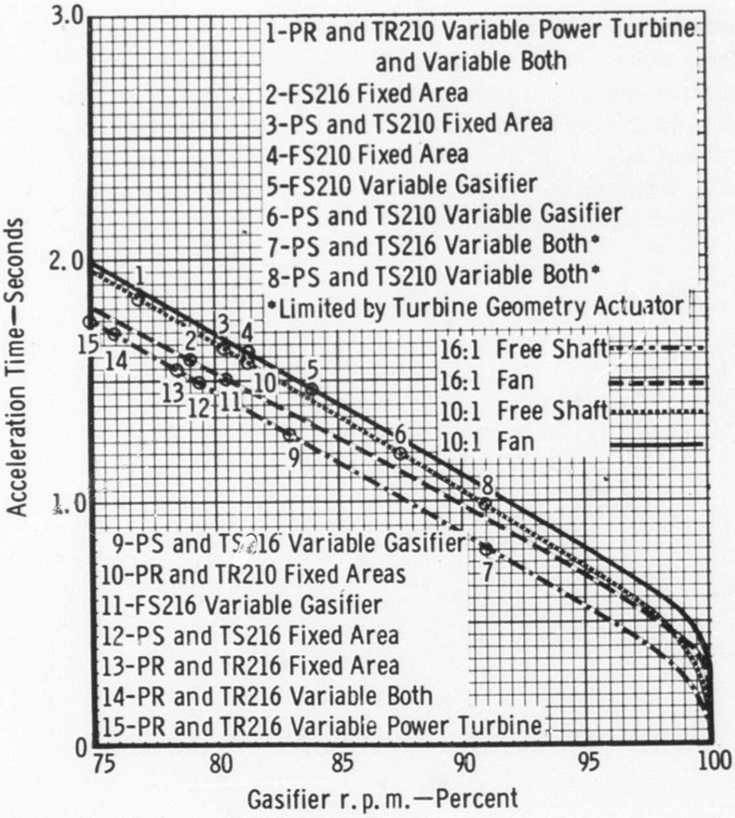


Figure 62. Acceleration Time as a Function of Percent Gasifier R. P. M.

The required time to achieve a power transient for the single-shaft engine is a function of control response time, since the rotor system is at design speed throughout the power range. The transient time of the fixed area turboshaft engine is a function of the fuel control response time which is approximately 0.1 to 0.2 second. With variable geometry, the transients are limited to one second because of the turbine actuator response time. The single-shaft turboprop engine transients are limited by the propeller blade angle actuator response time, which is approximately one to two seconds. The response time of a given prop actuator or fuel control, however, is a function of the hardware size.

A typical, small two-shaft helicopter engine can be used as an example to compare actual acceleration times with computed values. During the development of this engine, the computed time for a flight idle (64-percent gasifier speed) to 100-percent power acceleration was 2.4 seconds. A typical test value based on the developed engine for the same type of acceleration is 2.6 seconds. Both the computed and actual times are based on no compressor bleed or accessory load.

CONCLUSIONS

This study has been sufficiently comprehensive to permit generalized qualitative conclusions as to the potential value of variable turbine geometry. For the most part, the assignment of quantitative values is necessarily restricted to the particular thermodynamic cycles investigated, although some extrapolations to the general case appear warranted and have been made. The following conclusions are categorized according to the engine configuration.

ALL CONFIGURATIONS

- With one exception, variable turbine geometry can be used to effect constant pressure ratio and/or constant temperature operation from 100-percent down to 30-percent power without exceeding acceptable limits of turbine nozzle area change. Thus, the compressor characteristics become the limiting factor in the ability to operate at maximum thermal efficiency levels. The exception is the single-shaft, constant-speed engine, which requires an excessive turbine nozzle area variation to operate at constant temperature.
- Variable turbine geometry provides more improvement in specific fuel consumption in a 10.0:1-R_c, 2500°F. turbine inlet temperature cycle engine than in a 16.0:1-R_c, 3000°F. turbine inlet temperature cycle engine.
- The beneficial effect of variable turbine geometry increases in most cases as power is reduced from 100 percent down to 30 percent.

FREE-SHAFT ENGINE

- Variable gasifier turbine geometry is an effective means of reducing part throttle specific fuel consumption in a simple cycle engine. Variable power turbine geometry has a detrimental effect on fuel consumption for this configuration.
- Variable power turbine geometry is an effective means of reducing part throttle specific fuel consumption in a regenerative cycle engine, but variable gasifier geometry has a detrimental effect.
- Simultaneous varying of both the gasifier and power-nozzle areas provides no advantage in specific fuel consumption when compared with varying only the gasifier nozzle in the simple-cycle engine and varying only the power-turbine nozzle in the regenerative-cycle engine.
- Variable turbine geometry in either the gasifier or the power turbine nozzle will provide approximately 8- to 10-percent hot day power recovery if the engine is designed for sea level static, standard day conditions.
- The simple-cycle engine acceleration time is reduced by the use of variable gasifier turbine geometry.

SINGLE-SHAFT ENGINE

- Variable turbine geometry is an effective means for reducing the specific fuel consumption of the single-shaft, constant speed, simple-cycle engine, provided throttling is effected at constant pressure ratio.
- Variable geometry has no significant effect on the performance of the single-shaft, constant-speed, regenerative-cycle engine.

FAN ENGINE

- The limited scope of the fan engine investigations does not permit a general conclusion as to the potential value of variable turbine geometry. For the particular case examined, the use of variable turbine geometry was not justified.

RECOMMENDATIONS

The case for variable turbine geometry should be evaluated in any consideration of a new engine design.

The application of variable turbine geometry to an engine must be justified on the basis of a particular requirement or set of requirements in terms of trade-offs among specific fuel consumption, engine weight, cost, and complexity.

A control system analysis study should be conducted to evaluate various variable turbine geometry control modes and their influence on overall engine performance.

A program should be conducted to determine the mechanical problems associated with variable turbine geometry operating in a high-temperature environment. This program should include an evaluation of the losses attributable to the particular configuration.

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13. ABSTRACT

An analytical investigation of the transient and steady-state performance of a series of gas-turbine engines utilizing variable geometry in the turbine has been completed. Shaft-power engines with and without regeneration and incorporating either free- or single-shaft configurations were investigated at compressor pressure ratios of 10 and 16. In addition free-shaft, simple-cycle, high bypass, fan engines were evaluated using the 10- and 16-pressure-ratio gas generators for the high pressure system. Extensive use was made of the IBM 7094 II digital computer to analyze both the turbine and overall engine performance.

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