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PRELIMINARY DESIGN STUDY OF CONVERTIBLE FAN/SHAFT ENGINES

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April 1968

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

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ALLISON DIVISION, GENERAL MOTORS

INDIANAPOLIS, INDIANA

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General Motors Corporation
Indianapolis, Indiana

April 1968

DEPARTMENT OF THE ARMY
U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA 23604

This report has been reviewed by the U.S. Army Aviation Materiel Laboratories and is considered to be technically sound.

The report presents the results of a study of several conceptual arrangements for convertible fan/shaft engines and includes preliminary design data on performance, weight, and envelope for possible incorporation into advanced aircraft studies.

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PRELIMINARY DESIGN STUDY OF CONVERTIBLE FAN/SHAFT ENGINES

Report No.
EDR 5640

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For

U. S. ARMY AVIATION MATERIEL LABORATORIES

FORT EUSTIS, VIRGINIA

FOREWORD

This final technical report on a preliminary design study of convertible fan/shaft engines is submitted by the Allison Division, General Motors Corporation, as required by Item 2b of Contract DAAJ02-67-C-0070, dated 22 June 1967.

This seven-month study was conducted for the U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, under the technical cognizance of Mr. Michael Seery of the Propulsion Division. Principal Allison Division personnel associated with the program were Messrs. G. E. Chapman, R. P. Atkinson, R. L. Messerlie, R. D. McLain, and C. C. Raymond.

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SUMMARY

In June 1967, the United States Army Aviation Materiel Laboratories (USAAVLABS) awarded the Allison Division, General Motors Corporation, a contract for preliminary design studies of convertible fan/shaft engines. Major emphasis was placed on defining and evaluating the solutions to the problems of configuring and sizing the engine to meet the dual requirement for shaft power and fan thrust. Emphasis was also placed on reducing or eliminating the fan power and thrust during hover, on the development of efficient fan/shaft power transfer methods, and on devising a control system for coordinating shaft power and fan thrust during all flight modes, especially during conversion.

Conceptual design arrangements were investigated to evaluate both supercharged and nonsupercharged gas generators, fan unloading by variable geometry, fan decoupling, and unloading or decoupling of the fan bypass section only. Engine configurations were restricted to those arrangements having the fan concentric with the gas generator. Design studies were made to define and evaluate mechanical arrangements for extracting rotor power and fan decoupling.

Convertible fan/shaft engines apply to a wide variety of advanced rotary-wing aircraft; however, to provide a basis for engine comparisons, USAAVLABS defined hover power and fan thrust requirements for a representative two-engined, stowed-rotor aircraft of approximately 25,000-lb gross weight. The basic requirements were 2000 shp/engine at 6000 ft, 95°F, and 3500-lb thrust/engine at 400-kn V_{max} at sea level. While these requirements were specified, it was also recognized that variations in vehicle design characteristics can significantly alter the required power/thrust ratio.

Analysis of the study requirements led to the selection of a 4:1 bypass ratio, a 1.7 pressure ratio fan, and a common gas generator cycle for all engine designs. The gas generator had a basic pressure ratio of 14:1, unsupercharged, and a turbine inlet temperature of 2200°F. Component technology consistent with a 1970 engine development initiation was used.

The numerous study variables were resolved into three basic configurations defined as follows:

- Type I—Supercharged gas generator, variable geometry and/or decoupling of total fan

- Type II—Supercharged gas generator, variable geometry and/or decoupling of fan bypass section only
- Type III—Nonsupercharged gas generator, variable geometry and/or decoupling of fan bypass section only

Each of these basic configurations was first sized to the cruise thrust requirement and then examined for shaft power capability and thrust at the hover condition.

The Type II and Type III configurations achieved adequate power through the use of a variable primary nozzle and variable fan geometry; however, the Type I engine was deficient in power. Fan thrust in hover was excessive for all configurations. The further addition of fan decoupling enabled the Type I configuration to exceed the power requirement slightly and substantially increased the power capability of the Type II and Type III configurations. Fan thrust at hover was eliminated.

A comparison of performance characteristics, potential development problems, and risk areas led to the selection of the Type I configuration with torque converter decoupling for further definition studies. This definition included a power-takeoff drive assembly that can be located in the fore and aft sections of the engine, and an effective control system that meets the requirements of fan/shaft engine operation.

While fan decoupling offers the only approach to the complete elimination of fan thrust, preliminary studies indicate that the use of extreme inlet and exit guide vane angles may reduce fan thrust to a tolerable level. Experimental data on a high pressure ratio fan are needed to verify this approach.

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LIST OF SYMBOLS

A_B	Surface area of afterbody	$in.^2$
A_F	Surface area of fan shroud	$in.^2$
A_{JP}	$\frac{\text{Area of primary jet nozzle}}{\text{Design area}}$	%
A_{JS}	$\frac{\text{Area of secondary (fan) jet nozzle}}{\text{Design area}}$	%
A_T	Total wetted area, $A_B + A_F$	$in.^2$
BPR	Bypass ratio, bypass airflow/gas generator airflow	
B/P	Bypass	
BTU	British thermal units	
CDP	Compressor discharge pressure	$lb/in.^2$
CIT	Compressor inlet temperature	°F
C_T	Nozzle thrust coefficient	
CVG	Compressor variable geometry	
D_{fan}	Fan diameter	in.
D_T	Turbine diameter	in.
EGV	Fan exit guide vanes	
F, °F	Fahrenheit, degrees Fahrenheit	
F_{NP}	Primary thrust	lb
F_{NS}	Secondary or bypass thrust	lb
F_{NT}	Total thrust	lb
fpm	Feet per minute	ft/min

fps	Feet per second	ft/sec
HP_{gross}	Horsepower produced by low-pressure turbine	
$HP_{fan\ hub}$	Horsepower absorbed by low-pressure compressor or hub portion of the fan	
HP_{net}	HP_{gross} minus $HP_{fan\ hub}$	
HP_{bypass}	Horsepower absorbed by bypass portion of the fan	
SHP	HP_{net} minus HP_{bypass} or HP_{gross} minus total fan horsepower	
HP_{in}	Input horsepower	
HP_{out}	Output horsepower	
HP	High pressure	
HPT	High-pressure turbine	
ID	Inner diameter	in.
I_{fan}	Fan polar moment of inertia	slug-ft^2
I_R	Polar moment of inertia of the helicopter rotor plus the low-pressure turbine	slug-ft^2
I_S	Scaled version of Type I engine	
IGV	Inlet guide vanes	
ktas	Knots, true airspeed	kn
kn	Knots	kn
L	Length	in.
lb	Pound	lb
L_E	Engine length	in.

LHV	Lower heating valve	BTU/lb
LP	Low pressure	
LPT	Low-pressure turbine	
M	Ratio of number of ring gear teeth to number of sun gear teeth	
N	Rotor speed	rpm
N_{LP}	Low-pressure spool speed	rpm
N_{HP}	High-pressure spool speed	rpm
N_{fan}	Fan speed	rpm
N_T	Turbine speed	rpm
$N_{P\ ref}$	Reference torque converter input speed	rpm
N_S	Sun gear speed	rpm
N_R	Ring gear speed	rpm
N_C	Carrier speed	rpm
N_{out}	Output speed	rpm
N_{in}	Input speed	rpm
O/B	Overboard	
OD	Outside diameter	in.
OGE	Out of ground effect	
P, ΔP	Pressure, Pressure difference	lb/in.^{2}
PTO	Power takeoff	
psi	Pounds per square inch	lb/in.^{2}
QR	Helicopter rotor load torque	lb-in.

QT	Fan load torque	lb-in.
R_c	Compression ratio	
$R_{c\ oa}$	Overall compression ratio	
rpm	Revolutions per minute	
R_E	Turbine expansion ratio	
sfc	Specific fuel consumption	
shp	Shaft horsepower	
SL	Sea level	
SLS	Sea level standard	
STD	Standard	
SR	Torque converter speed ratio	
t	Time	sec
TIT	Turbine inlet temperature	°F
TSFC	Thrust specific fuel consumption	
T_{eng}	Engine output torque	lb-in.
T_P	Torque converter input torque	lb-in.
T_T	Torque converter output torque	lb-in.
T_T/T_P, T_R	Torque converter torque ratio	
$T_{P\ ref}$	Reference input torque	
V	Aircraft velocity	kn
V_{max}	Maximum aircraft velocity	kn
W, W_a	Airflow	lb/sec

W_T	Total airflow	lb/sec
W_{ap}	Primary or gas generator airflow	lb/sec
W_{as}	Secondary or bypass airflow	lb/sec
W_f	Fuel flow	lb/hr
W_e	Engine weight	lb
β	Turbine design parameter	
δ	Ambient pressure, psia/14.7	
Δ	Difference symbol	
η	Efficiency	
θ	Ambient temperature, °R/518.7	
ϵ	Turbine design parameter	

INTRODUCTION

Recent studies of advanced VTOL aircraft have indicated that a convertible fan/shaft engine is a competitive propulsion system concept in compound/composite aircraft.* Such an engine could provide shaft power for driving a lift rotor in the helicopter flight mode, and it could then be converted to a pure turbofan operation for cruise and high-speed flight. A potentially attractive engine arrangement can be derived from a basic turbofan engine by adding a power-takeoff drive and variable geometry features that increase the power extraction capability of the engine.

However, the future application of this convertible fan/shaft engine concept is contingent upon the successful solution of the following problem areas: (1) development of an efficient fan/shaft power transfer method, (2) reduction or elimination of fan thrust and power during hover, (3) sizing and configuring the engine to satisfy both shaft power and fan thrust requirements throughout the operating envelope, and (4) development of an engine control system for coordinating shaft horsepower and fan thrust requirements during all flight modes, especially during conversion of the engine from shaft power to fan power or vice versa.

A seven-month preliminary design study was initiated in June 1967 to investigate several possible solutions to the foregoing problem areas; to identify the resulting engine characteristics, risk areas, and potential development problems; and to give preliminary definition to a practical convertible fan/shaft engine configuration. This report describes the results of that study.

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*Dean, F. H., Prager, P. C., Schneider, J. J., FEASIBILITY STUDY OF CRUISE FAN PROPULSION SYSTEMS AND ASSOCIATED POWER TRANSFER SYSTEMS FOR COMPOUND/COMPOSITE AIRCRAFT, The Boeing Company; USAAVLABS Technical Report 67-28, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, September 1967.

DEVELOPMENT OF PROBLEM

The composite fan/shaft engine, as studied, has a configuration generally similar to a conventional two-spool turbofan. The differences consist primarily of the addition of variable fan geometry and a power-takeoff drive with which shaft power may be extracted from the low-pressure spool. A typical example is shown in Figure 1.

The approach to extracting substantial amounts of shaft horsepower consists of several steps. One is a speed reduction. When the low-pressure (LP) rotor is operating at 100% speed, the turbine power is equal to the power absorbed by the fan. As the speed is reduced, at constant gas generator speed or TIT, the turbine power is greater than the fan power and the difference is available as shp. In addition, the turbine power can be increased by opening the jet nozzle, to increase the expansion across the turbine. Further, the fan power may be reduced by adding variable geometry to the fan, or by disengaging the fan completely. These changes will cumulatively increase the available shp and, fortunately, will also decrease the fan thrust. It is essential that the thrust be substantially reduced or eliminated during hover.

This study is concerned with defining and evaluating various engine concepts wherein controlled changes can be made to the engine components during normal flight to achieve the specified shp and thrust characteristics.

To ensure the broadest possible scope commensurate with available funding, USAAVLABS and Allison jointly established certain specific requirements and limitations as guidelines for the conduct of the study. Study configurations were restricted to a concentric fan/gas generator arrangement. Within this restriction, design and/or engineering analyses were to include, at least, the following:

1. Both supercharged and nonsupercharged gas generators
2. Shaft power extraction with and without fan disengagement
3. Total fan disengagement, and disengagement of the fan bypass section only
4. Fan unloading by variable fan geometry including vanes, blades, and nozzle

5. Shaft power extraction at design and at reduced engine speeds

6. Combinations of the foregoing

The designs were to be of a technological level commensurate with a 1970 engine development initiation. Parameters such as component efficiencies and turbine inlet temperatures defined by this technology level shall be common to all designs considered.

The many design variations possible in compound/composite aircraft can significantly alter the power-to-thrust requirement of the convertible fan/shaft engine. To fit the limited scope of this study, a set of basic aircraft requirements was selected to define the required power and fan thrust levels for a representative stowed-rotor composite aircraft with a disc loading of 10 to 13 lb/ft^2.

Power required per engine—helicopter mode	2000 shp at takeoff (See Figure 2)
Thrust required per engine—fixed-wing mode	3500 lb at 400 kn (See Figure 3)
Aircraft gross weight	25,000 lb (approx)
Number of engines	2 convertible fan/shaft types
Hover conditions	6000 ft, 95° day
V_{max}	400 kn (military power rating)

From Figure 2 it was assumed that the engines must produce 2000 shp each at 6000 ft, 95°F day conditions. To simplify the computations, all performance comparisons were made on the basis of a sea level, standard day power requirement of 2750 shp, which corresponds to the normal lapse rate for the basic engine cycle used in the study.

Using the foregoing vehicle requirements, a mission study was conducted to determine the degree of cycle and configuration commonality that could be used without seriously compromising the desired engine comparisons. This is shown in Appendix I. The results of this study established the validity of using a common gas generator arrangement and common fan cycle parameters for all engine configurations. This commonality permitted concentration on the major design problem areas. The basic cycle parameters selected for the study are shown in Table XX. Note that modest changes in cycle parameters will not have a significant influence on the choice of power transfer and fan unloading schemes.

OPERATIONAL REQUIREMENTS

Discussions were held with aircraft preliminary design groups and flight test personnel to obtain opinions on additional requirements from the operation and aircraft design standpoints. Some of the significant points noted are:

1. In most aircraft, the thrust at hover must be low (less than 600 lb/engine is desired). However, there may be some aircraft which use the excess thrust for pitch and yaw control with thrust vectoring.

2. During the engine conversion, the time period for increasing the fan thrust, to accelerate the aircraft, should be approximately 15 sec minimum, to give the pilot time to react in controlling the altitude and airspeed.

3. Engine thrust during the shaft/fan or fan/shaft conversion should not have a drastic step change.

4. The rotor drive gearing should be capable of handling the necessary power output for a single-engine emergency condition.

5. Some helicopter designs may have higher disc loadings and would require more power than shown in Figure 2. Consequently, consideration should be given to configurations which can obtain as much as twice the power indicated for takeoff.

STUDY CONFIGURATIONS

CONCEPTUAL ARRANGEMENTS

All study engines used, as a basis, the familiar concentric two-spool turbofan arrangement, consisting of a high-pressure gas generator spool and a low-pressure fan/power turbine spool.

The various design features designated in the study requirements dictated three basic engine cycles. These three engine configurations, identified as Types I, II, and III, are shown schematically in Figure 4. Table I shows the engine features and indicates the various factors which will be evaluated.

TABLE I. DEFINITION OF BASIC ENGINE ARRANGEMENTS AND FACTORS TO BE EVALUATED

	I	IA	II	IIA	III	IIIA
Engine Features						
Supercharged	X	X	X	X	-	-
Independent Bypass Control	-	-	X	X	X	X
Nonsupercharged	-	-	-	-	X	X
Decoupled Fan	-	X	-	X	-	X
Variables Investigated						
N_L	X	X	X	X	X	X
A_{JP}	X	X	X	X	X	X
Fan IGV Angle	X	X	X	X	X	X
Fan Blade Angle	X	-	X	-	X	-
Fan EGV Angle	X	X	X	X	X	X

Type I is a conventional fan engine arrangement with the fan supercharging the gas generator. Fan geometry variations and/or decoupling will affect both the bypass flow and the flow into the gas generator and, hence, the degree of supercharging.

Type II also has a supercharged gas generator, but the bypass and the gas generator streams are separated to permit independent control of the bypass stream through the use of fan tip (only) variable geometry and/or decoupling. These variations do not affect the degree of supercharging.

Type III represents the nonsupercharged case. Separation of the bypass and gas generator streams permits independent control of the bypass flow, as in Type II. (The choice of either a front-mounted fan or an aft-mounted fan is a matter of detail design considerations and does not influence the basic nature of the cycle.)

Each of these configurations provides a baseline design on which the following factors can be evaluated (these are also indicated in Table I):

1. Power extraction at various rotor speeds

2. Increase in area of turbine exit nozzle

3. Variable fan geometry

4. Fan decoupling

Because fan decoupling introduces major changes in engine design and operation, a distinction was made between configurations with and without provisions for decoupling. This resulted in a matrix of six study engines: Types I, II, and III and the decoupled versions, Types IA, IIA, and IIIA (also shown in Table I).

PERFORMANCE ANALYSIS

The three engine types were sized to meet the fan engine thrust requirements, and the capabilities of each as a power-producing shaft engine were determined. Specifically, the engines were required to produce 3500 lb of thrust at 400 kn at sea level and 2750 shp at the sea level static condition (equivalent to 2000 shp at 6000 ft, 95°F). A further objective was to minimize fan thrust and power during hover.

Power in excess of the fan requirement can be made available if the fan speed is reduced while maintaining gas generator speed. Additional power can also be obtained by increasing the size of the primary jet nozzle and by applying variable geometry to the fan. Decoupling of the fan will make shaft power available and will also eliminate the fan thrust for hover. These methods and additional techniques for further reducing the fan thrust during hover were examined.

SIZING

The digital computer program used for engine cycle calculations is part of the Allison Building Block Program concept. This concept utilizes standardized subroutines which can be grouped together by a short master program to give a mathematical model of the engine cycle under consideration.

The common cycle for the study was selected as discussed in Appendix I, and the design constants at the sea level static condition are listed in Table II. A level of technology commensurate with the 1970 time period was assumed.

Performance of each engine in the conventional fan mode is shown in Figures 5 through 10. These plots show power turbine (fan) horsepower, thrust, rotor speeds, fuel consumption, airflow, and bypass ratio versus speed of the aircraft.

Table III is a summary of the sizing data for each engine at zero velocity and at 400-kn velocity. This sizing is based on a standard jet nozzle area selected for cruise and on fixed fan geometry.

TABLE II. ENGINE CONSTANTS AT SEA LEVEL STATIC CONDITION

Altitude, ft	0
Mach Number	0
Day	Standard
Inlet Loss	0
Fan R_c	1.769
Fan Efficiency, %	87.54
Gas Generator R_c—Supercharged	13.00
Gas Generator R_c—Nonsupercharged	14.00
High-Pressure Efficiency, %	82.70
Burner Efficiency, %	99.00
Burner Pressure Loss, %	4.0
LHV, BTU/lb	18,400
TIT, °F	2200
HPT Cooling, %	2.81
HPT Efficiency, %	88
LPT Cooling, %	1.69
LPT Efficiency, %	88
O/B Bleed, %	1.00
C_T (Nozzles)	0.985
Duct Loss, %	0.5

Notes:

1. Turbine cooling and O/B bleed are taken from the HPC discharge.
2. Efficiencies are adiabatic.
3. Losses are percent total pressure at inlet to station.

POWER EXTRACTION

For helicopter flight, power must be extracted from the engine to drive the rotor. Power can be made available by reducing the fan speed while holding the gas generator speed constant. The amount of power can be increased by opening the primary jet nozzle or by applying variable geometry to the fan. Increasing the primary jet nozzle area increases the turbine expansion ratio and, therefore, the output of the power turbine.

TABLE III. ENGINE SIZING SUMMARY

Sea Level - Standard Day
Constant Gas Generator Rotational Speed
Sizing Condition F_n = 3500 lb at SL 400 kn

	Engine Type					
	I		II		III	
Velocity, kn	0	400	0	400	0	400
Total Airflow, lb/sec	154.56	183.70	152.82	182.19	145.0	172.87
Primary Thrust, lb_f	1325.4	923.0	1310	954	1395	1085
Secondary Thrust, lb_f	4002.8	2577	3958	2544	3754	2422
Total Thrust, lb_f	5328	3500	5268	3500	5149	3500
Thrust Specific Fuel Consumption, lb/lb/hr	0.413	0.697	0.413	0.698	0.456	0.753
Fan Power, hp	5506	6361	4356	5095	4129	4852
TIT, °F	2200	2200	2200	2200	2200	2200
R_c oa	23.0	20.4	23.0	20.8	14.0	12.59
Bypass Airflow, lb/sec	123.34	148.25	122.26	146.77	116.03	139.46
Gas Generator Airflow, lb/sec	31.22	35.45	30.56	35.42	29.01	33.41
BPR	3.94	4.17	4.0	4.14	4.0	4.17

The effect of increasing the nozzle size has been examined for each of the three engine types, and the results are shown in Figure 11. An increase in area to 180% has been chosen as the maximum desirable change for this study because of the decreasing rate of power gain and the mechanical complexity required.

If variable angle guide vanes are added to the fan inlet, it is possible to increase the available shaft power by reducing the power absorbed by the fan. Fan thrust will also be reduced by this method. Figures 12 and 13 show fan characteristics which have been estimated for use in this study. These two maps are for the fan with vanes in the normal position and in the maximum reset position. Maximum reset represents the maximum vane turning position for which performance can be accurately calculated, based on available cascade data. This information has been used as input for the computer program in estimating the amount of power which can be made available. Additional calculations will be presented later, for larger turning angles, but the accuracy of these calculations is questionable and they should be revised when proper experimental data are available.

Type I

Figure 14 shows the available shaft horsepower and the total thrust over a range of low-pressure turbine (fan) speeds. The effects of consecutively opening the primary jet nozzle area and resetting the inlet guide vane are also shown.

With the 0-degree IGV - 100% A_{JP} combination, there is no shaft power available at 100% low-pressure turbine speed, since all of the power is going to the fan. Thrust is at a maximum. As the fan/low-pressure turbine speed is reduced, the required fan power drops faster than the power turbine output, and the excess is available as shaft power. Unfortunately, the reduction in fan speed also decreases the amount of supercharging of the gas generator. This effect causes the shaft power to peak in the 60 to 70% speed range.

Increasing the primary jet nozzle area produces a significant increase in shaft power. The increase is greatest at high-power turbine speeds, since the amount of supercharging and the turbine expansion ratio are larger at higher speeds. However, the decrease in thrust is small, because the primary nozzle area change does not affect the fan thrust. The influence of the primary nozzle becomes less as power turbine speed is reduced.

Resetting the inlet guide vane has its greatest effect on both shaft power and thrust at 100% fan speed. The reset also reduces the degree of supercharging which, in turn, offsets some of the potential power gain due to fan unloading.

Figure 14 shows that the Type I engine sized for the 3500-lb-thrust, 400-kn requirement will not develop the 2750 hp required as a shaft engine. The engine must be scaled approximately 17% (airflow) to meet the power requirement; it will then develop 4100-lb thrust at 400 kn. The scaled version will be identified as Type I_S.

The thrust of the Type I engine during power extraction is greatly in excess of the desired 600 lb at hover. Figure 15 shows the division of thrust between the primary (gas generator) and secondary (bypass) streams and indicates that acceptable thrust levels may be obtained by decoupling.

Type II

Power and thrust data for Type II are shown in Figure 16. The performance characteristics are basically similar to those of Type I, except that there are some important differences caused by the removal of the variable inlet guide vanes from the fan hub section and by the addition of a longer splitter to separate the bypass flow from the gas generator flow upstream from the fan.

With 0-degree IGV and 100% A_{JP}, there is no power available at 100% low-pressure turbine (fan) speed. Thrust is at the maximum level. Reducing the fan/turbine speed results in available shaft power; however, the amount is not as great as that with Type I. This is due to changes in matching and the amount of supercharging which is applied to the gas generator. The gas generator airflow is taken from the fan hub since the splitter has been moved forward. The amount of supercharging is related only to the pressure rise of the hub section and not to the average rise of the entire fan blade. Since the pressure ratio of the hub is more affected by speed than is the tip portion, the turbine expansion ratio and the turbine power output are less.

Increasing the primary jet nozzle area increases power and decreases the thrust, as before, with the largest changes occurring at the higher speeds.

Resetting the inlet guide vanes affects only the bypass portion of the inlet airflow and does not reduce the gas generator supercharging. Therefore, there is a larger increase of available power with Type II than with Type I. The largest effect is at high speed and the smallest is at lower speeds.

Figure 16 also shows the effect of increasing the fan jet nozzle area A_{JS}. A significant amount of additional shaft power can be made available, and thrust can be reduced slightly at 100% fan/turbine speed by increasing this area to 125%. The effect decreases at lower speeds.

The thrust of Type II during power extraction is much higher than desired. Figure 17 shows the primary and secondary thrusts with maximum reset guide vanes. However, decoupling could reduce the thrust to within the acceptable limit.

There is a possibility of fan hub surge at reduced power levels with Type II engines. When reducing power, the gas generator rotor speed and airflow reduce. However, the fan remains at constant speed, since it is connected by gearing to the helicopter rotor. The reduction in airflow at a constant speed moves the operating point toward surge on the fan hub map; this is illustrated in Figure 18, which shows that surge may occur at low power levels with maximum reset guide vanes. A bleed system could be arranged between the bypass and the gas generator inlet to avoid such a problem, by removing a part of the air discharged from the fan hub.

Type III

Figure 19 shows the available shaft horsepower and thrust levels of the Type III engine versus power turbine (fan) speed.

As with the other types, no shaft power is available with a 0-degree IGV setting and 100% A_{JP} at 100% fan/turbine speed, and thrust is at the maximum level. Since there is no supercharging, the inlet conditions to the gas generator are relatively unaffected by changes in fan speed. The inlet pressure does not decrease with decreased fan speed, as it does with Types I and II. Therefore, the available power is not decreased by this factor as fan/turbine speed is reduced, and the available power is greater than with the other types.

The effect of enlarging the primary jet nozzle area is relatively constant over the range of speed, since the nozzle pressure ratio remains relatively constant. Figure 19 shows that sufficient power is available over the full range of N_{LP} speed with the maximum guide vane reset and increased primary jet nozzle area. It is also indicated that it may be possible to obtain sufficient power without variable guide vanes at approximately 70% N_{LP} speed. This was not found possible with the other two types.

Figure 20 shows that engine thrust is excessive at any N_{LP} speed which could be used. At reduced speeds, the primary thrust is higher than with Types I and II.

REDUCTION OF HOVER THRUST

Both fan decoupling and the use of inlet plus exit variable fan geometry have been investigated as methods to reduce hover thrust.

Decoupling

The most effective method to reduce hover thrust is to decouple the fan. However, the desirability of this must be established based on mechanical considerations. Figure 21 shows the available power and thrust of each of the three engine types with decoupled fans.

Type IA

With the fan decoupled, air for the gas generator must be drawn through the fan or through the fan nozzle in a reverse direction. This will cause an inlet pressure loss and will decrease the power output. There is some uncertainty as to the magnitude of this loss. As there is a great amount of inlet area available in the fan flow path and the fan nozzle, it is considered that the air velocities and the pressure loss will be low. The loss is estimated to be approximately 3%. Figure 21 shows that 2750 hp can be obtained at 85% N_{LP}. Approximately 5% more power is available at 100% N_{LP}. Note that these values are based on 100% N_{HP} at a reduced TIT of 1940°F. If the engine is designed to permit overspeed of the gas generator, a higher TIT can be used with a corresponding increase in power.

The power available with Type IA is less than that with Types IIA or IIIA, as this engine, which was sized with supercharging, is now operating without supercharging and with an inlet pressure loss. The thrust during hover is below the 600-lb/engine objective.

Type IIA

The split fan wheel design permits decoupling the bypass fan while the hub portion of the fan is still operating and supercharging the gas generator. This creates an excess of power and also additional undesired thrust. Part-throttle operation, to reduce power, would bring thrust within the acceptable limits.

The surge problem of Type II is also present with Type IIA. As power and gas generator airflow are reduced, the operating point of the fan hub moves toward surge on a constant speed line. Figure 22 shows that 1600 shp is the lowest power that can be extracted without encountering LP compressor (fan hub) surge at 70% N_{LP}. This is below the anticipated operating speeds. Surge would occur at higher power levels with higher N_{LP}. A bleed system could be designed to solve this problem.

Type IIIA

Since the engine is unsupercharged, stopping the fan does not affect the power output capability of the turbine. Excess power is available over a wide range of turbine speeds. There is no surge problem at reduced power levels.

Since the gas generator is unaffected by the fan, thrust is high over the entire speed range. It does not appear that a thrust level below 600 lb at hover could be accomplished with this engine at full power; however, the thrust at reduced power would be acceptable.

Inlet and Exit Guide Vane Reset

It may be possible to reduce fan thrust to a low level by the combined action of variable inlet and exit guide vanes and, thus, to achieve greater simplicity by avoiding the use of a decoupler. Recent studies have been made to investigate this possibility.

The analytical studies indicate that coordinated variable vanes plus increased fan nozzle area may reduce thrust to values which are only marginally higher than the desired level. It is estimated that these changes may reduce fan thrust to the range of 500 to 800 lb at the design speed. Thrust would be greatly reduced at lower fan speeds. Attainment of these low values requires the use of IGV angle changes of about 60 degrees. The studies clearly indicate a requirement for variable exit vanes to preclude the vibratory problems that would otherwise arise from severe stalling. EGV angle changes of 25 to 35 degrees are envisioned.

The use of variable geometry changes of these magnitudes is outside the realm of existing cascade data. Hence, the credibility of the analysis is open to some question. The many uncertainties involved suggest the desirability of experimental work to determine if lower values of thrust can be attained.

POWER TRANSFER ANALYSIS

The problems of power transfer are considered to include the fan-decoupling devices and the power-takeoff drive for extracting power. Four methods of decoupling the fan were studied as a means of increasing shp and eliminating thrust at takeoff and hover. The problem of extracting the power to drive the helicopter rotor through a power-takeoff drive assembly was also studied, and preliminary designs were made for both forward and aft locations. Designs which had output shafts extending at 90- and 45-degree angles to the engine axis were studied. A discussion of the results follows:

DECOUPLING DEVICES

Decoupling the fan during the helicopter mode offers a method for eliminating fan thrust and parasitic fan power so that power can be extracted from the engine to drive a helicopter rotor.

If the decoupler is to be an attractive device in the design, it must have the following desirable characteristics:

1. Small size
2. Low weight
3. Simplicity
4. Compatibility with the aircraft operating requirements
5. Good development potential
6. Low heat rejection
7. Reliability and adequate life

Each of the four decoupler candidates was examined with the foregoing requirements in mind; the hydraulic torque converter was selected as the most desirable type.

The decouplers considered were:

1. Differential gears
2. Friction clutch

3. Fluid coupling plus overspeed gears

4. Hydraulic torque converter

Differential Gears

A schematic drawing of a differential gear arrangement is shown in Figure 23. This arrangement uses a double planetary gearset with brakes to stop either the ring (Number 4) or the planet carrier. The engine drives the sun gear (Number 1). The power output to the fan is taken from the planet carrier (Number 5). A second planetary gearset is used to bring the fan shaft to the desired operating speed (Numbers 3 and 8).

The helicopter rotor drive is taken from the ring gear through a bevel gearset (Numbers 6 and 7), as shown. While operating in the rotor mode, the planet carrier and fan are stopped, and the ring gear is free to rotate and to drive the rotor through the bevel gearset. The speeds of the sun gear, the planet carrier, and the ring gear are related by the equation

$$N_S = -M\,N_R + N_C\,(1 + M)$$

where

N_S = sun gear speed

N_R = ring gear speed

N_C = carrier speed

M = number of ring gear teeth/number of sun gear teeth

If the speed of the turbine N_S is considered to be constant, as would be desirable during shifting, a decrease in ring gear speed would require a corresponding increase in carrier speed or vice versa. In a shift from the helicopter mode to the fan mode, the helicopter rotor drive would be required to decrease speed as the fan speed increased. The power absorbed by the rotor decreases approximately as the cube of the speed. If the speed of the rotor is decreased, the rotor will quickly lose its ability to support the aircraft.

The fan, on the other hand, will be relatively slow to develop thrust. At 80% speed, the fan will develop slightly over half of its rated thrust. This is the approximate amount of thrust that is required to sustain flight at 120 kn.

If the fan and rotor shafts conform to the speeds required by a differential gear system, there will be an interruption of flight power, and the aircraft will lose either altitude or speed while shifting is taking place.

It is assumed that the helicopter rotor will be driven through an overrunning clutch. When the driving shaft is suddenly braked, as would be the case during the shift described, the rotor inertia may support the rotor speed momentarily; this would sustain the aircraft in flight. See Figure 24. Rotor inertia would have the effect of smoothing the changeover; however, it is improbable that a differential gear system could be devised to provide a smooth transition without loss of altitude or speed.

The design of brakes for the differential gear is not unlike the design of clutches for a friction clutch system, and the amount of cooling oil required for a brake system may make the system unattractive because of weight.

The undesirable operating characteristics and the complexity of the gear and brake system are the principal reasons for not recommending the differential gear decoupler.

Friction Clutch

A study was made of a friction clutch decoupler, assuming that coupling would occur at 100% fan speed. Table IV lists the important parameters of the study.

An oil-cooled multiple-disc clutch was sized to fit the space requirements and to provide acceleration of the fan in 15 sec. During the engagement period, a considerable amount of heat will be rejected to the oil. The rate of heat rejection is shown in Figure 25. The total heat rejected for the 15-sec engagement is 3615 BTU.

Subsequent studies have shown that by engaging the fan at approximately 85% speed and with a maximum reset IGV, the clutch power transmitted can be reduced to about 50%. This would result in an approximate 50% reduction in heat rejection and 40% reduction in weight.

While heat rejection due to inefficiency will be present with any of the decouplers considered, the problem is more critical with the clutch design. During engagement of the clutch, the discs are clamped together to produce a torque. Since heat is generated at the surface of each thin disc, the distribution of cooling oil is critical. Lack of cooling to any section of a disc will result in damage to the clutch surface and possible warpage of the discs.

TABLE IV. FRICTION CLUTCH DESIGN DATA	
Fan Horsepower	4400
Fan Polar Moment	3.9 slug-ft^2
Fan Operating Speed	11,500 rpm
Friction Surfaces	44
Friction Surface, OD	10 in.
Friction Surface, ID	5.72 in.
Hydraulic Piston, OD	6.5 in.
Hydraulic Piston, ID	4.0 in.
Disc Bearing Area	53 in.^{2}
Maximum Crushing Stress	50 psi
Maximum Clutch Torque	48,200 lb-in.
Cooling Oil Flow Rate	1060 lb/min
Oil Temperature Rise	100°F
Estimated Weight (Includes pump and controls; does not include oil cooler, oil, or tank)	90 lb

The discs would be designed with closely spaced grooves to distribute oil between the discs to remove generated heat. Any blockage of these grooves will seriously impair the effectiveness of the oil in removing heat. In comparison to other methods of decoupling, the clutch system will be more sensitive to foreign particles in the oil.

While a friction-clutch arrangement can be designed to handle fan decoupling by using the present state of the art, this method of decoupling is not recommended because of its questionable service reliability.

Fluid Coupling Plus Overspeed Gears

A fluid coupling arrangement can be used to drive the fan. The flexibility of a fluid device is desirable; however, couplings of this type will not transmit torque without a difference of speed between the input and output shafts, and a resulting inefficiency. It is desirable to use the coupling to accelerate the fan and then to engage a lockup device to drive the fan.

Study of the problem reveals that an overspeed gear train is needed to bring the fan up to the power turbine speed for lockup. A schematic drawing of such an arrangement is shown in Figure 26. In this sketch, cluster gears are used to overspeed the input to the coupling. It will then be possible to drive the coupling output member up to the turbine speed in spite of the coupling slip.

The fluid cavity will be filled during operation, causing the coupling to drive. This fluid clutch has marked advantages over friction clutches, where the mechanical wear on the engaging surfaces and the required even distribution of the oil to control the generated heat become problems.

Typical curves of fluid-coupling torque and efficiency versus speed ratio of the input and output are shown in Figure 27. The torque is the same for the input and the output shaft. Since horsepower is equal to torque times speed, efficiency $= (T \times N_{out})/(T \times N_{in})$ or $= (N_{out})/(N_{in}) =$ speed ratio. This relationship is not true near 1.0 speed ratio, since torque transmitted drops to zero at this point.

An empirical relation is taken from Wislicenus* for an approximate sizing of the coupling.

$$hp = \frac{6.84}{10^{13}} \left(1 - \frac{N_2}{N_1}\right) D^5 N_1^3$$

High speed and low power are required to minimize the coupling size; however, it appears that the size of the coupling is not a major factor.

The fan is accelerated to power-turbine speed by filling the transmission with oil. A splined coupling is then engaged to provide a solid mechanical drive with the turbine. The coupling is drained of oil when the lockup is complete.

During the engagement, the low efficiency of the coupling will result in more heat being rejected to the oil. The heat rejected at any speed ratio is the product of the input power and the inefficiency, which is $0.707\ hp_{in} \times (1 - \eta) =$ BTU/sec. The total heat rejected during the engagement will be the integration of the BTU/sec versus time curve.

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*Wislicenus, G., FLUID MECHANICS OF TURBOMACHINERY, Volume II, New York Dover Publishing Company, 1965, page 394, Eq (470).

The major disadvantage of this arrangement is the requirement for the gear train due to the inability to achieve a no-slip condition. This can be avoided if a torque converter is used.

Hydraulic Torque Converter

The torque converter is similar to the fluid coupling except that it incorporates a third member, which is stationary. This change permits the elimination of the overspeed gearing, since it is possible to design the torque converter such that it will transmit torque with the output shaft speed equal to the input shaft speed. It also provides a torque multiplication, which is useful in accelerating the fan to operating speed.

A typical operating curve for a torque converter of the type considered is shown in Figure 28; note that the input and output torques are different and that there is a torque multiplication at each speed ratio. The efficiency of the converter is higher than that of the fluid coupling at the low-speed ratios.

Approximate sizing of the torque converter is based on an existing design for which performance data are available. The relationship that horsepower is proportional to the fifth power of diameter and the third power of shaft speed is true for torque converters as well as for fluid couplings.

During operation, the torque converter would be filled in the same manner as the fluid coupling. However, lockup speed would occur at a 1.0 speed ratio. Efficiency at this point would be approximately 0.83. The heat rejected by the torque converter is expected to be approximately the same at the lockup point but slightly less than that of the fluid coupling at lower speed ratios, due to the higher efficiency values for the converter.

This high-speed design concept which permits small physical size must be considered as a risk area. However, the main limitations to speed are the possibility of cavitation and the increased stress level.

The main question of cavitation is primarily concerned with the initial filling of the converter while it is running at high speed. At this condition, the slip is nearly 100% (depending on the windmilling) and the oil, which is initially admitted while the efficiency is very low, will undergo a high temperature rise. This condition will last for a very short time, perhaps only 2 or 3 sec, but it deserves investigation in any development program.

If the converter could be filled instantaneously, then full output torque would be available at all speed ratios, and the fan acceleration rate could be calculated, based on the output torque versus speed ratio of the filled converter. In the actual case, some finite time will be required to fill the converter. This will depend partly on the power requirements of the rotor. The fan torque available during each time interval of the fill cycle will be dependent on the amount of fluid in the converter and on the efficiency of the partly filled converter during that time interval.

Likewise, the amount of heat rejected will depend upon the efficiency of, and the power input to, the partly filled converter during each time interval.

As an approximate calculation procedure, it may be assumed that the efficiency of the partly filled converter is the same as that of the full converter and that the torque values are linearly proportional to the amount of oil in the converter. If these assumptions are made, then curves of the type shown in Figure 29 can be developed. This has been the method used for an analog computer study which is described in Appendix I.

In general, it is observed that there will be a peak in the heat rejection rate. The highest rate will occur with the shortest fill times. It appears that fill times of from 10 to 30 sec are reasonable and do not result in excessive temperatures in the oil. In general, fan acceleration time will approximate the converter fill time.

While the stress level is higher than that of industrial-type couplings, the use of aircraft type materials appears to be a satisfactory solution for the stress condition.

ROTOR DRIVE GEARS

The requirements for the design of power-takeoff gears to drive the helicopter rotor have been examined, and it has been found that it is feasible to design a gearset to lie within the engine inner flow path.

Preliminary design studies have been completed for both front and aft locations of the rotor drive assemblies, and the weight and size effects of varying both the input and the output speed have been determined.

Design Requirements

The steady-state hover power is approximately 2000 hp/engine. Considering the climb rate requirements, it is estimated that a desired thrust/weight ratio for the aircraft will be 1.3. Therefore, 2600 hp was used for the design power for the rotor drive gears. Since the tooth stress values and the bearing life for this design were based on approximately 5000 hr of life and 1000 hr of time between overhaul, the assembly will be capable of handling an overload for the short period of time required for a single-engine emergency rating. It may be desirable to operate the turbine at a slightly lower speed while the engine is operating in the helicopter mode. The result of decreasing the speed of the input gear, while keeping the rotor horsepower constant, is to increase the torque and to make the diameter larger. Therefore, an effort must be made to provide some excess room for this gear.

Method of Sizing Gears

The Gleason method has been used for the design of the bevel gears. Hardened and ground aircraft quality spiral bevel gears are used. Each of the designs shown is considered to be within the limits of good aircraft practice. The maximum recommended tooth bending stress based on this method is 25,000 lb/in.^{2} It should be emphasized that this is a stress limit which is based on fatigue properties and is recommended by Gleason in this design procedure. The crushing stress has been held below the maximum allowable value of 250,000 lb/in.^{2}

Description of Designs

Figure 30 shows the front drive with the 45-degree output shaft angle, while Figure 31 shows the rear drive with the 90-degree output drive. In both of these drawings, the turbine input speed was assumed to be at 100%. Both gearsets lie within the centerbody formed by the engine flow paths. There is a weight advantage of approximately 10 lb when using the 45-degree set. Figure 32 shows the 90-degree set used as a front drive with the power turbine speed reduced to 85%; therefore, the gearset has become larger. However, it is still contained within the centerbody. This would not be true with a 45-degree shaft-angle gearset designed for the same conditions. Therefore, there is an advantage to the 90-degree shaft angle when extracting power at 85% turbine speed.

A high output shaft speed is selected for the front drive, since this minimizes the shaft size and the size of the strut which contains the shaft. This is important to minimize blockage of the inlet air. In the helicopter mode and at the maximum horsepower point, the shaft speed will be 18,000 rpm and the gear pitch line velocity will be 29,400 ft/min. The increase of this velocity, when the gears are unloaded, is considered to be a risk area which may require additional study. The advantages gained by these high speeds are a lowered gear-tooth load and smaller, lighter gear sections.

The maximum length of shafting without a damper bearing will be approximately 19 in. to avoid natural frequency vibration problems. The outboard bearing installation is not shown. However, it is probable that a speed reduction would take place at this point.

MECHANICAL ARRANGEMENTS

Using the results presented in this report under "Performance Analysis," the configuration features were selected for each of the six engine types, and a mechanical arrangement sketch was completed. The power-takeoff drive and the torque converter were used, as required for certain configurations, as defined by the "Power Transfer Analysis."

The variable geometry, which was selected for the various engine types, is shown in Table V. The engine features are also shown in Table V.

TABLE V. VARIABLE GEOMETRY SELECTED FOR ENGINE TYPES

	Types					
	I	IA	II	IIA	III	IIIA
Engine Features						
Supercharged	X	X	X	X	-	-
Independent Bypass Control	-	-	X	X	X	X
Unsupercharged	-	-	-	-	X	X
Decouple Fan	-	X	-	X	-	X
Variable Geometry Features Selected						
IGV	X	X	X	X	X	X
EGV	-	-	X	-	X	-
A_{JP}	X	X	X	X	X	X
LP Compressor Bleed	-	-	X	X	-	-

A description of the design and arrangement studies follows.

TYPE I ENGINE

This arrangement is shown schematically in Figure 33. The variable fan geometry consists of the full-length IGV as shown in Table V. A sketch of the complete engine assembly is shown in Figure 34, which includes a 45-degree PTO drive in the front location. This shows that the drive assembly presents a problem in containing the bearings and oil seals of the driven gear within the centerbody. It also shows the strut which houses the output drive shaft. To avoid aerodynamic interference with the high-pressure compressor, this strut must be thin and not too close to the first HP compressor stage; Figure 34 shows the general arrangement and indicates that the aerodynamic problem may dictate the length of the centerbody.

The variable pitch fan blade was studied for this type of engine. Figure 35 shows a schematic of this design. Because of the high tip speed of the fan blades used in this study, the centrifugal forces on the blades produce excessive thrust loads on the blade attachment bearings and are consequently unacceptable. However, this study was carried further to determine the merits of the system because it may be practical in an engine with a fan having a lower tip speed. It was indicated previously in this report that the variable inlet guide vane performance analysis indicated a tendency for the vane to choke the airflow to the gas generator as the vane was turned, and thus the power was reduced to such an extent that it was impossible to reduce the bypass thrust to a large degree. The same is true of the variable pitch blade, although there is a desirable effect where the area in the bypass portion of the blade will choke off to a greater degree than at the hub. The mechanical arrangement required is illustrated in Figure 36.

It is noted that the axis of pitch change was defined so that it would extend through the tip at the leading edge. Consequently, as the blade is rotated to a flat pitch, the clearance will increase at all points except the leading edge and, thus, will avoid interference with the shroud.

A study was then made to define the throat area between the blades as they rotate to flat pitch. A sketch is shown in Figure 37. A pitch change of approximately 25 degrees is possible before the blades contact each other at the tips and before further movement is prevented.

Figure 38 shows the throat area between the blades plotted against the blade angle change. The passage area was divided by a hypothetical plane to separate the gas generator and the bypass flow air streams. The area of each is plotted.

These curves show a desirable characteristic in that the area for the bypass flow decreases more rapidly than the area for the gas generator flow. The effects of this would have to be evaluated with separate maps for the hub and tip.

From the stress standpoint, the high tip speed of 1650 ft/sec results in extremely high bearing loads for the blade attachment. Since the blade spacing is close, a very small bearing—having inadequate capacity—must be used. Consequently, a variable pitch blade is unsatisfactory and could be considered only with a lower tip speed.

TYPE IA ENGINE

Type IA is shown schematically in Figure 39. It is very similar to the Type I engine, with the addition of a decoupler. A sketch of the complete engine, Figure 32, shows the addition of a decoupler, combined with a 90-degree PTO drive. In this example, the drive assembly and the decoupler are designed for operating the power turbine at 85% design speed when in the helicopter mode. The decoupler design is also based on engaging the fan with the IGV in the full reset position so that the torque required to drive the fan through the torque converter is substantially reduced at 85% fan speed.

This shows that the centerbody is increased in length, that the 90-degree drive has more radial clearance than the 45-degree drive, and that the strut which houses the output shaft is not so close to the HP compressor.

The variable pitch blade was not studied on the decoupled-type engines because the hover fan thrust is eliminated with the decoupling, and the variable pitch is not needed.

TYPE II ENGINE

The Type II engine arrangement is shown schematically in Figure 40, with the variable geometry and features shown in Table V. Figure 41 is a sketch of the forward portion of this engine with the 45-degree PTO drive. Figure 42 shows a schematic of the variable pitch bypass fan.

In applying the variable pitch blade analysis to this engine, note that the centrifugal forces are too large to be practical. However, in this case, this device is very effective in eliminating fan thrust and fan parasitic power at hover without the use of a decoupler. Also, an additional problem is encountered. Each blade must be supported by individual struts which extend across, and rotate in, the flow path leading to the gas generator. This results in considerable blockage and turbulence in the gas generator air stream.

TYPE IIA ENGINE

The Type IIA arrangement, shown schematically in Figure 43, illustrates the variable geometry and features shown in Table V. Figure 30 is a sketch of the forward portion of this engine. The torque converter in this case is large because it was designed for engagement at 100% fan speed with the IGV in the 0-degree (axial) position.

There is a unique problem with this arrangement. The fan blades do not extend into the gas generator airflow region; their roots are attached to a continuous ring which carries the loads by "free-ring" tension in the ring itself. This blade-supporting ring is piloted on four radial spokes, which attach firmly to the wheel but slide freely in the ring. Therefore, these spokes carry no radial load, but they must carry bending due to thrust and torque. The large-diameter spokes are considered to be preferable to a larger number of small ones, since a large-diameter rod is much stronger than a small one when exposed to bending loads. One disadvantage of this approach is that the free ring has a large diametral growth due to a tension stress of approximately 100,000 psi, as designed. Using a high-strength titanium, the growth would cause the tip clearance of the fan blades to reduce by 0.080 in. as speed is increased from zero to 100% rpm. This would result in a small reduction in fan efficiency at the fan cruising speed. The large movement of the ring in both the radial and the axial (due to thrust loads) directions will cause leakage problems in the seals between the fan and the gas generator flow-path splitter vane, causing some further performance loss. This construction is unconventional and may be undesirable for the following reasons:

1. A concentricity problem may result unless the spoked construction is developed to a high degree so that the ring will center itself freely on the spokes. This configuration could result in severe engine vibration.

2. The rotation of the spokes in the gas generator flow path may cause excessive pressure drop or a critical aerodynamic disturbance in the HP compressor.

3. Performance losses will occur because of air leakage in the seals between the two flow paths fore and aft of the free ring, and because of variations in fan tip clearance.

TYPE III ENGINE

The Type III engine, shown schematically in Figure 44, illustrates the configuration described in Table V. This arrangement requires the free-ring construction described for the Type IIA engine when a front-mounted fan is used, and it has the same disadvantages. Another arrangement that is a "natural" for this type of engine is the aft fan. This arrangement lends itself more readily to the nonsupercharged engine, since the aft location eliminates the need for a power shaft extending through the gas generator to the front of the engine. It also simplifies the engine air inlet. However, there are serious problems of turbine-blade stresses and leakage of hot gas into the fan inlet. The arrangement is shown in Figure 45.

An analysis has been made which shows extremely high turbine blade stresses when using a single-stage fan having $R_c = 1.77$. In an effort to overcome this problem, a two-stage aft fan design was studied. This design permitted a fan speed reduction from 12,350 to 9540 rpm, but it also increased the number of power turbine stages from three to four. On the last two turbine stages which carry the fan blades, 50 blades per stage were required on the turbines, and 100 blades per stage were needed on the fan stages because of the large fan diameter. This required each turbine blade to carry two very long fan blades.

In spite of the speed reduction to 9540 rpm, the turbine blade stresses are still prohibitive. In addition, as the number of fan stages increases, the leakage is increased at the seal between the high-pressure hot gas in the turbine and the ambient pressure at the fan inlet. This causes a serious deterioration in fan performance.

A variable-pitch blade was also studied for the Type III engine shown schematically in Figure 46. The construction and problems are identical to those described for the similar approach in the Type II engine. That is, there is excessive loading on the blade attachment bearings, and the supporting struts are undesirable in the gas generator inlet flow path.

TYPE IIIA ENGINE

This arrangement is shown schematically in Figure 47, which illustrates the configuration with features and variable geometry listed in Table V.

This is similar to the Type III schematic, but it does not lend itself to an aft-fan arrangement, since a decoupler is included. Figure 48 shows a full-length engine sketch with the PTO drive mounted aft of the power turbine.

POWER-TAKEOFF DRIVE ASSEMBLY

A detailed sketch of the aft 90-degree drive is shown in Figure 31. Generally, the aft location involves approximately the same penalties in space, weight, and complication. The heat problems in the aft location must be handled with insulation. A slight increase in heat rejected to the gearbox oil may result. The output shaft from the PTO drive gear will terminate at a drive pod at the outer diameter of the engine. A drive-extension shaft may then extend in a straight line from the engine to the main rotor transmission, or a bevel gearset may be mounted directly on the pod. If it is desired to reduce the speed of the shafting between the engine and the transmission, the bevel gearset will present the opportunity. This, of course, applies to either a front or a rear location.

CONTROL REQUIREMENTS

The control analysis study consisted of three basic tasks. The initial task was to determine how a convertible fan/shaft engine might be operated in stowed-rotor-type composite aircraft, and to define the associated control requirements. The second task was to evaluate, on a comparative basis, the controllability of the various engine configurations studied. This was one of the considerations in the selection of a final configuration. The third task was to define a control system for this final configuration. This task is discussed in the following paragraphs.

The convertible fan/shaft engine control requirements fall into three basic categories. The categories are related to engine usage and include:

1. Control of the engine when operated in the helicopter mode

2. Control of the engine when operated in the conventional airplane mode

3. Control of transition from one of these modes to the other

In the helicopter mode of operation, the engine loading is controlled by the pilot via collective and cyclic pitch; the engine control system must govern the speed of the low-pressure rotor, which drives the helicopter rotor. The control system must provide modulation from idle to maximum power. Maximum power should be restricted by limiting high-pressure rotor and/or turbine inlet temperature, whichever is encountered. The fan must be controlled by whatever "handles" are available so that its power requirement and thrust production are minimized. This would be done primarily by variable fan geometry or decoupling. For multiengine installations, load sharing may also be a control requirement during the helicopter mode.

In the normal airplane mode of operation, the engine must be controlled so that thrust modulation is provided as a function of power lever position.

Starting, transient scheduling, control of high-pressure compressor variable geometry, etc., are control requirements which exist regardless of helicopter or airplane mode.

During transition between operating modes, the control requirements are primarily engine configuration and application oriented. However, in general, it may be established that transitions must be smooth, rotor speeds and turbine temperature must be limited, and the pilot must have the capability of manually overriding any automatic transition sequencing.

Six configurations, as defined previously, were included in the comparison. These configurations were compared on the basis of what controls are required, without detail consideration of the specific controls. The control requirements are listed in Table VI. The basic engine control, which includes fuel control and high-pressure compressor variable geometry control, is common on each configuration. The next column is fan guide vane control. In the Type IA, IIA, and IIIA engines, this is a control for inlet guide vanes only. For Types II and III, it controls both inlet and exit vanes; but since both sets of vanes are to be moved in relation to each other, the control should be similar with just additional actuation linkage involved.

The primary jet nozzle area control for each configuration requires only a two-position control. The decoupler control column reflects only which configurations have decouplers. A significant item evolving from this analysis was the requirement to add a bypass bleed valve on Types II and IIA, to avoid a low-pressure compressor surge problem during power reduction in the helicopter mode. The prime cause of this surge is the fact that the gas generator speed and the airflow reduce as horsepower output reduces. Since the low-pressure compressor is running at constant speed and since its flow must match that of the gas generator, the operating line moves along a constant low-pressure rotor speed line on the compressor map toward surge, as mass flow reduces. Figures 18 through 22 illustrate, on Types II and IIA respectively, this surge problem prior to the addition of the bypass bleed.

TABLE VI. CONTROL REQUIREMENTS

Configuration	Fuel Control	Fan Guide Vane Control	Nozzle Area Control	Decoupler Control	Bypass Bleed Valve Control
I_S	Yes	Yes	Yes	No	No
IA	Yes	Yes	Yes	Yes	No
II	Yes	Yes	Yes	No	Yes
IIA	Yes	Yes	Yes	Yes	Yes
III	Yes	Yes	Yes	No	No
IIIA	Yes	Yes	Yes	Yes	No

COMPARISON OF CONFIGURATIONS

Comparisons were made of the six engine configurations as defined, on the basis of the analyses described. Each engine was rated, where possible, on the ten characteristics in the following list, and a final selection was made to conduct further definition of the Type IA engine.

1. Performance
2. Mechanical complexity
3. Risk areas and potential development problems
4. Weight
5. Control requirements
6. Systems integration
7. Installed volume
8. Scalability
9. Shaft-to-fan and fan-to-shaft conversion time
10. Installation characteristics

The following discussions and tables show the results of this evaluation.

PERFORMANCE

Based on the performance calculations presented earlier, the resulting comparison for the six engine types is presented for the takeoff condition at sea level standard. As previously stated, the capability of an engine to deliver 2000 shp at 6000 ft, 95°F is equivalent to the capability of delivering 2750 shp at sea level standard conditions. For simplification, the engines were compared for the latter condition, which ensured the capability to meet the 6000 ft, 95°F power requirement.

A comparison of various performance characteristics has been made and is summarized in Table VII. The performance curves showing shp, F_{NT}, F_{NP}, and F_{NS} plotted against percent N_{LP} (Figures 14 through 21) were used to determine the thrust and shp data in Table VII. Column 1 shows the thrust at 400 kn, sea level for each engine. All engines except Type I_S are sized by the 3500-lb thrust requirement at this condition. Type I_S was scaled up 17% in airflow to achieve 2750 shp. Consequently, its thrust at 400 kn, sea level is 4100 lb.

TABLE VII. FAN/SHAFT ENGINE COMPARISON PERFORMANCE

Type	(1) F_N at 400 kn	(2) TSFC at 400 kn at 3500 lb F_N	(3) Max SHP at SLS	(4) F_{NS} at Max SHP	(5) F_{NS} at 2000 SHP at 6000 ft/95°F	(6) Shaft SFC at 2000 SHP at 6000 ft/95°F
I_S	4100	0.697	2750** at 80% N_{LP}	2030	1483 at 80% N_L	0.699**
IA	3500	0.697	2805* at 100% N_{LP}	0	0	0.464* at 100% N_{LP}
II	3500	0.698	2780** at 89% N_{LP}	2091	1587 at 89% N_L	0.732**
IIA	3500	0.698	5300* at 100% N_{LP}	0	0	0.450* at 100% N_{LP}
III	3500	0.753	3270** at 73% N_{LP}	1425	950 at 73% N_L	0.697**
IIIA	3500	0.753	4900* at 100% N_{LP}	0	0	0.480* at 100% N_{LP}

*Fan decoupled
**Maximum reset

TABLE VIII. FAN/SHAFT ENGINE COMPARISON OF MECHANICAL COMPLEXITIES

	IGV	EGV	B/P Bleed	Decoupler	Variable Nozzle	Double Fan Wheel	Spoked Fan Wheel	Total Required
I_S	X	-	-	-	X	-	-	2
IA	X	-	-	X	X	-	-	3
II	X	X	X	-	X	-	-	4
IIA	X	-	X	X	X	X	X	6
III	X	X	-	-	X	-	X	4
IIIA	X	-	-	X	X	-	X	4

The maximum shp at sea level static is shown in column 3. The minimum power required is 2750 shp, which is the maximum attainable by Types I_S and II. Greater power is available from Types IA, IIA, and IIIA, by decoupling.

The fan thrust (F_{NS}, secondary thrust) at the maximum power point is shown in column 4. These power and thrust values are for a maximum reset IGV and 100% area A_{JS}.

With the coupled fan engines, the thrust values given in column 5 are for 2000 shp at 6000 ft, 95°F. These are with the maximum IGV reset angle previously defined. As explained in the Performance Analysis, it is believed that through experimental testing, additional data can be obtained to show a substantial reduction in thrust by a combination of larger resets on the IGV combined with EGV and fan exit nozzle changes. This may demonstrate fan thrust values sufficiently low for hover. For such an approach, it is desirable to operate the fan at as low a speed as possible, for operation in the helicopter mode.

Shaft sfc values for hover are shown in column 6. These values are for 2000 shp at 6000 ft, 95°F, and they correspond to the same engine operating speeds as the points shown in column 5.

MECHANICAL COMPLEXITY

Various complex assemblies must be incorporated in a fan/shaft engine in addition to the usual gas turbine components. The following items have been considered as features that increase engine complexity over that of a simple basic fan turbine:

1. Variable IGV and EGV for the fan
2. Bypass bleed valve and control
3. Torque converter for fan decoupling
4. Variable primary exhaust nozzles
5. Double wheel for the fan
6. Spoked fan wheel

Table VIII shows a tabulation of these mechanical complexities for each engine with a total indicated for each. Care must be taken not to consider each of the complexities as equally difficult to accomplish. Some of the items are features of present-day turbines, while others are new and are discussed below.

RISK AREAS AND POTENTIAL DEVELOPMENT PROBLEMS

Fan/shaft engines will incorporate certain new risk areas as well as have certain development problems which may involve previously established turbine design features. The following is a summary of the most significant risk and development problems.

1. Torque Converter (Types IA, IIA, and IIIA)

   a. Lightweight unit of this speed and power is new.

   b. Proper characteristic of speed versus efficiency must be achieved.

   c. Heat rejection is high; therefore, an adequate oil system in the aircraft is required.

   d. Initial filling under high-speed conditions may cause oil heat problems.

2. Fan Inlet and Exit Guide Vane Variable Geometry and Control System

3. Spoked Fan Wheel (Types IIA, III, and IIIA)

   a. Concentricity problem may cause vibration.

   b. Spokes will cause ΔP and possible aerodynamic disturbance to HP compressor.

   c. Air leakage exists between the two passages at the front and rear of the free ring and at blade tips.

Table IX lists the risk and development problems for the six configurations including the total number for each. Again, it should be remembered that the relative risks of the four items are not necessarily equal.

TABLE IX. FAN/SHAFT ENGINE COMPARISON—RISK AND DEVELOPMENT PROBLEMS						
Type	Torque Converter	Variable IGV	Variable EGV	Spoked Wheel	LP Bleed	Number of Problems
I_S	-	X	-	-	-	1
IA	X	X	-	-	-	2
II	-	X	X	-	X	3
IIA	X	X	-	X	X	4
III	-	X	X	X	-	3
IIIA	X	X	-	X	-	3

WEIGHT

Table X shows the calculated weights for the six engines. For ease of comparison, the relative weights are shown on the basis that the heaviest engine is rated at 100%.

TABLE X. FAN/SHAFT ENGINE COMPARISON—WEIGHT*

Type	Fan Assembly (lb)	Bearing Support and Transition (lb)	Torque Converter (lb)	90° Rotor Drive (lb)	Gas Generator (lb)	Total Weight* (lb)	Rating (%)
I_S	219	60	-	47	428	754	89.5
IA	162	77	35	47	370	691	82
II	168	64	-	47	370	649	77
IIA	210	79	35	47	370	741	88
III	189	55	-	47	512	803	95.5
IIIA	166	81	35	47	512	841	100

*Control system and miscellaneous weights are not included.

CONTROL REQUIREMENTS

The additional components and functions of a fan/shaft engine will require added complication to the engine control system. The control functions are shown in Table XI, and the total requirements are listed.

SYSTEMS INTEGRATION

It is believed that all of the engines can be satisfactorily integrated into the various aircraft systems although no relative comparison has been made. Changes in the aircraft oil system may be required when using the torque converter.

TABLE XI. FAN/SHAFT ENGINE COMPARISON—CONTROL REQUIREMENTS

Type	Fuel Control	Fan Guide Vane Control	Nozzle Area Control	Decoupler Control	Bypass Bleed Valve Control	Number of Control Functions
IS	Yes	Yes	Yes	No	No	3
IA	Yes	Yes	Yes	Yes	No	4
II	Yes	Yes	Yes	No	Yes	4
IIA	Yes	Yes	Yes	Yes	Yes	5
III	Yes	Yes	Yes	No	No	3
IIIA	Yes	Yes	Yes	Yes	No	4

INSTALLED VOLUME

Table XII shows the diameters and lengths of the six engines, together with a wetted area factor for an approximate nacelle for each engine. A relative percentage is shown using 100% for the largest wetted area factor.

TABLE XII. FAN/SHAFT ENGINE COMPARISON—NACELLE WETTED AREA FACTOR

Type	D_F (in.)	D_T (in.)	L_E (in.)	A_T	Rating (%)
I_S	32.8	21.6	38.5	3280	100
IA	30.7	21	36	2800	85.5
II	31.5	21	36	2905	88.5
IIA	32.8	21	36	3070	93.5
III	29.5	21	40	2870	87.5
IIIA	29.5	21	40	2870	87.5

The approximation was determined by the following calculation for the outer surface of the shroud and the afterbody (Table XII):

D_F = fan diameters, in.

D_T = turbine diameters, in.

L_E = length of engine aft of fan, in.

A_T = wetted area factor

SCALABILITY

All of the configurations are considered to be scalable within the probable limits expected, and no comparison is made for the parameters.

SHAFT-TO-FAN AND FAN-TO-SHAFT CONVERSION TIME

In engine Types I, II, and III, it is basically a problem of moving the fan inlet and exit vanes. These vanes can be moved in a matter of less than 1 sec. It has been suggested that the pilot will require a time period of about 15 sec to make a conversion. While the propulsive force shifts from the rotor to the fan, and the lift force shifts from the rotor to the wing, the pilot must have time to react, since he must maintain correct speed and altitude.

In the case of the torque converter, as used in Types IA, IIA, and IIIA, the shaft-to-fan conversion time is a function of the filling time for the converter coupling and the resulting heat rejection and peak converter oil temperature. The minimum engagement time is approximately 10 to 20 sec.

INSTALLATION CHARACTERISTICS

From the installation standpoint, all fan/shaft engines studied will have additional problems compared to the present-day turbofan engines, as shown by the additional control functions. For example, the IA, IIA, and IIIA types may have a requirement for a larger oil system to accommodate the greater heat rejection encountered with use of any of the decoupling devices.

FINAL SELECTION

To summarize the results of the comparisons of the parameters used for the evaluation, Table XIII shows the relative position of the six engines with respect to each other. As previously mentioned, the number of complexities or risk areas, etc., which an engine has is not a direct measure, since some problem areas may be far more serious than others. Therefore, the ratings must be considered in light of the specific problem areas discussed throughout this report.

In making an engine selection for final evaluation, the following factors are to be considered:

1. The basic performance requirements have been met—3500 lb minimum for 400-kn SL cruise and 2750 shp, or over, as a capability at SLS.

2. The low fuel consumption for hover and cruise is commensurate with the duty cycle required by the mission.

3. The engine is free from serious risk and development problems.

4. Zero fan thrust at takeoff is very desirable. It is assumed that a value of 600 lb can be tolerated in the present selection.

TABLE XIII. COMPARISON OF FAN/SHAFT ENGINE CHARACTERISTICS

Type	SFC* Cruise/Hover	Mechanical Complexity	Risk and Development Problems	Weight (%)	Number of Control Functions	Relatively Wetted Area (%)	Conversion Time (sec)
I_S	0.697/0.699	2	1	89.5	3	100	1
IA	0.697/0.464	3	2	82	4	85.5	15
II	0.698/0.732	4	3	77	4	88.5	1
IIA	0.698/0.450	6	4	88	5	93.5	15
III	0.753/0.697	4	3	95.5	3	87.5	1
IIIA	0.753/0.480	4	3	100	4	87.5	15

*Thrust sfc at 400-kn SL/shaft sfc at 2000 shp, 6000 ft, 95°F.

Type IA is selected for further preliminary design definition for the following reasons:

1. It has a fuel consumption as low as any of the types considered.

2. It has a relatively low number of mechanical complexities, risk and development problems, and control functions. None of these problems is of a serious nature, although the decoupler adds significant complication.

3. It has a relatively low weight.

In view of the lack of data required for the analysis of a high-speed variable geometry fan, operating at extreme angle changes of the IGV and EGV, it is recommended that consideration be given to the merits of a configuration which does not require a decoupling device.

As an alternate selection, it is recommended that consideration be given to the Type II engine if hover fan thrust can be reduced to an acceptable value. This selection is based, primarily on the fact that this type of engine does not require a decoupling device, it has favorable weight and performance, and it does not have major complexities or mechanical risk areas.

COMPARISON AND SELECTION OF A DECOUPLER

Four devices were analyzed for possible use in decoupling the fan of the fan/shaft engine. The decision to select the torque converter as the preferred device was based on the following comments.

Differential Gear

The differential gear is considered to be one of the least promising systems for the following reasons:

1. The speed relationships required between the fan and rotor shafts during shifting is basically incompatible with the constant-speed helicopter rotor mode of operation.

2. The resulting gap in power, which will occur during shifting, makes it very improbable that constant altitude and aircraft speed can be held.

3. The required combination of gears and brakes is mechanically complex.

4. The heat rejection problem is still present with this system due to the braking force required.

Friction Clutch

The friction clutch is considered to be a possible solution to the engagement problem. However, it is not recommended because the cooling of the clutch plates is very critical. It requires very high oil-flow rates, and a slight variation in oil distribution to all the plate surfaces can result in plate warpage and low service reliability.

Hydraulic-Type Couplings

Two types of hydraulic devices have been considered. The simple two-element hydraulic coupling requires a gearset and is, therefore, more complicated and heavier than a three-element torque converter, which requires no gearing. While the torque converter will be a development problem, it is nevertheless feasible.

Therefore, the torque converter is recommended as the most preferable fan decoupling device.

DEFINITION OF SELECTED CONFIGURATION

The Type IA engine was selected for further definition, with the intent of making available detailed information which could aid in the preliminary design of compound/composite aircraft. The general design and a possible engine arrangement are shown, and basic performance characteristics are presented. Scaling data are provided, feasibility and risk areas are defined, and a conversion analysis of the aircraft operation is shown as an initial step in analyzing the shaft-to-fan and fan-to-shaft operations of an aircraft.

DESIGN ARRANGEMENT

A sketch of the Type IA arrangement is shown in Figure 32. The fan assembly incorporates a full-length IGV and a fixed EGV. The bypass and gas generator flow streams are split aft of the EGV. In the cruise mode, the fan is driven through a solid mechanical drive. During fan engagement and disengagement, the hydraulic torque converter, located adjacent to the fan, is filled with oil so that the mechanical drive may be disengaged while the converter is carrying the full torque load. When the engagement or disengagement is complete, the converter is emptied of the oil. During converter operation, the IGV is in the full reset position to reduce the power transferred and to lower the heat rejection. The primary jet nozzle has two operating positions. In the shaft power mode this area is 180% of the area in the fan mode of operation.

A power-turbine speed of 85% was selected for operation in the helicopter mode (10, 500 rpm), which partially dictated the sizing of the PTO drive and the torque converter.

It was assumed that the rotor transmission would have the proper gear ratio to operate the rotor at 100% of its design speed. This means that the fan will operate at 85% speed after engagement; then after the rotor is decoupled, the fan speed may be increased to 100% N_{LP}.

The selection of 85% N_{LP} for takeoff was based on the following considerations:

1. The power output of the turbine of the Type IA engine is only slightly reduced by reducing the speed from 100% and is still equal to 2000 hp for takeoff at 6000 ft on a 95°F day.

2. The fan power is appreciably reduced at 85% N_{LP} with the IGV at the maximum reset position, thus making power available for the rotor and thereby permitting fan engagement at a lower air-speed for greater acceleration.

3. Lower fan engagement power results in less heat rejection from the torque converter to the oil, thus reducing the size of the heat exchanger required.

4. Decreasing the power turbine speed increases the size of the bevel gearset required to drive the rotor. A power turbine speed of 85% N_{LP} results in the largest gearset which will fit within the fan flow path of the Type IA engine.

Note, however, that approximately 5% more shaft power is possible if the engine and rotor speed can be increased to 100% N_{LP}. This may be a desirable operating technique to obtain additional hover power.

Table XIV shows engine characteristics of the Type IA engine and Table XV shows a weight breakdown.

TABLE XIV. ENGINE CHARACTERISTICS

	Helicopter Mode	Fan Mode
Airspeed, Kn, SL Standard Day	0	400
Power Turbine Speed, rpm	10,500 (85% N_{LP})	12,350
Maximum shp	2750 (85% N_{LP})	0
Total Airflow, lb/sec	20.6	183.7
Total Engine Thrust, lb	304	3500
Fan Speed at Maximum Rating	0 to 10,500	12,350
Shaft sfc-Thrust sfc	0.462	0.697

The major dimensions of the engine are included in the scaling data which follow.

Operation of Torque Converter

The torque converter will be filled with oil and will transmit torque only for the short period of time which is required to engage the fan and for a similar short period during disengagement. For cruise, fan power will be transmitted through a solid mechanical drive and the torque converter will be empty.

TABLE XV. WEIGHT BREAKDOWN FOR TYPE IA ENGINE	
	Weight (lb)
Fan Assembly	162
Bearing Support and Transition	77
Torque Converter	35
90° Rotor Drive	47
Gas Generator	370
Fuel and Control System	99
Miscellaneous (Including Torque Converter Supply Pump)	60
Total Engine Weight	850

Due to the inefficiency of the converter, heat will be rejected to the oil during the short engagement and disengagement periods. Based on the Appendix II studies, a maximum of 4000 BTU will be rejected during the 10- to 15-sec period required to accelerate the fan and to lock it in solid engagement. Approximately 2500 BTU will be rejected during disengagement when the converter will be filled to facilitate removal of the lockup spline.

These periodically high heat rejection rates may require that the normal turbofan oil system be slightly modified. It is estimated that, in the fan mode, the engine will reject about 1000 BTU/min and require oil flow of approximately 40 lb/min. During the engagement and disengagement periods the oil flow will need to be temporarily increased to about 190 lb/min. This appears to be no particular problem but will require an additional engine-furnished pump which would normally bypass the converter. A slightly larger oil tank and heat exchanger may also be required. This would be a subject for additional study.

Definition of Control System

To define an engine control system for the Type IA engine and explain how it operates in the aircraft, the pilot control inputs must be assumed. The engine control system which has been defined requires the following pilot inputs:

1. Throttle (equivalent to aircraft throttle and helicopter twist grip)

2. Collective and cyclic pitch of helicopter rotor

3. Helicopter rotor speed trim ("beeper")

4. Inlet guide vane position lever

5. Fan "decoupler" switch (2-position)

6. Rotor clutch switch (2-position)

7. Primary exhaust area setting

The control system operation is so interrelated to the aircraft operation that the following control description is presented in relation to aircraft flight modes.

Helicopter Mode Operation

Operation in the helicopter mode is essentially identical to a normal turboshaft installation. Before takeoff the fan is decoupled and the fan inlet guide vanes are placed in the maximum reset position. The primary exhaust nozzle area is placed in the open (180% of design) position. The low-pressure rotor speed governor is nominally set for 85% of the design speed. The basic engine control mode is shown in the functional diagram in Figure 49. In the helicopter mode, its operation is as follows:

The pilot uses conventional helicopter techniques of modulating collective and cyclic pitch for normal flight and maneuvering. Low-pressure rotor speed is governed for primary power control from flight idle (zero horsepower) to maximum. This governing is of the proportional (droop as opposed to isochronous) type. A coordinated reset of the governor setting, as a function of collective pitch, minimizes steady-state droop, and it provides anticipation which minimizes transient speed excursions. A dynamic lag function is also included to ensure torsional stability compatibility with various possible helicopter rotor systems.

The high-pressure rotor speed governor, with appropriate adjustments, is set as a function of the throttle position. This is an all-speed governor, but for the helicopter application it will normally be set either at ground idle or at maximum for high-pressure rotor speed limiting, with the engine power modulation accomplished by the low-pressure rotor speed governor.

The turbine temperature limiter is a limited-authority proportional-plus-integral closed-loop control which provides steady-state limiting with zero temperature error. The temperature limiter functions by resetting the high-pressure rotor speed governor. The outputs of the electronic computer are converted from electrical signals via torque motors.

The start and acceleration scheduling is provided by scheduling W_f/CDP as a function of high-pressure rotor speed and as a compressor inlet temperature bias. The lowest value of W_f/CDP is selected between the start and acceleration schedule, the high-pressure rotor speed governor, and the input from the low-pressure rotor speed governor electronic computer. Deceleration scheduling is provided by limiting the minimum value of W_f/CDP. Multiplying the resultant W_f/CDP by compressor discharge pressure defines the metered fuel flow which must be between the minimum and maximum fuel stops.

The compressor variable geometry position is scheduled as a function of high-pressure rotor speed and compressor inlet temperature. Fuel will be employed as the hydraulic fluid for positioning the geometry. A variable-position feedback will be used in the control loop to ensure proper positioning.

The output shaft is prevented from being exposed to excessive torque by properly setting the maximum fuel flow stop.

The optional load-sharing control receives a torque signal from each engine and attempts to bring the output torque of each engine up to the level of the highest individual engine. This is accomplished by increasing the low-pressure rotor speed governor setting of all but the highest output torque engines.

The fuel cutoff valve is directly positioned mechanically by the throttle lever. The cutoff valve will be open when the throttle is at, or above, the ground idle position.

Transition

The transition cycle consists of two phases. One phase is to bring the fan up to speed and engage it to the low-pressure turbine. The other phase is the portion associated with aircraft conversion wherein the rotor is ultimately unloaded, stopped, and stowed.

The fan engagement cycle, using the torque converter to bring the fan up to synchronous speed, was studied on the analog computer. The simulation included characteristics of the Type IA engine and fuel governor, the rotor system inertia and load maximum reset IGV, and the torque converter. Details of the simulation are included in Appendix II. This study compared the heat rejection and the LP rotor speed droop resulting from different torque converter filling rates. Since inertias were estimated, they were also varied to assess their significance. Sample traces of the results are also included in the appendix. The results are summarized in Figure 50, which shows the peak heat rejection and speed droop as a function of converter filling time. The effect of various fan inertias is also shown on the curves. Variations in rotor inertia were less significant.

This study showed that a linear filling rate of 5 sec produces a heat rejection and a rotor speed droop that are quite acceptable. Longer filling times could be selected if they more nearly match the desired aircraft requirements. Shorter filling rates require detailed analysis of oil cooling and the rotor speed droop effect on the aircraft.

Once the fan speed becomes synchronous with the low-pressure rotor speed, a helical spline is engaged to provide a solid fan drive, and the torque converter is emptied. The helicopter rotor and fan are now both running at 85% N_{LP} (100% helicopter rotor speed). The fan thrust provides aircraft acceleration and can be modulated by the pilot through manual selection of the inlet guide vane position between maximum reset and 0 degree.

As wing lift replaces rotor lift, the collective pitch is reduced by the pilot. This quite likely occurs simultaneously with guide vane modulation. When sufficient airspeed is attained so that rotor lift is no longer required, the throttle is retarded until it causes a reduction in low-pressure rotor speed. This is an indication that the engine is operating on the high-pressure rotor speed governor. The collective pitch is then reduced to zero, and the helicopter rotor clutch is disengaged to permit rotor coastdown. Disengagement of the clutch also signals the primary jet nozzle area to close down to the design value, and it resets the low-pressure rotor speed governor to 100%, for limiting purposes, during fan operation.

Aircraft Wingborne Mode

Once the rotor has been stopped and stowed,the engine is operated as a fan engine. Inlet guide vanes are in the 0-degree position, and primary jet nozzle area is at the design value. Thrust modulation is attained by throttle manipulation,which sets the high-pressure rotor governor. The basic engine control is functionally identical to that shown in Figure 49 for the helicopter operating mode with only the mode of operation changed.

Control System Weight

An estimate of the control system weight for the Type IA engine is shown in Table XVI. This estimate is quite preliminary and is based upon the following assumptions.

1. Fuel is used for actuating power.
2. Ignition is independent of aircraft system.
3. Contaminated fuel capability is incorporated without in-line filtration.
4. Combination electronic-hydromechanical fuel control is used as indicated on Figure 49.
5. Boosted, single-element fuel pump operates at 10, 000 rpm.
6. Anti-icing is required.
7. No fuel heater or fuel to oil heat exchanger is required.

The total control system weight is approximately 100 lb, as shown in Table XVI.

PERFORMANCE CHARACTERISTICS

The selected Type IA engine will provide the required shaft power for the helicopter mode and also provide sufficient tnrust for 400-kn flight at sea level. The sea level static operating envelope is illustrated in Figure 51, which shows the thrust and horsepower available.

Point B shows the shaft power and thrust available when operating as a shaft engine with the fan disengaged and the power turbine speed at 85%. Any condition between points A and B may be obtained at part throttle.

When the fan is engaged with the IGV in the maximum reset position, the thrust/power relationship changes from the disengaged condition at point B to the fully engaged condition at point C.

TABLE XVI. ESTIMATED CONTROL SYSTEM WEIGHT BREAKDOWN—TYPE IA ENGINE			
Component	No./Engine	Weight of Each Item (lb)	Total Weight (lb)
Fuel Pump	1	13.0	13.0
Fuel Control	1	18.0	18.0
Fuel Nozzle	16	0.35	5.6
Flow Divider	1	2.5	2.5
Amplifier	1	4.0	4.0
Alternator, Ignition	1	4.5	4.5
Exciter (Dual Circuit)	1	4.0	4.0
Igniter	2	0.4	0.8
Ignition Leads	2	0.7	1.4
Flameout Sensor	1	1.0	1.0
Thermocouples and Harness	1	4.0	4.0
Anti-Ice Valve	1	1.5	1.5
Actuator (Fan - IGV)	2	2.0	4.0
Actuator (CVG)	2	2.0	4.0
Primary Exhaust Nozzle Solenoid Control	1	2.5	2.5
Primary Exhaust Nozzle Actuator	4	2.0	8.0
Torque Converter Solenoid Valve	1	2.5	2.5
Electrical Harness	1	4.0	4.0
Fuel Plumbing	1	14.0	14.0
			99.3 Total

As the IGV is moved from the maximum reset position to the 0-degree position, the thrust/power values change from point C to point D.

The next operation in the sequence is to change the jet nozzle from the 180 to 100% area, which changes the power/thrust to that shown by point E.

The maximum thrust value shown by point F can now be achieved by increasing the N_{LP} from 85 to 100%. At this point the shp is zero since all of the turbine power is now being absorbed by the fan.

Note that the engine operates as a shaft engine from point A to B, as a pure fan engine from F to A, and as a fan/shaft engine from F to B. Steady-state operation in the area ABC is not possible since this represents partial fan engagement. Part throttle operation is possible in the area ACF.

The line from B to F represents full throttle operation. Operation in the area ACF is possible at part throttle.

Figure 52 shows the estimated sfc versus shp characteristics of the engine as it would be operated in the helicopter mode at sea level. Data are presented for the hover condition and for 300-kn flight speed.

Figure 53 shows similar characteristics as a pure fan engine when no shaft power is available. Thrust specific fuel consumption versus thrust characteristics are shown at zero and at 400-kn flight velocity.

Figures 5 and 6 show the original sizing curves for the Type I engine; therefore, they represent the Type IA engine performance in the fan mode at maximum output (2200°F) at sea level, standard flight conditions.

Figure 21 also shows shaft power and thrust of the Type IA engine for various N_{LP} values at sea level.

Additional data are furnished for the Type II engine in Figure 54,so that an analysis may be made of a conversion with a nondecoupled fan. Note that point B is omitted since this engine does not operate with the fan disengaged.

DIMENSIONAL AND SCALING DATA

To assist in making preliminary design and trade-off studies of compound/composite aircraft, dimensional and scaling data for the Type IA engine are furnished. This includes engine weight and scaling curves over a range of 70 to 150% of the design study size. Table XVII presents all of these major values over the range of 80 to 120%. In addition, curves are furnished to show the size and weight changes in the power-takeoff drive assembly which result from changes in the output shaft speed. These data may be used for trade-off studies of power transmission shafting from the engine to the rotor transmission.

TABLE XVII. SCALING DATA FOR TYPE IA ENGINE						
(Sea Level Standard Inlet Conditions)						
Scale Factor		0.8	0.9	1.0*	1.1	1.2
Helicopter Mode Horsepower		2200	2480	2750	3040	3300
Fan Mode, 400-Kn Thrust		2800	3150	3500	3850	4200
A	Height	6.9	7.3	7.7	8.1	8.4
B	Diameter	27.2	28.8	30.3	31.8	33.2
C	Diameter	11.0	11.7	12.25	12.9	13.4
D	Diameter	26.1	27.6	29.1	30.6	31.9
E	Diameter	19.0	20.2	21.2	21.2	23.2
F	Diameter	11.8	12.5	13.2	13.9	14.5
G	Length	77.9	81.5	85.0	88.4	91.5
H	Length	2.8	2.9	3.0	3.1	3.2
I	Length	61.0	64.0	66.6	69.1	71.6
J	Diameter	15.0	15.9	16.7	17.6	18.3
K	Diameter	20.8	22.0	23.2	24.4	25.4
L	Diameter	12.9	13.7	14.4	15.1	15.8
M	Length	11.8	12.4	12.9	13.4	13.9
Engine Weight, lb		712	782	850	920	985

Notes:
1. See Figure 55 for location of dimensions.
2. All dimensions are in inches.

*Sizing point for this study

Basic Engine Scaling

For the purpose of scaling the basic engine, Figure 55 shows a schematic of the Type IA engine with reference letters indicated for the major dimensicns. These are used for reference with Table XVII, which tabulates the corresponding dimensions for a scaled engine in the size range of 0.8 to 1.2 times the basic engine, with data shown in 0.1 increments. Figures 56 and 57 show curves of scaling factors for radial and longitudinal engine dimensions and weight from 0.7 to 1.5 times the basic engine size.

Power-Takeoff Drives

For the purpose of scaling the power-takeoff drive with the 45-degree output shaft, Figure 58 shows the actual length and the radial dimensional changes for various output shaft speeds plotted against turbine speed. Figure 59 shows weight data.

Similar data for the drive having the 90-degree output shaft are shown in Figures 60 and 61, respectively.

CONVERSION ANALYSIS

The following analysis shows a proposed sequence of events to aid in achieving maximum aircraft performance from takeoff, through the conversion to the fixed-wing aircraft mode. In Figure 62, a comparison is made of the maximum engine power and thrust available and the aircraft power and thrust requirements for a takeoff and transition at 6000 ft, 95°F inlet temperature conditions for the Type IA engine configuration.

For each step in the complete conversion cycle, the end points have been calculated. The transient conditions between the end points will be the subject for future definition, requiring detail aircraft characteristics.

For this comparison, the fan is assumed to be engaged at the minimum aircraft velocity at which there is sufficient power to drive both the fan and the rotor, since rotor power required decreases with aircraft velocity. It is shown that if engagement is made at this velocity, there will be an excess power at all other points in the conversion operation. While it was assumed that there was no excess of power at the specific engagement point, there could be an excess at the engagement if a higher aircraft speed is selected for this step of the operation.

Figure 63 shows the aircraft power characteristic in the helicopter mode. For use in this study, it was assumed that the power required would include a 10% increment to provide for the effects of the altitude hot-day conditions and a small surplus power for aircraft maneuvering.

Figure 62 presents the proposed sequence. The data are not intended to define all conversion conditions precisely, but rather to show that with this sequence there can be excess power at all times; the most critical point will be at fan engagement. These data represent a fan engagement at 65 kn, the minimum aircraft speed at which there is sufficient power to operate both the rotor and the fan.

A takeoff and conversion from the helicopter mode to the fan mode at 6000 ft, 95°F inlet temperature are described as follows:

1. Takeoff and Acceleration

   At zero velocity and 85% turbine speed, the power available is equal to the power required. However, as the aircraft velocity increases the power required becomes less. The pilot may use the extra power for acceleration. Since the fan is not operating, the engine thrust shown comes from the primary jet. The fan may be allowed to windmill as the velocity increases.

2. Fan Engagement

The fan, with the maximum reset IGV setting, may be engaged when an aircraft speed of approximately 65 kn is reached, assuming the aircraft characteristics in Figure 63. This speed is determined to be the lowest speed at which there is sufficient power available to operate the helicopter rotor and to drive the fan through the torque converter. As shown in Figure 63 when the 65-kn speed is chosen, there is a period when there is nc excess power. A power margin may be obtained by engaging the fan at a higher aircraft speed, since less rotor power would be required.

As the fan speed increases, supercharging is added to the inner spool. This results in added turbine expansion ratio and additional shaft power output from the engine. The additional power is partly absorbed by the fan and by the torque converter heat loss prior to lockup. The fan power increases approximately as the cube of the speed; however, the input power to the torque converter will depend on the filling schedule of the oil and the efficiency of the partly filled converter. The characteristics of this transient have been analyzed by an analog computer and are presented in Appendix II. Additional thrust also becomes available as the fan is engaged. This added thrust causes added aircraft acceleration.

Table XVIII shows how the available power is divided with the fan and turbine operating at 85% rpm.

TABLE XVIII. POWER DISTRIBUTION ANALYSIS

(6000 ft, 95°F Condition)

HP Absorbed by Fan (Max Reset IGV)	1410
Torque Converter Efficiency	0.83
HP Lost to Heat	290
Torque Converter Input HP	1700
Total Engine Gross HP	3080
HP Available for Rotor	1380
Total Two-Engine Available HP	2760
Minimum Aircraft Velocity, Kn	65

3. <u>Operation of the Inlet Guide Vanes</u>

After fan engagement, the pilot may modulate the engine thrust by turning the fan inlet guide vanes. The pilot can use the IGV to bring the aircraft to the 120- to 140-kn speed which is necessary before the rotor can be unloaded.

4. <u>Unloading the Rotor</u>

After 120 kn is reached, the pilot may elect to unload the rotor by decreasing the collective pitch. During this period, the control of the throttle must transfer from the rotor governor to the pilot. At this time, the IGV will be locked in the zero setting.

After unloading, the rotor will be declutched and braked to a stop in the correct position for folding.

There is now sufficient power margin so that the jet nozzle may be reduced from the 180% area to the 100% area. When the nozzle area is decreased, the gross power decreases; however, the engine thrust increases. This is the final step in completing the fan/shaft engine conversion. The fan speed may now be increased to 100%.

5. <u>Fold and Store Rotor, Raise Flaps</u>

During this period the pilot will have an excess of thrust available. With the IGV now locked in the 0-degree setting, the pilot will control the thrust with the throttle to keep the aircraft speed within the 120- to 140-kn range, while the rotor is stored and the flaps are raised.

6. <u>Accelerate Aircraft</u>

The pilot may increase the throttle setting to provide the airspeed desired.

The conversion from the fan to the helicopter mode would essentially be the reverse of the preceding procedures, with some minor modifications.

Using the performance data defined previously for the Type IA engine, the following analysis is shown to illustrate the use of the engine performance data presented in Figure 51.

Figure 64 shows the fan thrust and shp versus flight speed at sea level standard conditions. (This must be corrected for flight conditions.) Point A shows the thrust and shp at takeoff with the fan decoupled. At point B, which is selected at the airspeed desired for fan engagement, the performance values move from the "disengage line" to point C on the "fan-engaged" line with the IGV in the maximum reset position. From point C to point D, the pilot controls the IGV position for fan thrust modulation. The airspeed values shown for these points are not intended to be specific values. They will be determined by the aircraft requirements.

After the rotor has been disengaged, the primary jet area can be moved to the closed (100%) position (point E to F). This could be an automatic, simultaneous control, or at the pilot's option at a later time.

Since the rotor is disengaged, the LP turbine-fan limit governor can be set to 100% N_{LP} (point G).

The engine is now in the cruise-fan mode for fixed-wing operation.

FEASIBILITY AND RISK AREAS

Feasibility

The component performance used in this analysis was based on 1970 technology level. The turbine, compressor, burner, and other component performance levels defined in Table II are consistent with this time schedule and are considered to be feasible for this program.

The PTO drive and torque converter parameters are completely feasible and are shown in Table XIX. The mechanical efficiency and tooth stresses are based on values that have been demonstrated. The design pitch line velocities are within current state of the art; however, higher values in this case are not desired because a large drive gear would be necessary to achieve them, and this would interfere with the transition flow path. Note that in the fan mode, the unloaded rotor drive gears achieve a pitch line velocity of 29,400 fpm when the turbine speed is 100%. This appears to be satisfactory for a no-load condition.

The torque converter size and performance were obtained by scaling an existing unit. The calculated diameter for the required converter in the Type IA engine is about two-thirds of the diameter of the reference converter, and the speed is about four times that of the reference converter. Investigation has revealed that a converter of the desired size has been run at high speed, approaching the requirement.

TABLE XIX. SUMMARY OF POWER-TAKEOFF DRIVE AND TORQUE CONVERTER PERFORMANCE	
Power-Takeoff Drive (2600 shp, 10,500 rpm N_{LP})	
Mechanical Efficiency, %	99
Tooth Stress, Bending (Gleason Rating), psi	25,000
Crushing (Hertz Stress), psi	175,000
Pitch Line Velocity, ft/min	
90-degree Set	25,000
45-degree Set	21,500
Torque Converter	
Peak Efficiency, %	87
Efficiency at 1:1 Speed Ratio, %	83

Stress analysis indicates that with aircraft-type materials,the required speed appears to be feasible from a mechanical standpoint. Heat problems may be encountered at the initial filling of an empty, high-speed converter.

This design is believed to be feasible, but the performance characteristics and the filling problems should be further studied with an experimental test.

The integration of the aircraft and the propulsion system will involve additional control problems compared with present conventional helicopters, as shown in Table XI.

Identification of Risk Areas

The Type IA engine is relatively low in the number of risk areas, which is a major reason for selecting it. Two specific risk areas have been defined; namely, the torque converter fan decoupler and the actual performance with the variable IGV.

Torque Converter

A lightweight, high-speed converter is new for aircraft applications. A stress analysis indicates that the high rpm can be safely accomplished with aircraft-type materials. There is, of course, a vast amount of background on automotive and industrial-type converters at lower speeds, but this application is unique in that filling the empty coupling is accomplished at high speeds, which may cause some oil heating problems. The performance was calculated by the usual equations by scaling the speed-torque characteristics of an existing model torque converter. The peak efficiency for the coupling was 87%, and the efficiency for 1.0:1 speed ratio was assumed to be 83%. These efficiency characteristics need confirmation at the higher speeds required.

Inlet Guide Vanes

The inlet guide vanes are used as a means of thrust modulation during the transition. Additional confirmation of performance from tests may be desired.

CONCLUSIONS

The following conclusions are specifically applicable to a convertible fan/shaft engine arrangement having the fan concentric with the gas generator axis.

1. The cruise-thrust/shaft power requirements specified for this study can be satisfied by the use of a variable primary jet nozzle and a variable fan geometry.

2. For aircraft requiring a substantially higher power/thrust ratio than specified for this study, fan decoupling is necessary.

3. A zero fan thrust requirement at hover can be satisfied only by fan decoupling.

4. If a small amount of fan thrust can be tolerated at hover, the use of extreme fan inlet and exit vane angles offers a potential means of achieving this objective. However, fundamental data on high-pressure ratio fan performance with extreme guide vane angles are not available.

5. Of the configurations studied, Type IA appears to be the best one for meeting the requirements specified for this study.

6. The torque converter appears to be the best means for fan decoupling.

7. A PTO drive can be located in either the fore or the aft section of the engine, and it presents no serious development problems.

8. A power control system for coordinating shaft power and fan thrust during all flight modes appears to present no serious development problems.

9. The sequence for operating engine variables during conversion requires correlation with airframe studies.

RECOMMENDATIONS

It is believed that the selected fan/shaft engine is sufficiently attractive and that subsequent steps should be taken toward developing the concept further. At the present stage of the program, consideration should be given to two approaches: the decoupled fan as in the Type IA engine, and the variable geometry fan as in the Type II engine. The following steps are recommended:

1. Further design and development is needed to better define a high-speed torque converter for fan coupling.

2. Experimental work should be conducted to determine the minimum fan thrust and power that can be obtained with variable fan geometry in the range of 70 to 100% rated speed.

3. Further discussions with aircraft companies should be conducted regarding conversion sequence, minimum fan thrust at hover, thrust modulation with fan IGV, and installation penalties associated with a torque converter for fan decoupling.

APPENDIX I
CYCLE SELECTION

SUMMARY

When the various configurations and the large number of combinations of cycle parameters are considered, it is desirable to obtain commonality wherever possible, so that maximum effort can be concentrated on the major problem areas in defining a fan/shaft engine. Accordingly, a preliminary analysis using mission studies, based on the vehicle requirements, was conducted to determine the extent of cycle and configuration commonality that could be used without seriously compromising the desired engine comparison.

The mission studies showed that for the purpose of a fan/shaft definition study, the parameters shown in Table XX are reasonable.

TABLE XX. CYCLE PARAMETERS SELECTED FOR FAN/SHAFT ENGINE DEFINITION STUDY

	R_c Overall	BPR	TIT(°F)
Supercharged Engine	23.0*	4.0	2200
Unsupercharged Engine	14.0*	4.0	2200

*Common HP compressor

MISSION ANALYSIS

The selection of bypass ratio, peak cycle temperatures, and pressure ratio for the stowed-rotor composite aircraft is dependent primarily on the following turbofan engine characteristics:

1. The relationship between the thrust available for the 400-kn V_{max} condition and the shaft power available for hover at 6000-ft, 95°F conditions

2. The engine fuel economy at primary operating condition in the aircraft mission

These engine characteristics were examined for a family of turbofan engines using an estimated mission.

Characteristics for 25 engines, which were used in the cycle selection, encompassed a range of cycle parameters as follows:

Bypass ratio	2, 4, 8, and 16
Overall pressure ratio	15, 23, and 30
Turbine inlet temperatures	1900, 2200, and 2500°F

Specifically, the available mission time was calculated and the effect of each parameter on mission time was determined.

Although the engine drag contribution is dependent on the details of the aircraft installation, a generalized trend of drag variation with bypass ratio was included in the study. This drag was calculated for appropriately sized nacelles in free stream at 400-kn true airspeed at sea level. Typical pod drag/net thrust ratio is shown in Figures 65 and 66 for variation in bypass ratio, pressure ratio, and turbine inlet temperature.

The 25 engines were sized for the critical output requirement (thrust required at 400 kn at sea level). The power available for the rotor drive at 6000 ft and 95°F was determined. In all cases, adequate power was available in the fan turbine to meet hover requirements. Variable geometry in the fan inlet and engine exhaust was included to minimize fan thrust and to maximize power output.

Engine weights were then calculated based on conventional turbofan data adjusted by a factor of 1.25 for installation effects.

The weight breakdown of typical composite aircraft was estimated. Nominal design propulsion system weight (i.e., engine-plus-fuel weight) of both 7500 and 4500 lb were considered. These values were selected to represent the likely range of propulsion system weight for a 25,000-lb stowed-rotor aircraft for extremes in aircraft structural efficiency and payload requirements. Representative aircraft weight breakdowns are:

	Aircraft	
	A	B
Empty weight less engines, lb	12,500	16,500
Crew and equipment, lb	1,000	1,000
Payload, lb	4,000	3,000
Engine and fuel, lb	7,500	4,500
Takeoff gross weight, lb	25,000	25,000

The available fuel was then calculated in each case considered. This weight was determined by subtracting the calculated installed engine weight from the nominal design engine-plus-fuel weight (7500 or 4500 lb).

Mission time was established based on the following typical power spectrums for a composite aircraft.

Flight Mode	Operating Time (%)
Hover	2
Helicopter flight	18
Conversion	10
Cruise (rotor stowed)	55
V_{max} (rotor stowed)	10
Ground	5

A mission time was calculated in each case, including a 10% allowance for reserves and a 5% conservative factor for calculated fuel flow. The variation of mission time was then studied to assess the effects of the various input parameters. This was done at three cruise speeds; namely, best cruise, 300 kn, and 380 kn. As noted previously, the engines were compared on the basis of mission time at design fuel-plus-engine weight of 7500 and 4500 lb, respectively. The variation in mission time with design bypass ratio and compressor pressure ratio at 2200°F turbine inlet temperature is as shown in Figure 67. This shows that the maximum time possible for both propulsion system weights is achieved by the 23 R_c engine. The best bypass ratio increases from the 2 to 3 range, for the low weight, to the 3 to 4 range for the high weight.

The results, when using the 2500°F turbine inlet temperature, are shown in Figure 68. Trends similar to the lower temperature engines are shown except that the best bypass ratio has increased to 3 for the lower weight and 4 for the higher weight at 23 R_c. Note that the mission time variation is quite small over a broad range of bypass ratios, indicating that the selection could be made on a basis other than maximum mission time. Since the average mission fuel flow is lower at the high end of the desirable range of bypass ratios, the 4 bypass ratio was selected. This trade in improved fuel economy for increased engine weight is estimated to reduce fuel consumption 5 to 6%, as compared to a selection of 2 bypass ratio, and would slightly reduce the fuel logistic problem.

Consequently, additional comparisons to determine the effect of turbine inlet temperature and overall pressure ratio were made at 4 bypass ratio. Figure 69 shows a cut of turbine inlet temperature and compressor pressure ratio for both propulsion system weights. The maximum mission time occurs at the higher temperatures and is essentially constant over the range from 2200 to 2500°F. The constancy results from the trade-off between engine weight and fuel weight, the 2200°F engine having the larger weight and the lower fuel usage. A comprehensive cost effectiveness study with well defined aircraft system and mission characteristics would be required to establish the most desirable choice. As such a study is beyond the scope of this program, we have elected to use the 2200°F value as representative of the technology level available in the 1970 time frame. The choice of pressure ratio is influenced by the desire for a versatile gas generator that can be used for both "supercharged" and "nonsupercharged" turbofan engine configuration studies. The 23 R_c engine offers near-maximum performance in the cycle selection studies at both propulsion system weights, as shown in Figure 69. At 4 bypass ratio, the 23 R_c engine has a gas generator compressor operating at 13 R_c. Unsupercharged, this compressor will operate at approximately 14.5 R_c. Figure 69 also shows a degradation of mission time at 15 R_c, 4 bypass ratio of only 4 to 5% compared to 23 R_c. Thus it appears quite reasonable to use a given gas generator configuration for all engine studies, with only a size scaling to meet thrust requirements.

The foregoing selections have been based on a cruise velocity of 300 kn at sea level. Figure 70 indicates that the cruise speed in the area of best range speed (approximately 220 kn) up to 380 kn has a minor effect on the bypass ratio selection. Figure 69 further shows that at extremely high bypass ratios, the mission time is severely reduced for this size aircraft, because the engine weight increases greatly, causing a large reduction in available fuel.

APPENDIX II
ANALOG COMPUTER STUDY OF TORQUE CONVERTER OPERATION AND CONTROL REQUIREMENTS

An analog computer study was conducted to investigate the operating characteristics and the control requirements associated with using a torque converter to bring the fan from zero to synchronous speed with the LP rotor. Simulation of the control system for the Type IA selected convertible fan/shaft engine was accomplished according to the block diagram shown in Figure 71, whereas a more detailed analog computer schematic is shown in Figure 72. The pertinent details of this simulation are as follows:

1. The engine and fuel governor characteristics were simulated by determining the engine torque as a function of N_P and N_T, as shown in Figure 73. A LP rotor governor gain of 3.0 lb/ft/rpm was assumed, which corresponds to 5% speed droop from zero to maximum horsepower. The HP rotor speed governor effect is included as a limiter on the maximum available engine torque. Since the fan provides supercharging of the gas generator, the engine torque limit is a function of N_T^2 (fan speed squared). A 0.50-sec first-order lag was placed on the engine torque to represent the engine time constant.

2. The rotor load torque was computed as a function of N_P^2 (rotor speed squared).

3. The fan load torque was computed as a function of N_T^2 (fan speed squared).

4. The torque converter performance characteristics were simulated by conventional techniques, which consisted of solving the following equations simultaneously:

$$N_{Pref}^{-2} = SR \tag{1}$$

$$TR = SR \tag{2}$$

$$T_P = (1285 \text{ lb-ft})(\% \text{ fill}) \frac{N_P}{N_{Pref}}^2 \tag{3}$$

$$SR = \frac{N_T}{N_P} \tag{4}$$

$$TR = \frac{T_T}{T_P} \tag{5}$$

The torque converter characteristic curves, Equations (1) and (2), were obtained by scaling typical converter performance curves to the necessary horsepower level. These two nonlinear functions (see Figures 74 and 75) were simulated on the analog computer by means of "function generators." The performance of the torque converter at partially full conditions was simulated by assuming the torque transmitted to be that for a full converter times the percentage of fluid in the converter. The heat rejection (BTU/sec) computation was based on the difference between input and output powers of the torque converter.

5. The rotor and fan speeds were computed by integrating the unbalanced torques with respect to time, i.e.,

$$N_P = \frac{1}{I_R} \left(T_{eng} - T_P - Q_R\right) \, dt \tag{6}$$

$$N_T = \frac{1}{I_F} \left(T_T - Q_T\right) \, dt \tag{7}$$

Polar moments of inertia of 5.5 and 3.0 slug-ft^2 were assumed for the helicopter rotor and low-pressure turbine, and the fan, respectively. These nominal inertial values were varied +50% and -33%, to note the effects on transient response.

Sample traces of the analog results are shown in Figures 76, 77, and 78, which show 2-, 5-, and 10-sec linear rate fill times, respectively. These traces show the more significant parameters as a function of time. The 2-sec fill time results in excessive rotor speed transient droop and in too hign a peak in the heat rejection transient. Fill times of 5 to 10 sec are acceptable in both these respe s.

Changing the rotor load torque level when initiating fan engagement was also investigated. This had essentially no effect on heat rejection, but it did show some increase in peak rotor speed droop. If conversion was attempted when the sum of rotor load torque and fan load torque exceeded engine torque available, the fan was still brought to synchronous speed with the low-pressure rotor by virtue of a large droop in rotor speed.

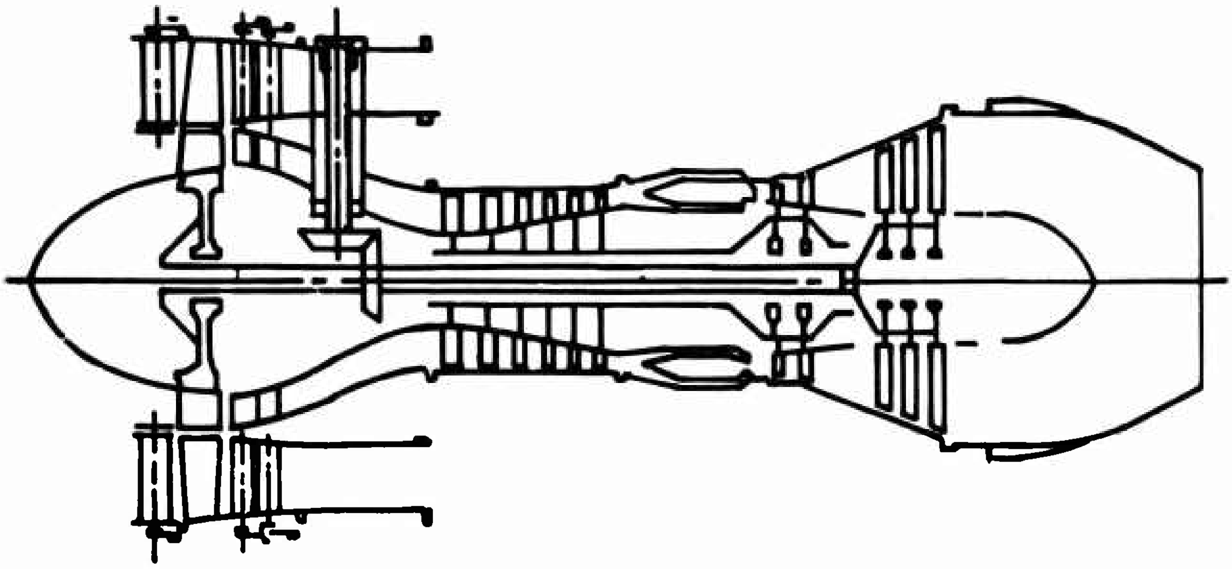


Figure 1. Typical Convertible Fan/Shaft Engine Configuration.

Sea Level, Standard Day

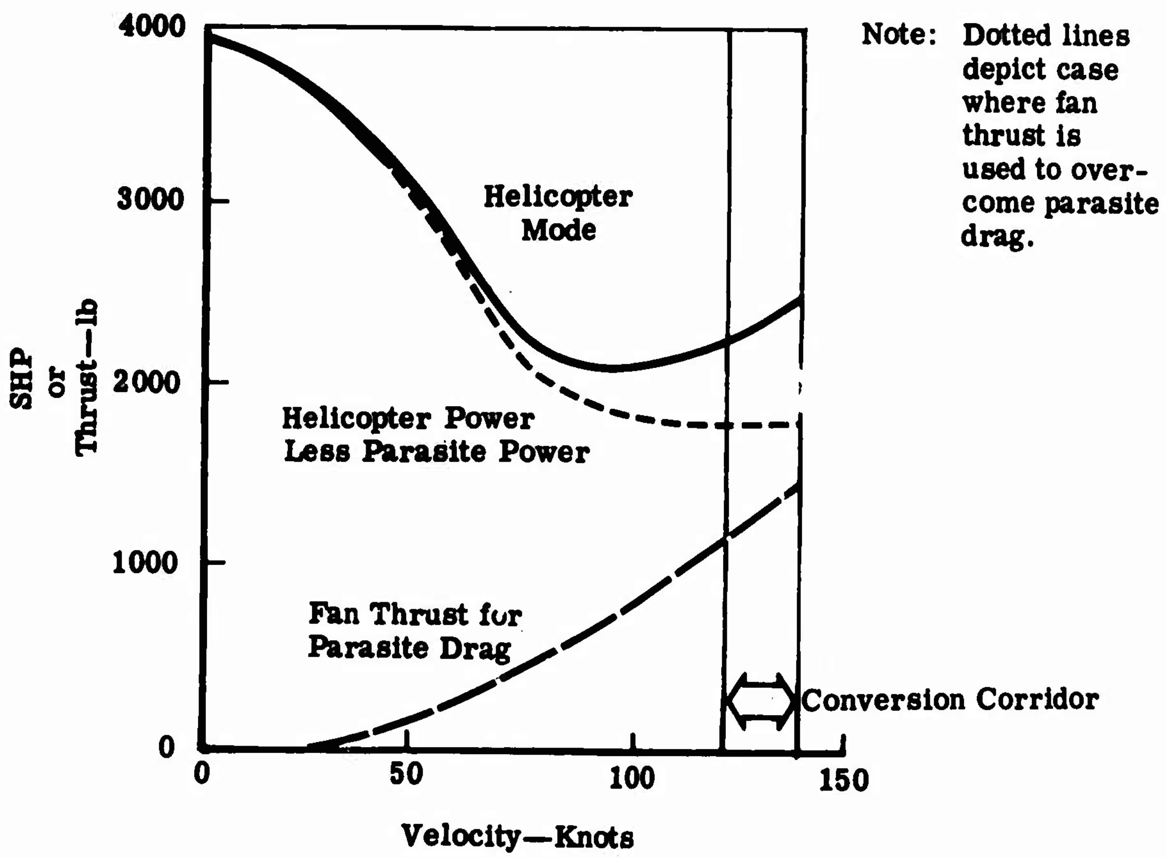


Figure 2. Power Required for Representative Advanced Rotary-Wing Aircraft.

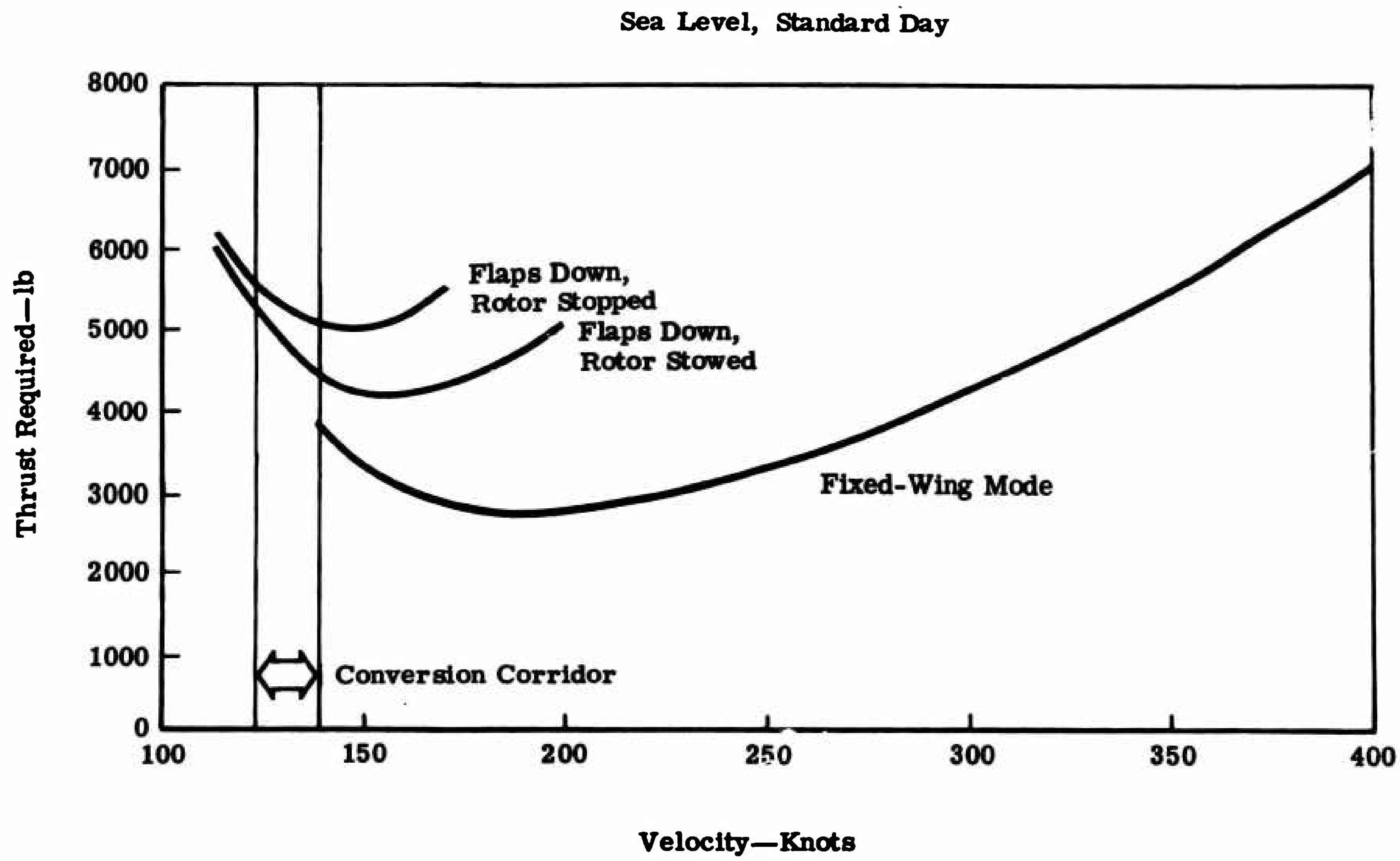


Figure 3. Thrust Required for Representative Advanced Rotary-Wing Aircraft.

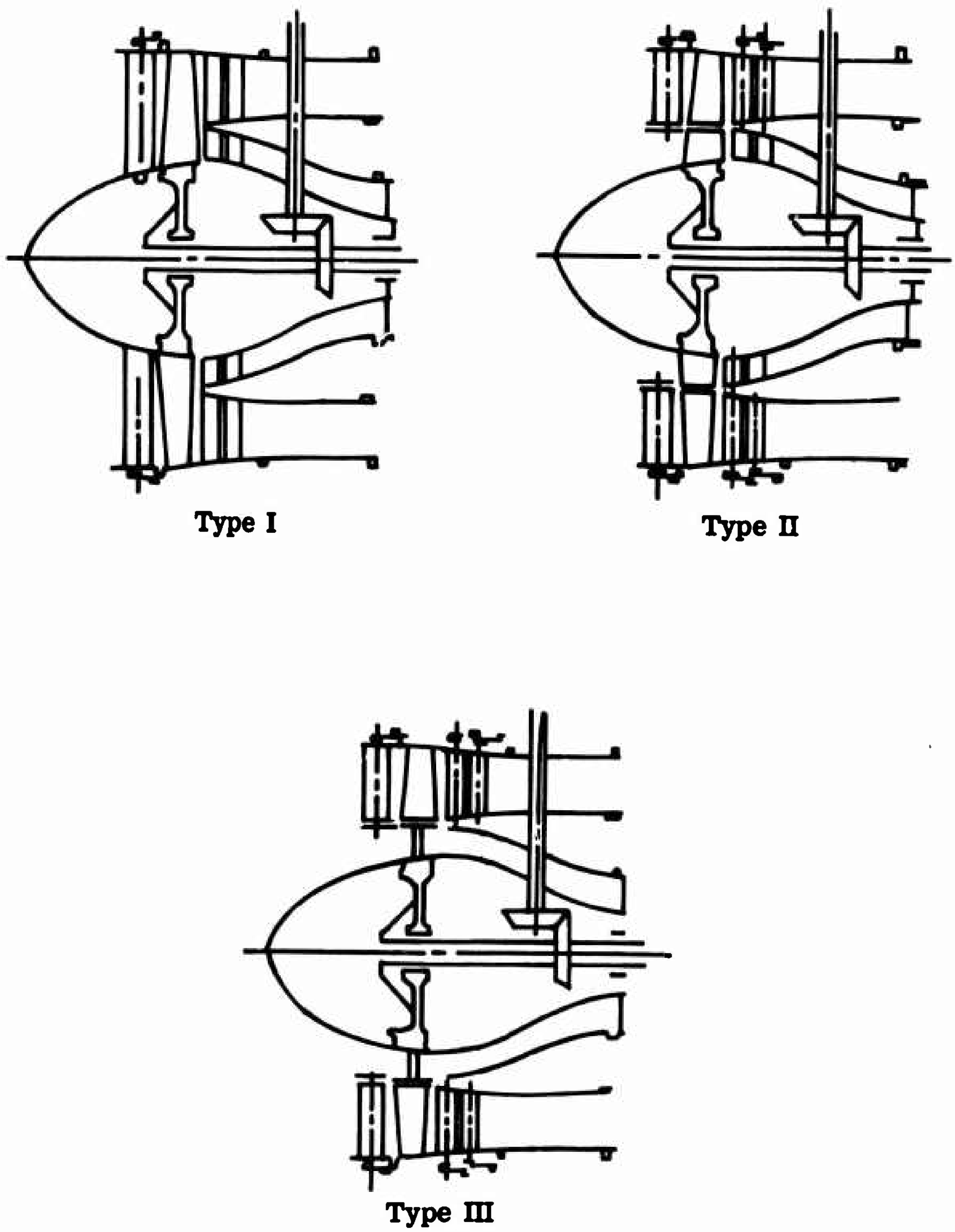


Figure 4. Three Basic Engine Configurations Used for Study.

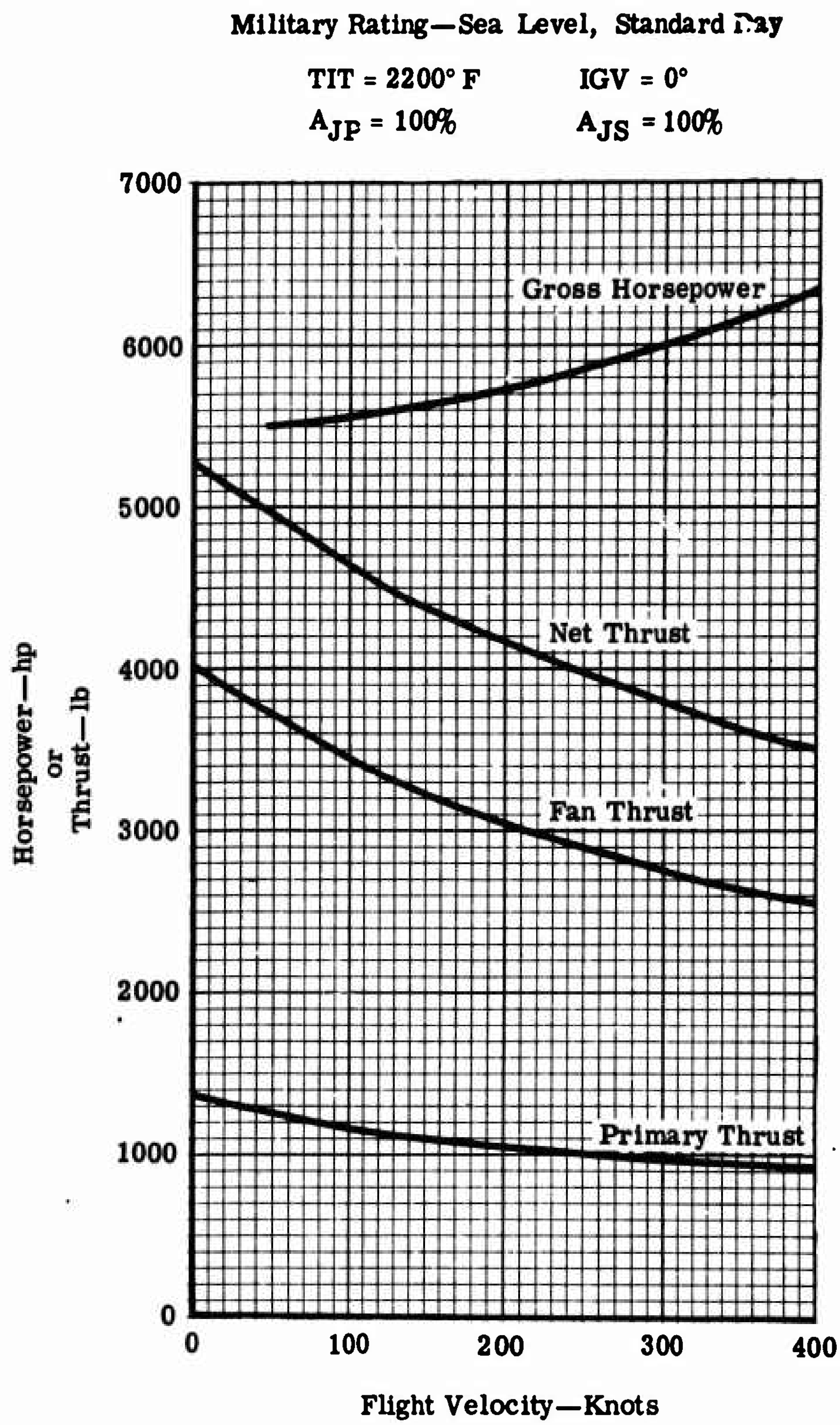


Figure 5. Type I Engine, Cruise Fan Performance Characteristics Versus Flight Speed.

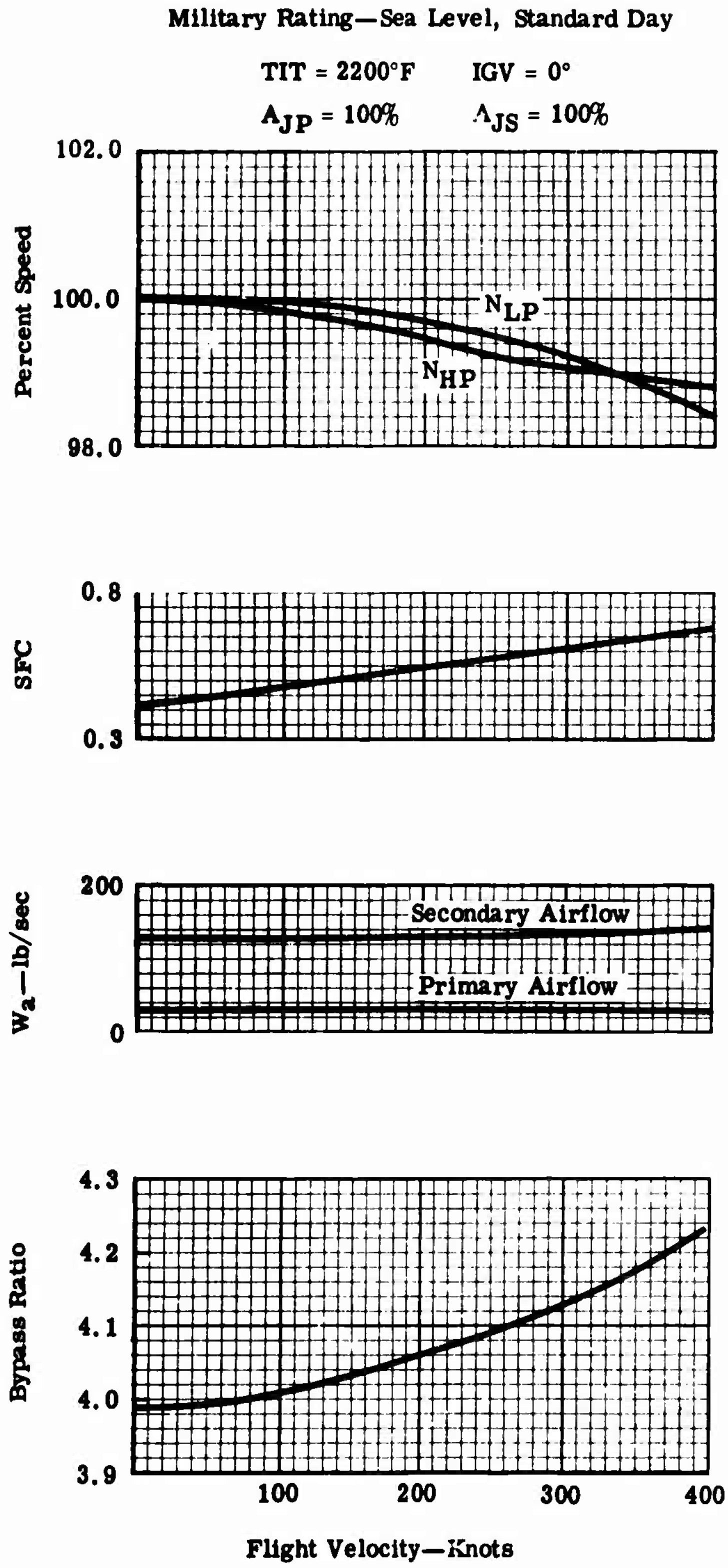


Figure 6. Type I Engine, Cruise Fan Performance Characteristics Versus Flight Speed.

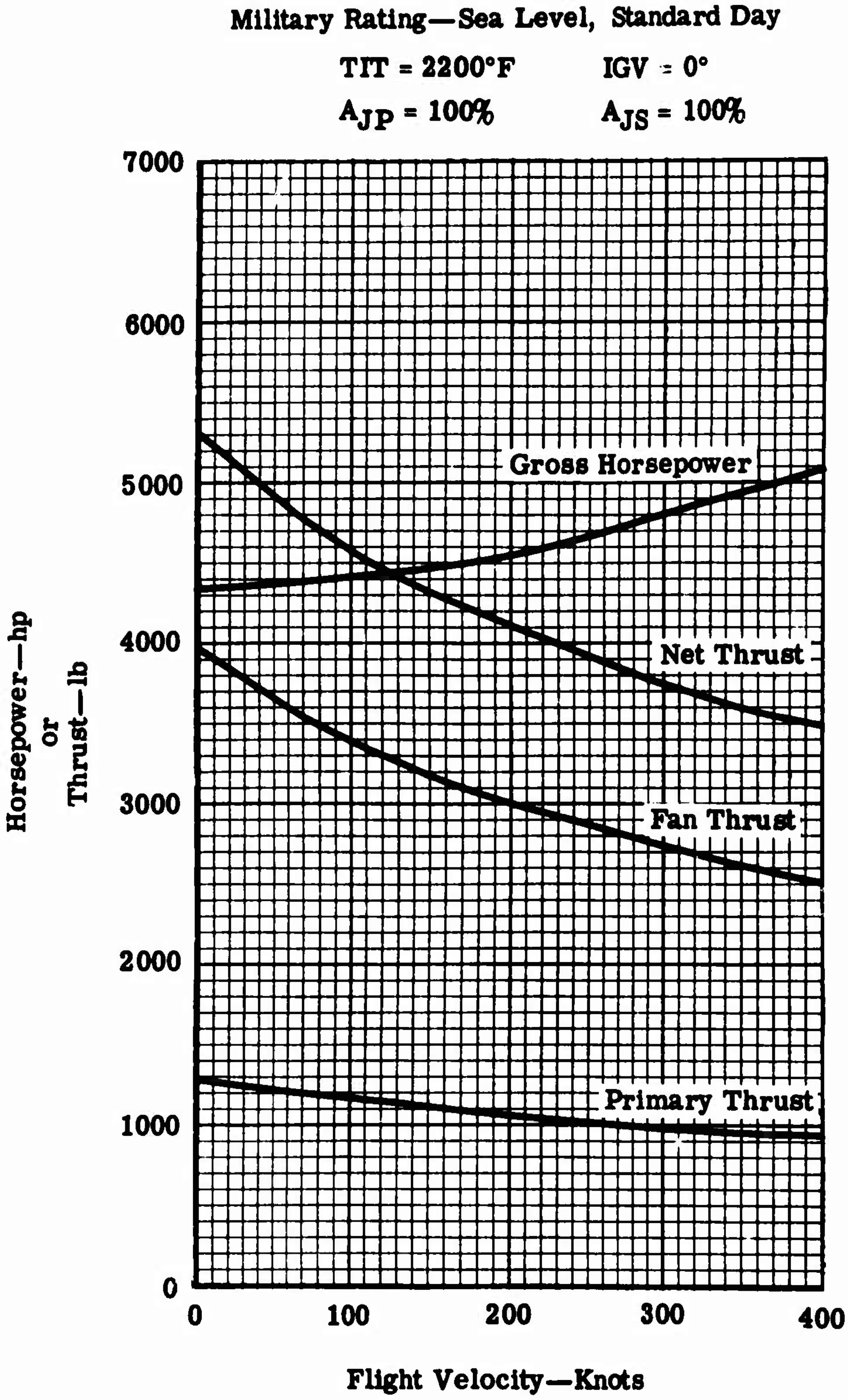


Figure 7. Type II Engine, Cruise Fan Performance Characteristics Versus Flight Speed.

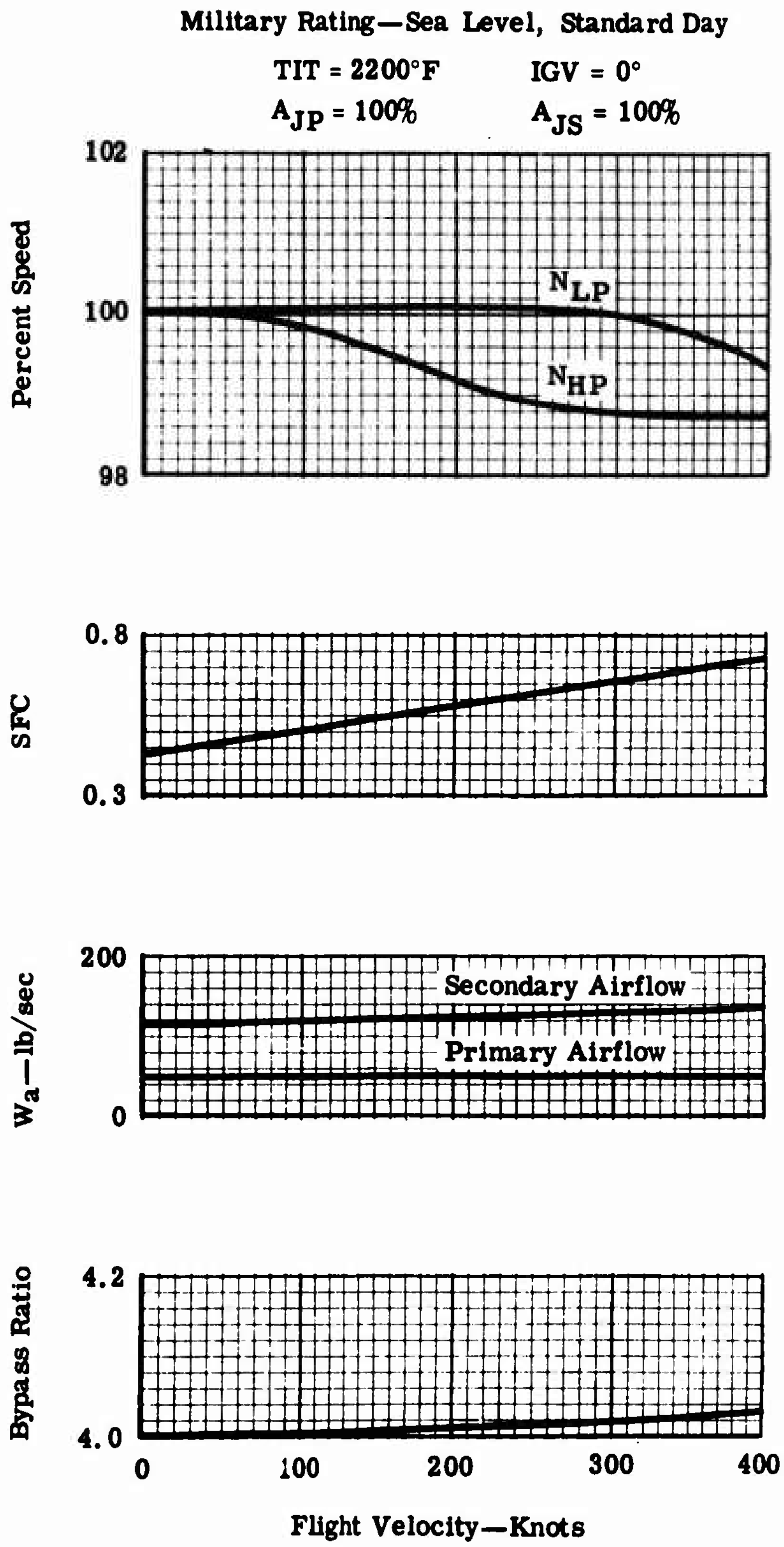


Figure 8. Type II Engine, Cruise Fan Performance Characteristics Versus Flight Speed.

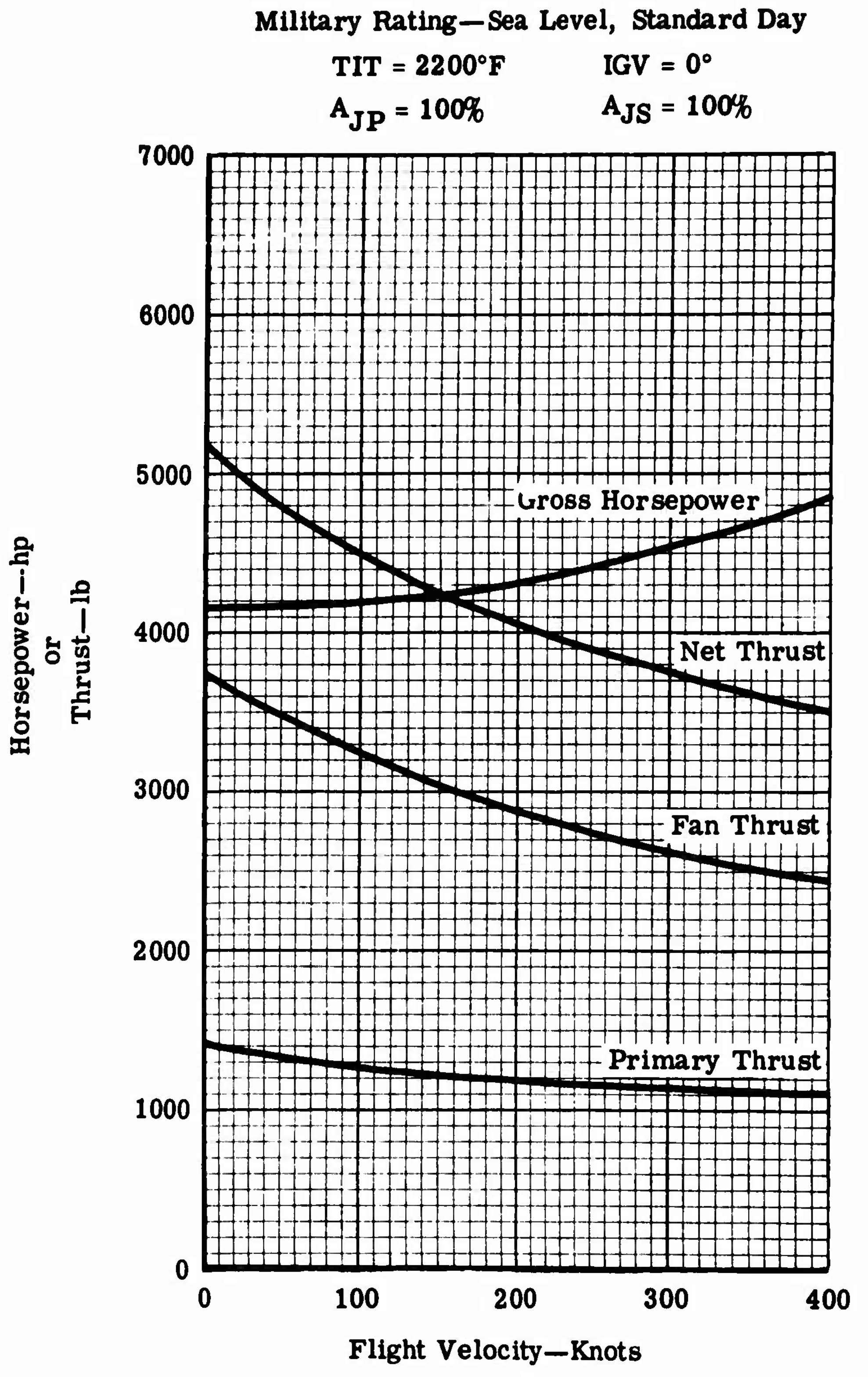


Figure 9. Type III Engine, Cruise Fan Performance Characteristics Versus Flight Speed.

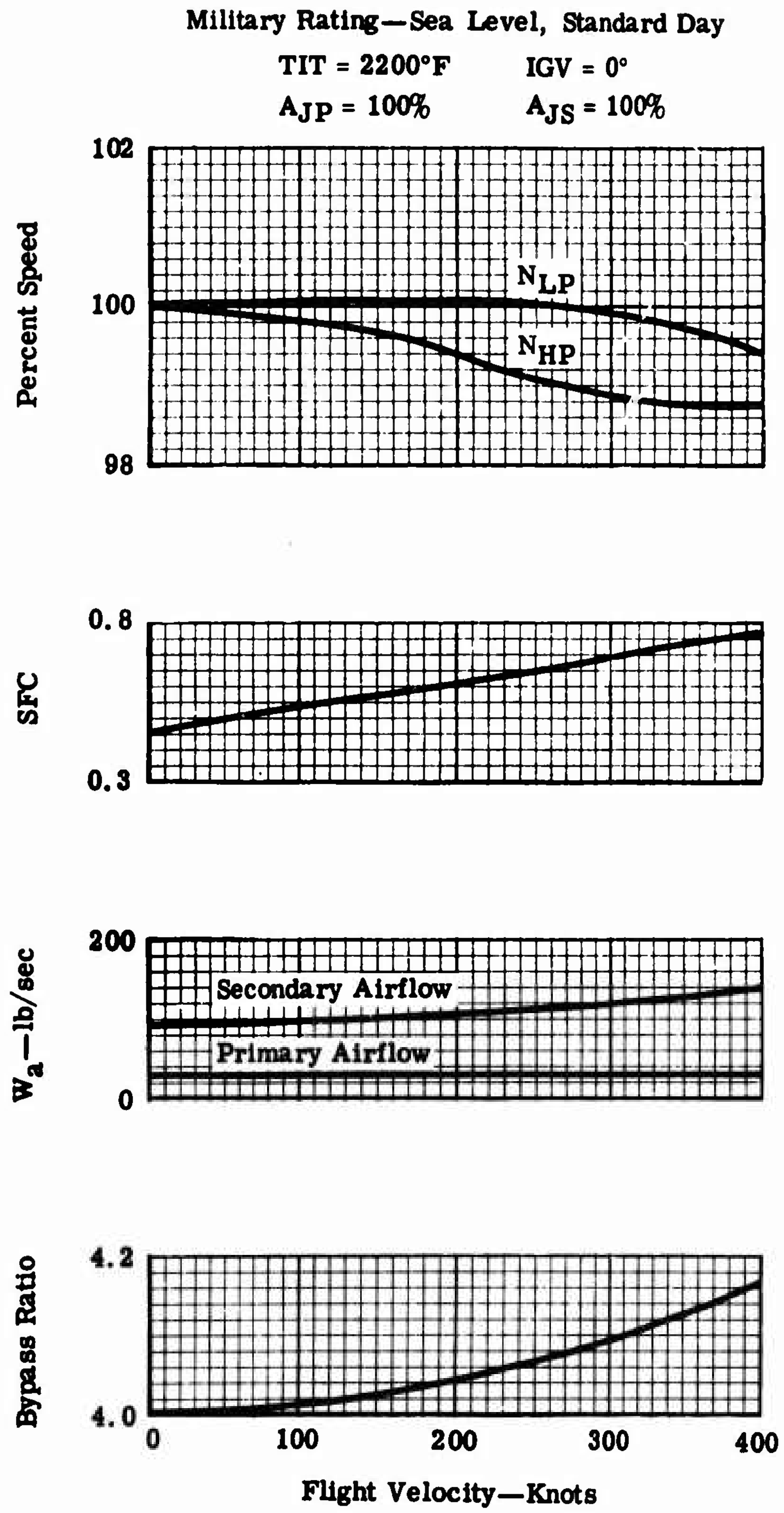


Figure 10. Type III Engine, Cruise Fan Performance Characteristics Versus Flight Speed.

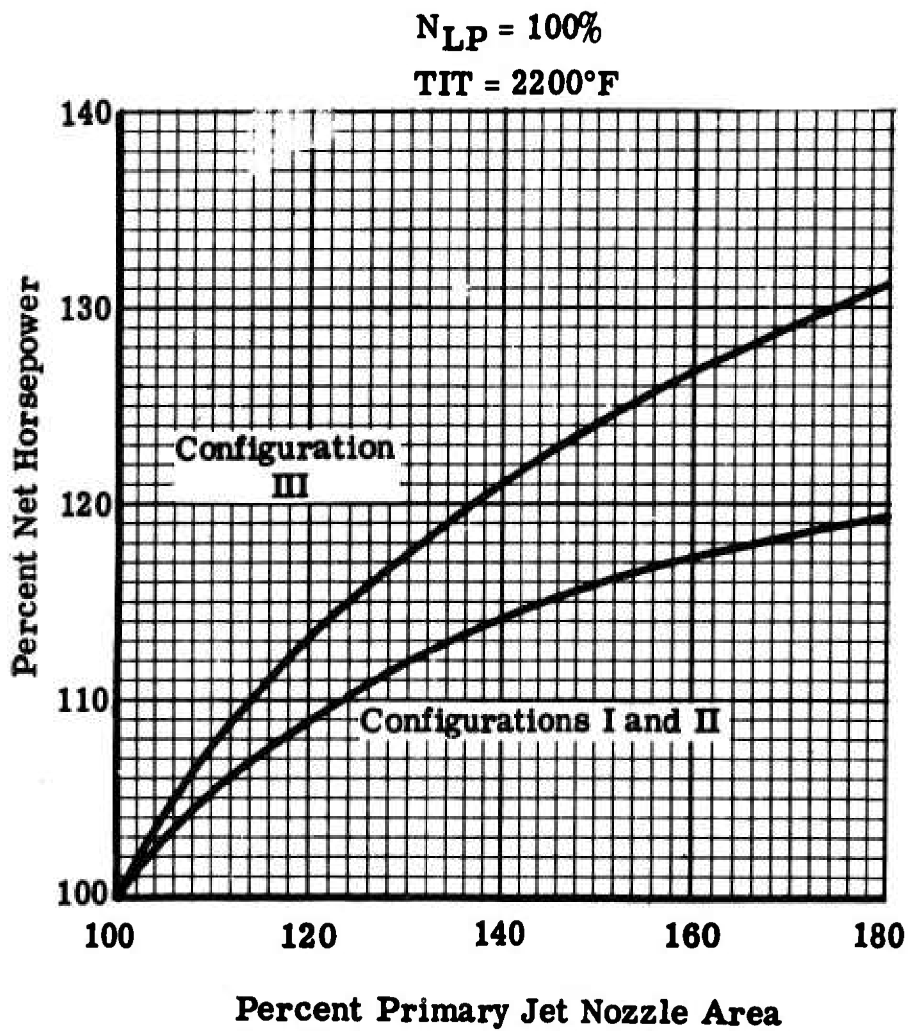


Figure 11. Effect of Primary Jet Nozzle Area on Net Horsepower.

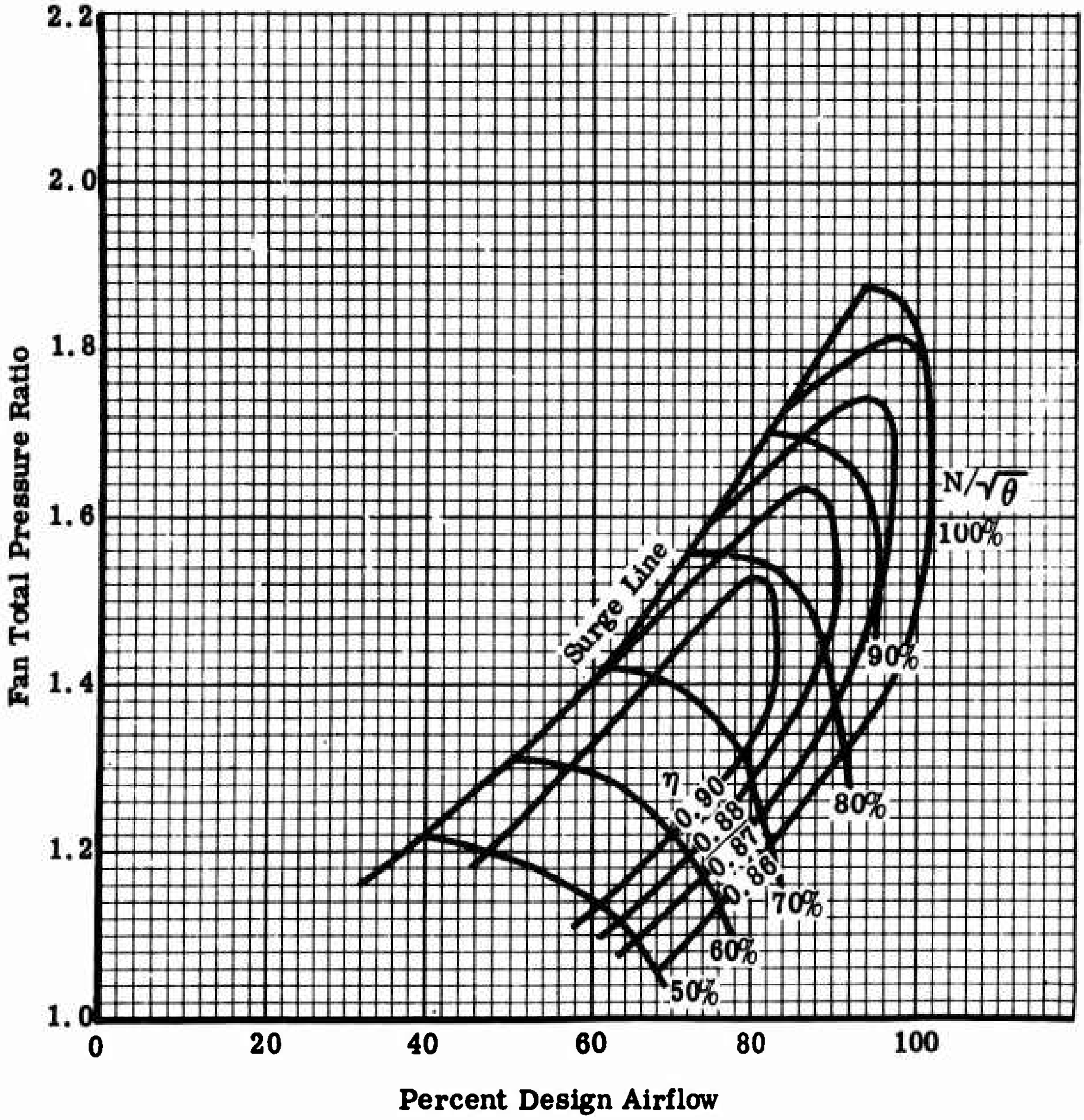


Figure 12. Fan Characteristics With Inlet Guide Vanes in the Normal Position.

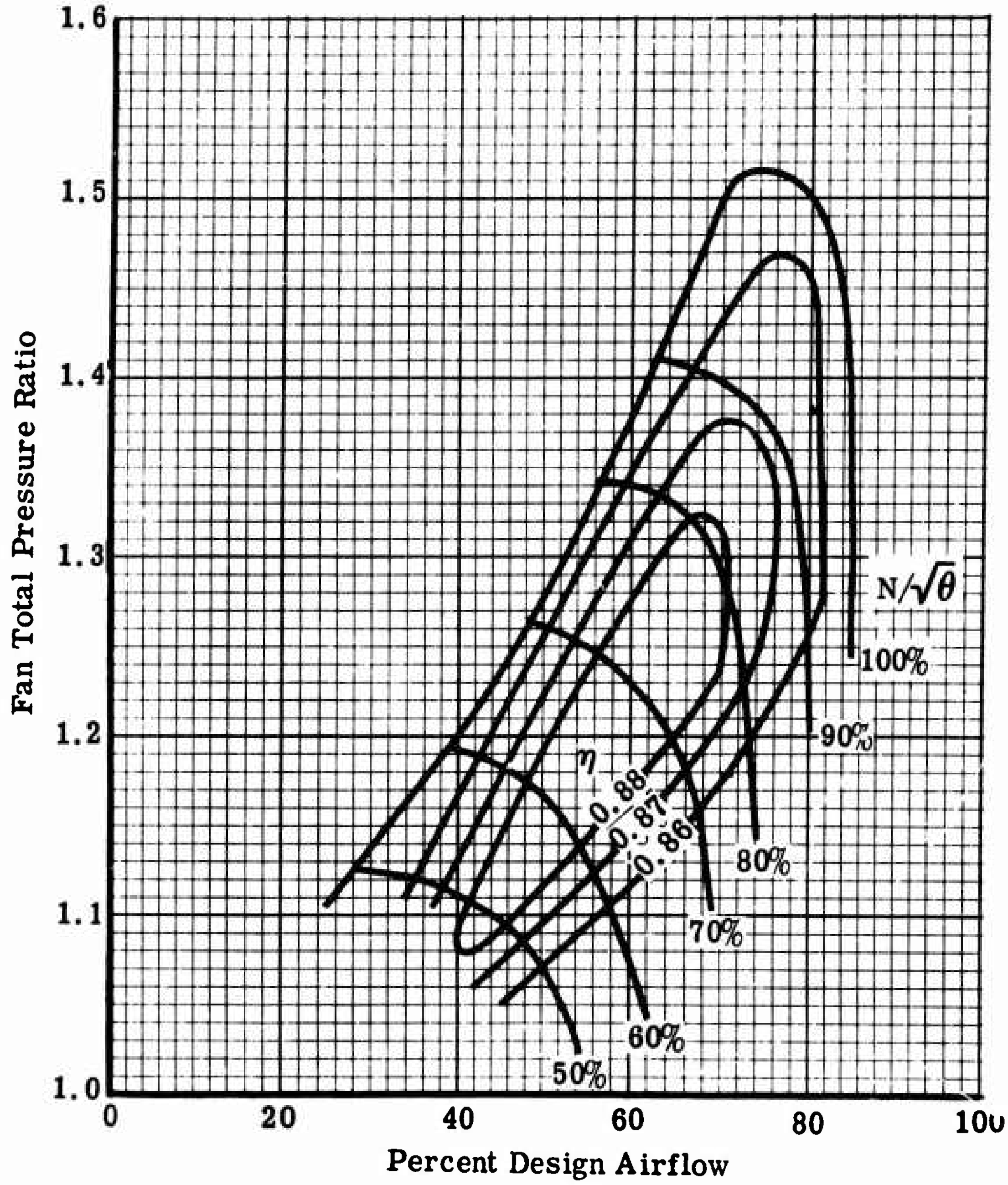


Figure 13. Fan Characteristics With Inlet Guide Vanes in the Maximum Reset Position.

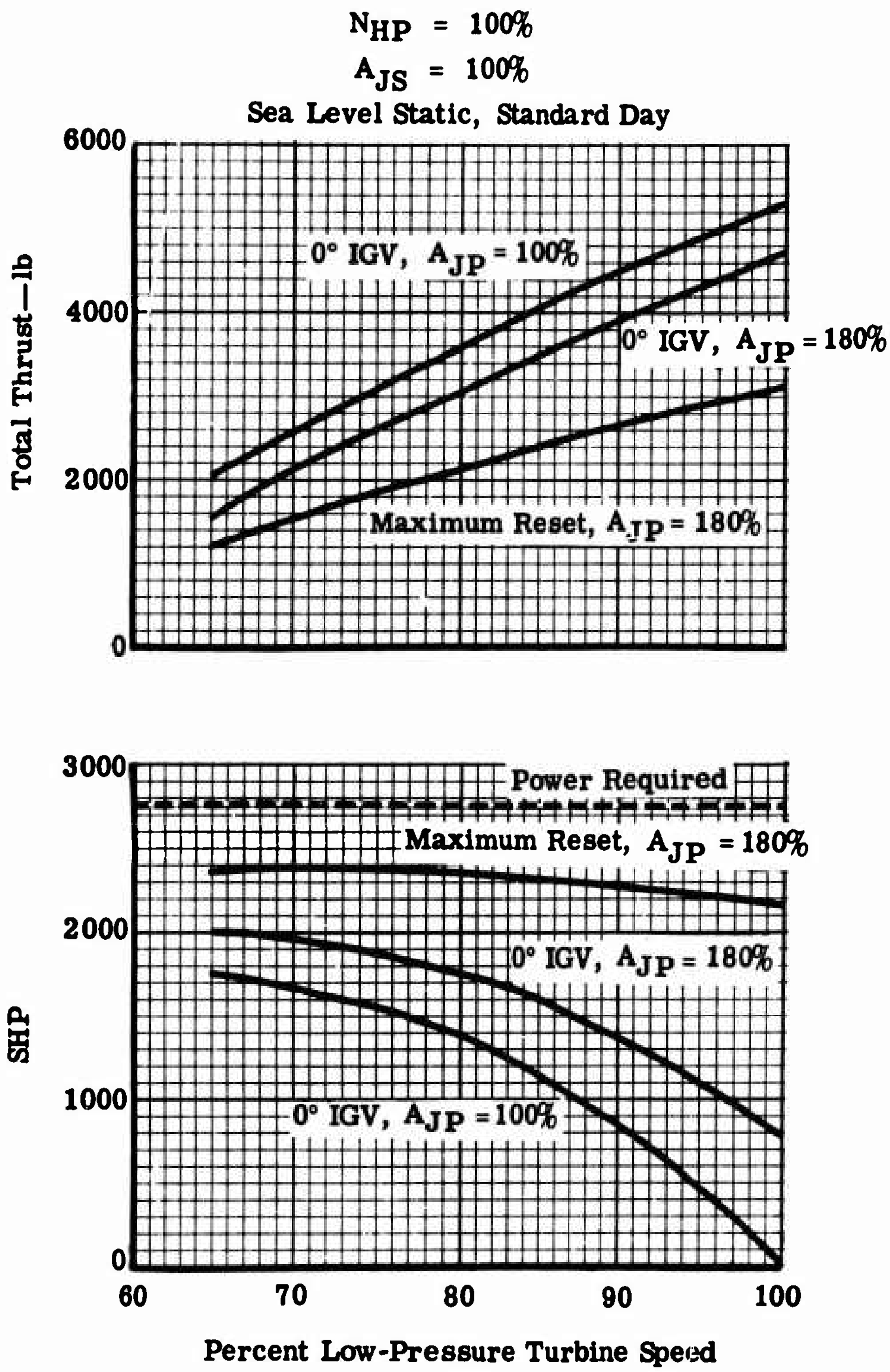


Figure 14. Shaft Horsepower and Total Thrust Available From Type I Engine at Reduced Low-Pressure Turbine Speed.

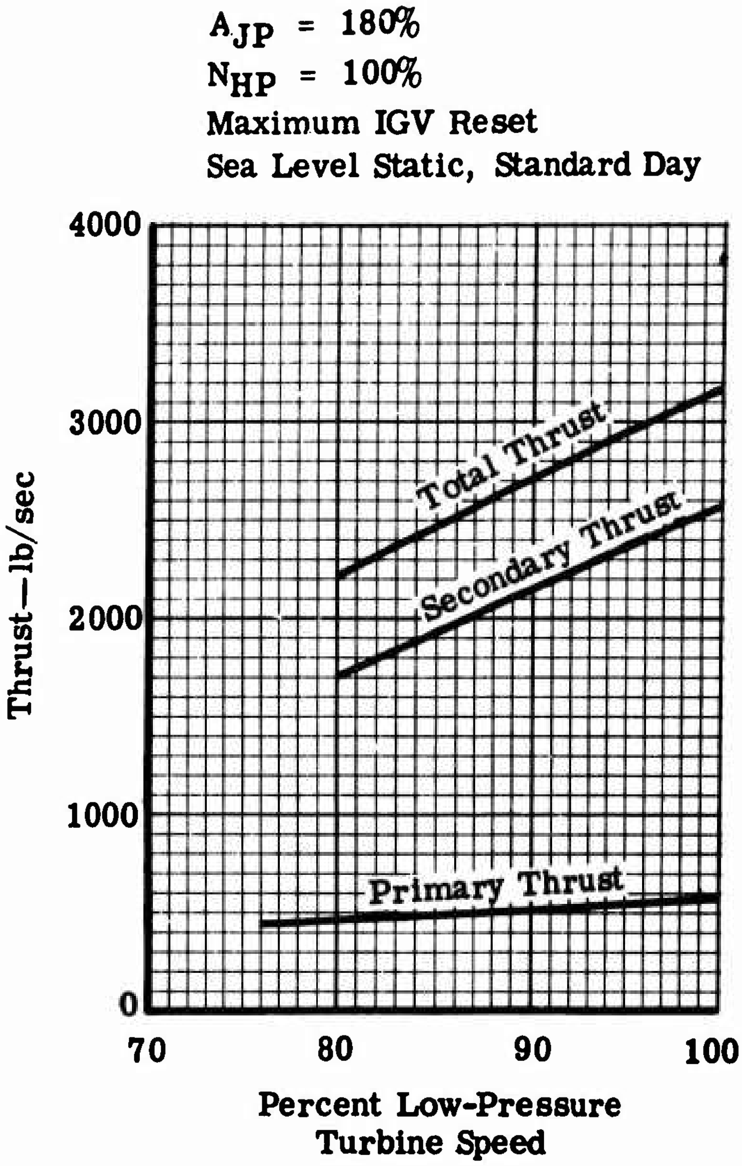


Figure 15. Thrust Available From Type I Engine at Reduced Low-Pressure Turbine Speed.

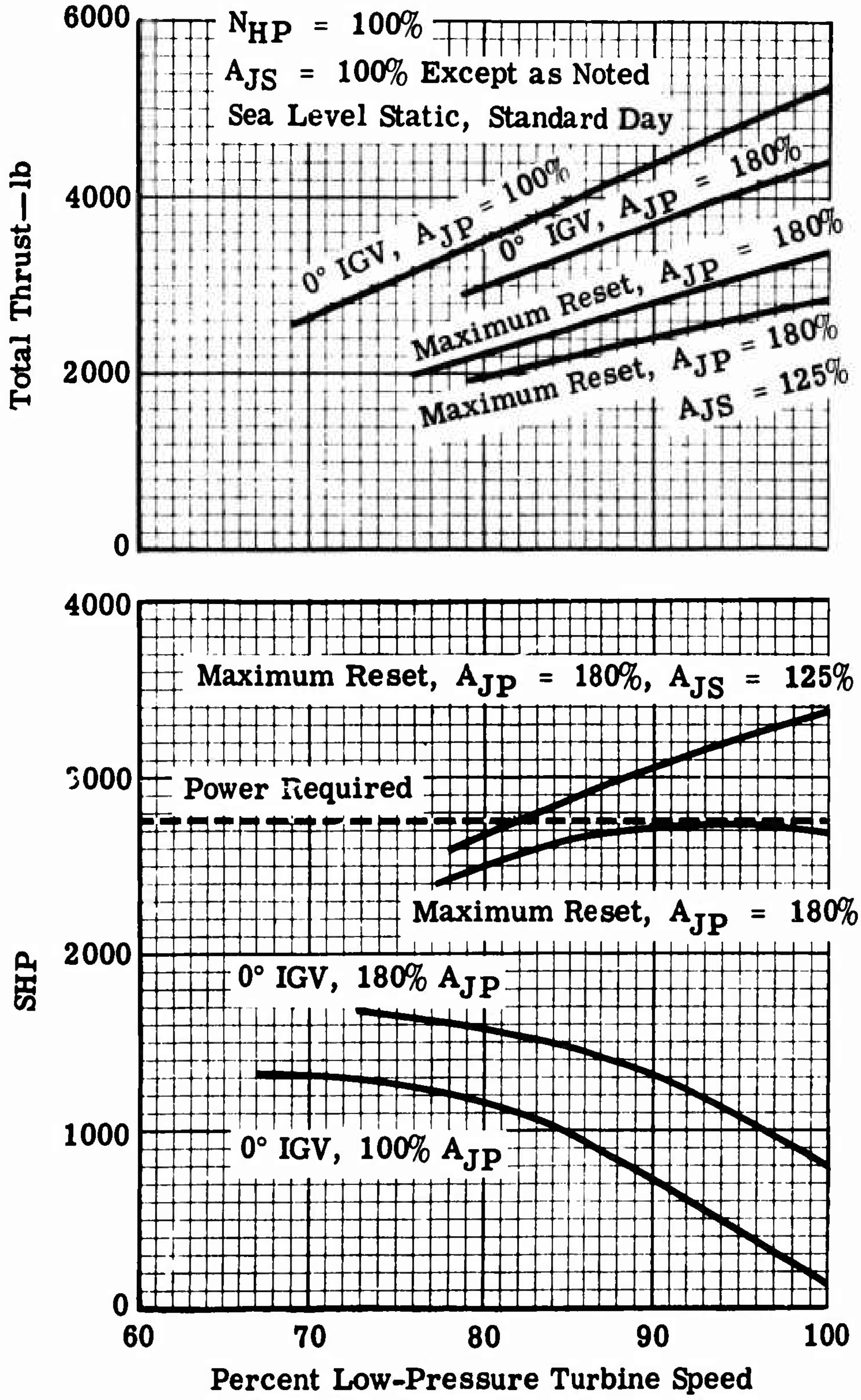


Figure 16. Shaft Horsepower and Thrust From Type II Engine at Reduced Low-Pressure Turbine Speed.

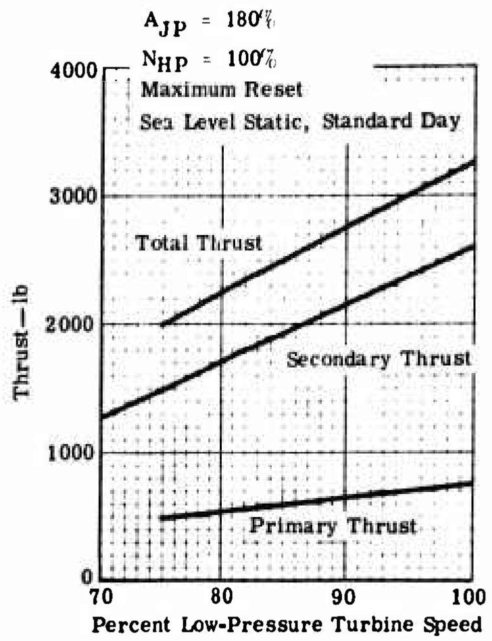


Figure 17. Thrust Available From Type II Engine at Reduced Low-Pressure Turbine Speed.

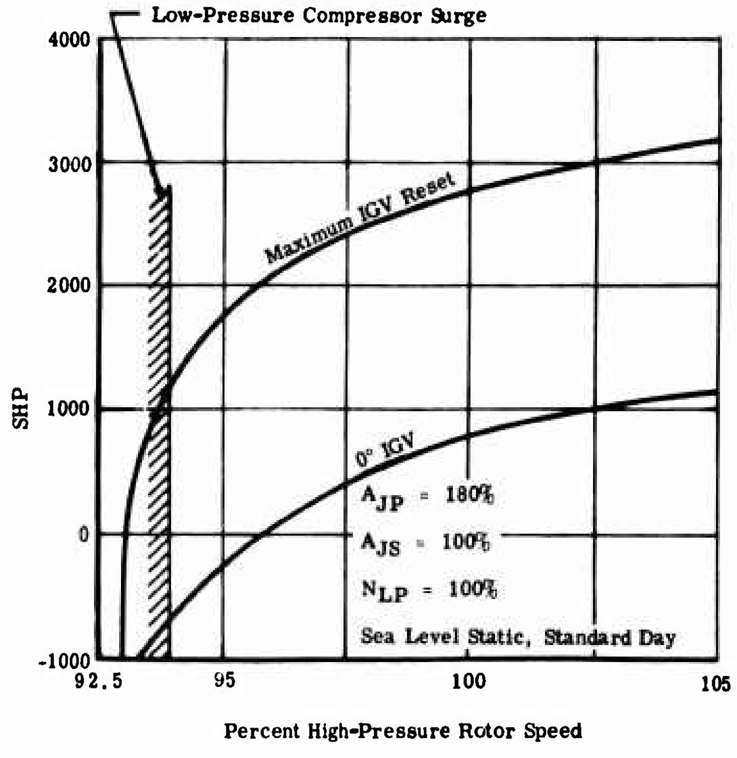


Figure 18. Engine Type II Fan Hub Section Surge Characteristics.

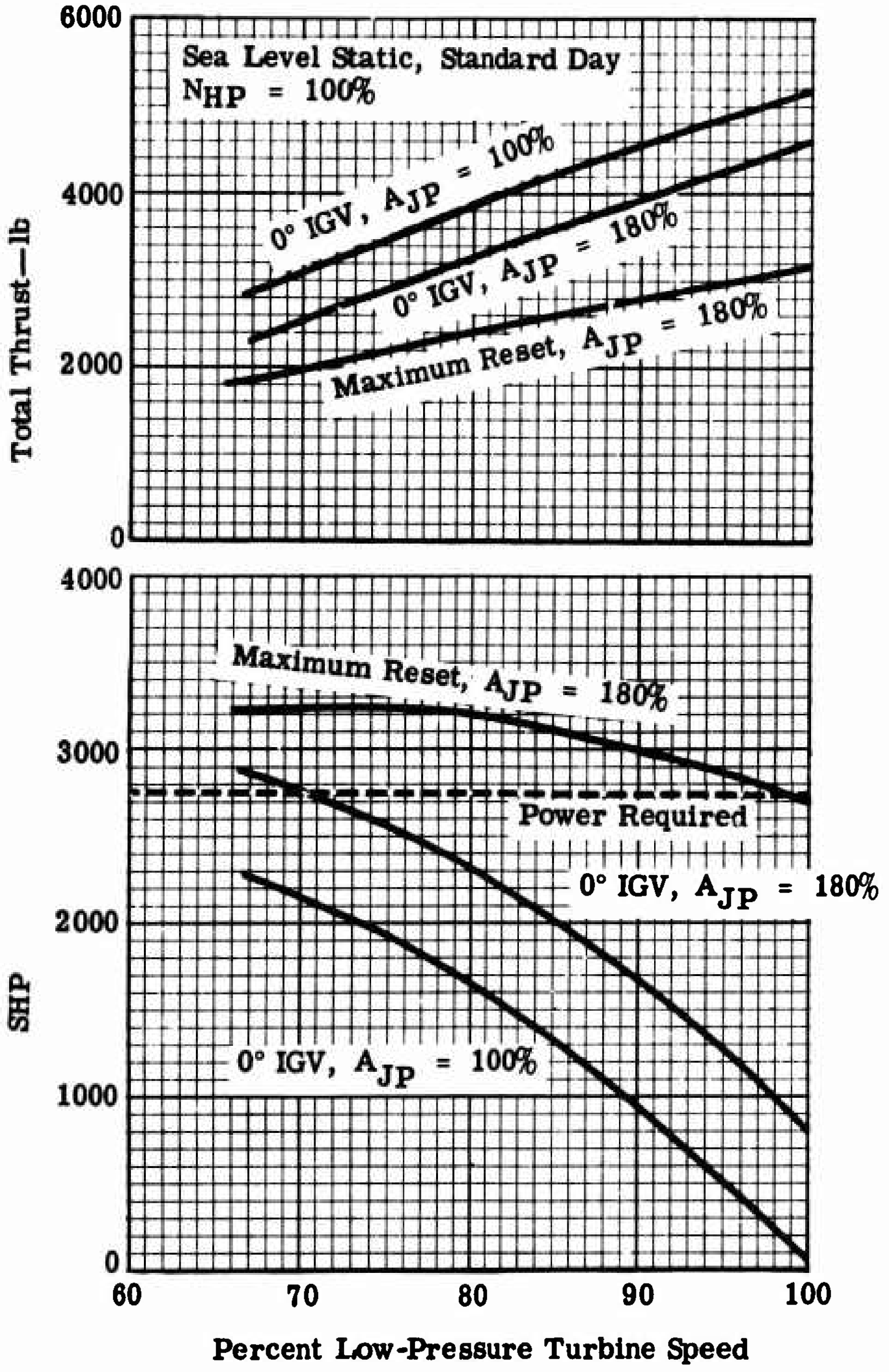


Figure 19. Shaft Horsepower and Thrust Available From Type III Engine at Reduced Low-Pressure Turbine Speed.

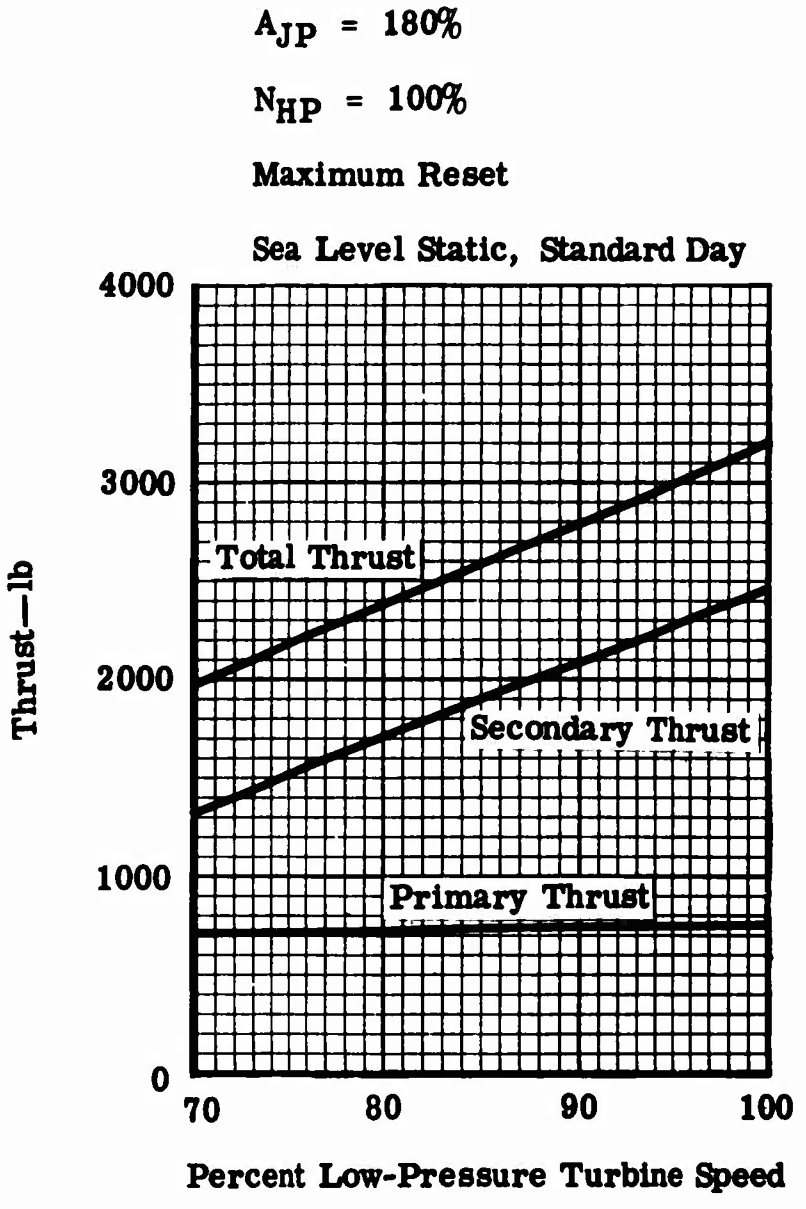


Figure 20. Thrust Available From Type III Engine at Reduced Low-Pressure Turbine Speed.

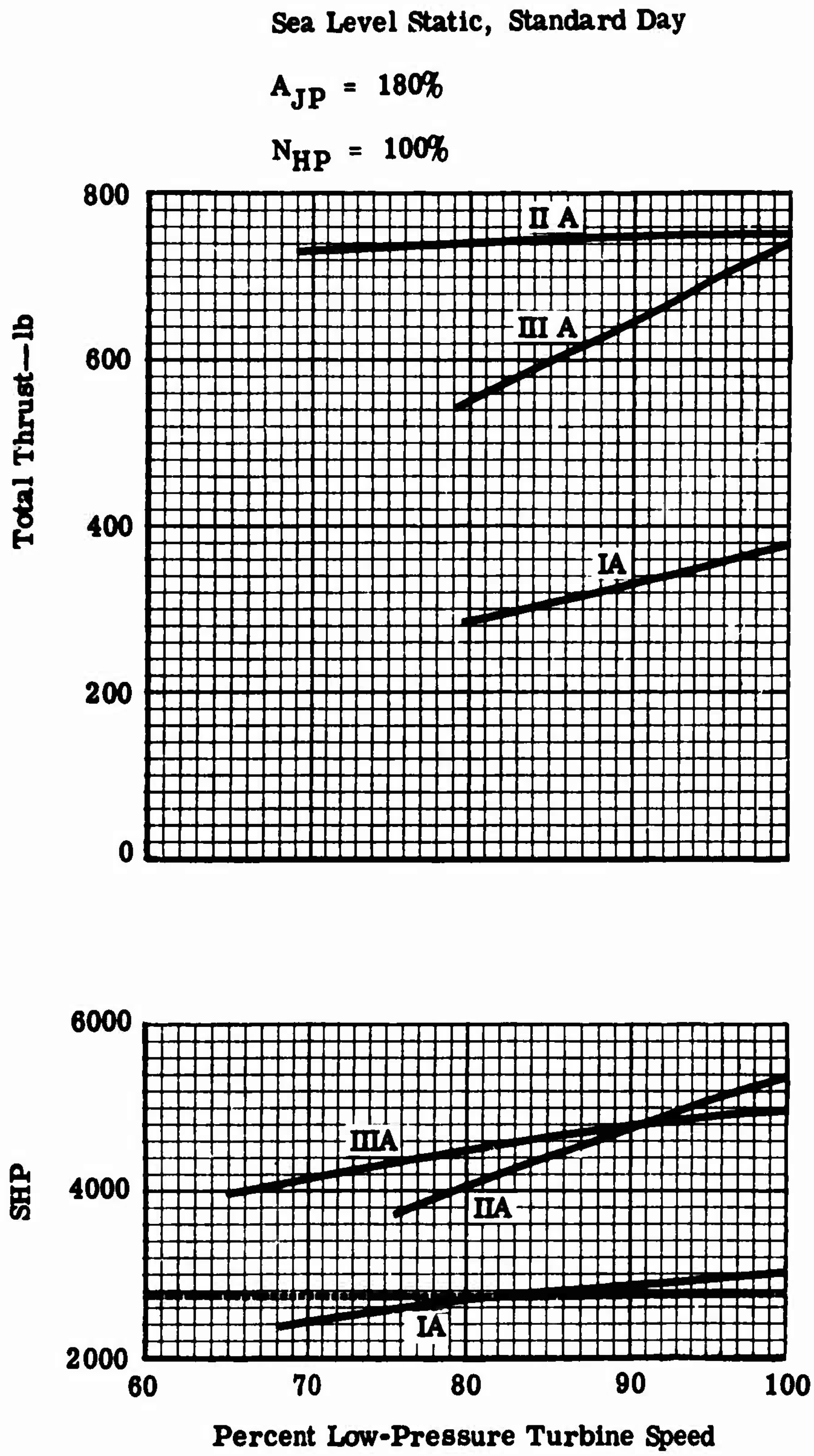


Figure 21. Comparison of Types IA, IIA, and IIIA Decoupled Fans.

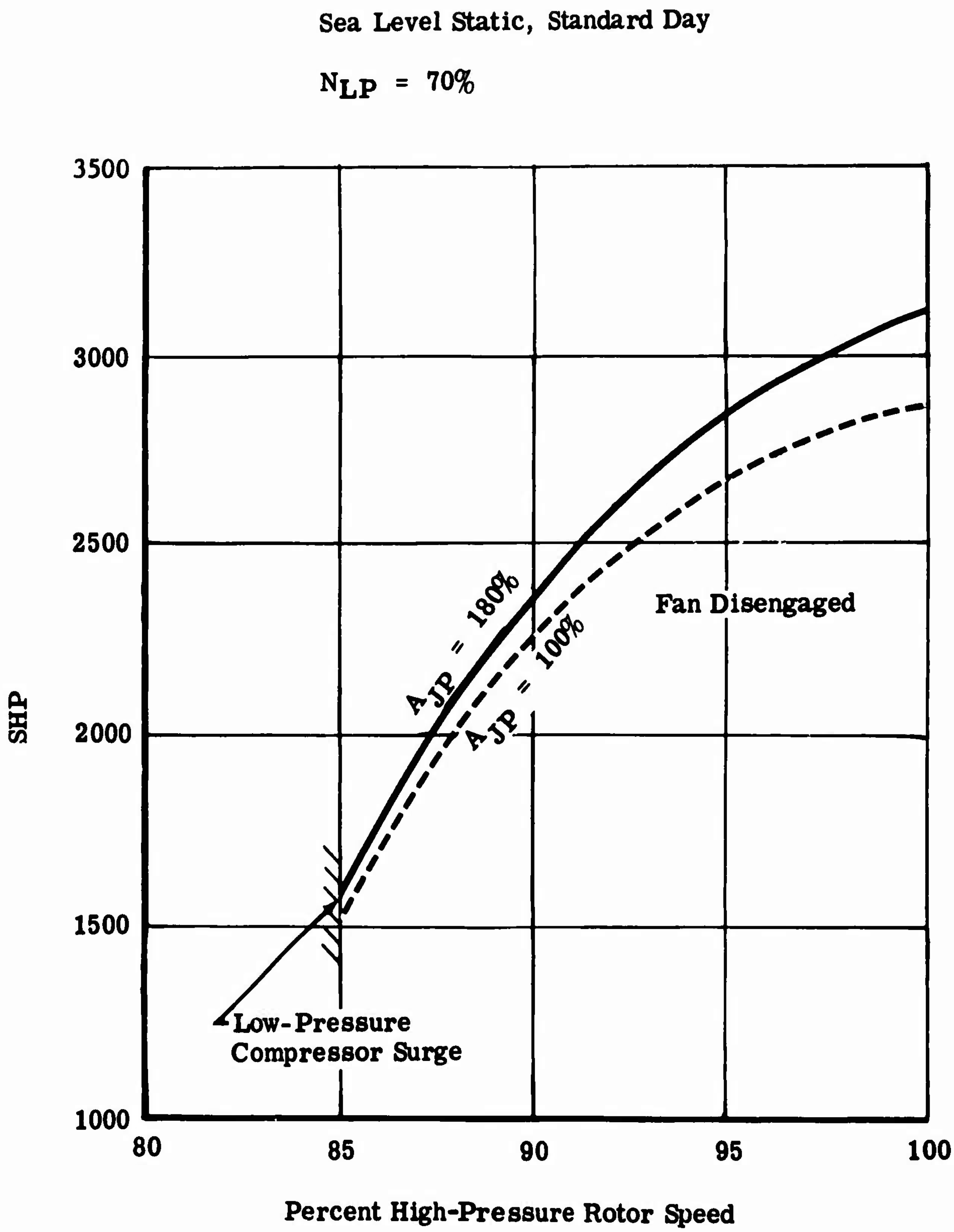
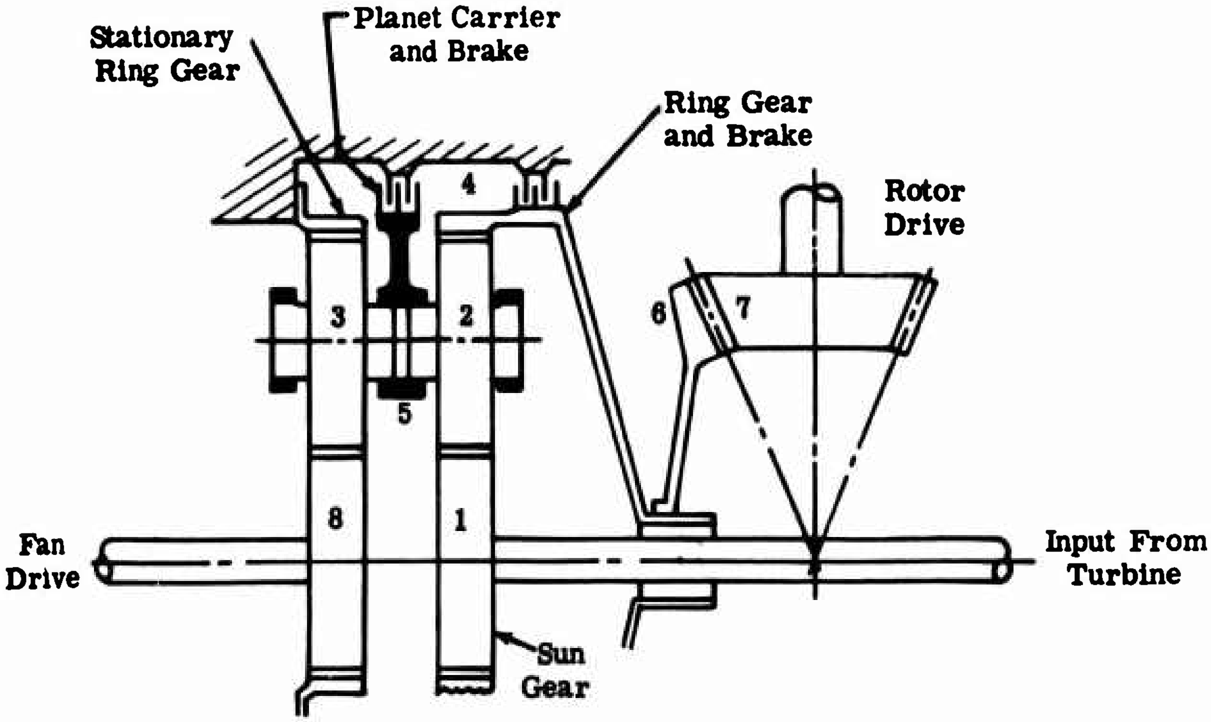
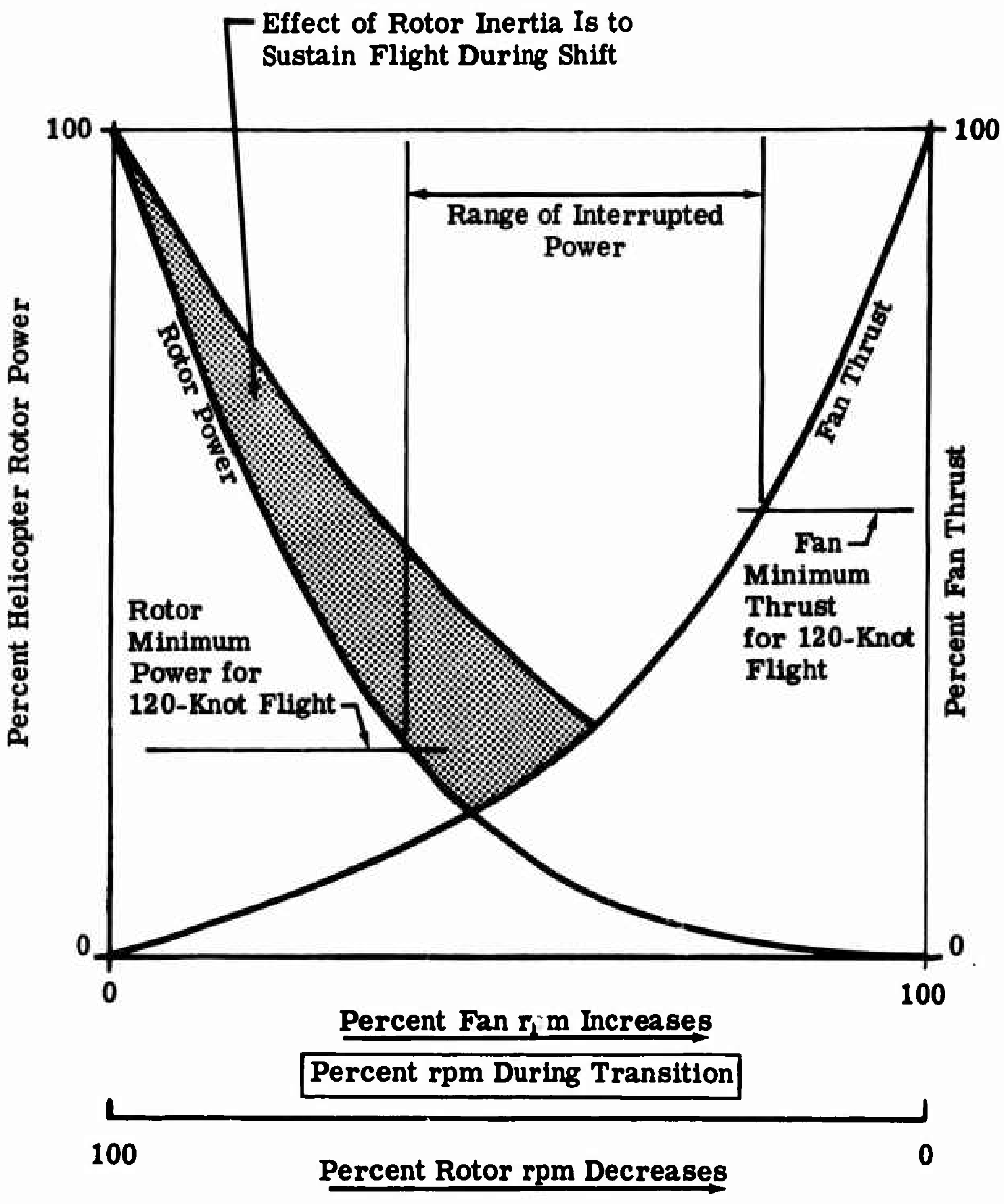


Figure 22. Engine Type IIA, Low-Pressure Compressor Surge Characteristics With the Fan Disengaged.



Gear	Fan Mode (rpm)	Helicopter Mode (rpm)	Pitch Diameter (in.)	No. Teeth	No. Required
1	12,350	12,350	4.72	32	1
2	9,000	11,980	4.86	33	5
3	9,000	0	4.86	33	5
4	0	-4,030	14.44	98	1
5	3,020	0	–	–	1
6	0	-4,030	5.0	20	1
7	0	14,900	13.5	54	1
8	12,350	0	4.72	32	1

Figure 23. Schematic Drawing of Differential Gear Arrangement.



Note: Turbine N_{LP} = Constant

Figure 24. Differential Gear System, Approximate Decay of Rotor Power and Increase of Fan Thrust During Engagement.

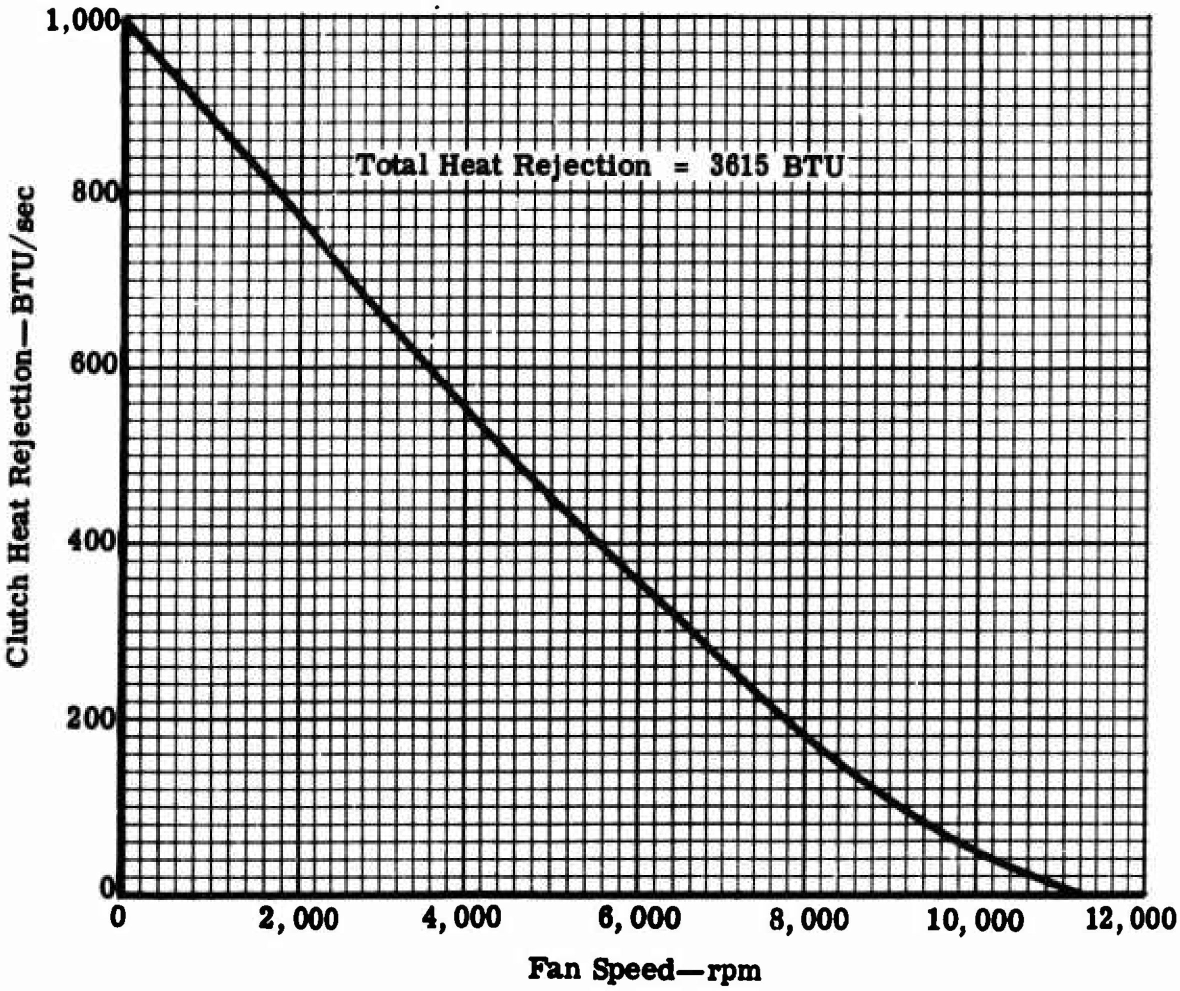
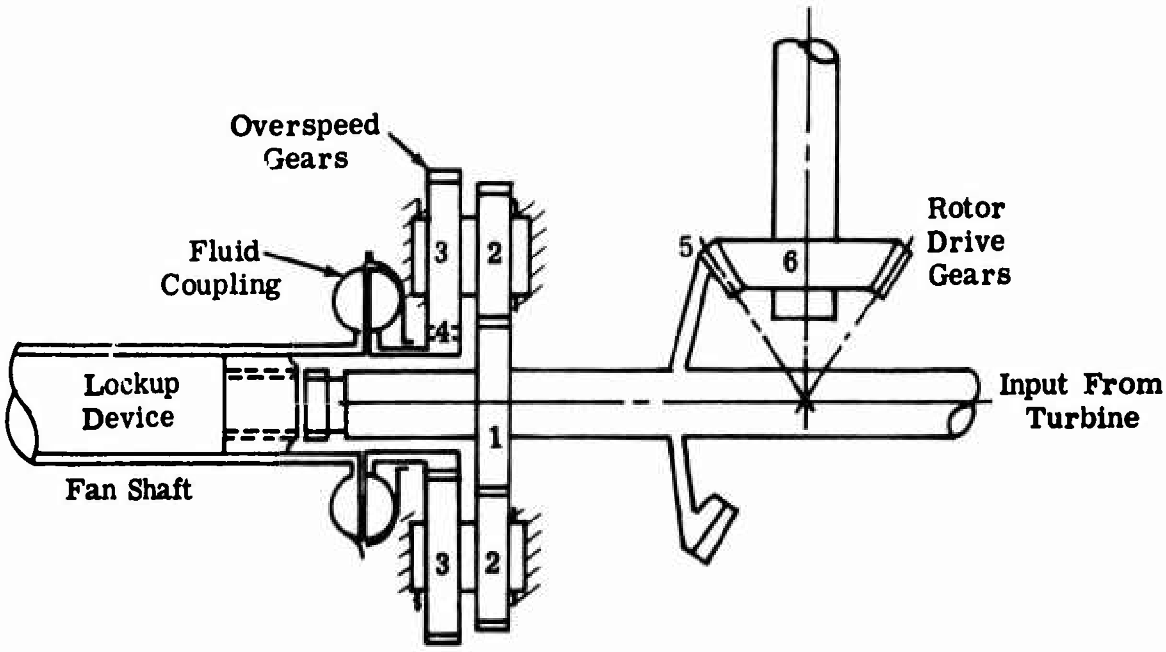


Figure 25. Friction Clutch Heat Rejection Rate Versus Fan Speed.



Gear	Fan Mode (rpm)	Helicopter Mode (rpm)	No. Teeth	No. Required
1	12,350	10,500	40	1
2	17,600	15,000	28	5
3	17,600	15,000	35	5
4	15,400	13,100	40	1
5	12,350	10,500	36	1
6	21,200	18,000	21	1

Figure 26. Fluid Coupling Plus Overspeed Gears.

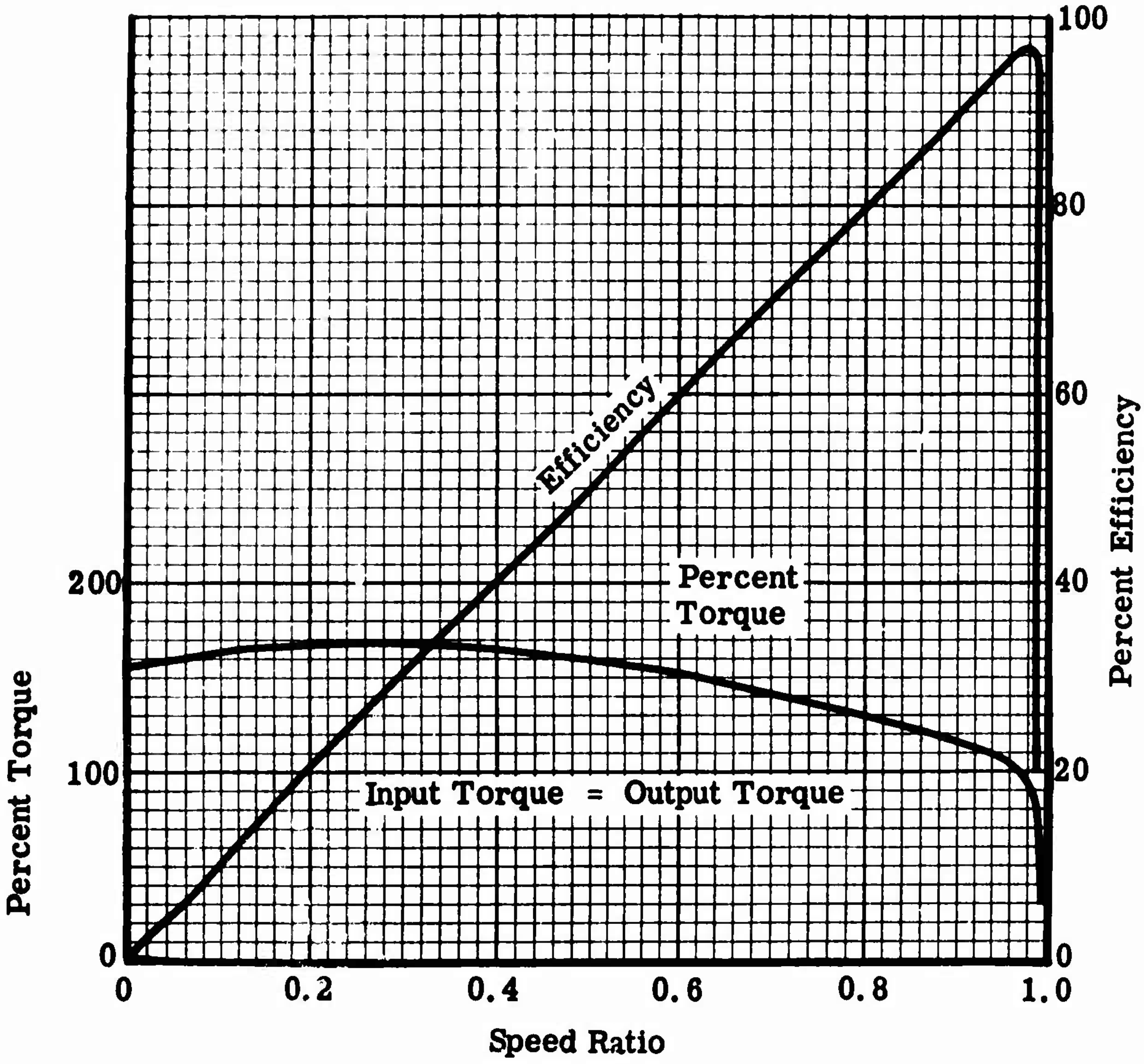


Figure 27. Typical Torque and Efficiency Characteristics of a Fluid Coupling.

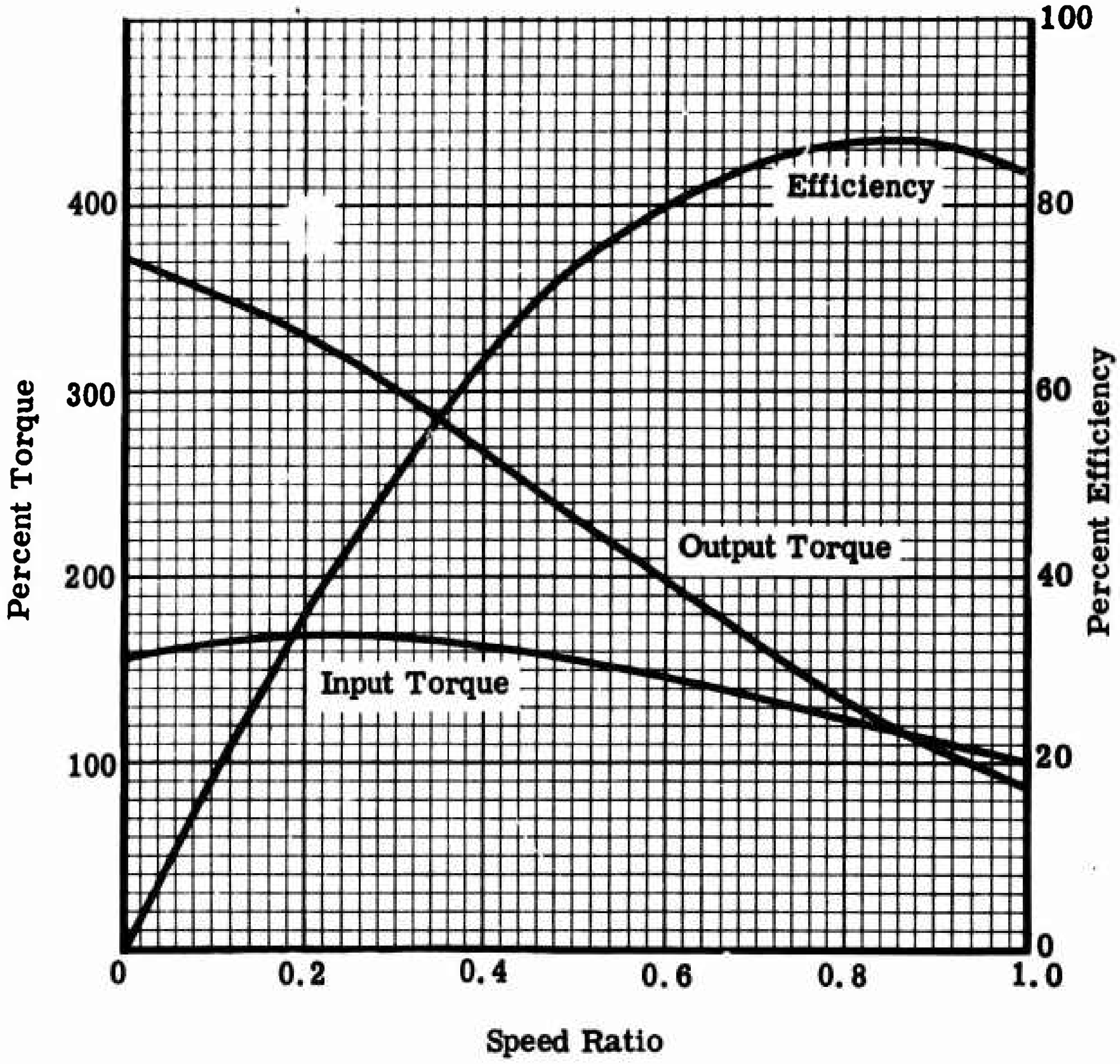


Figure 28. Typical Torque and Efficiency Characteristics of a Torque Converter.

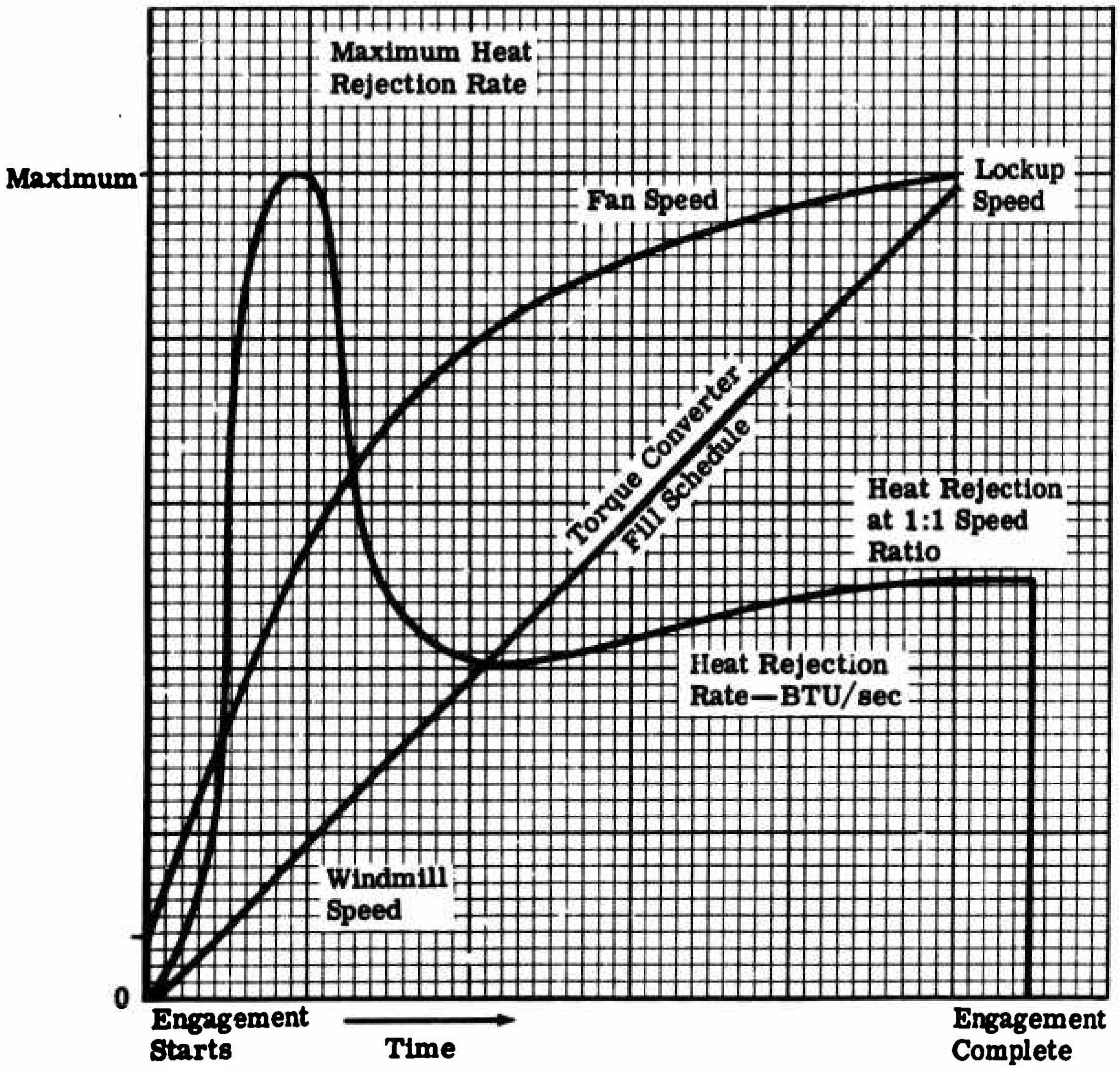


Figure 29. Typical Curves for Torque Converter Fill Study.

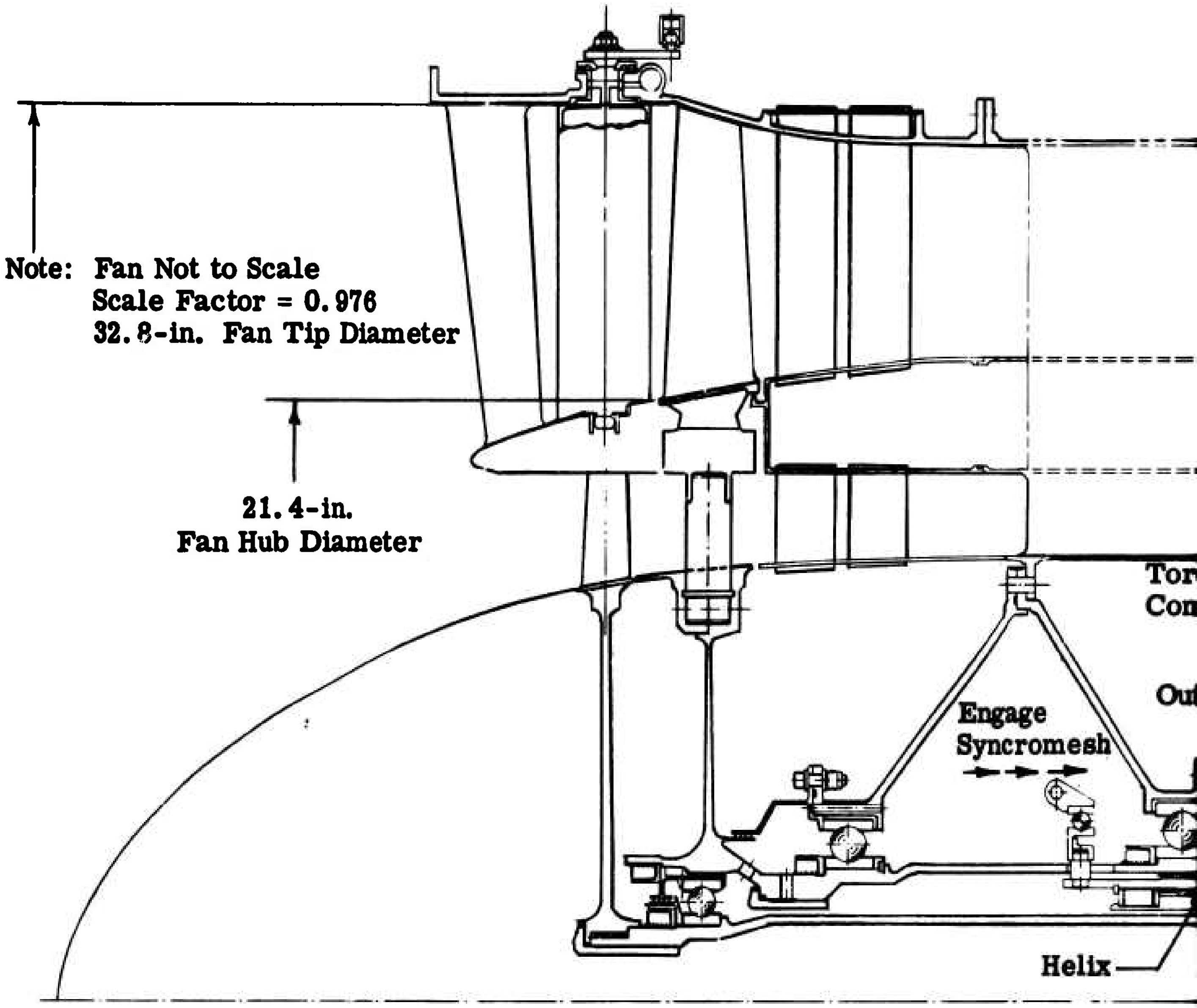
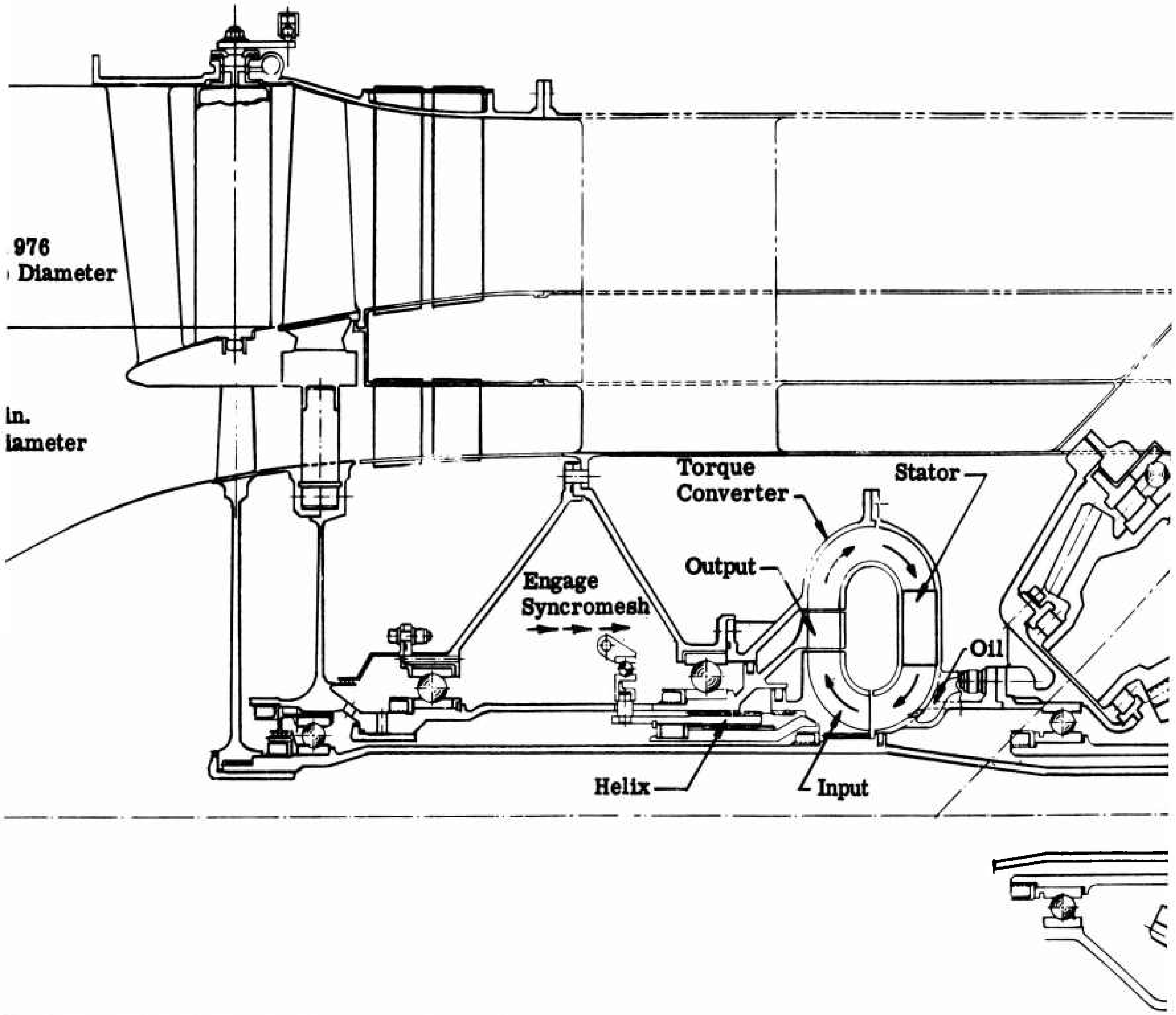


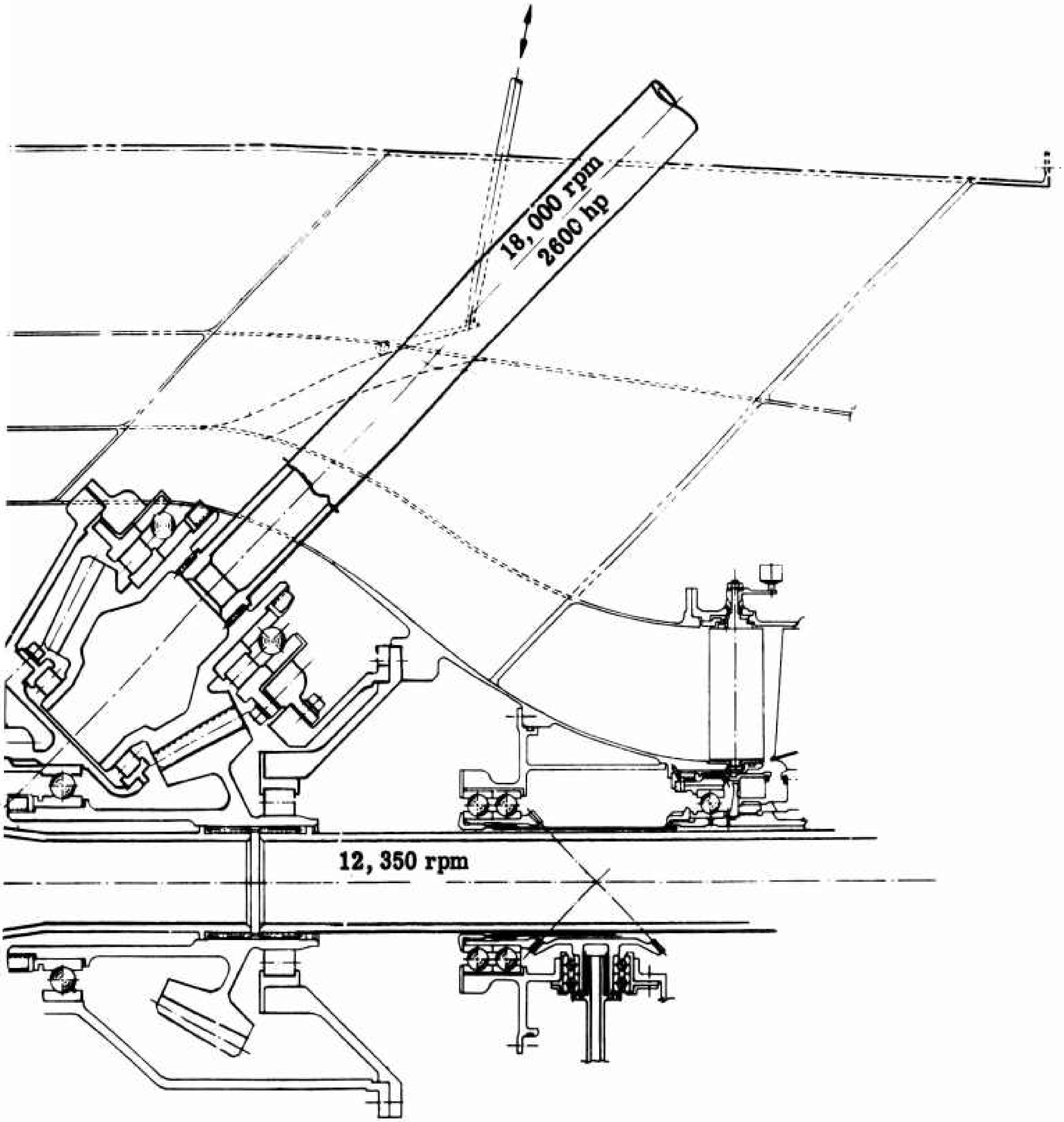
Figure 30. Type IIA, Supercharged With Torque Converter Decoupler for Bypass Fan.

A

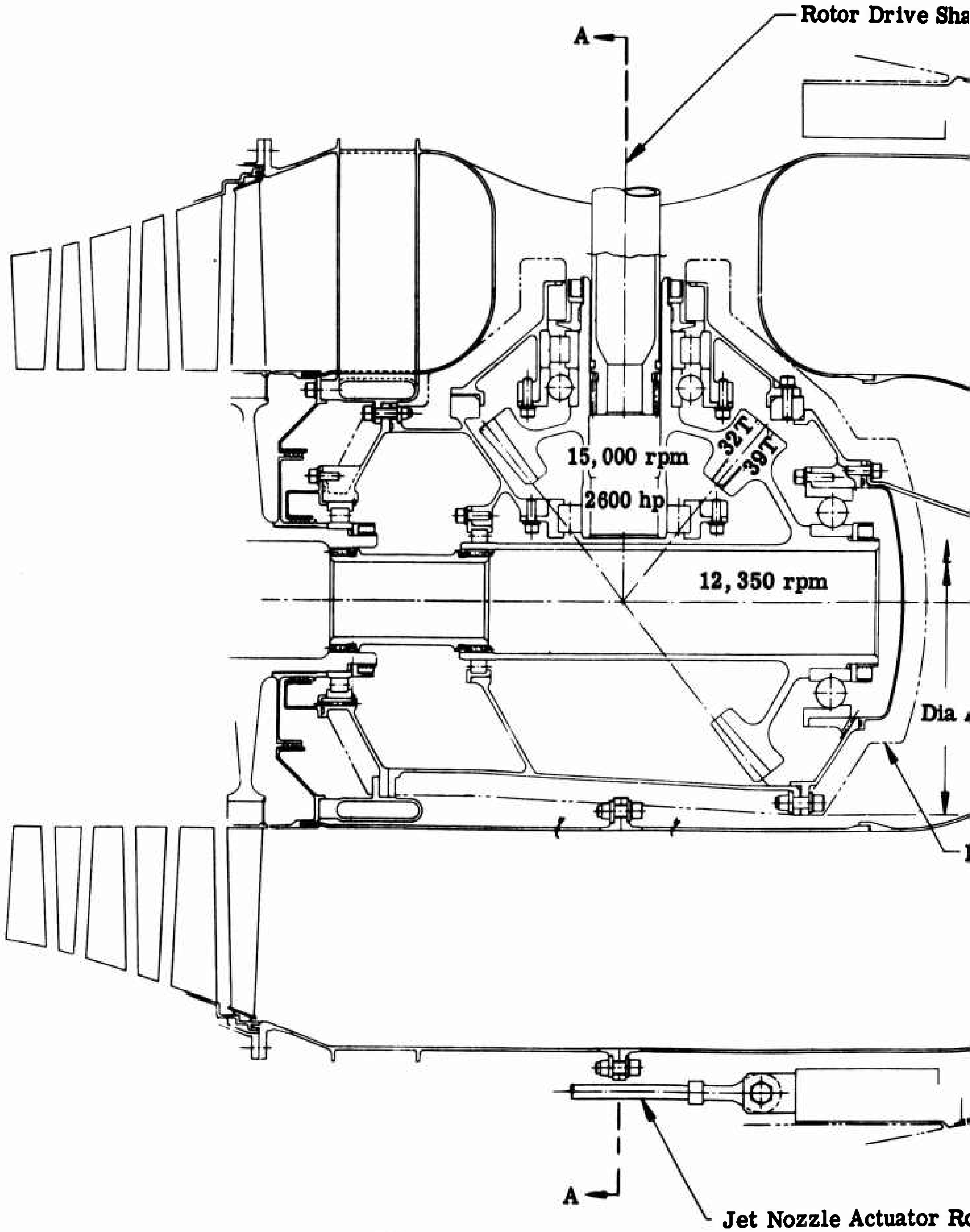
B



Supercharged With Torque Converter Decoupler
Fan.



C


Rotor Drive Sha
A
15,000 rpm
2600 hp
32T
39T
12,350 rpm
Dia
A
Jet Nozzle Actuator Ro

A B

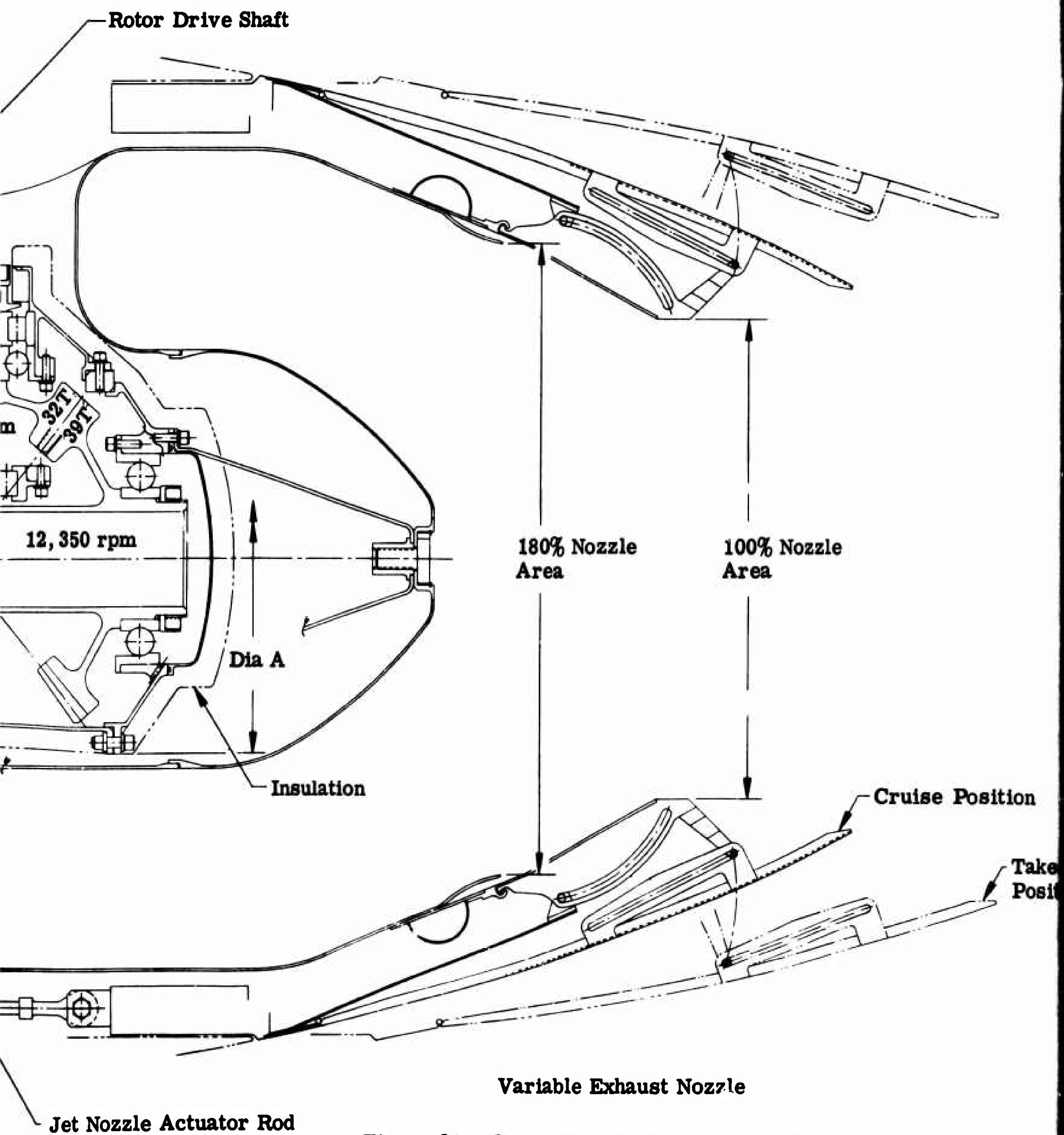
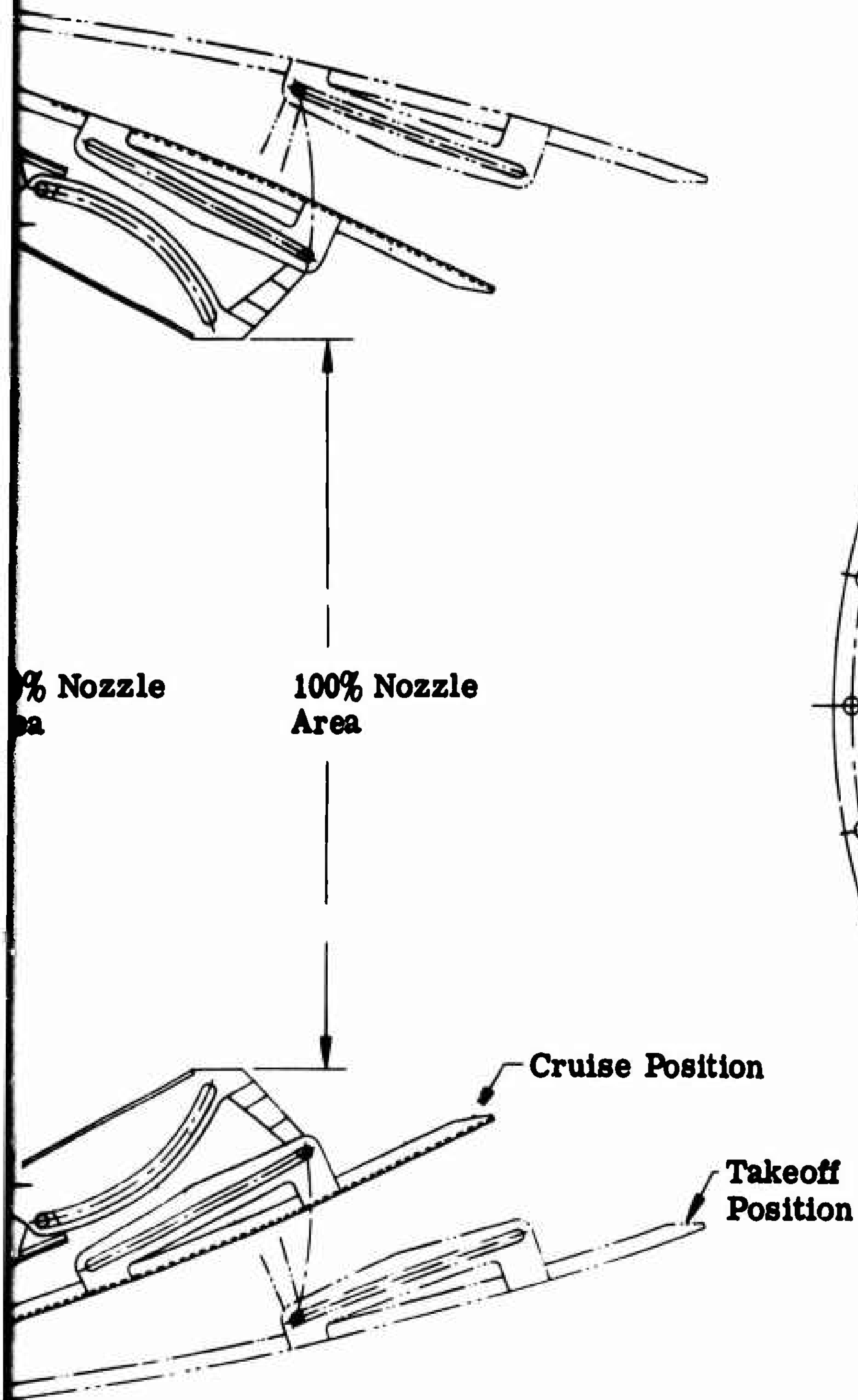
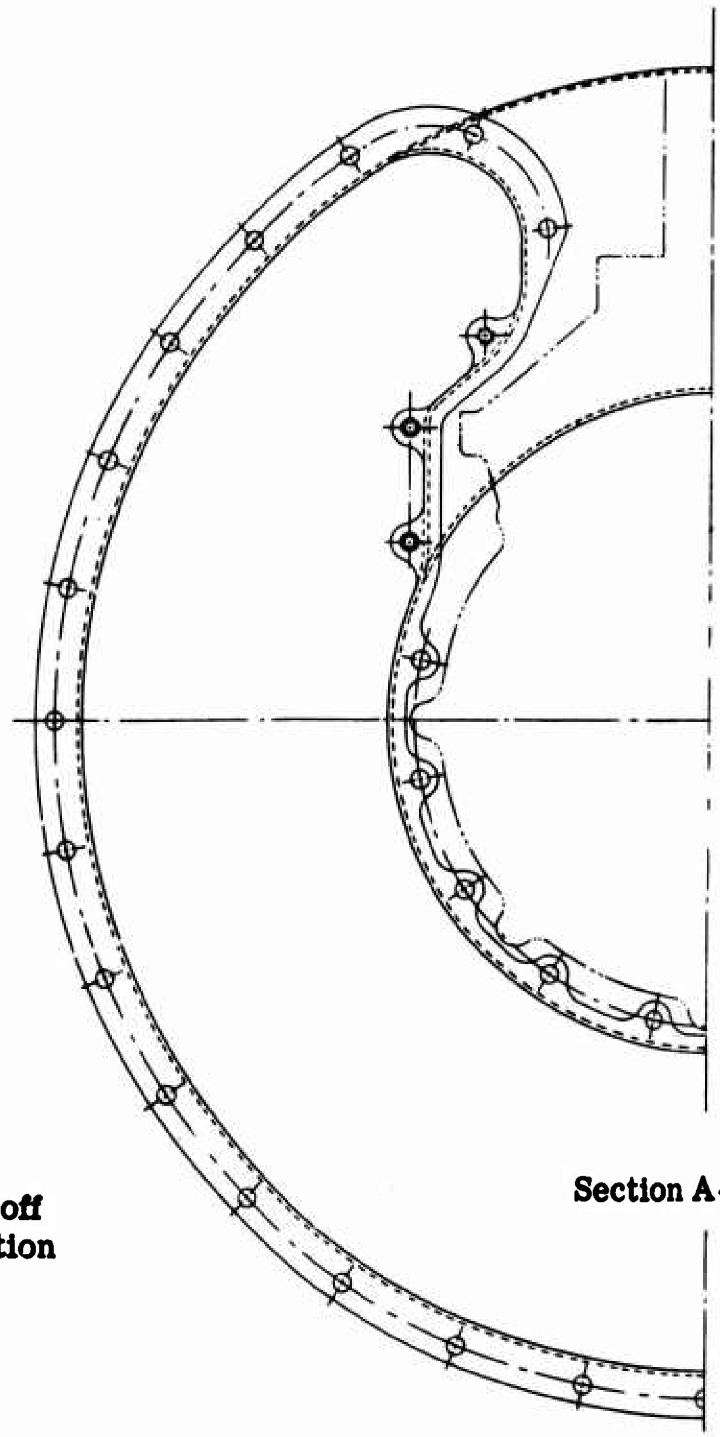


Figure 31. Convertible Engine Aft Rotor Drive Arrangement.

B





Section A-A

able Exhaust Nozzle

rtible Engine Aft Rotor Drive Arrangement.

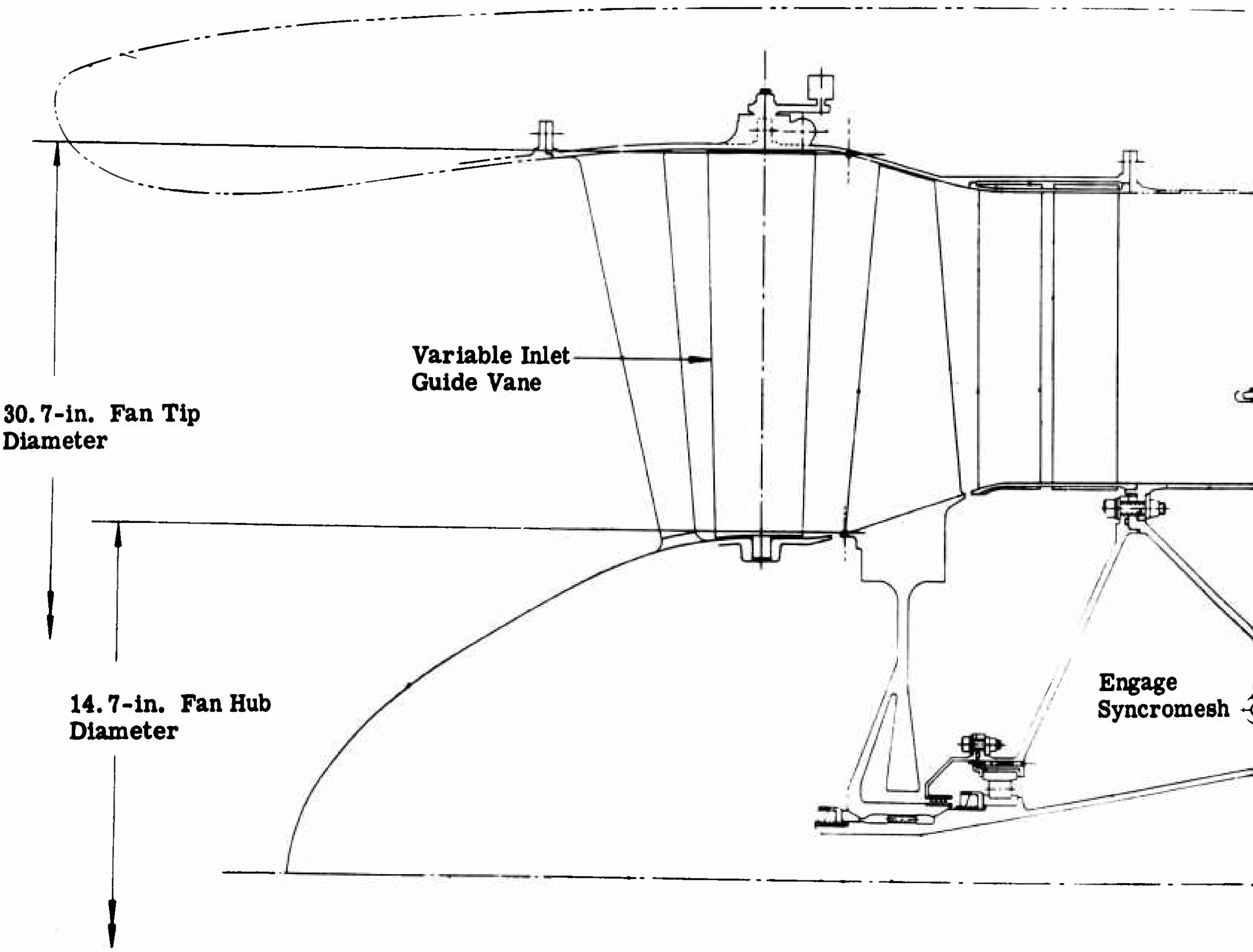
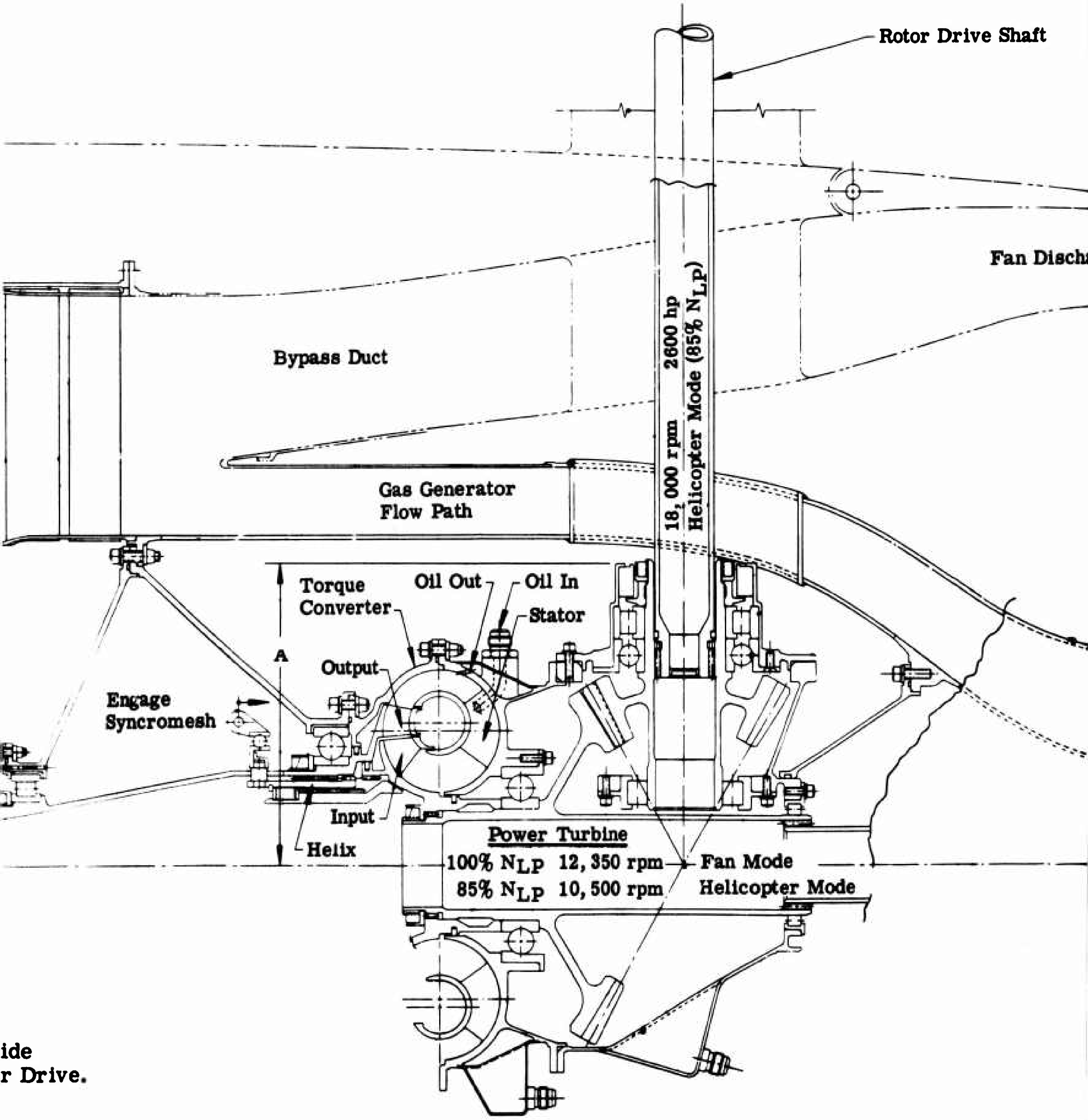


Figure 32. Type IA, Supercharged Engine With Variable Inlet Guide Vanes. Torque Converter, and Front 90-Degree Rotor Drive.

A

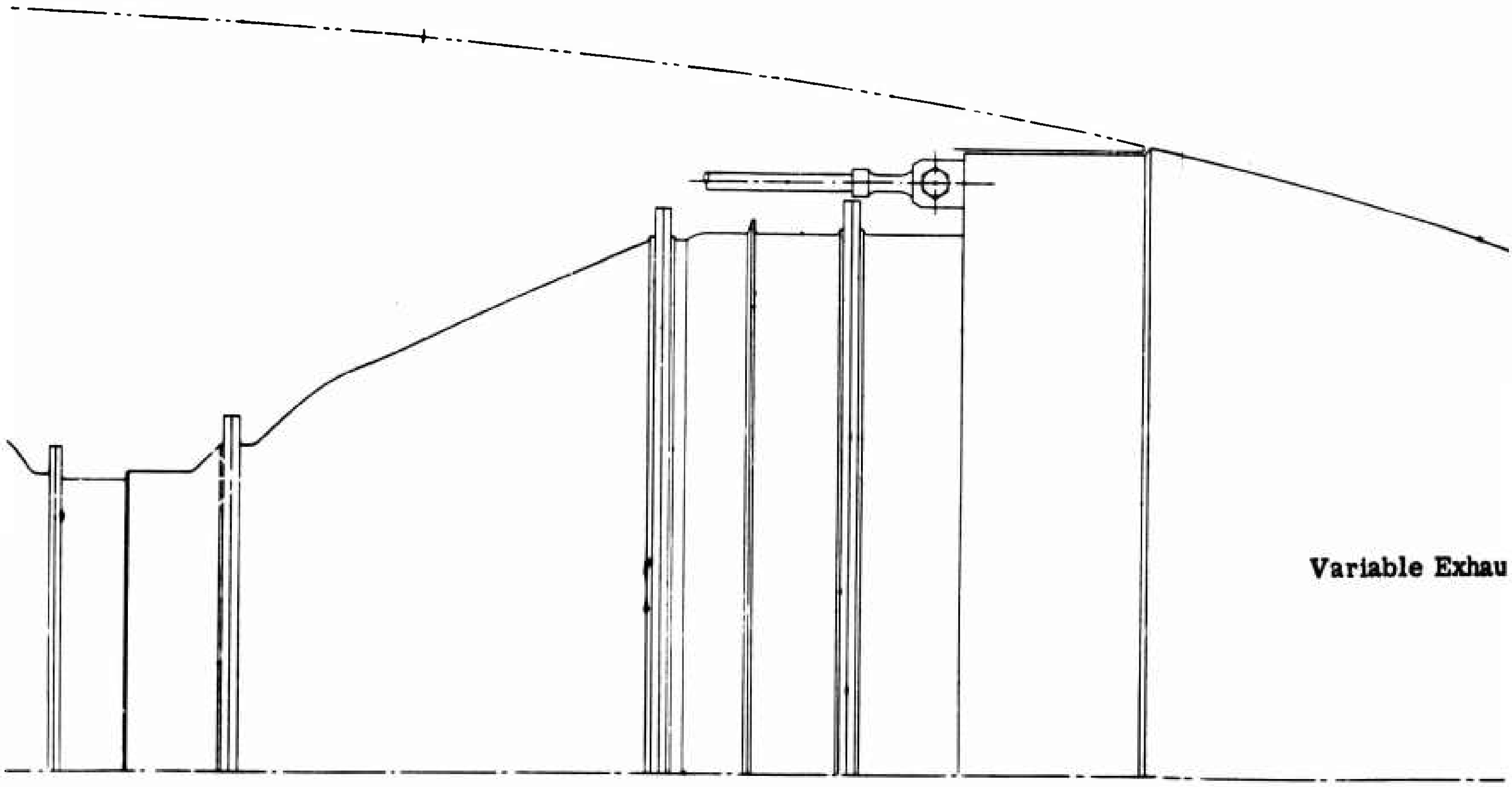
B



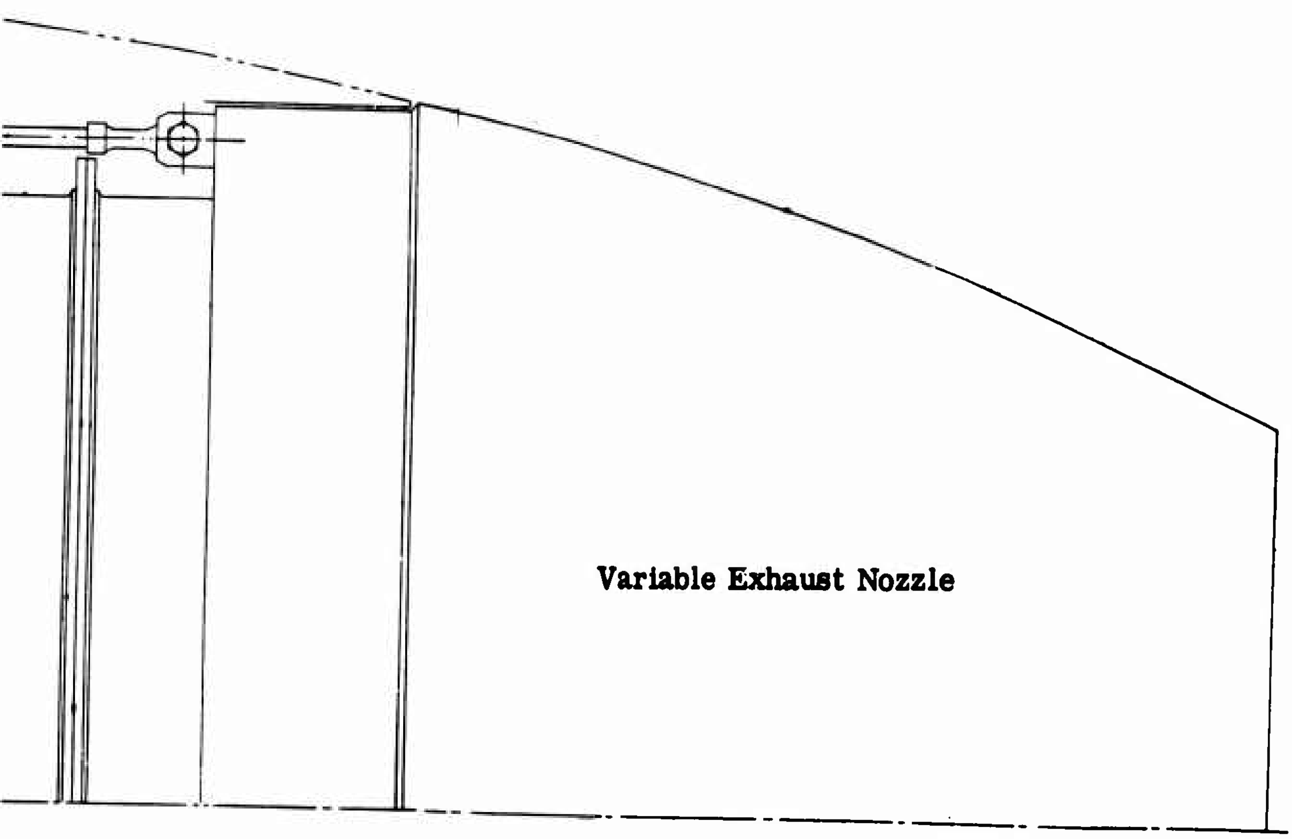
Rotor Drive Shaft
Fan Disch
Bypass Duct
18,000 rpm 2600 hp
Helicopter Mode (85% N_{LP})
Gas Generator
Flow Path
Torque
Converter
Oil Out
Oil In
Stator
A
Output
Engage
Syncromesh
Input
Helix
Power Turbine
100% N_{LP} 12,350 rpm
85% N_{LP} 10,500 rpm
Fan Mode
Helicopter Mode

ide
r Drive.

1



1



E

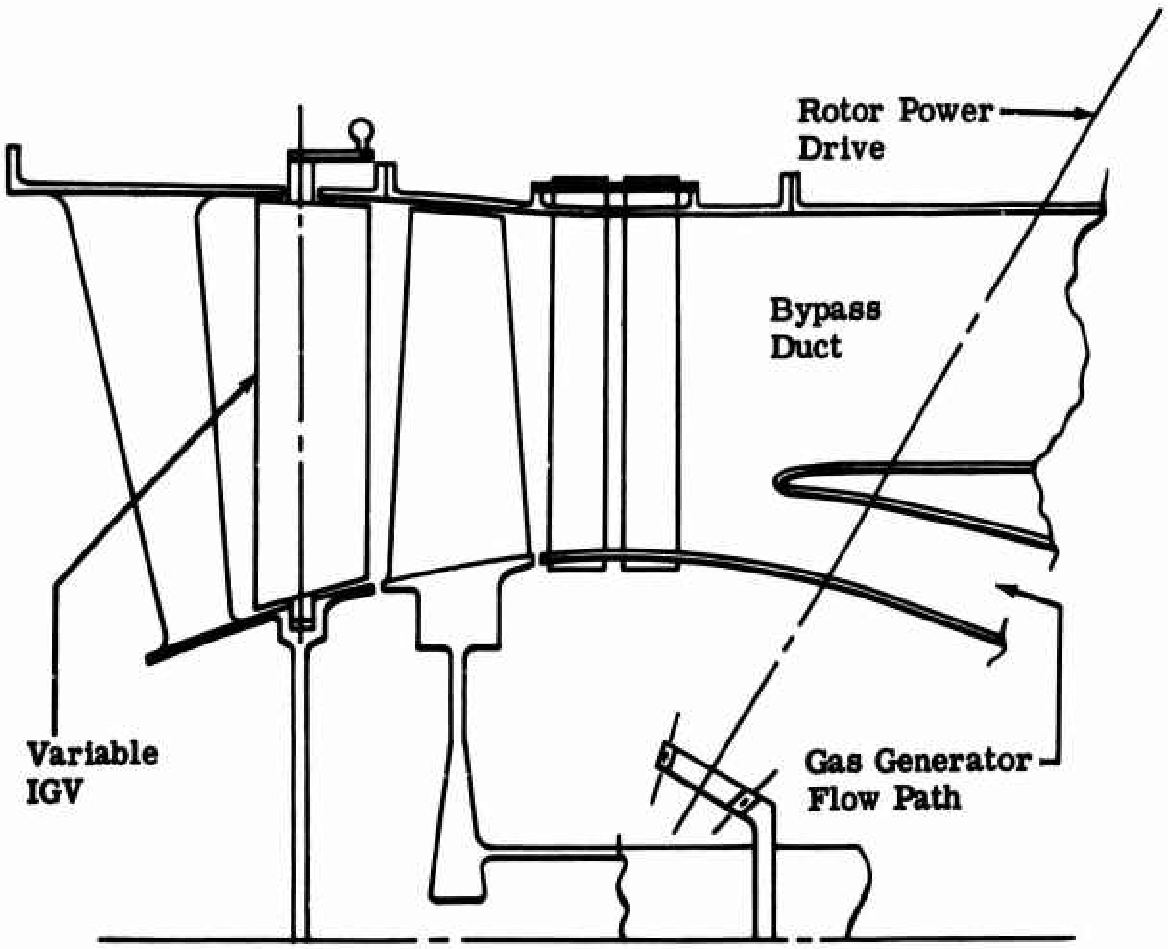


Figure 33. Type I Engine, Supercharged With Variable Total Inlet Guide Vanes and Fixed Total Exit Guide Vanes.

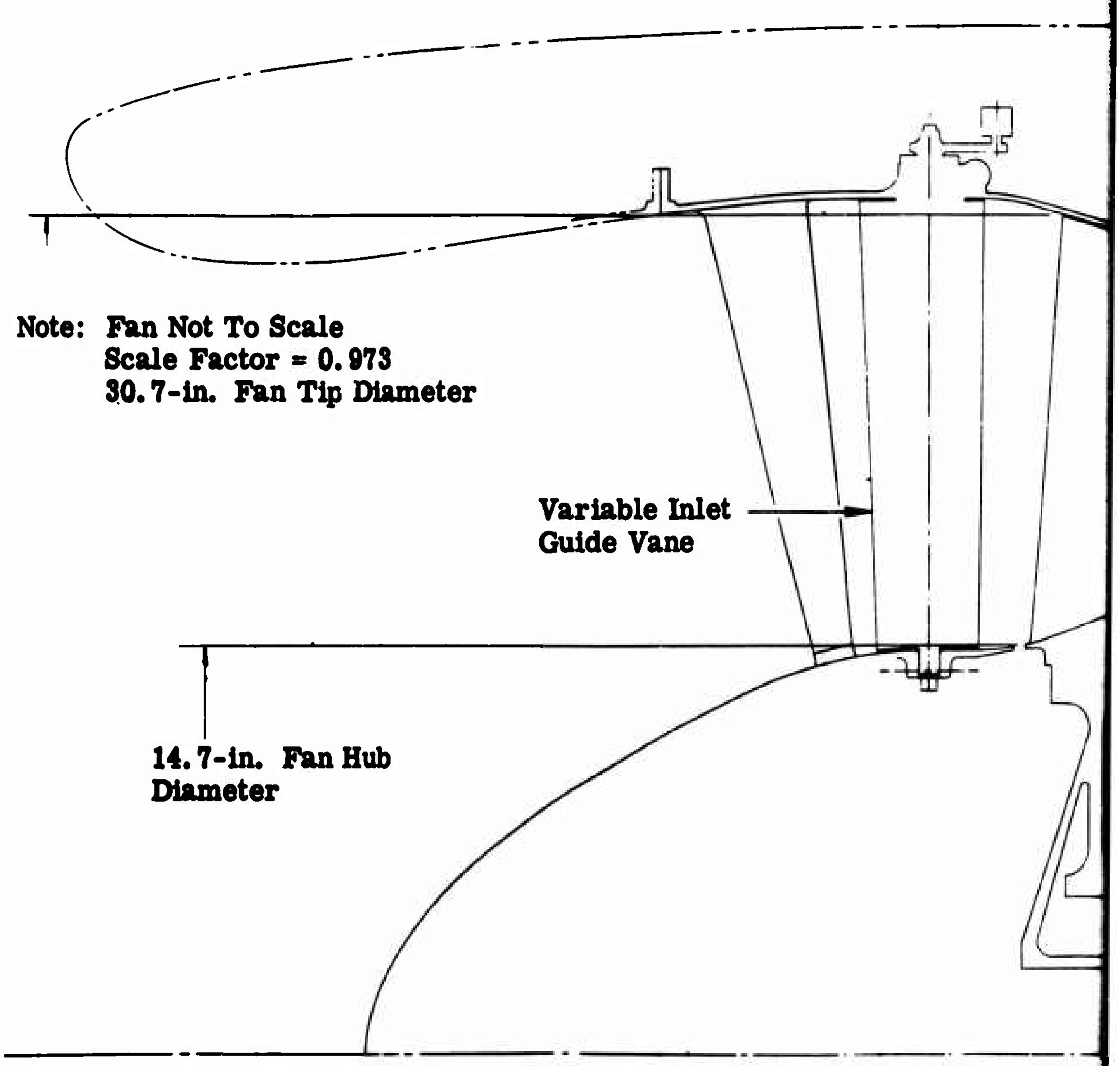
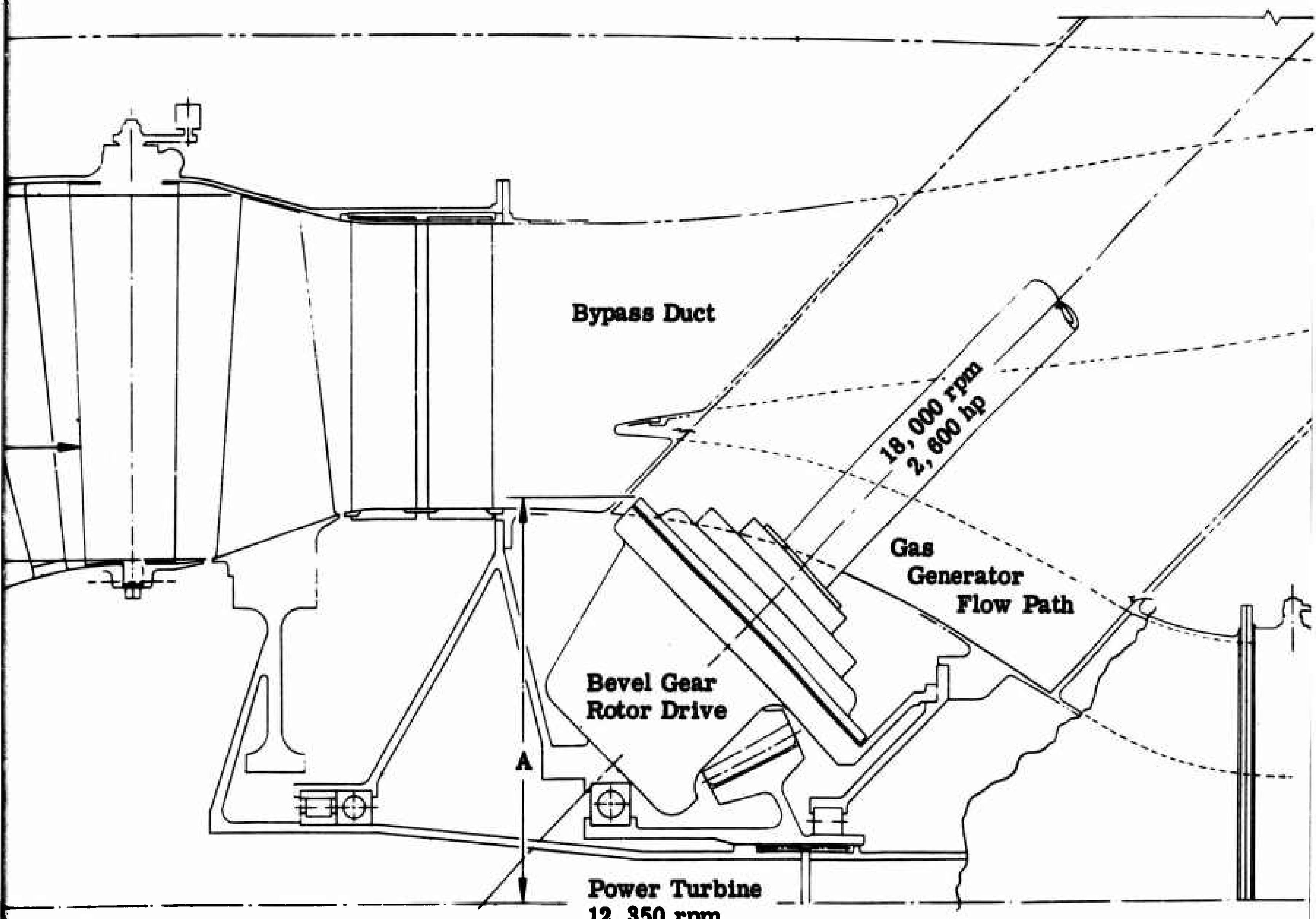


Figure 34. Type I Supercharged Engine With Variable Inlet Guide Vane
and Front 45-Degree Rotor Drive.

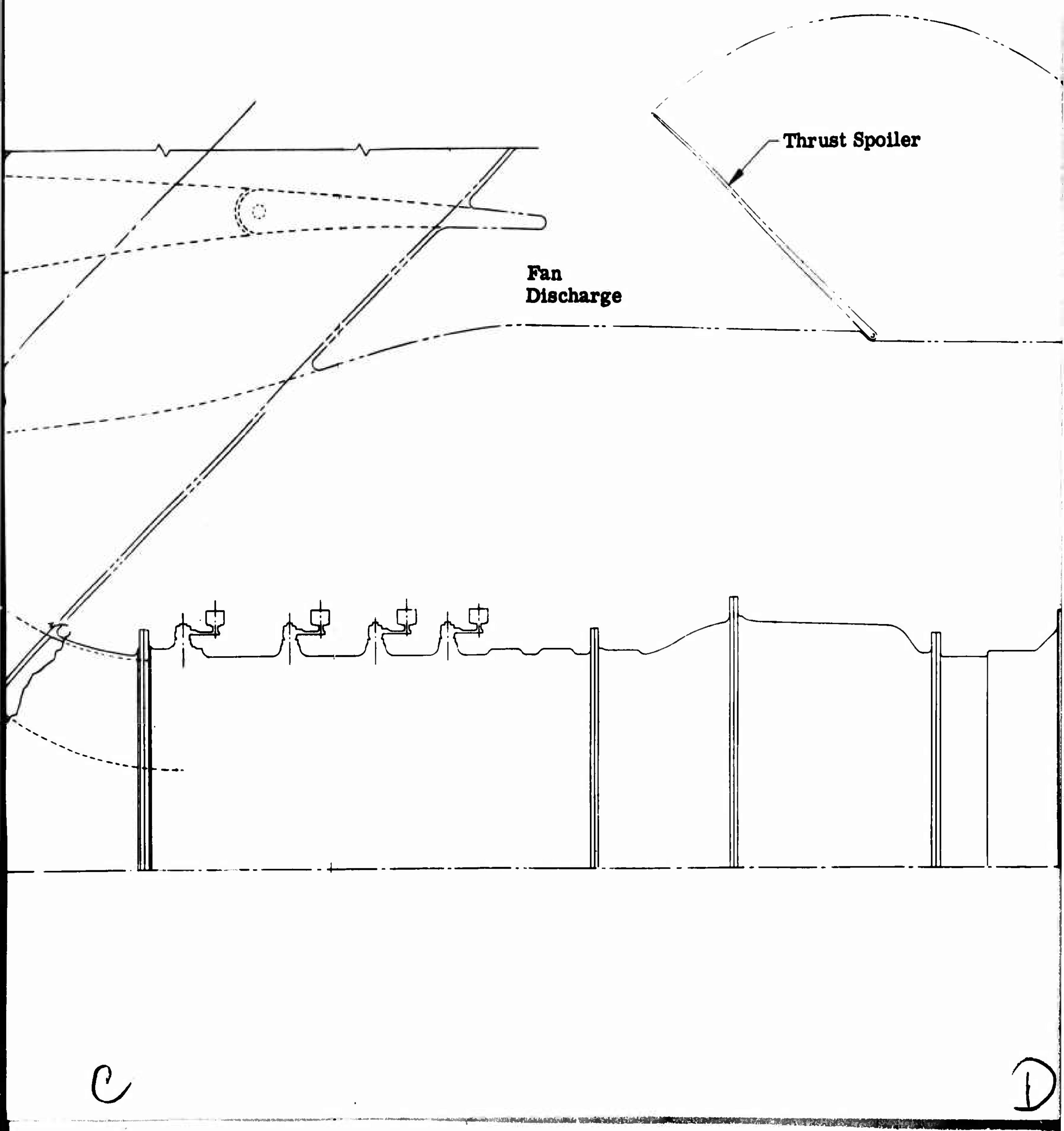
A B

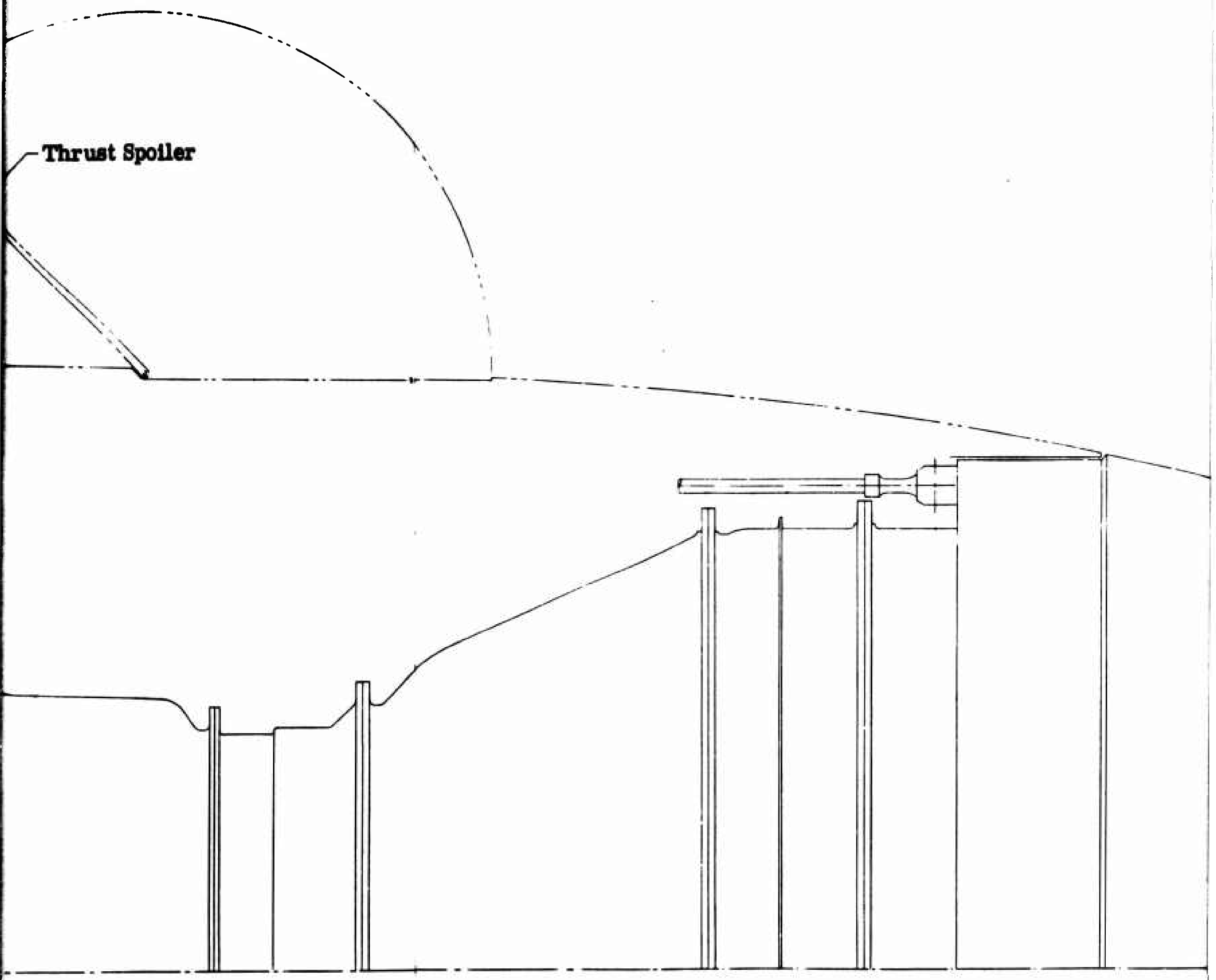


able Inlet Guide Vanes

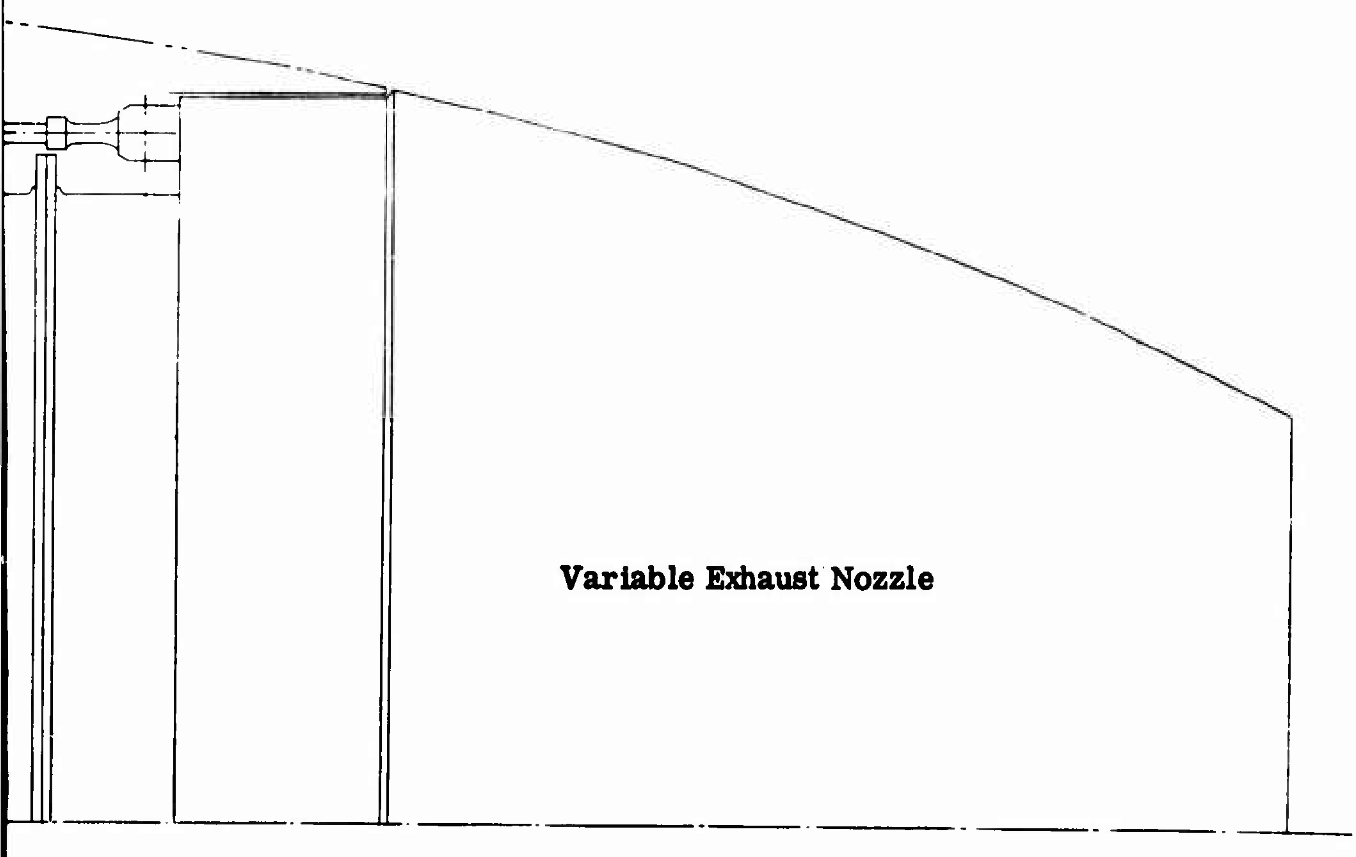
B

C


Thrust Spoiler
Fan
Discharge
C
D



D.



E

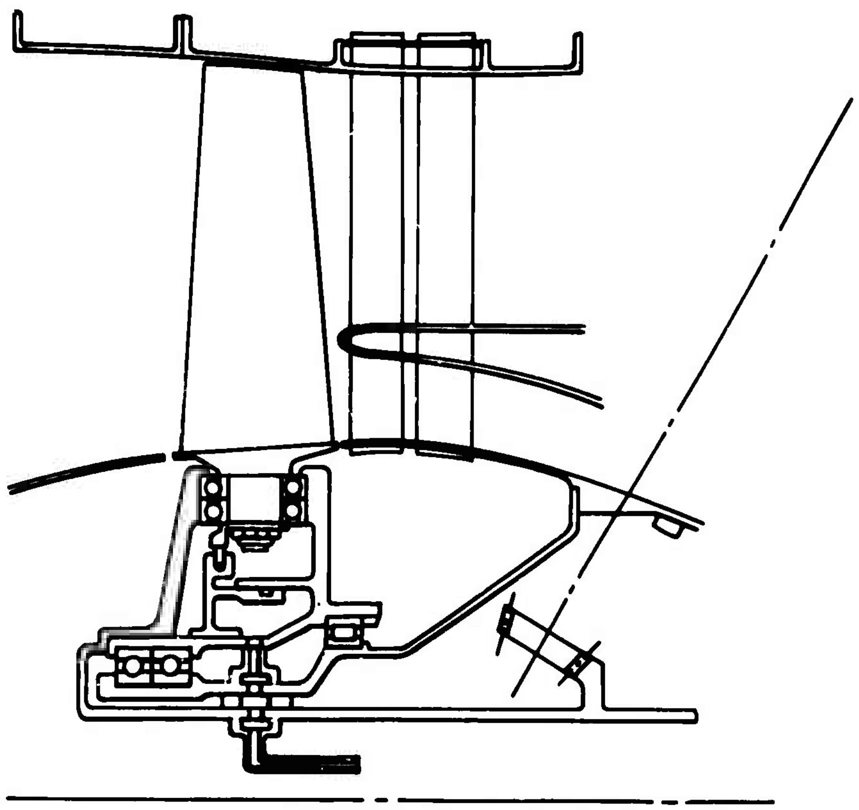


Figure 35. Type I Engine With Variable Total Fan Blade.

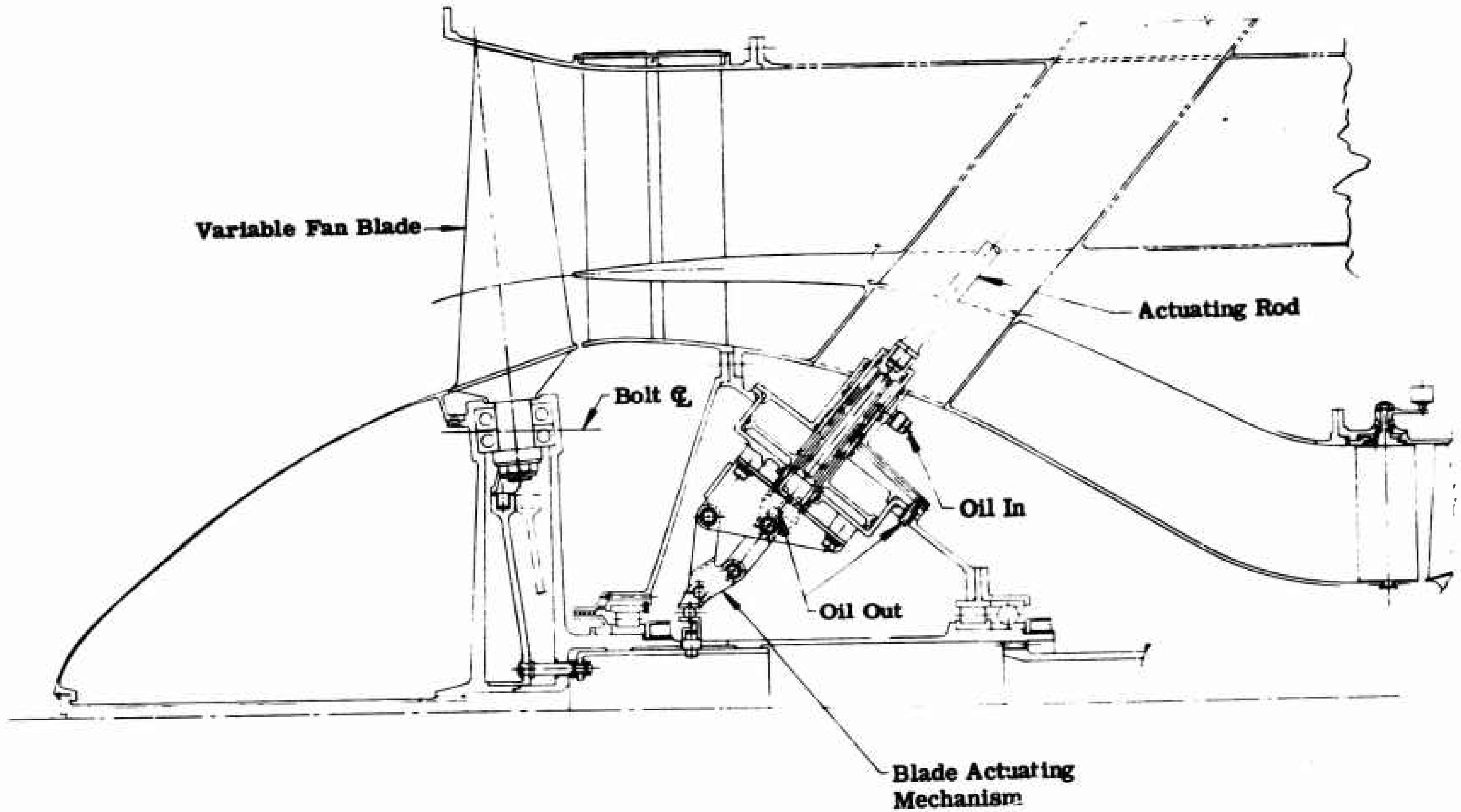


Figure 36. Convertible Fan/Shaft Engine With Variable Total Fan Blades—Mechanical Design Sketch.

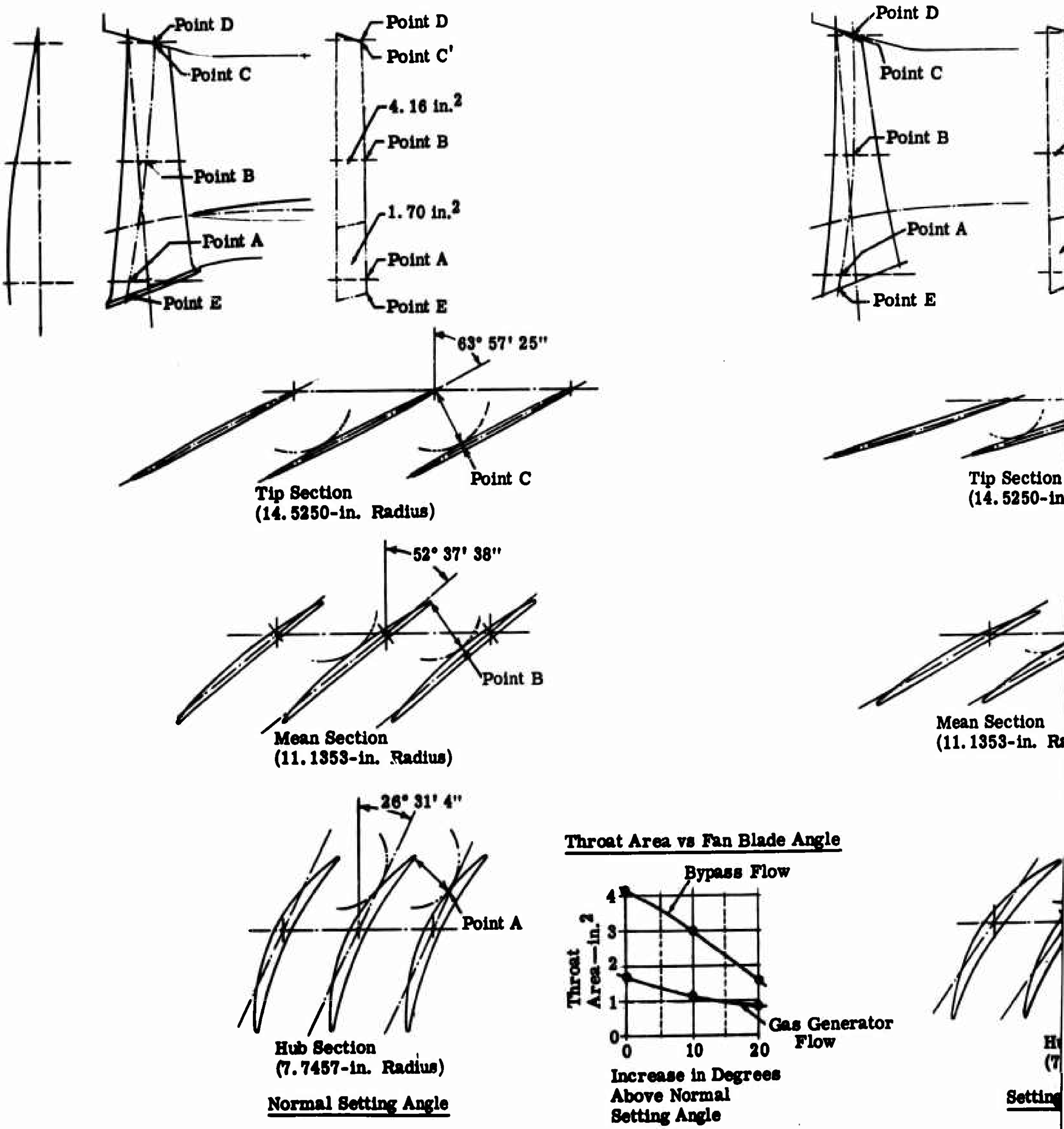
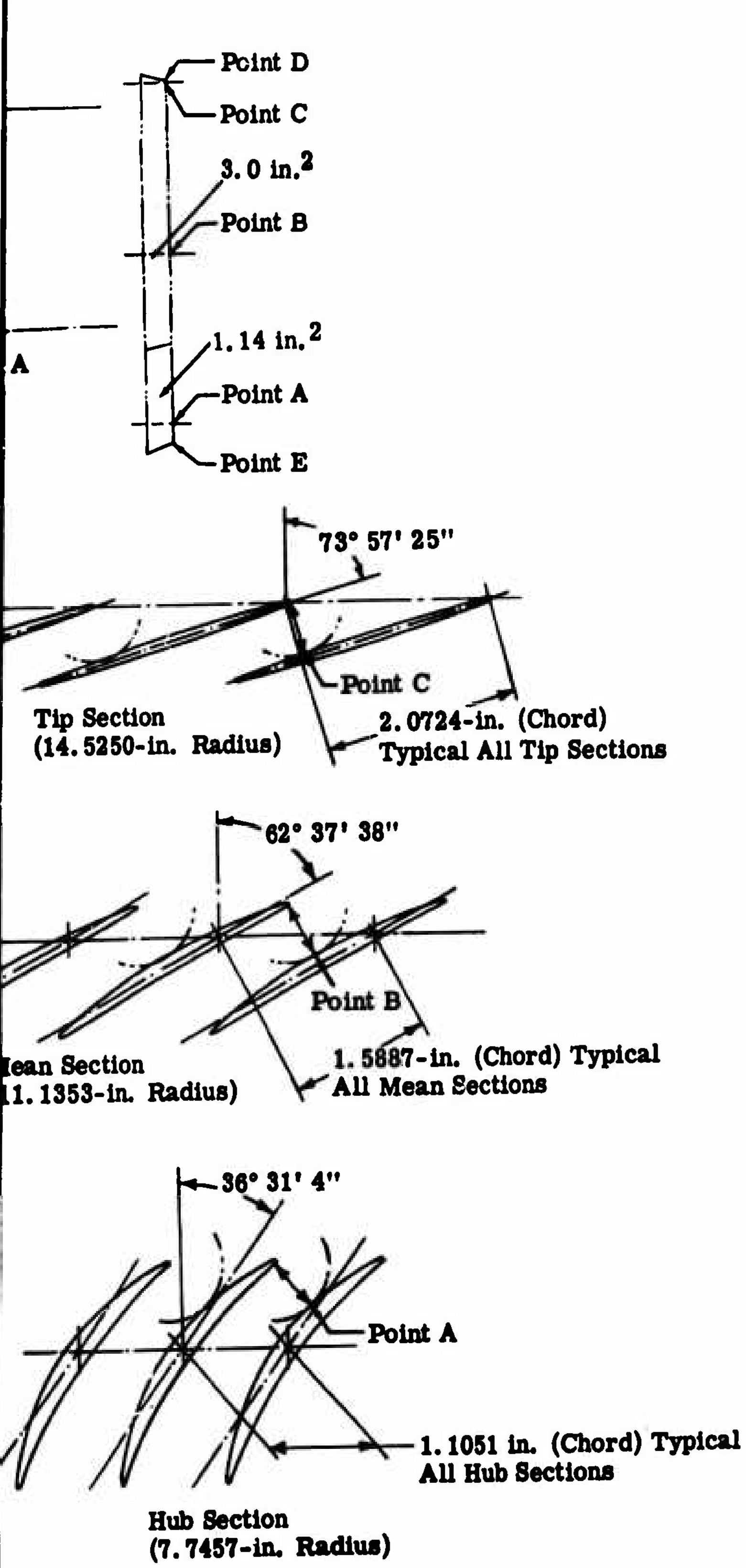
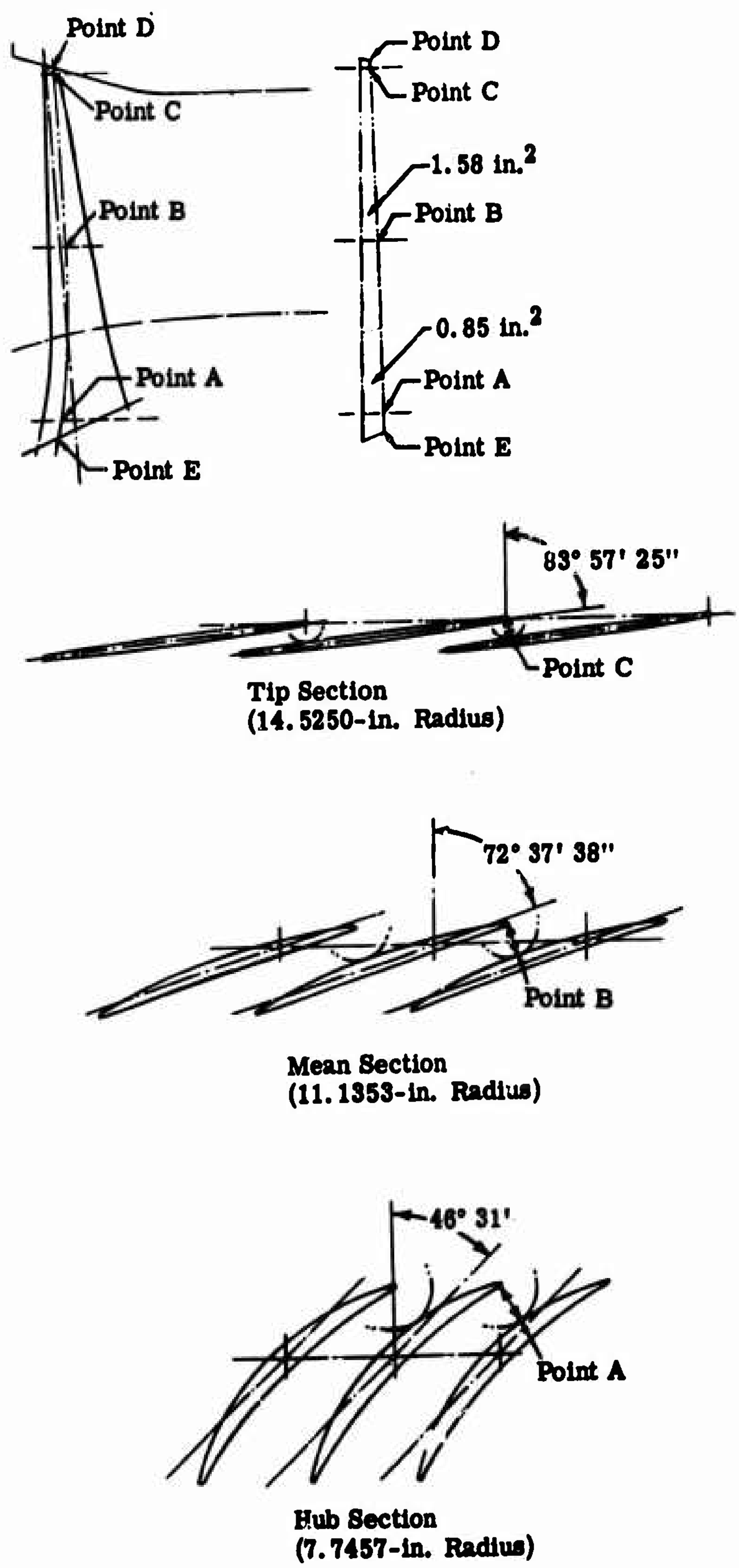


Figure 37. Convertible Fan/Shaft Engine With Variable Total Fan Blades—Blade Geometry Study.

A



Setting Angle Increased 10°



Setting Angle Increased 20°

B

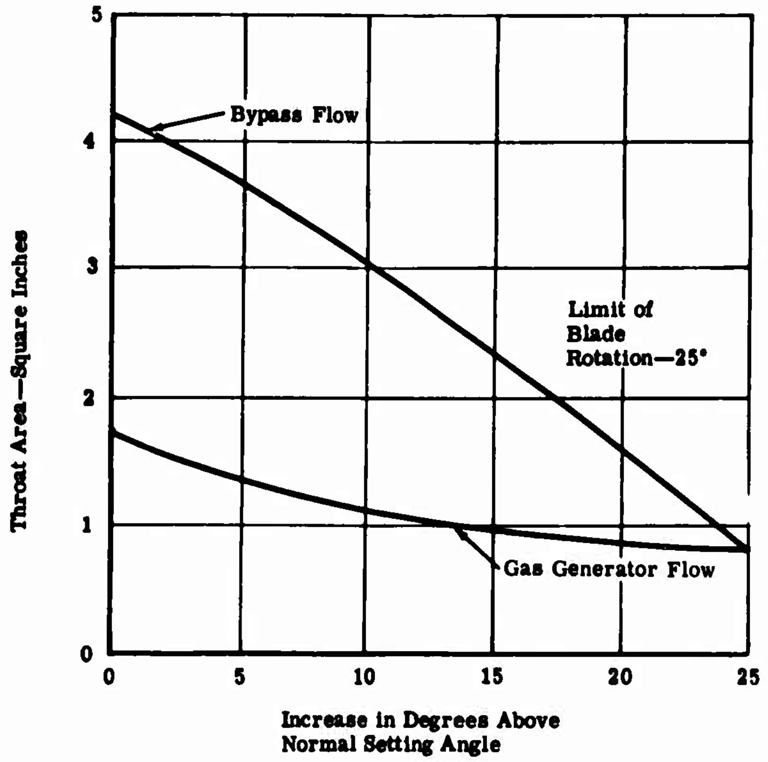


Figure 38. Variable Fan Blade Throat Area Versus Blade Angle Change.

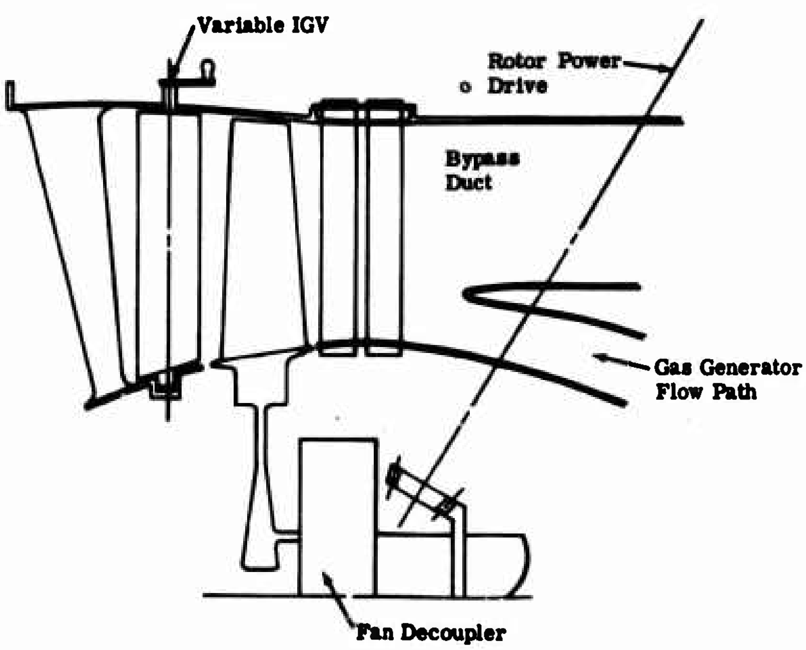


Figure 39. Type IA Engine, Supercharged With Variable Total Inlet Guide Vanes, Fixed Total Exit Guide Vanes, and Total Fan Decoupler.

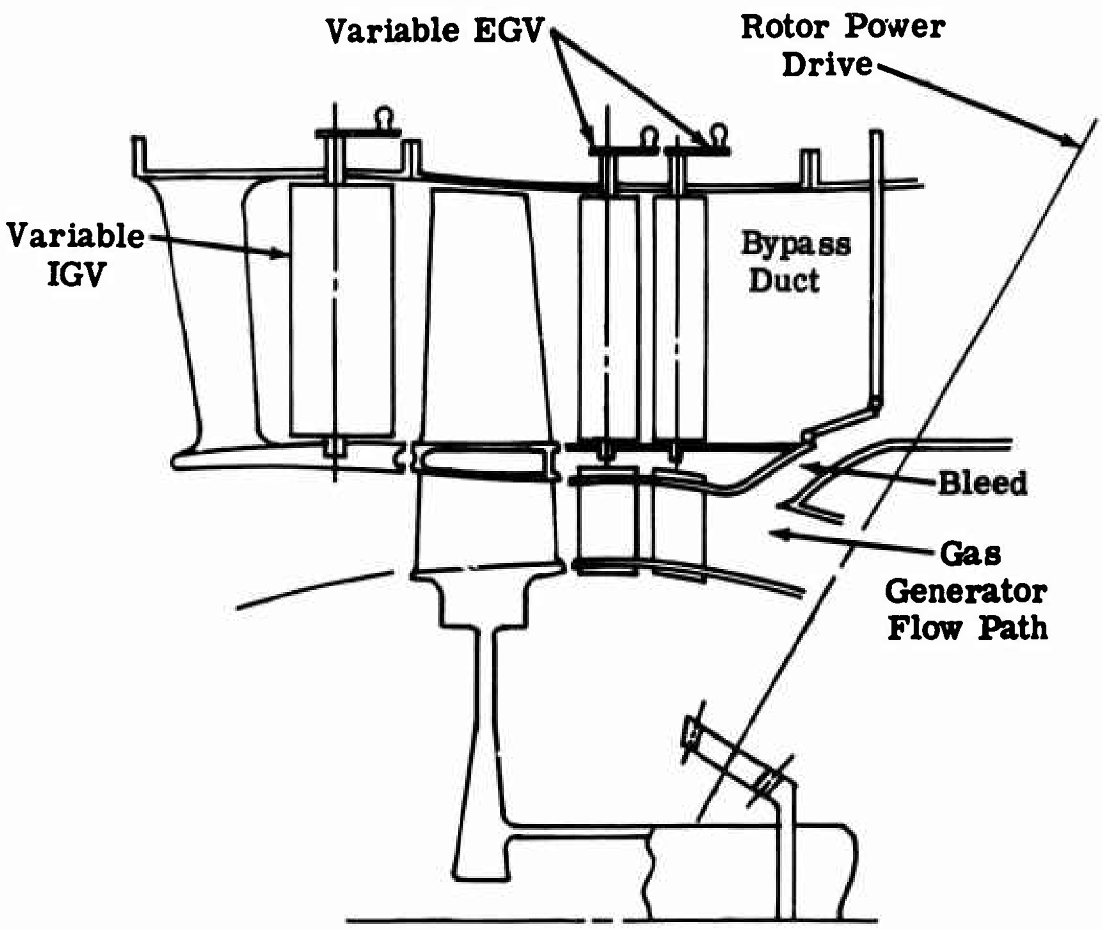


Figure 40. Type II Engine, Supercharged With Variable Bypass Inlet Guide Vanes, Variable Bypass Exit Guide Vanes, and Gas Generator Inlet Air Bleed.

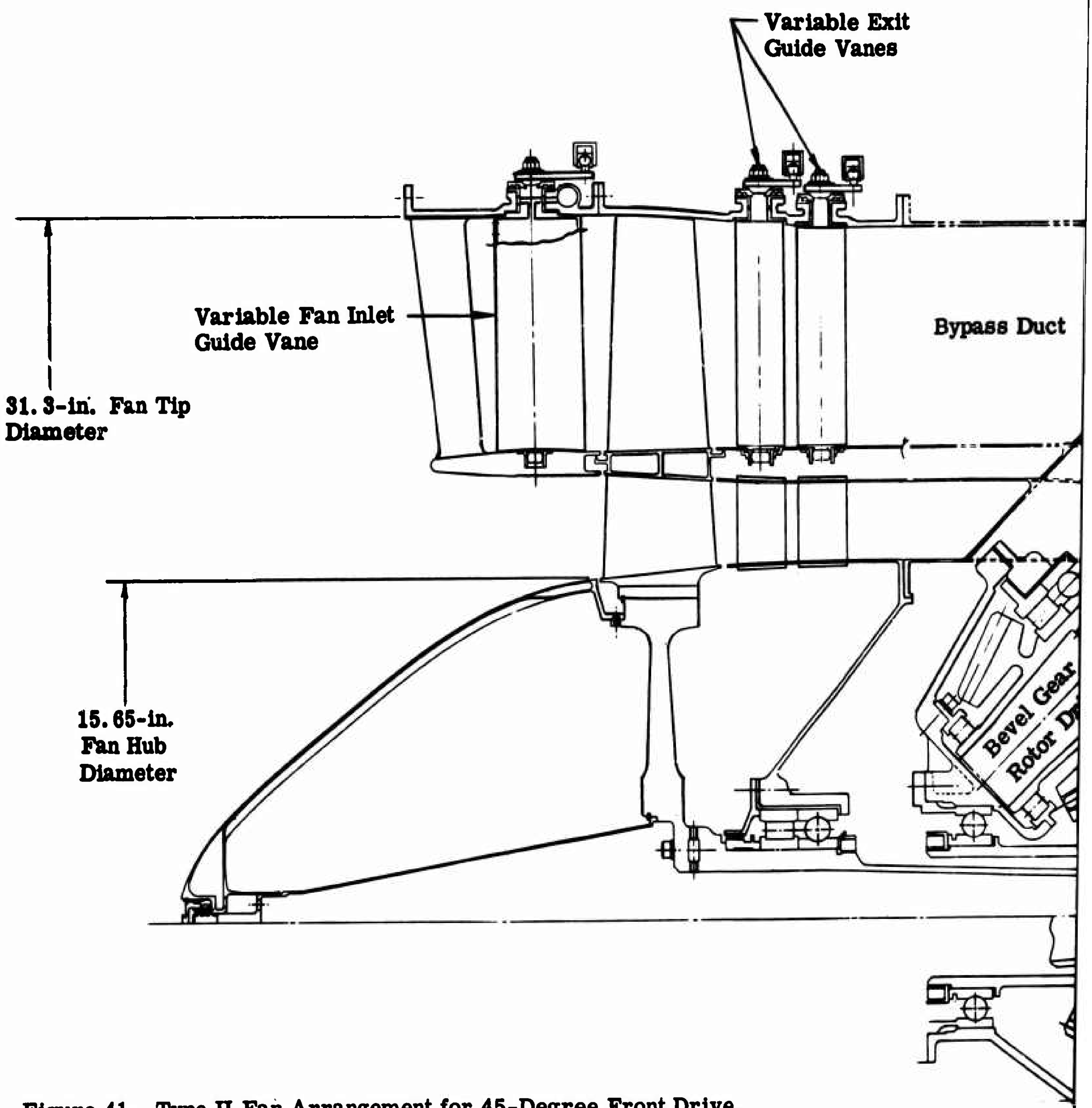
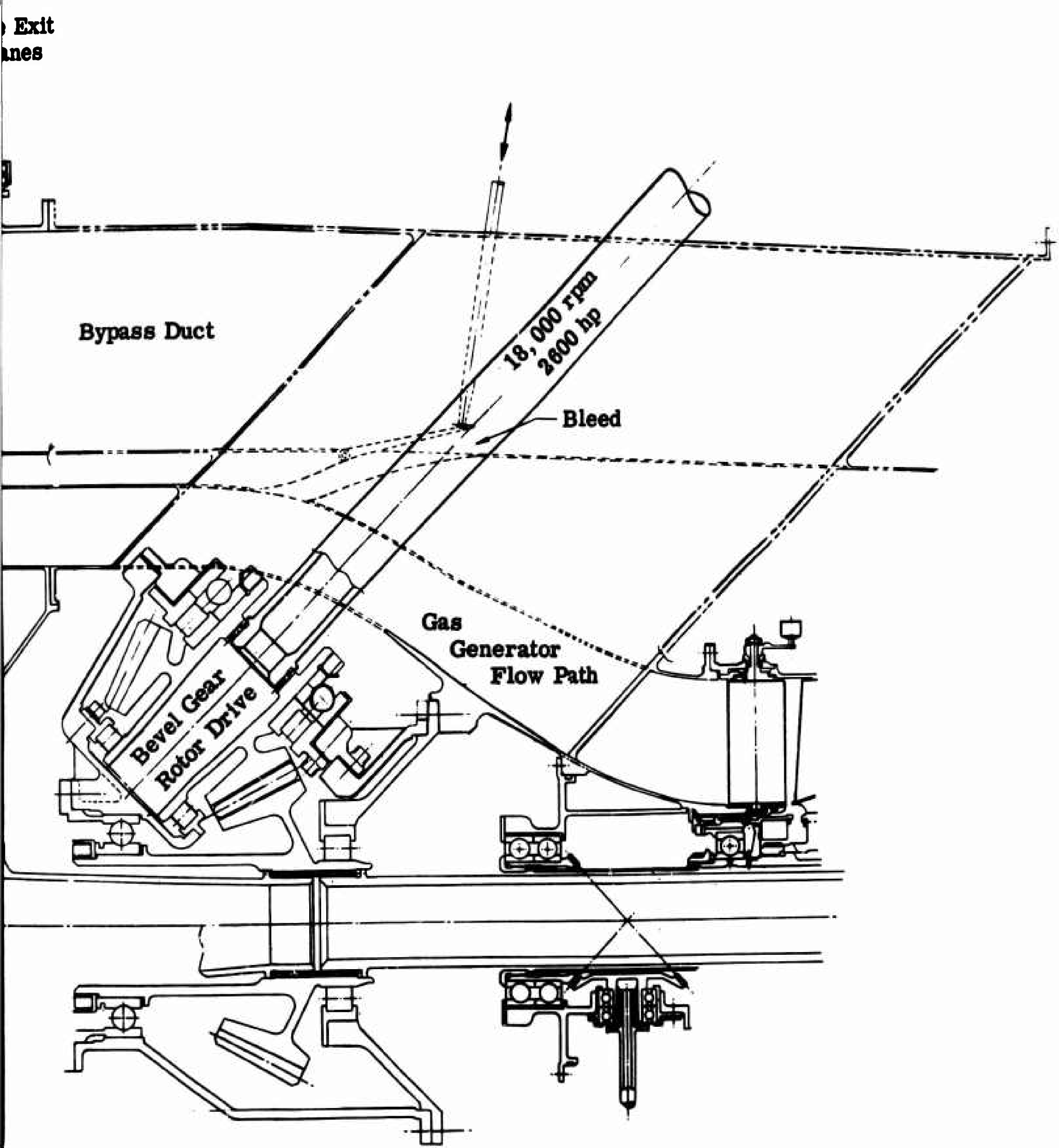


Figure 41. Type II Fan Arrangement for 45-Degree Front Drive.

A



Exit
nes
Bypass Duct
18,000 rpm
2600 hp
Bleed
Gas
Generator
Flow Path
Bevel Gear
Rotor Drive

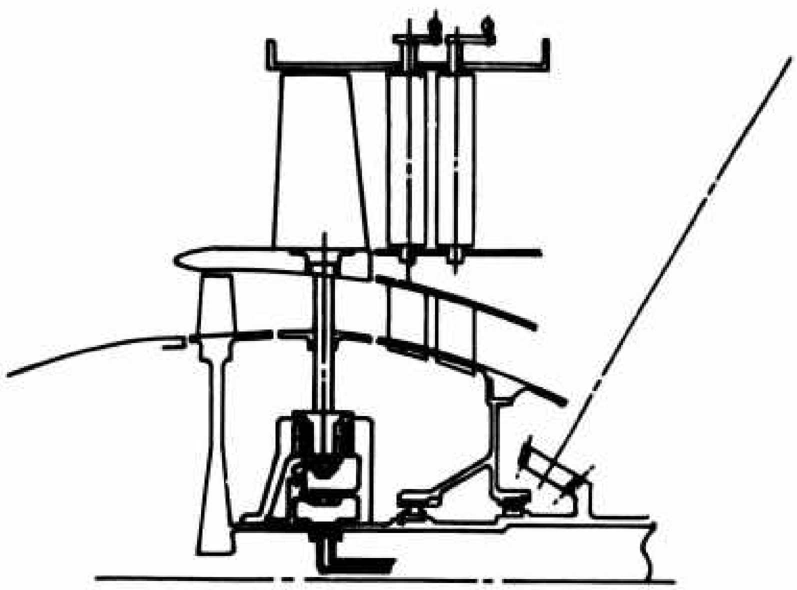


Figure 42. Type II Engine With Variable Fan Blade on Direct Coupled Fan.

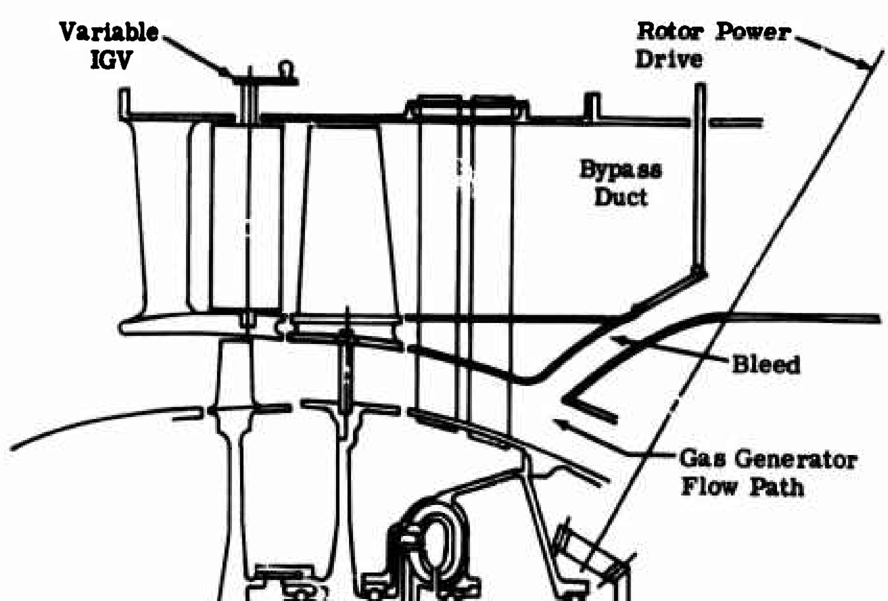


Figure 43. Type IIA Engine, Supercharged With Variable Bypass Inlet Guide Vanes, Fixed Bypass Exit Guide Vanes, Gas Generator Inlet Air Bleed, and Fan Decoupler.

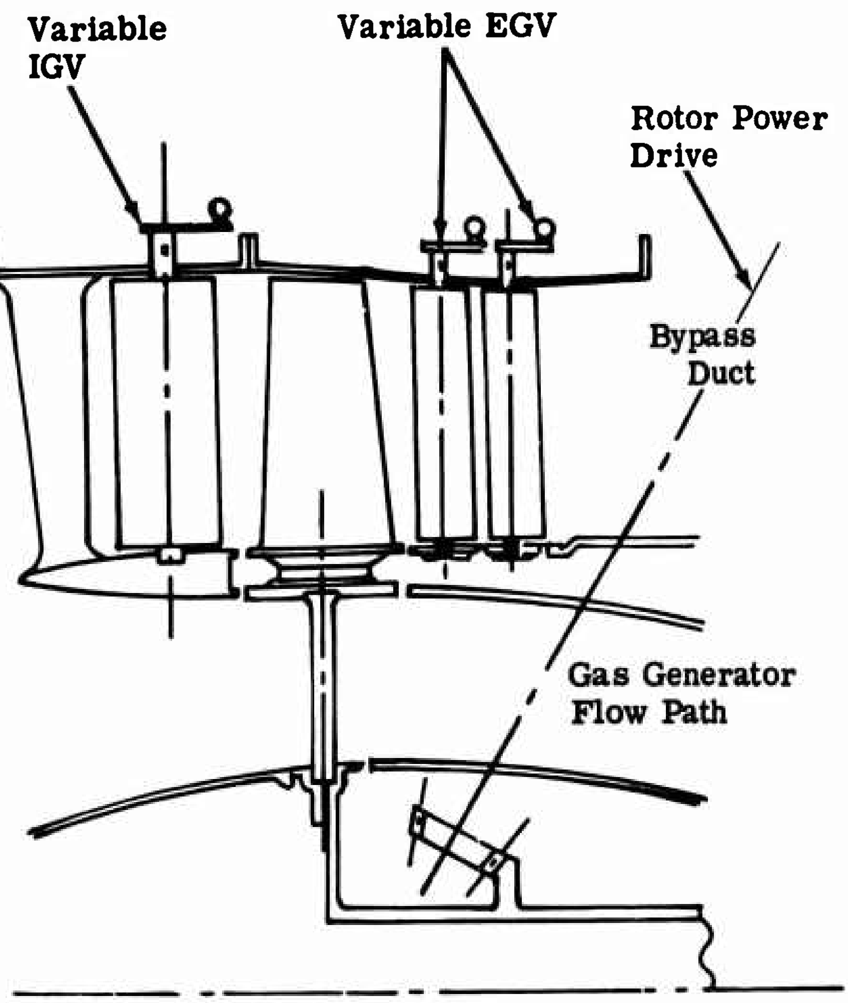


Figure 44. Type III Engine, Nonsupercharged With Variable Bypass Inlet Guide Vanes and Variable Bypass Exit Guide Vanes.

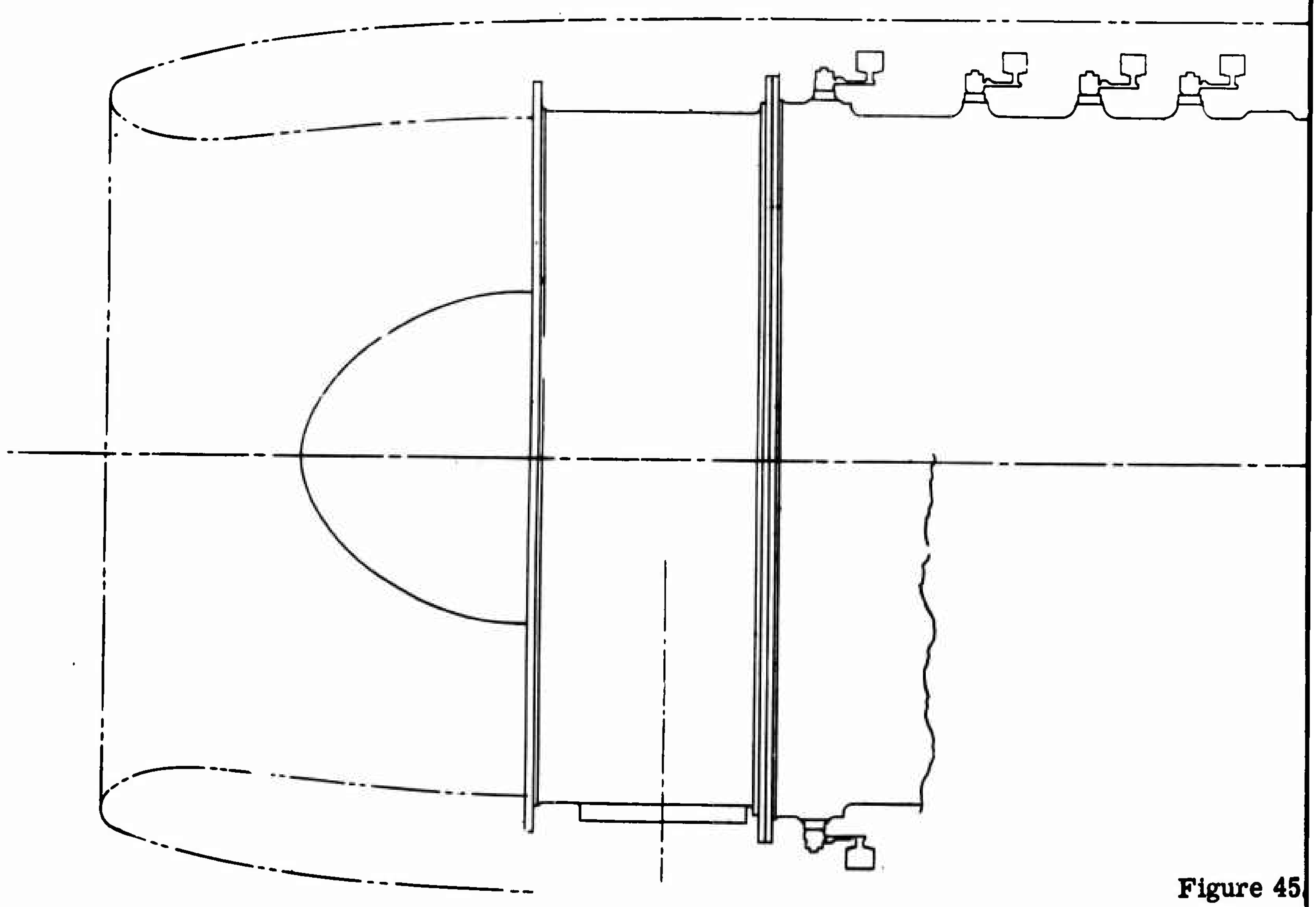
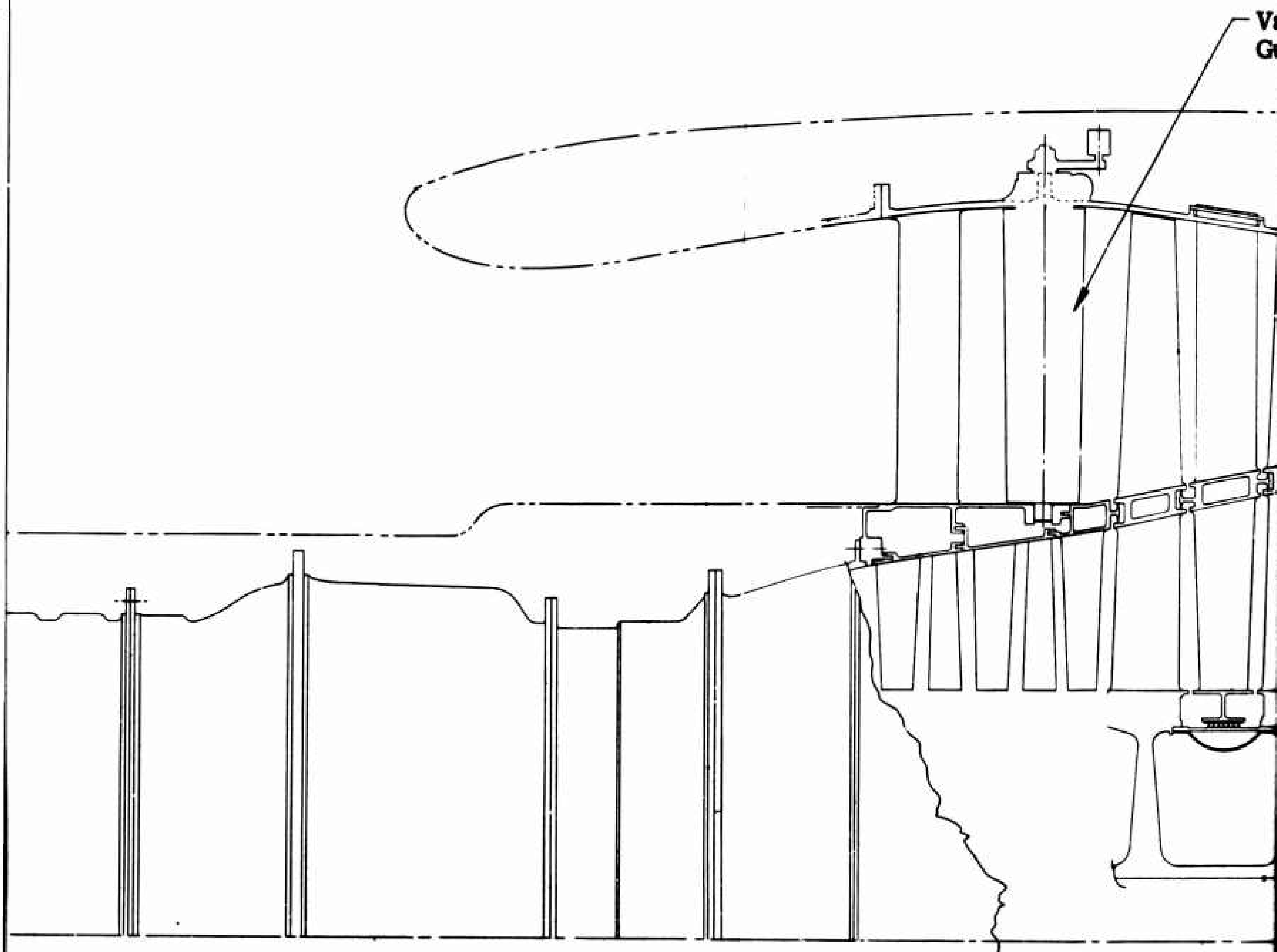


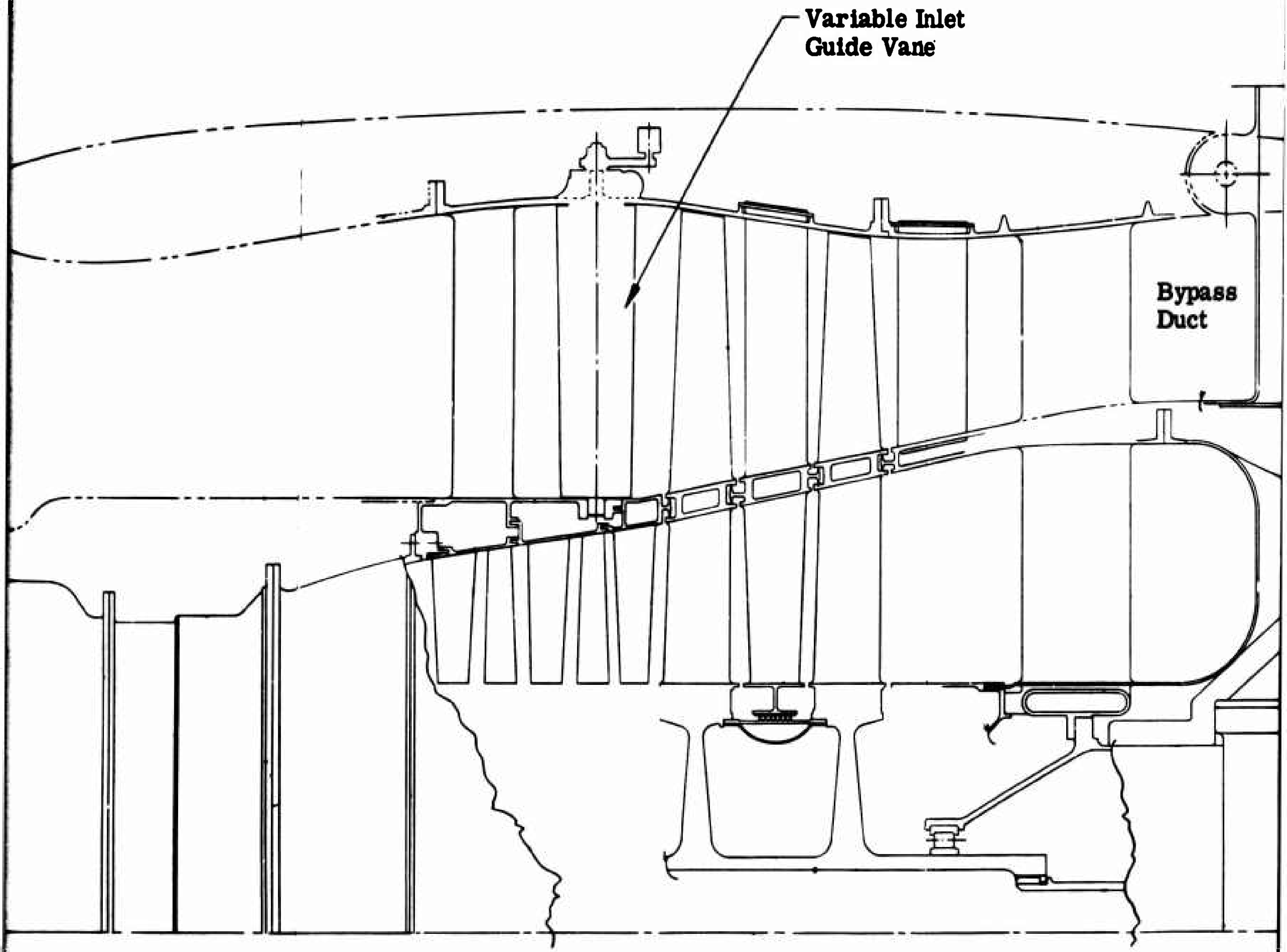
Figure 45.

A

B



45. Nonsupercharged Engine With Aft Fan, 90-Degree Rear Rotor Drive, and Variable Inlet Guide Vanes.

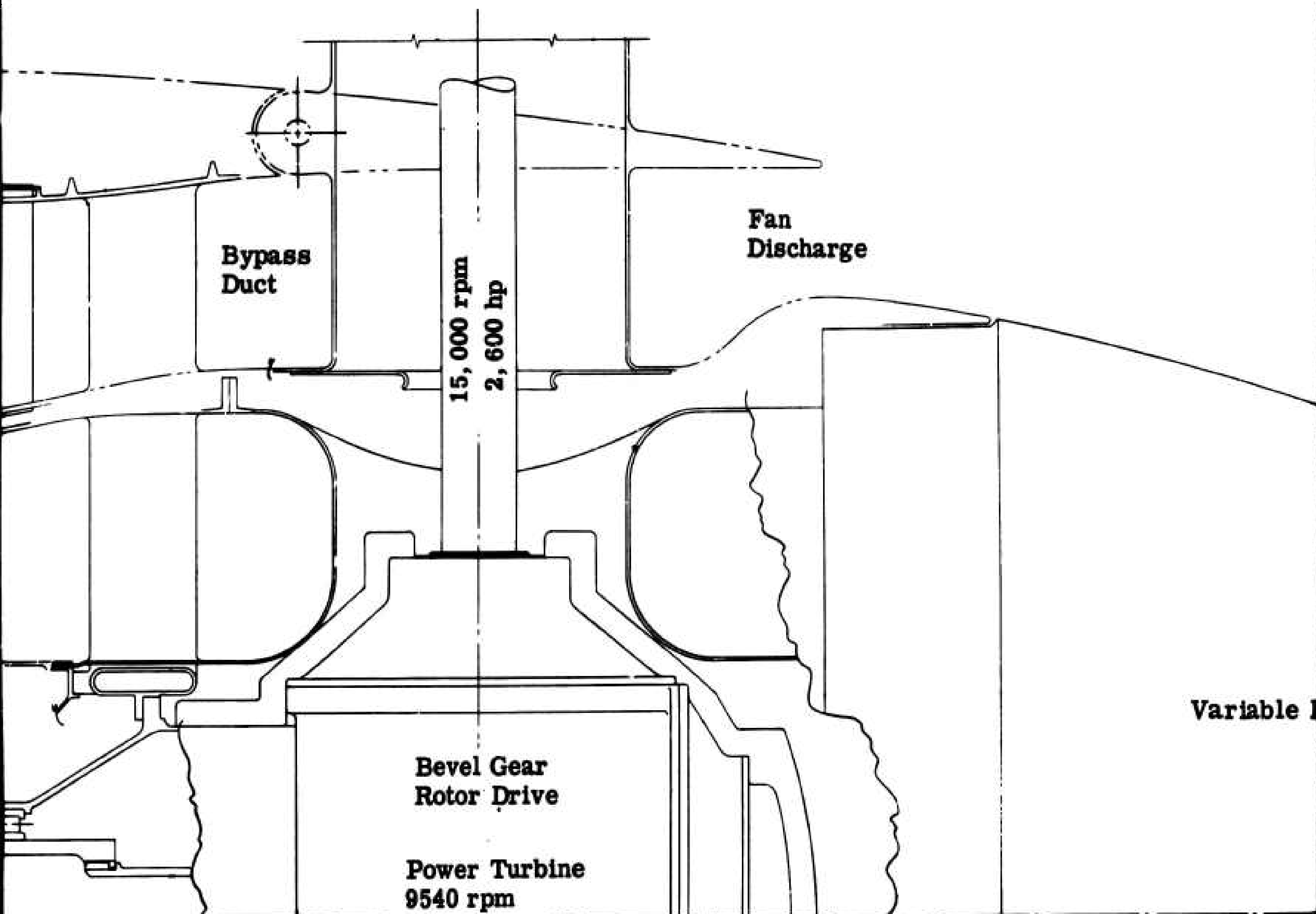


Aft Fan, 90-Degree Rear Rotor
Vanes.

D

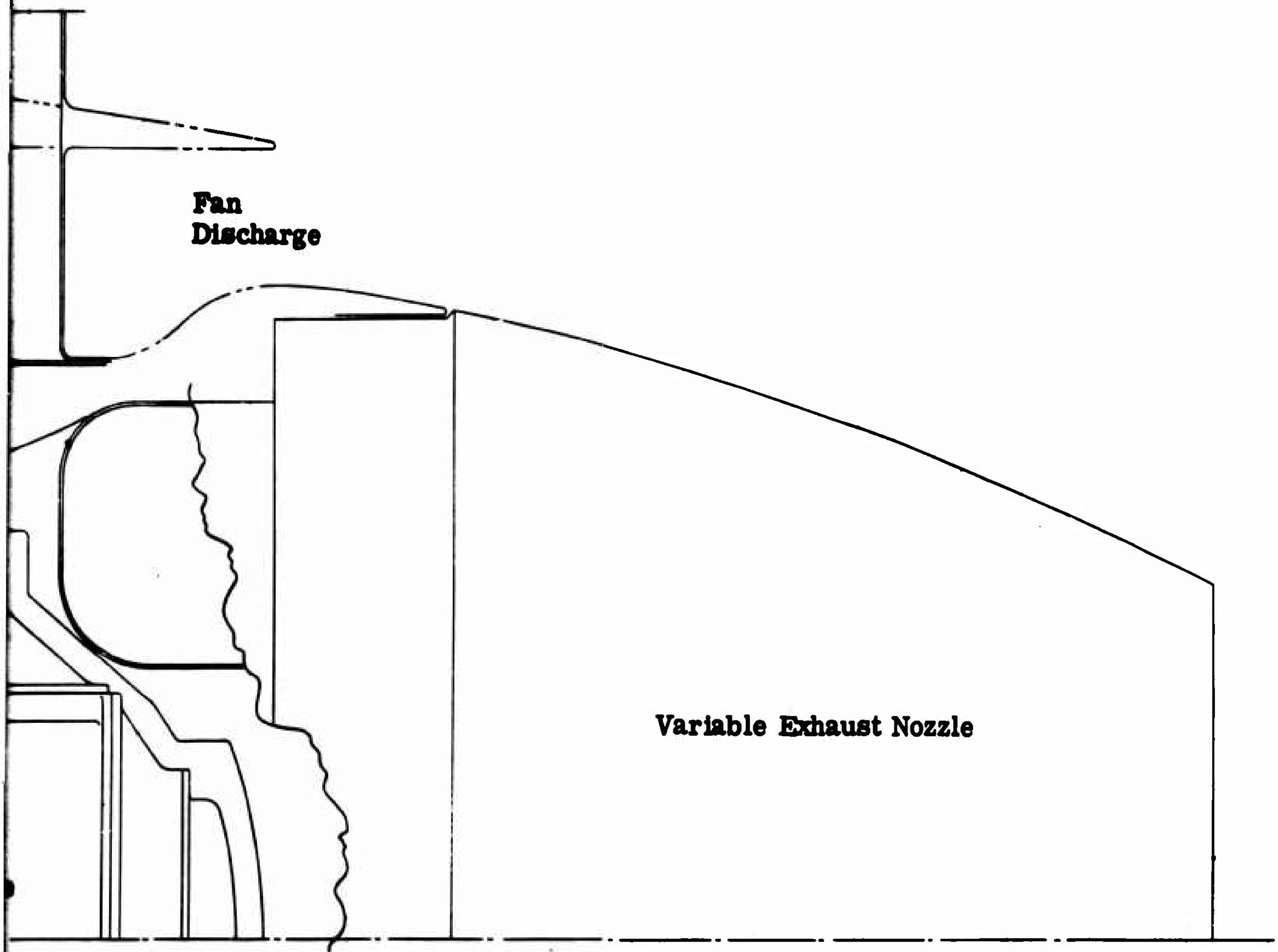
C

et


Bypass
Duct
15,000 rpm
2,600 hp
Fan
Discharge
Variable
Bevel Gear
Rotor Drive
Power Turbine
9540 rpm

D

E



E

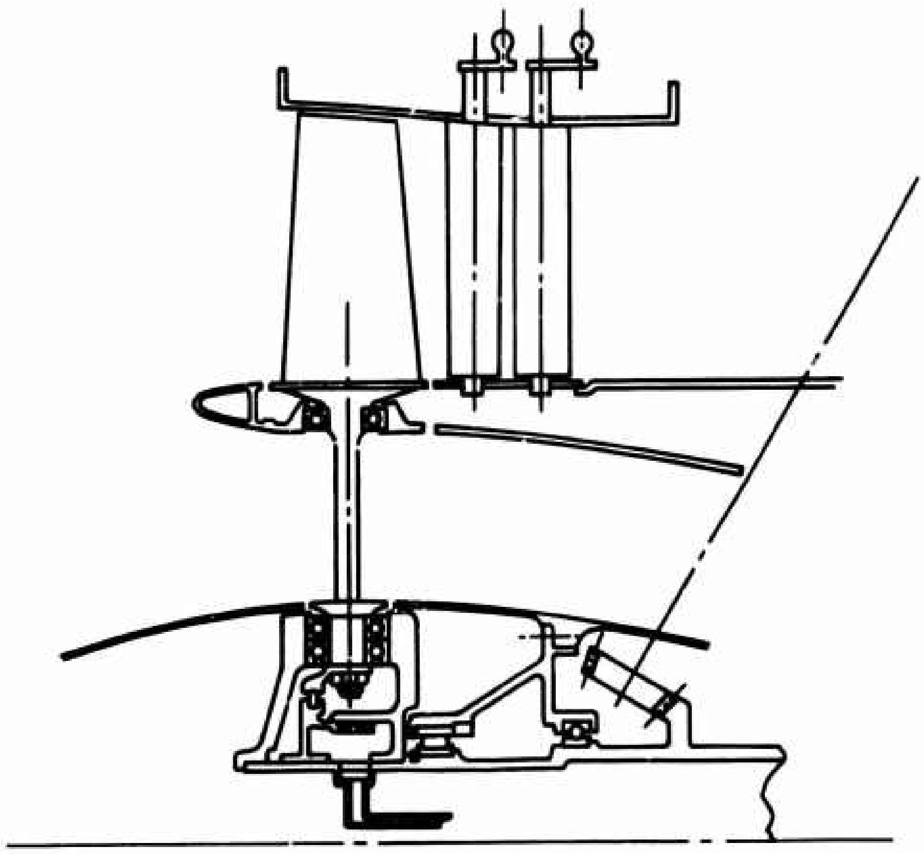


Figure 46. Type III Engine With Variable Fan Blade.

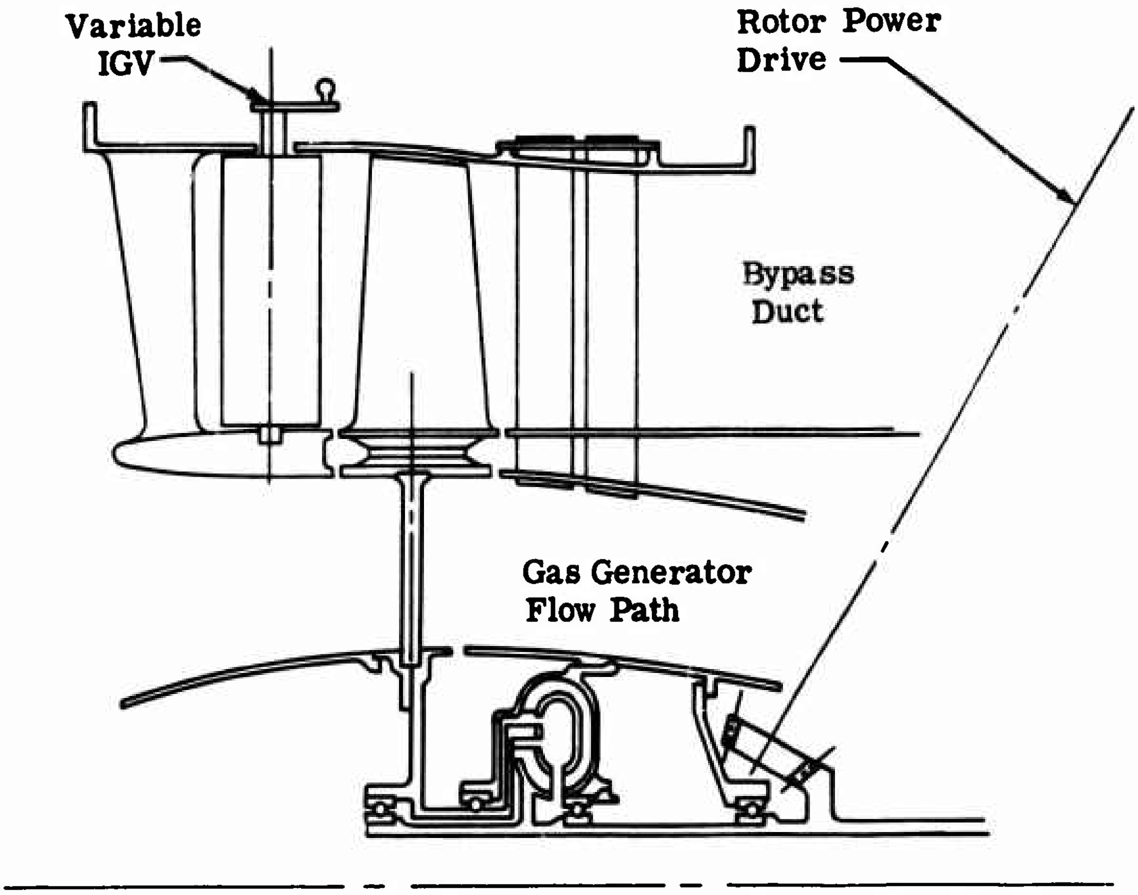


Figure 47. Type IIIA Engine, Nonsupercharged With Variable Bypass Inlet Guide Vanes, Fixed Bypass Exit Guide Vanes, and Fan Decoupler.

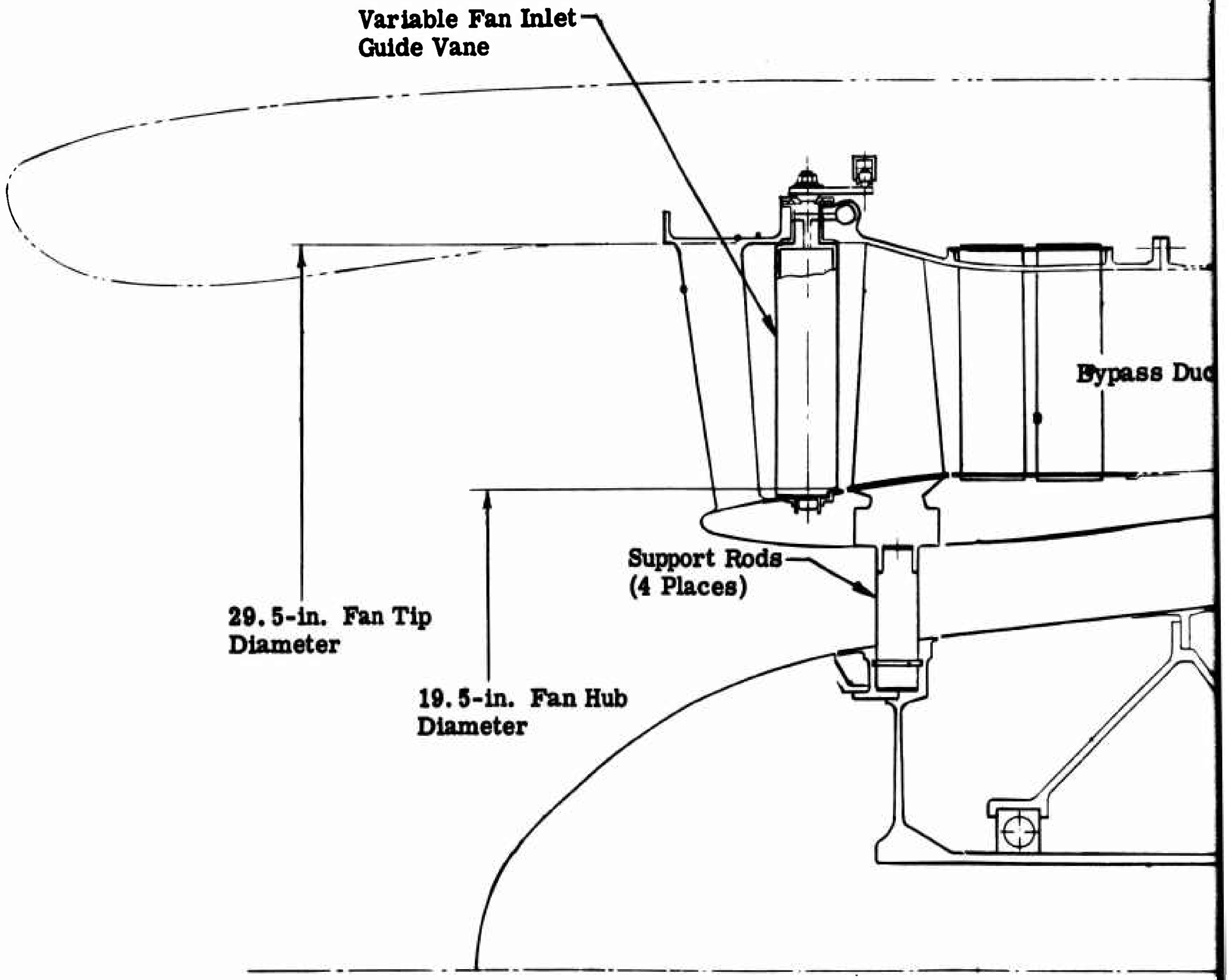
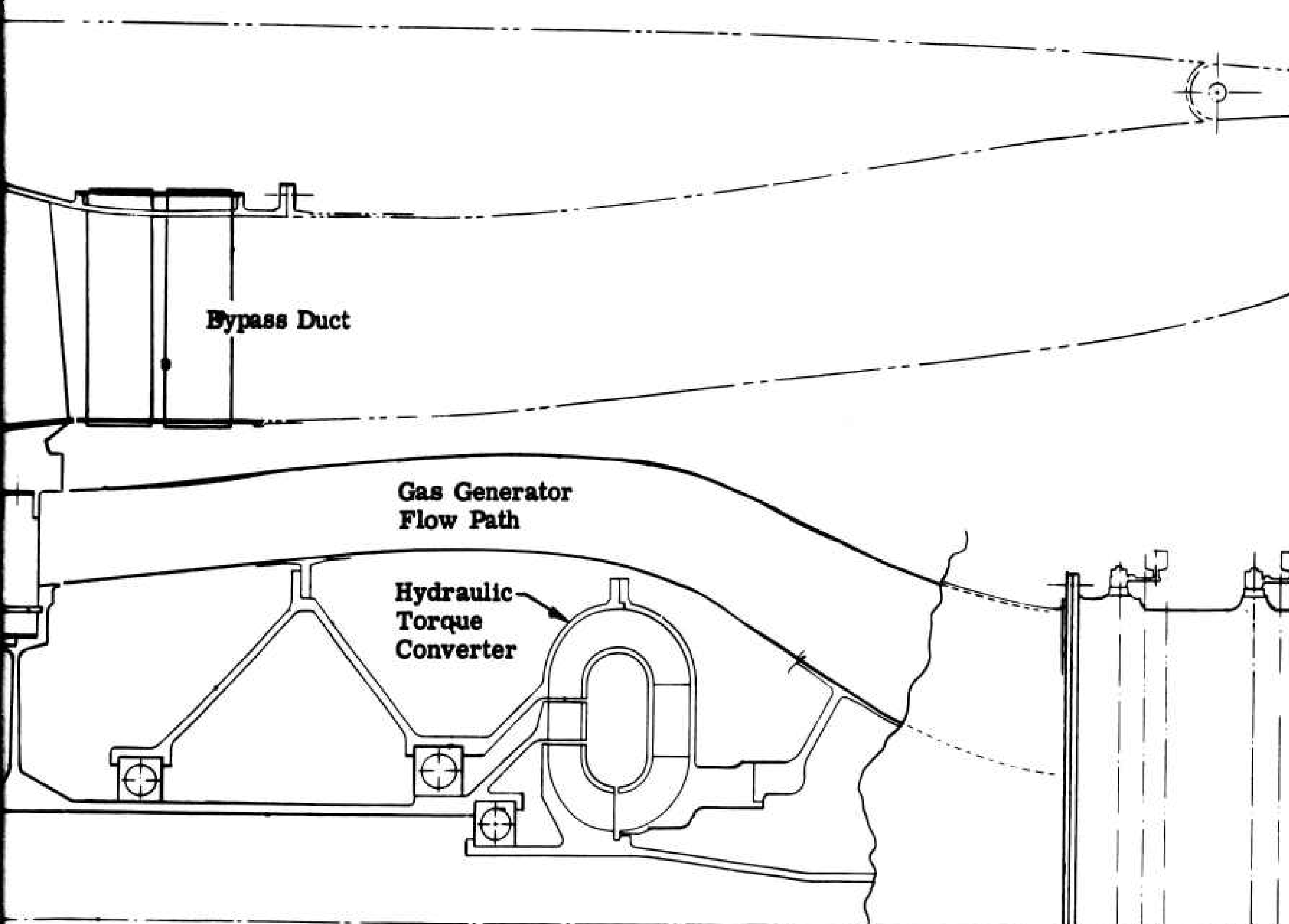


Figure 48. Type IIIA Nonsupercharged Engine With Aft Drive and Fan Decoupler.

A

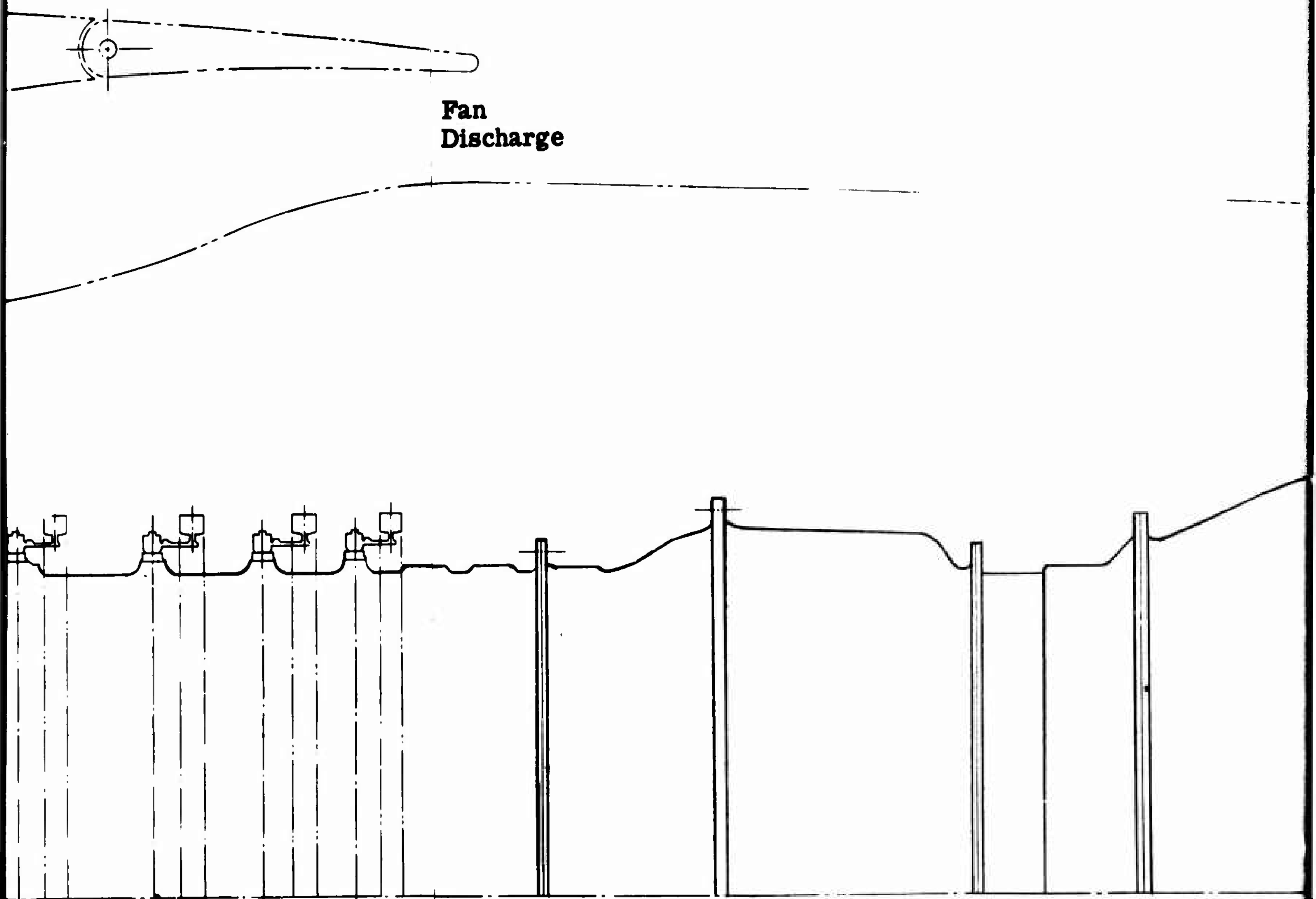
B


Bypass Duct
Gas Generator
Flow Path
Hydraulic
Torque
Converter

and Fan

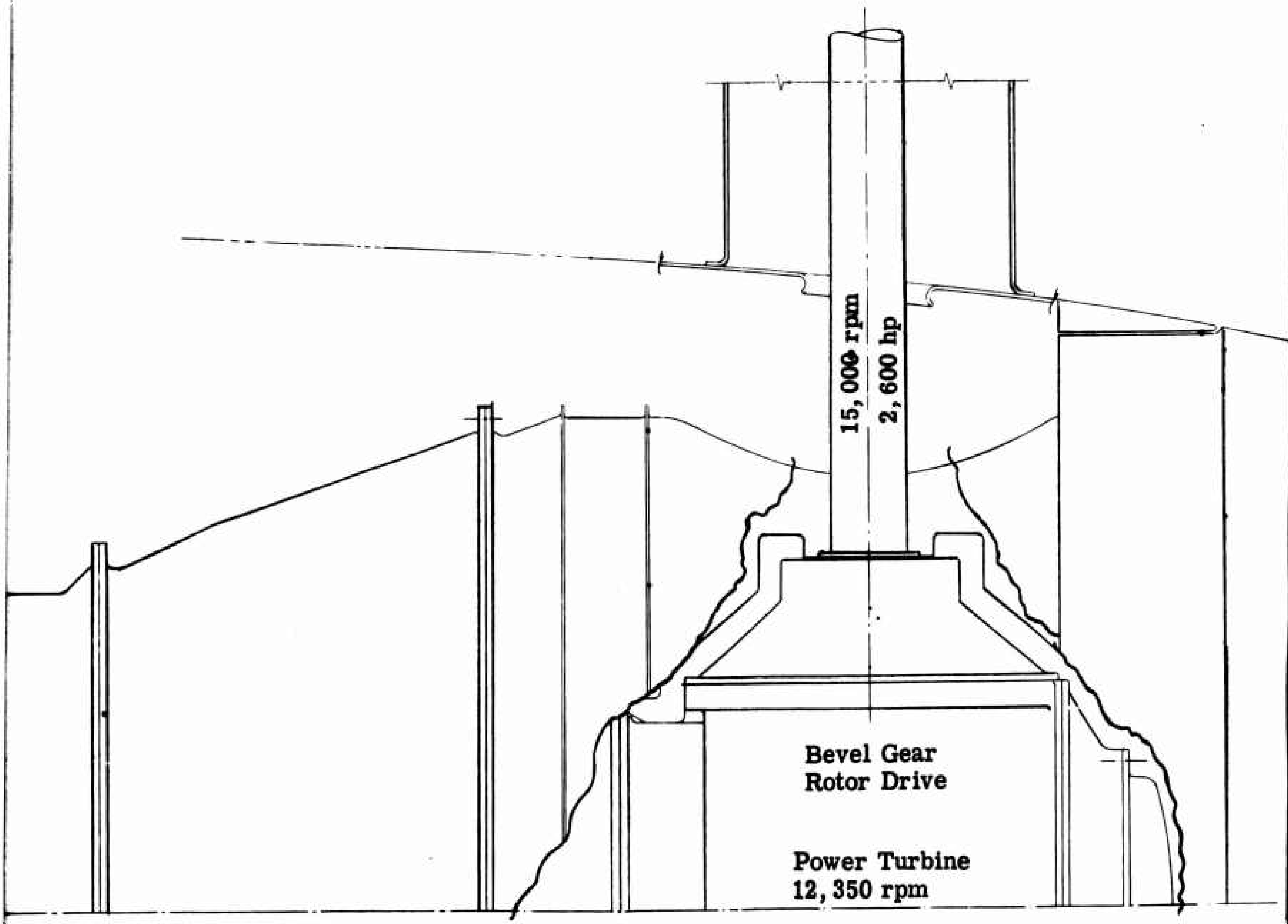
B

C

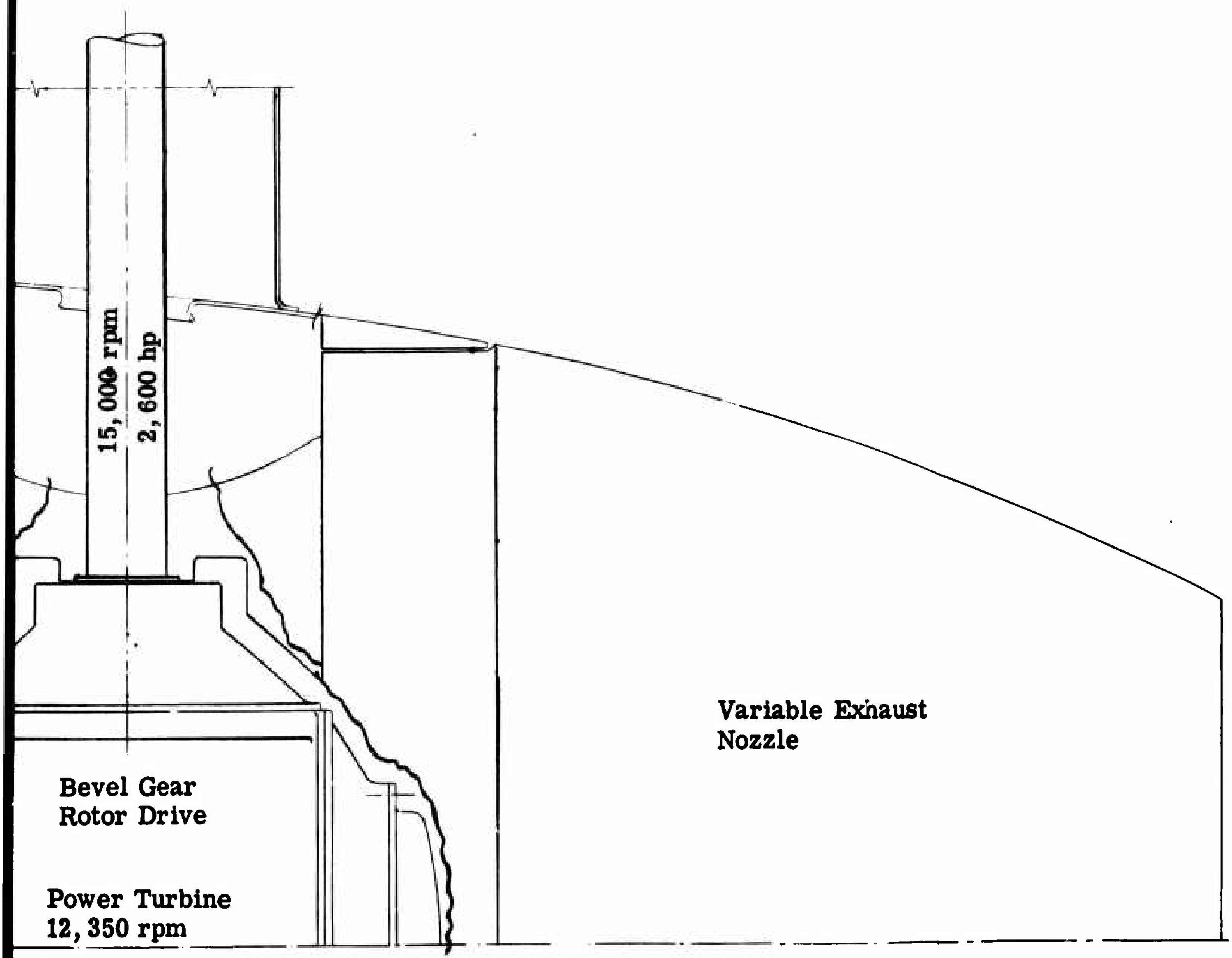


C

D


15,000 rpm
2,600 hp
Bevel Gear
Rotor Drive
Power Turbine
12,350 rpm

D


15,000 rpm
2,600 hp
Variable Exhaust
Nozzle
Bevel Gear
Rotor Drive
Power Turbine
12,350 rpm
E

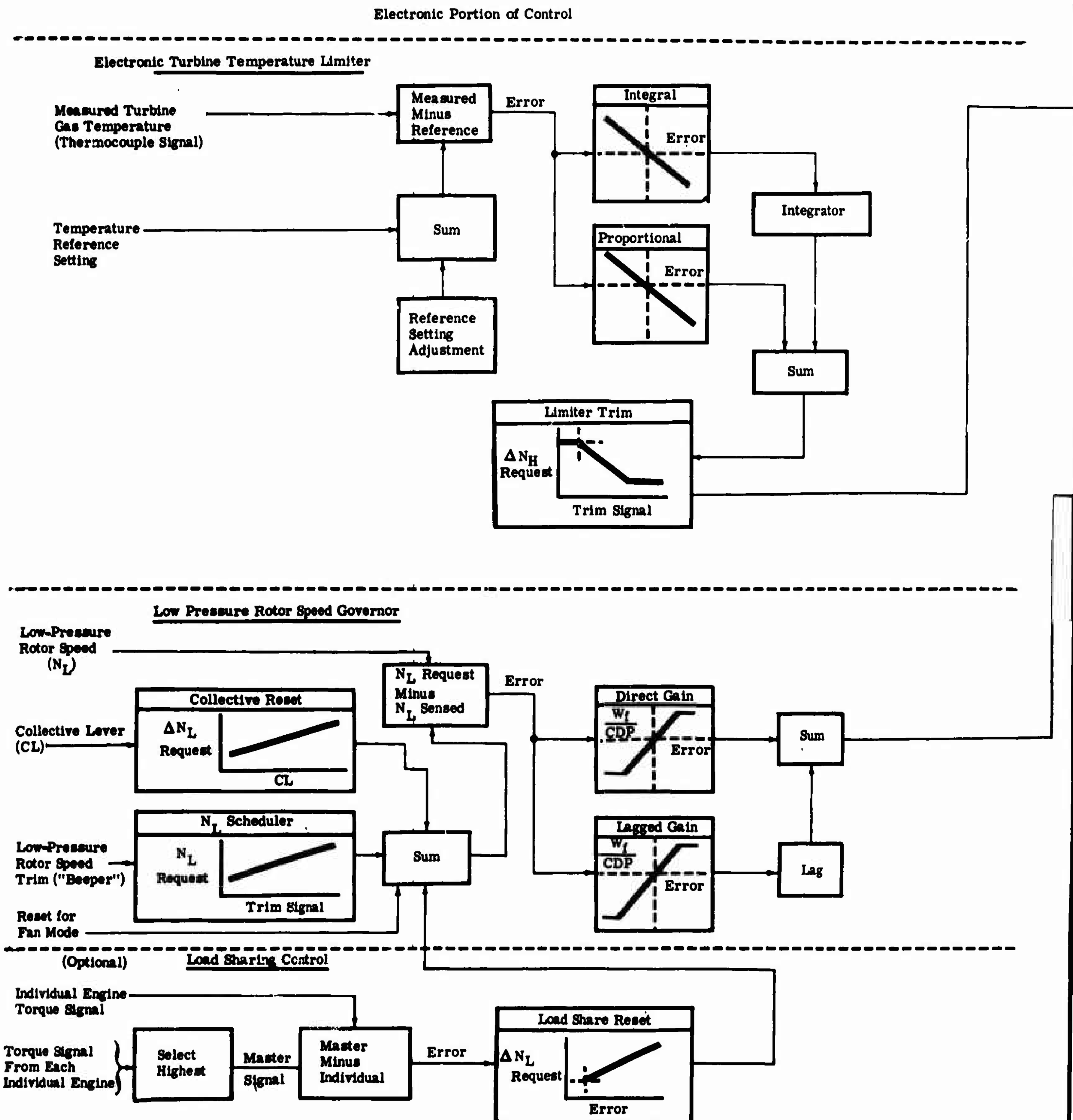
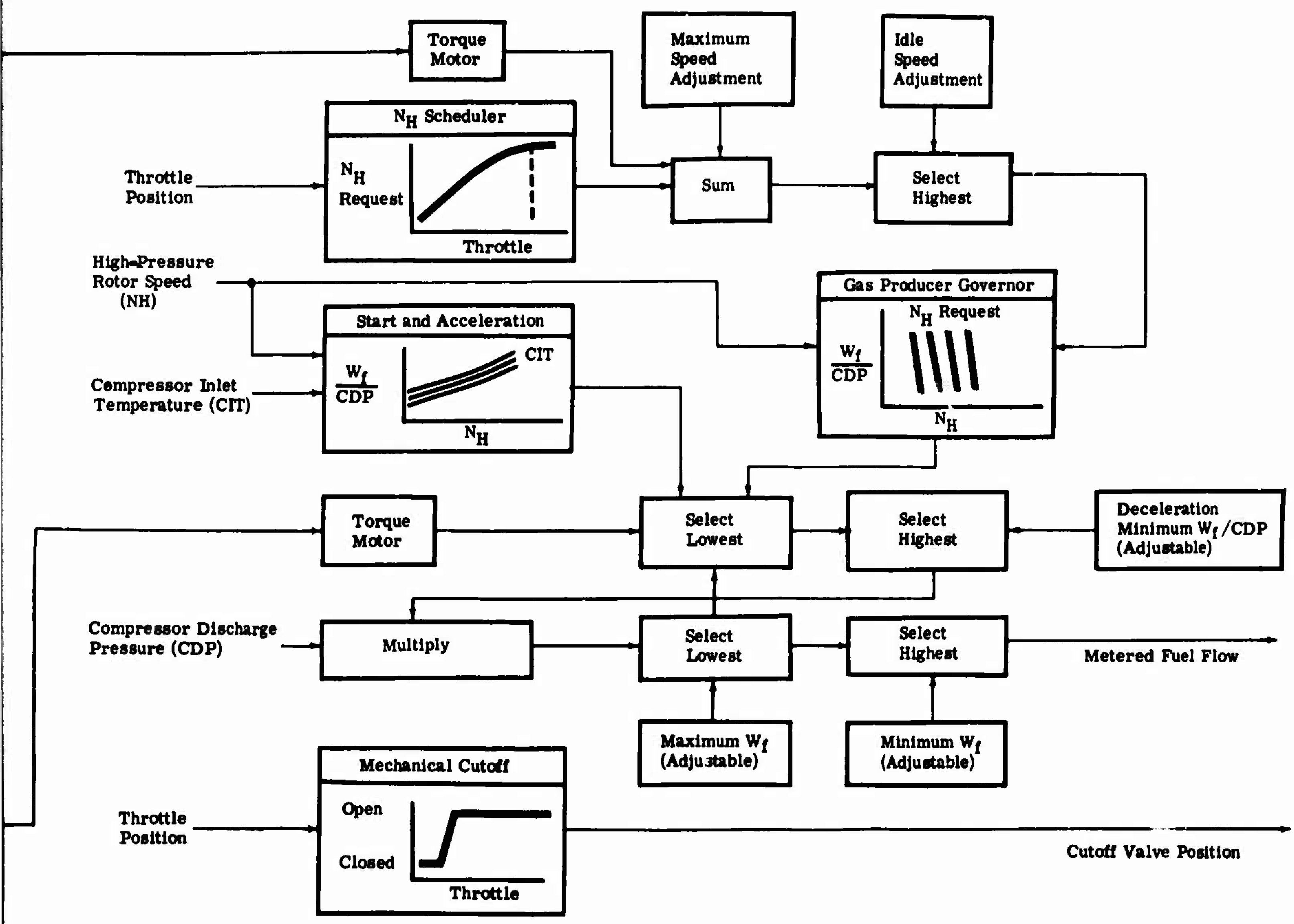
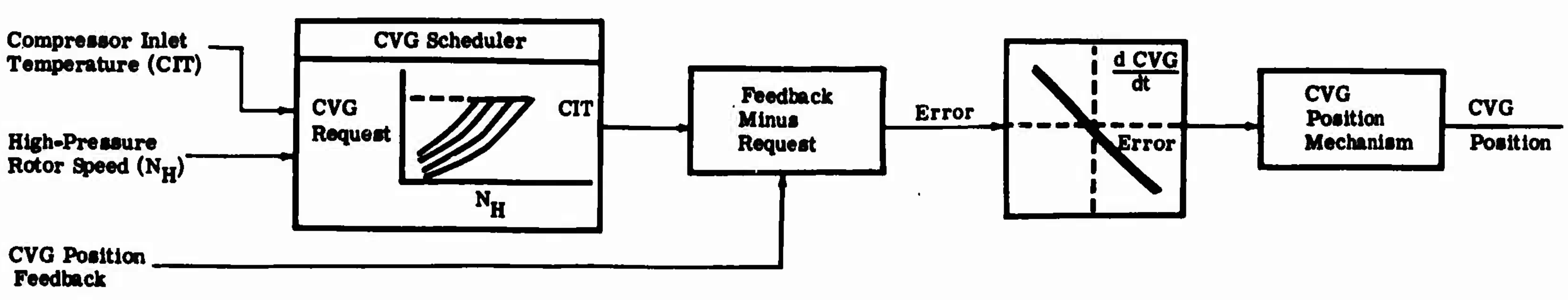


Figure 49. Basic Engine Control Functional Diagram.

Hydromechanical Portion of Control





B

BLANK PAGE

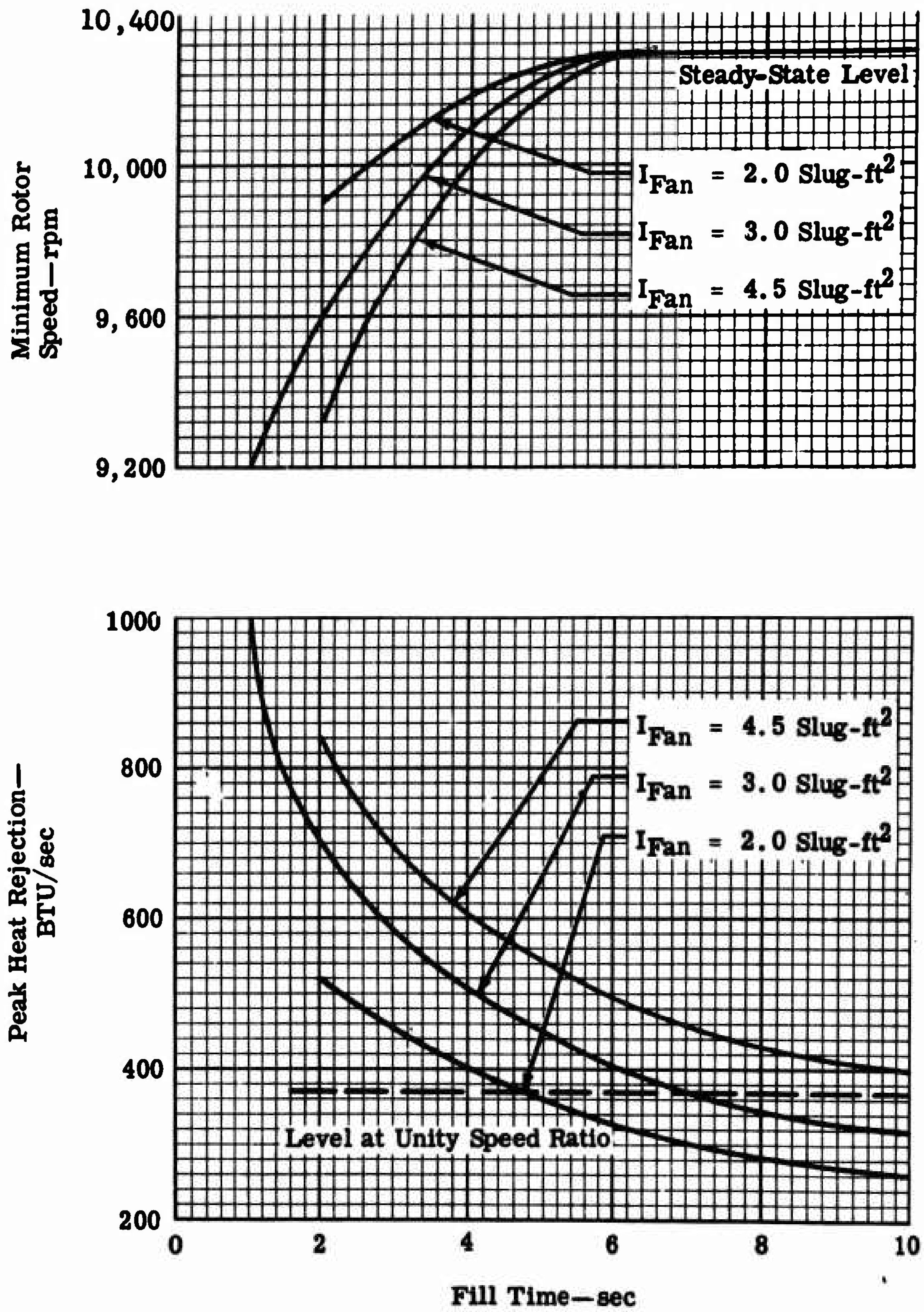


Figure 50. Analog Analysis of Torque Converter Filling Rate.

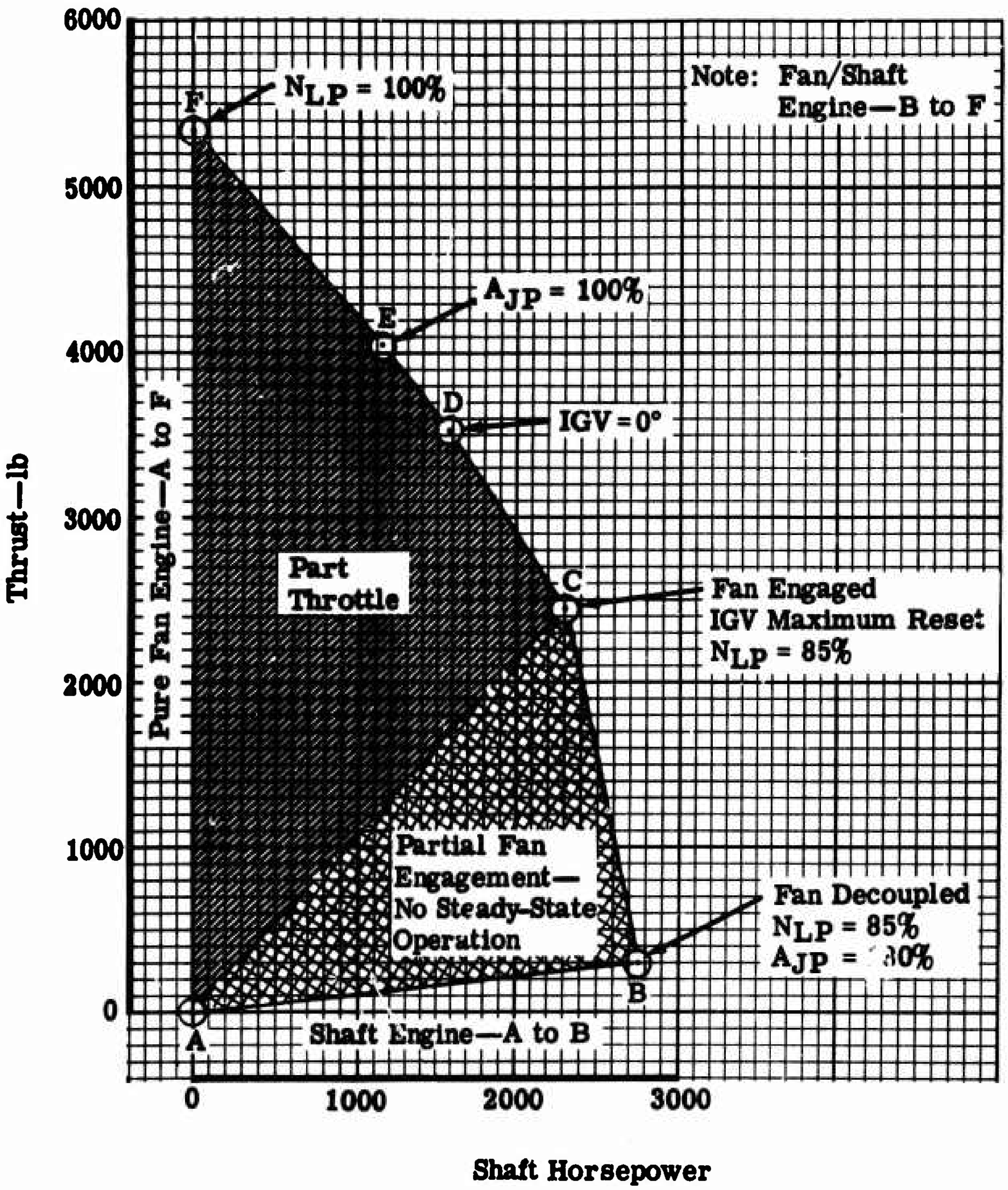


Figure 51. Operating Envelope of Type IA Engine at Sea Level Static, Standard Day.

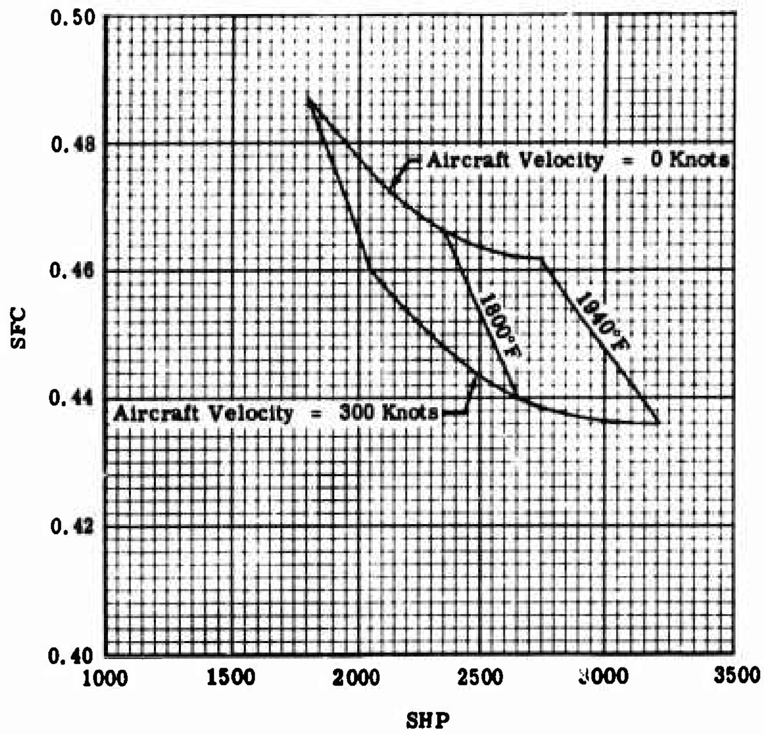


Figure 52. Type IA Engine Helicopter Mode Specific Fuel Consumption Versus Shaft Horsepower.

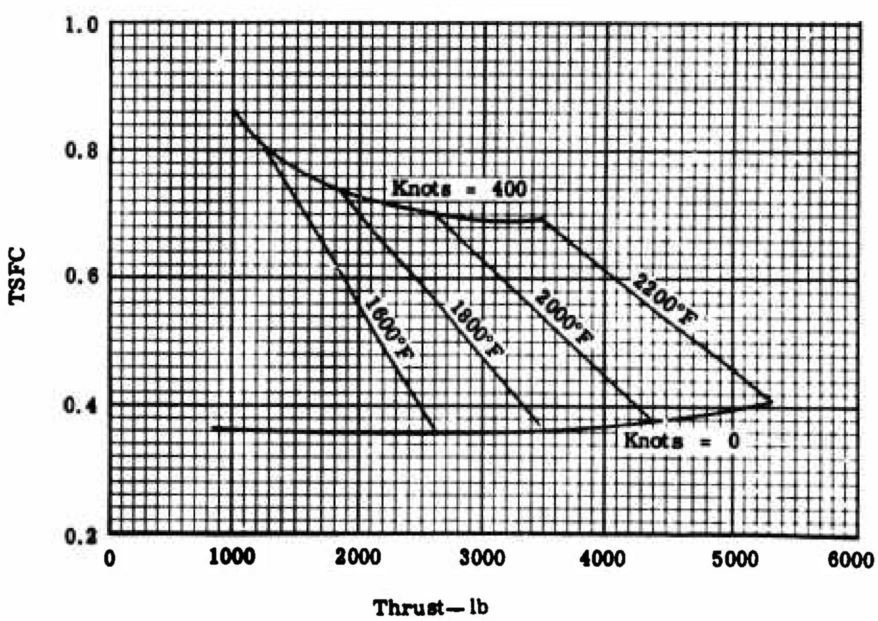


Figure 53. Type IA Engine Fan Mode Thrust Specific Fuel Consumption Sea Level Standard Day Conditions.

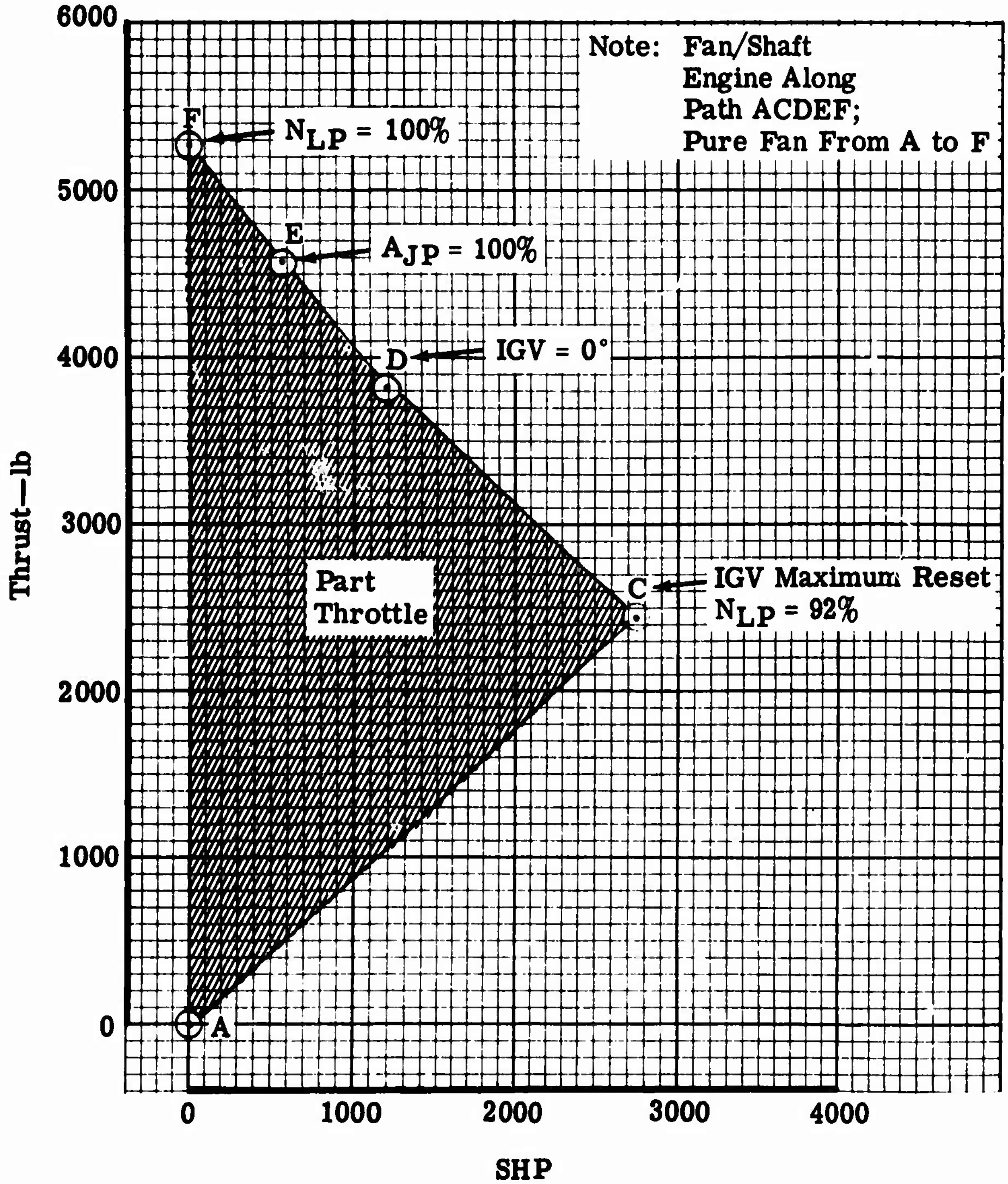


Figure 54. Operating Envelope of Type II Engine at Sea Level Static, Standard Day.

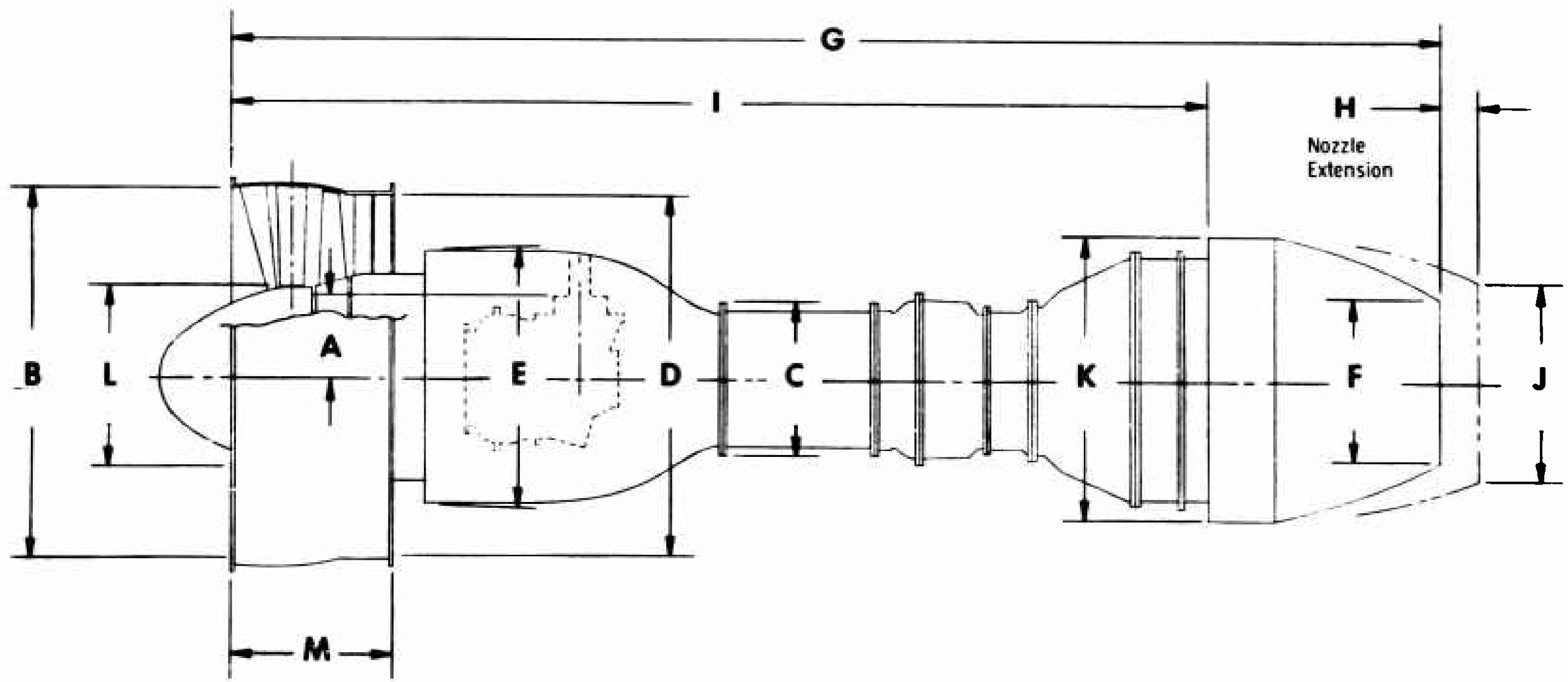


Figure 55. Type IA, Location of Major Engine Dimensions.

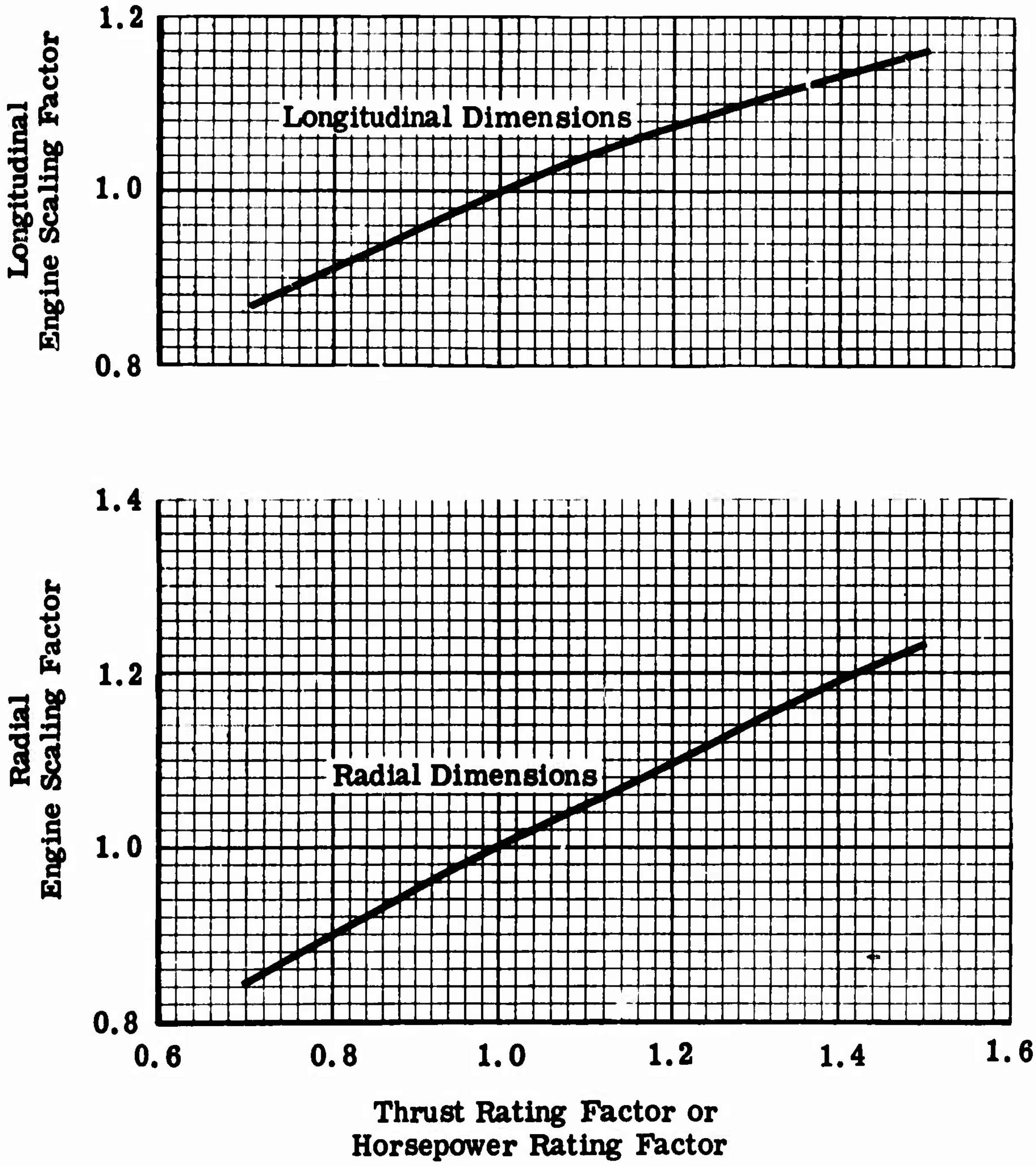


Figure 56. Type IA Engine Size Scaling Factors.

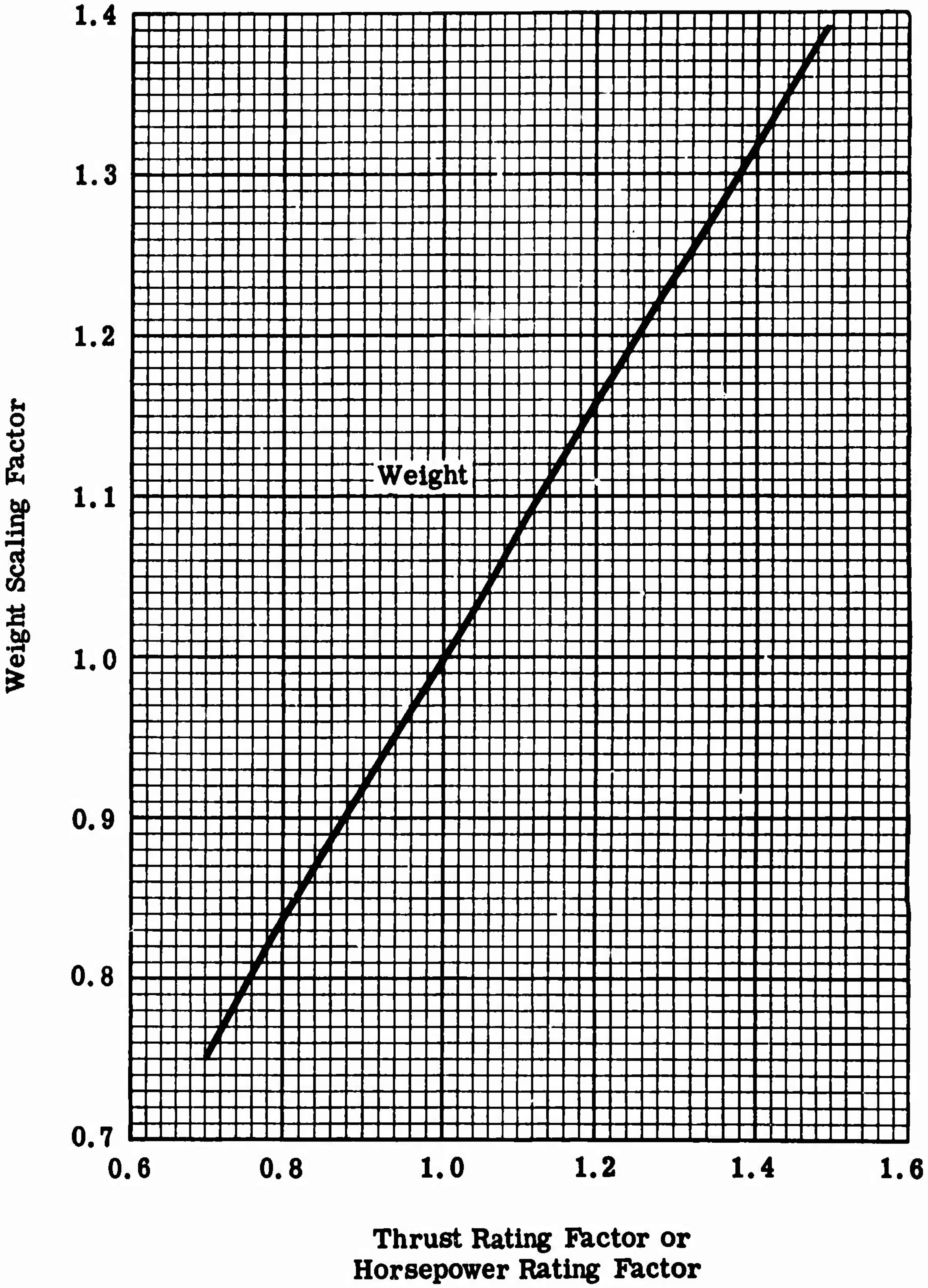


Figure 57. Type IA Engine Weight Scaling Factor.

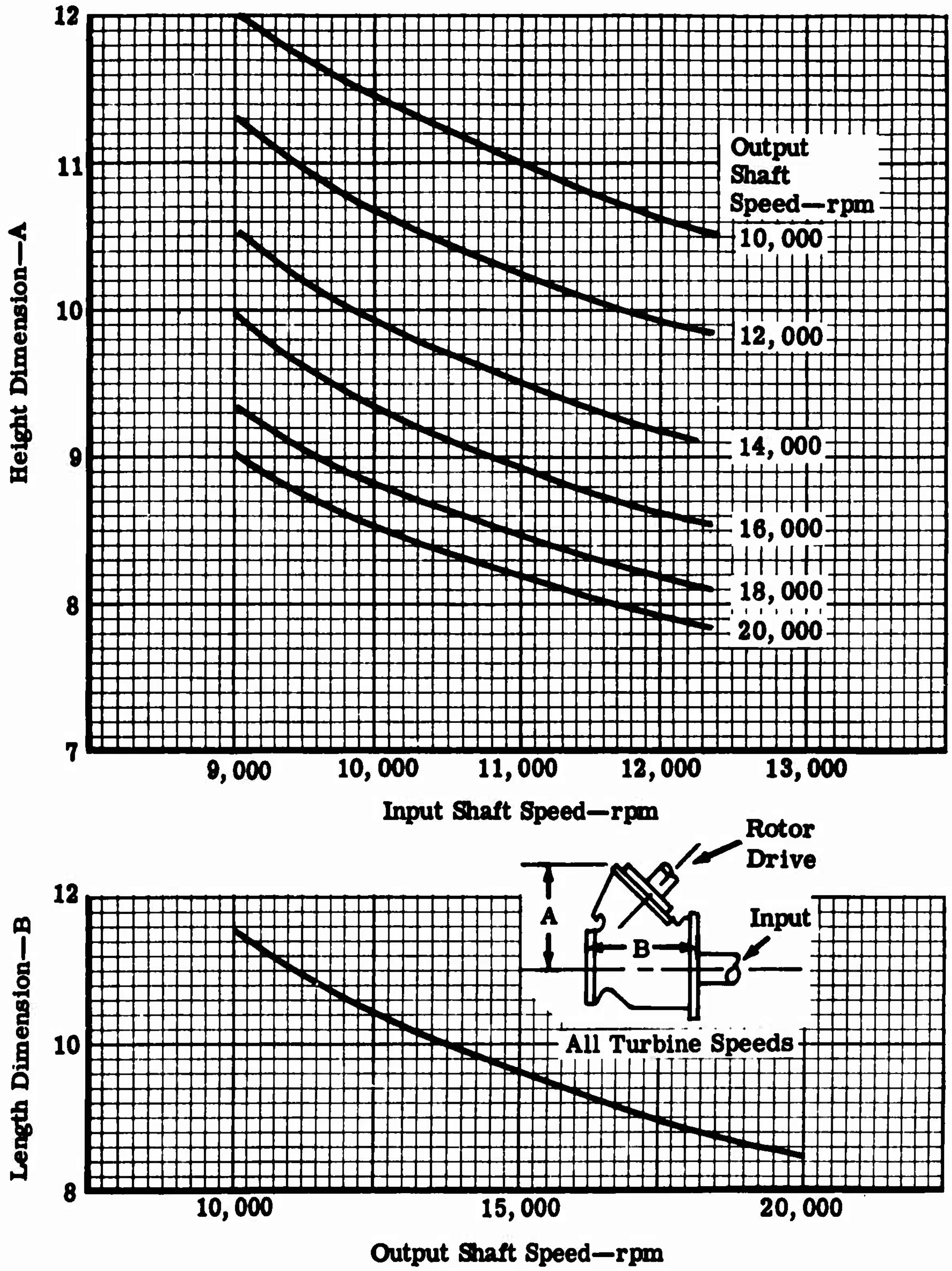


Figure 58. Size Scaling Data for Rotor Drive Gearbox 45-Degree Shaft Angle Design, 2600 Horsepower.

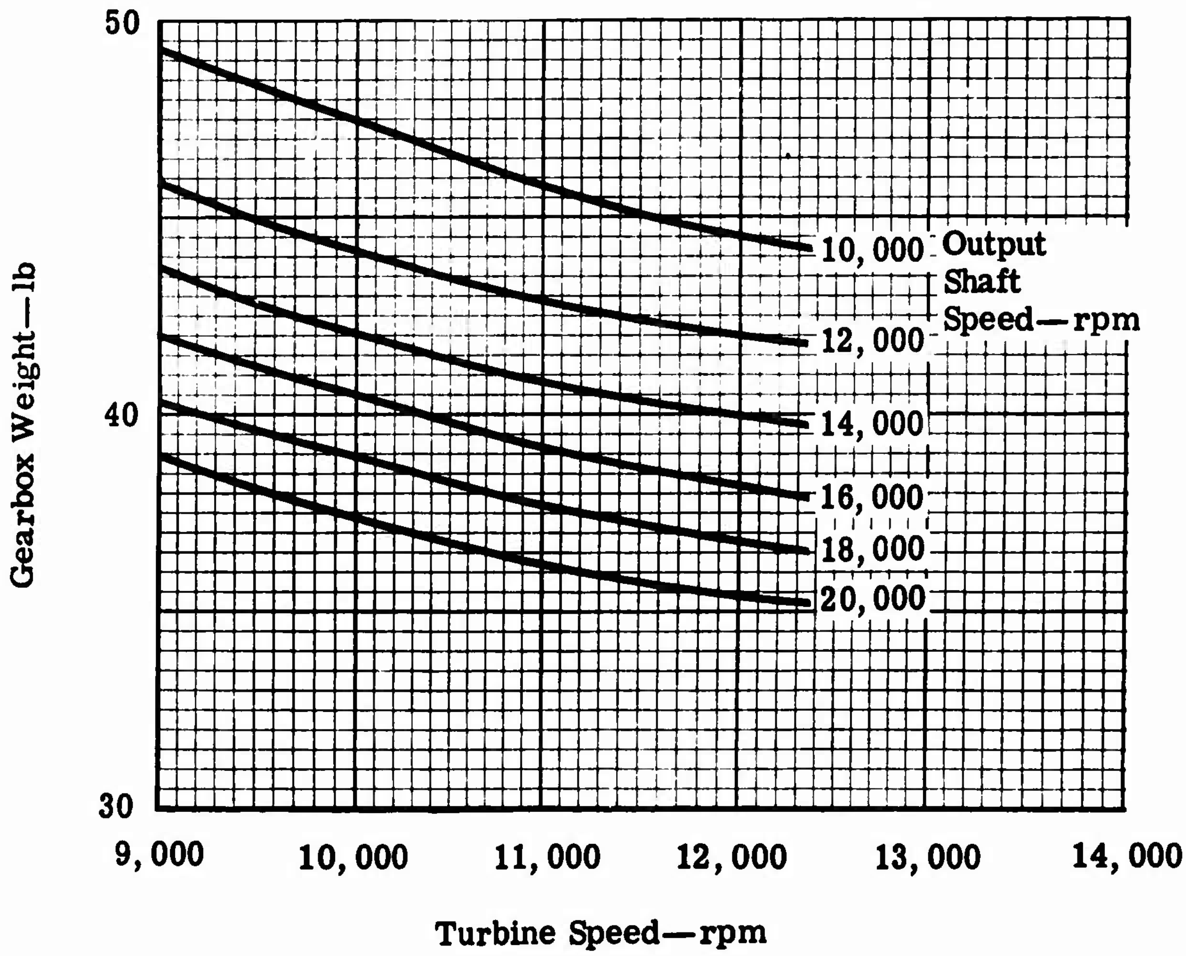


Figure 59. Weight Scaling Data for 45-Degree Shaft Angle Gearbox.

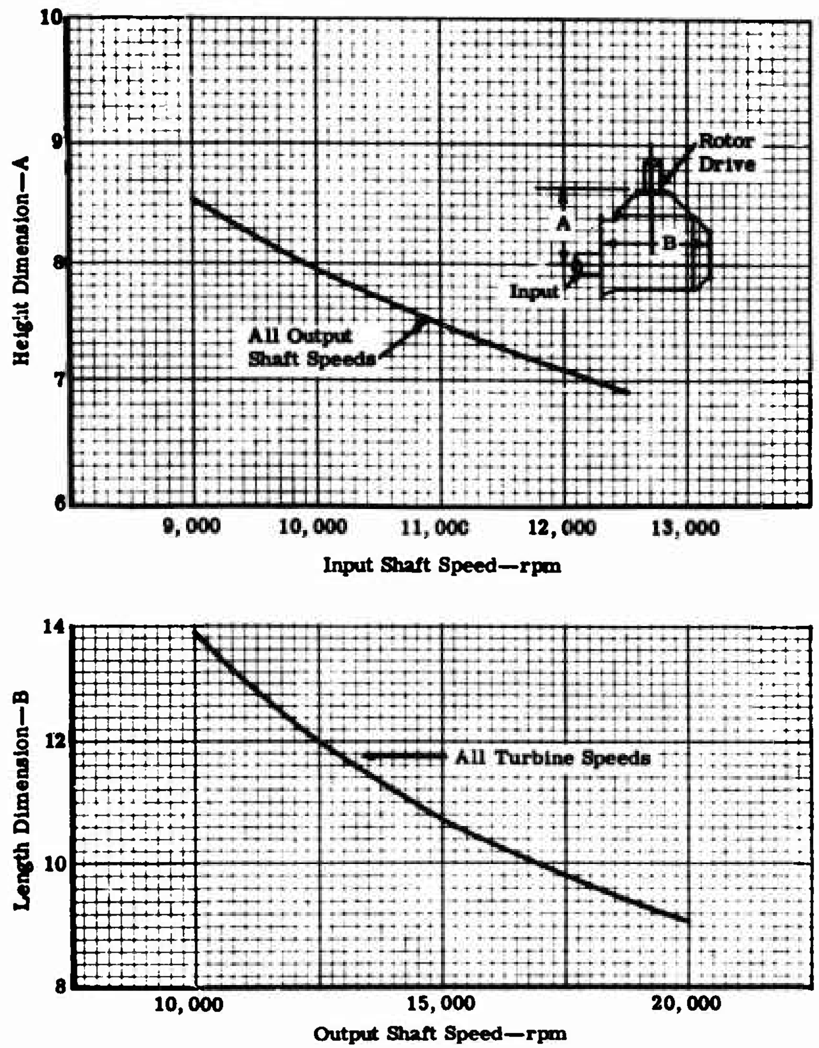


Figure 60. Size Scaling Data for Rotor Drive Gearbox 90-Degree Shaft Angle Design, 2600 Horsepower.

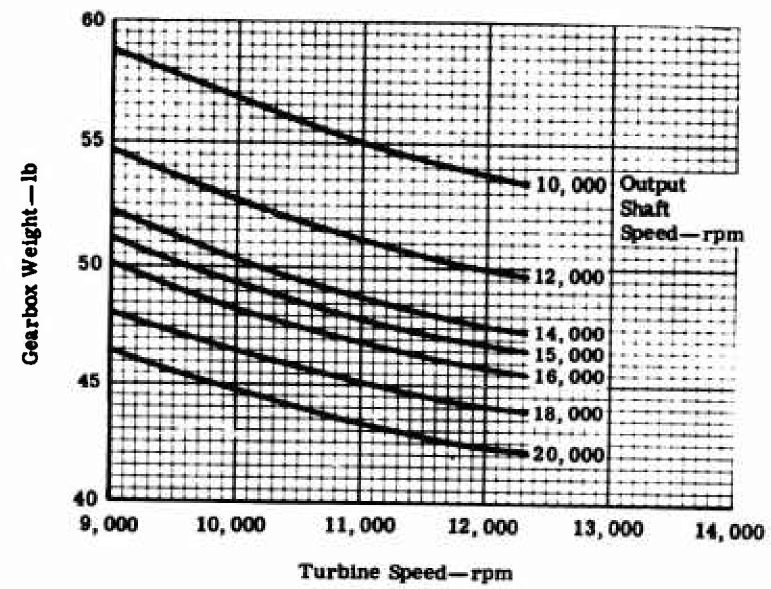
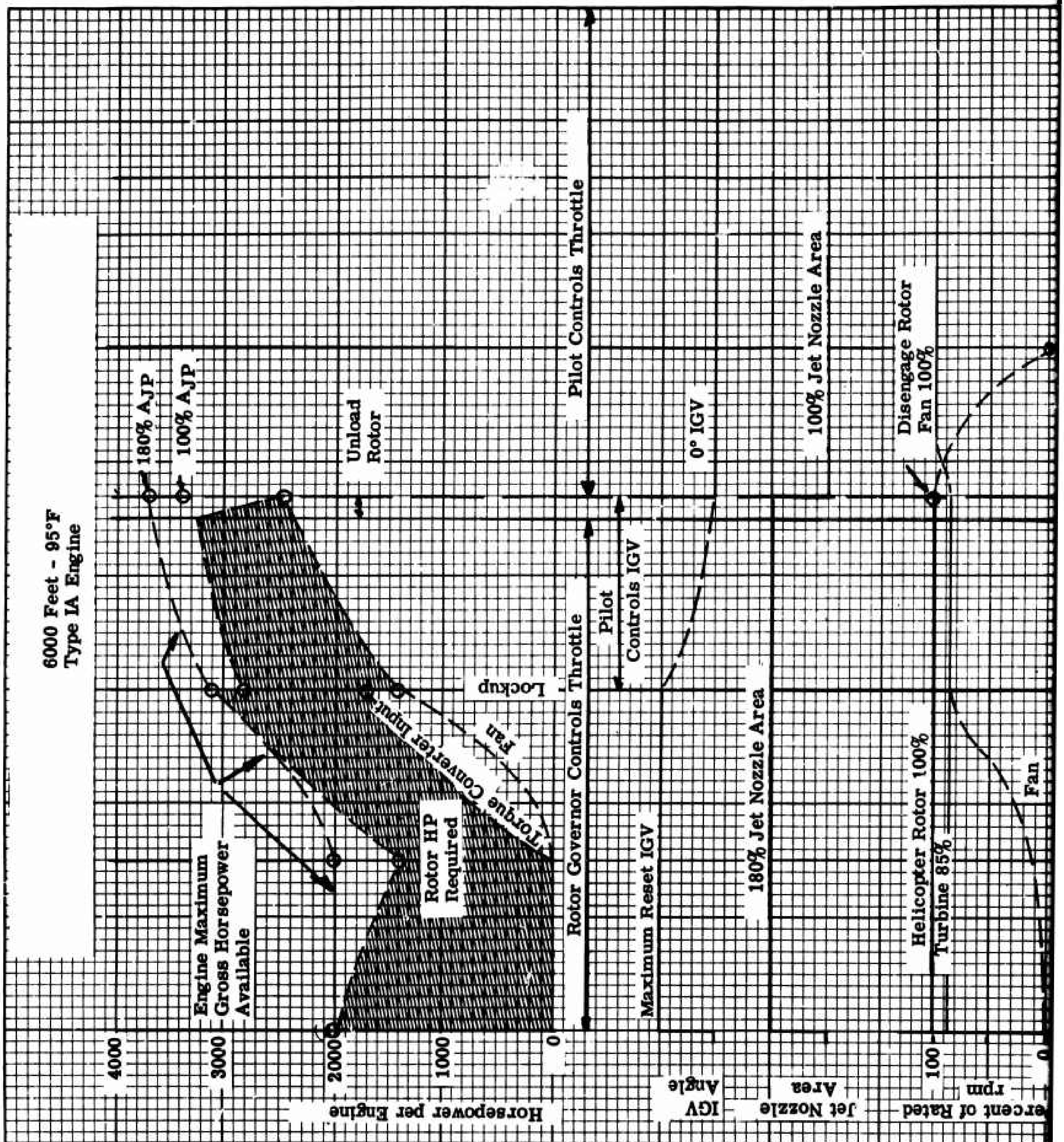


Figure 61. Weight Scaling Data for 90-Degree Shaft Angle Gearbox.


6000 Feet - 95°F
Type IA Engine
180% AJP
100% AJP
Unload Rotor
Pilot Controls Throttle
0° IGV
100% Jet Nozzle Area
Disengage Rotor
Fan 100%
Lockup
Fan
Torque Converter Input
Pilot Controls IGV
Rotor HP Required
Engine Maximum Gross Horsepower Available
Rotor Governor Controls Throttle
Maximum Reset IGV
180% Jet Nozzle Area
Helicopter Rotor 100%
Turbine 85%
Fan
4000
3000
2000
1000
0
Horsepower per Engine
IGV Angle
Jet Nozzle Area
ercent of Rated rpm
100
0

A

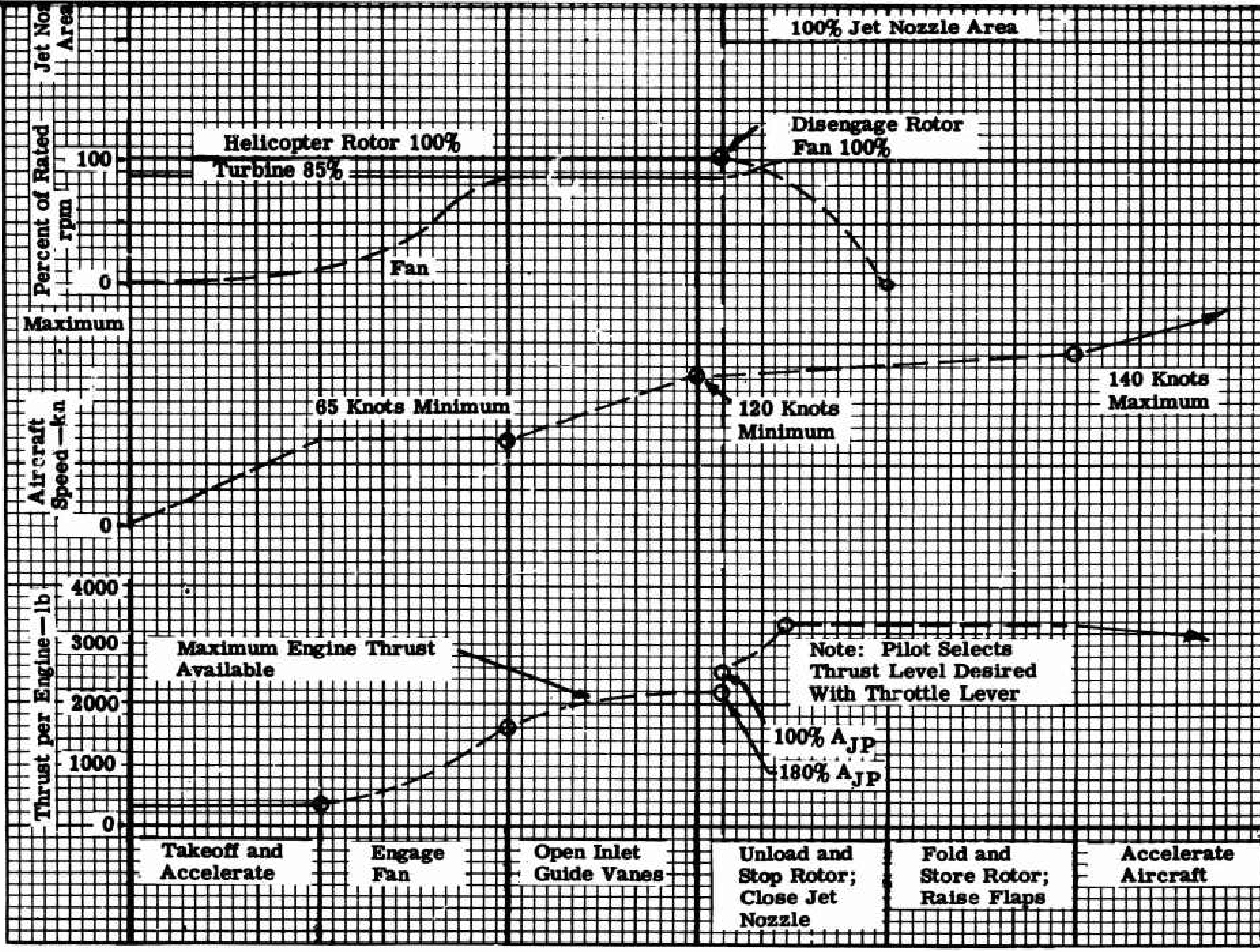


Figure 62. Proposed Conversion Sequence to Compare Aircraft Power Required and Maximum Power/Thrust Available.

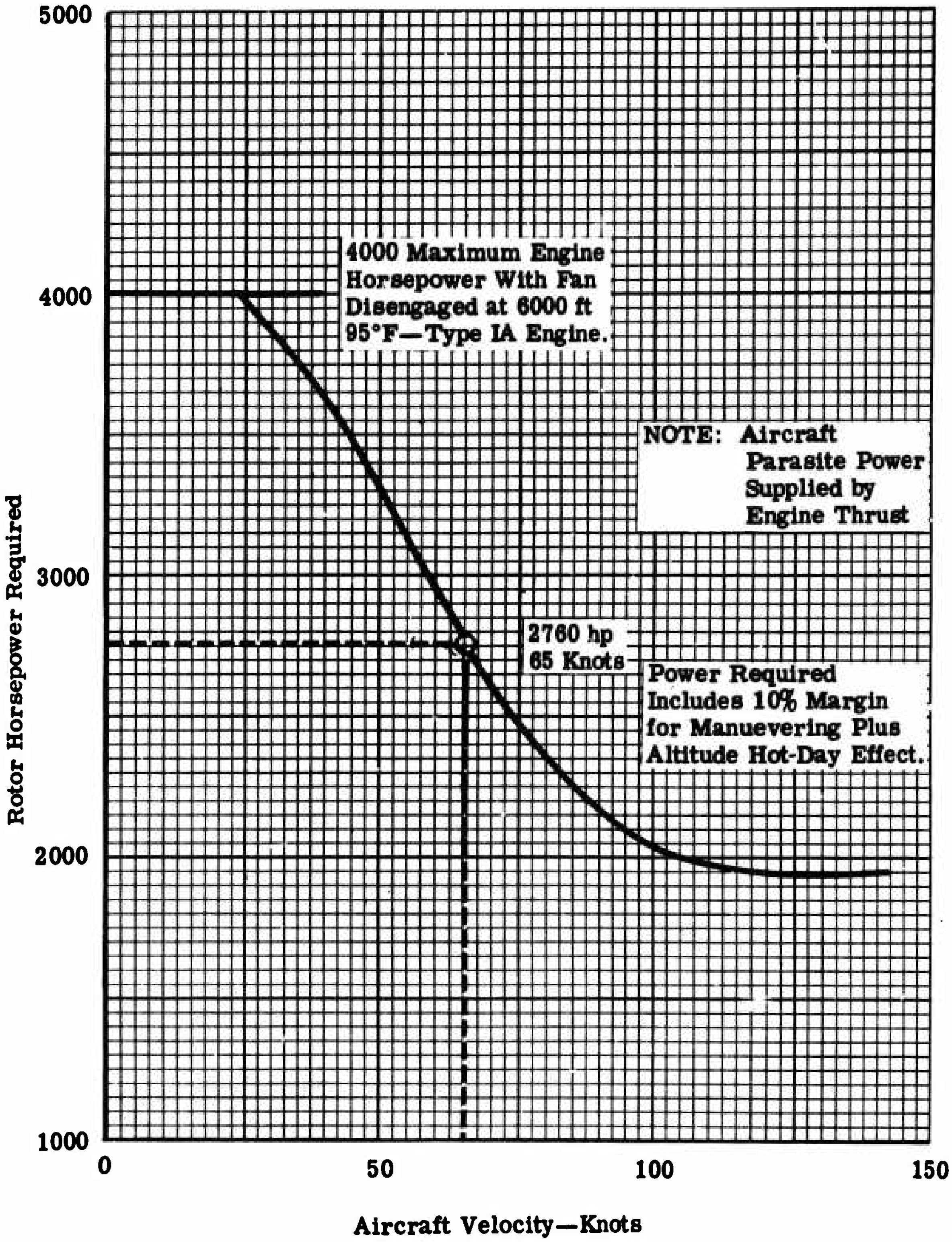


Figure 63. Rotor Power Required Versus Aircraft Velocity, 6000 ft, 95°F.

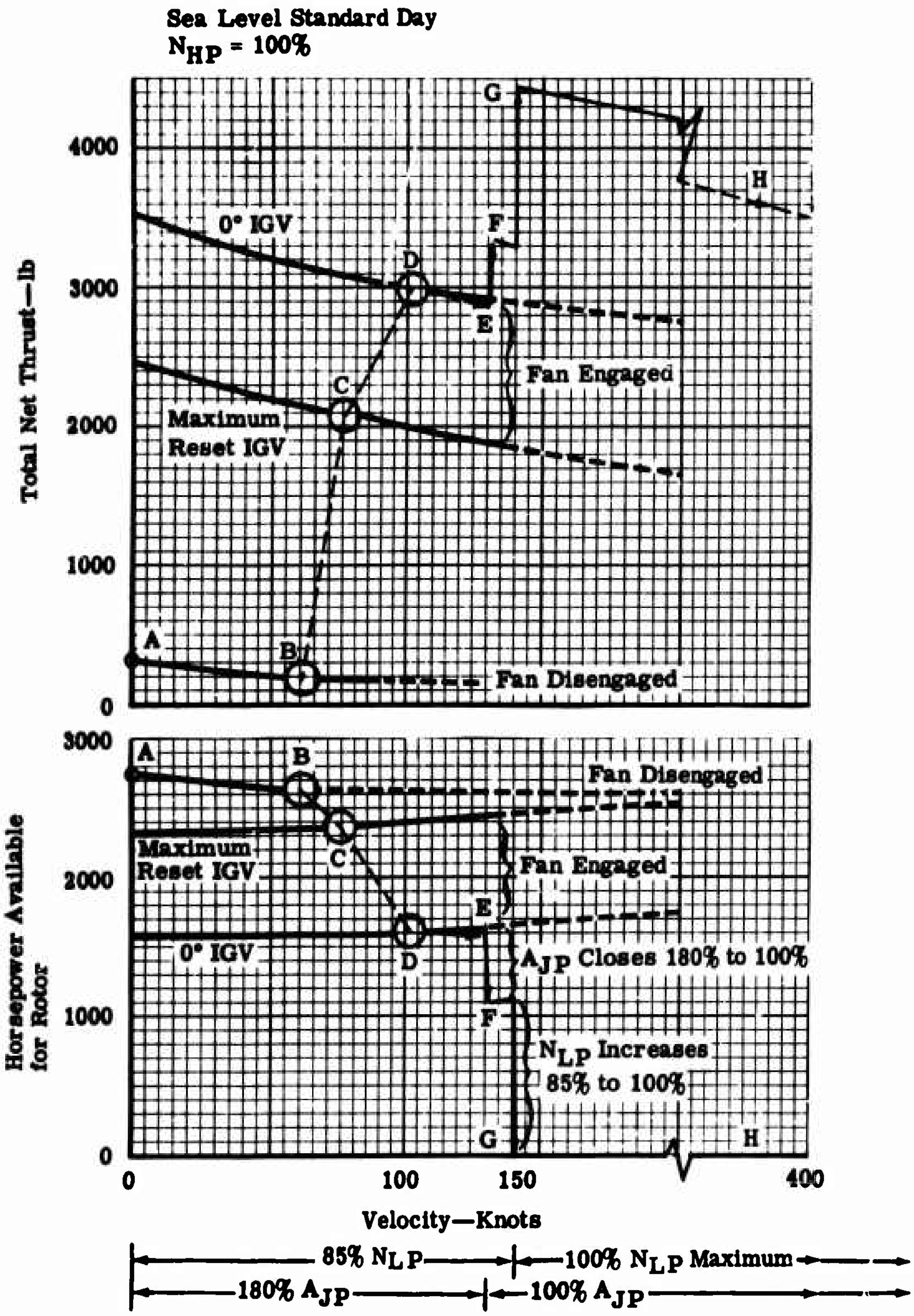


Figure 64. Type IA Shaft-to-Fan Conversion Analysis—Sea Level Standard Day.

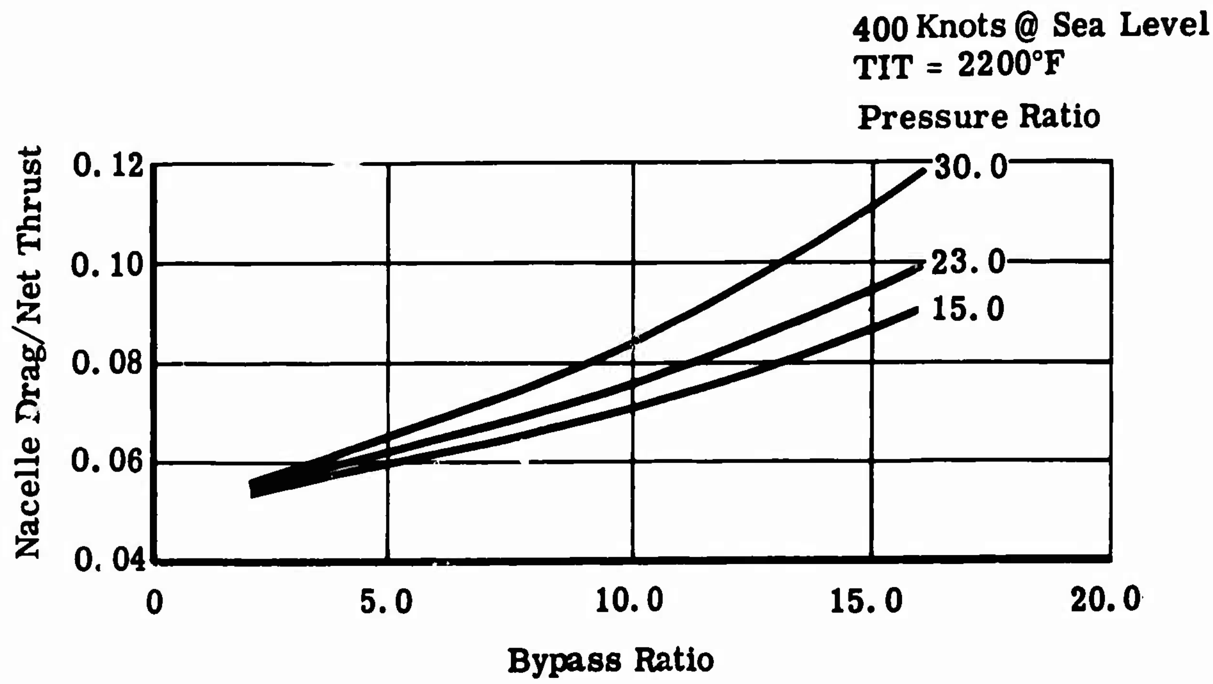


Figure 65. Study Engine Drag Characteristics Versus Bypass Ratio.

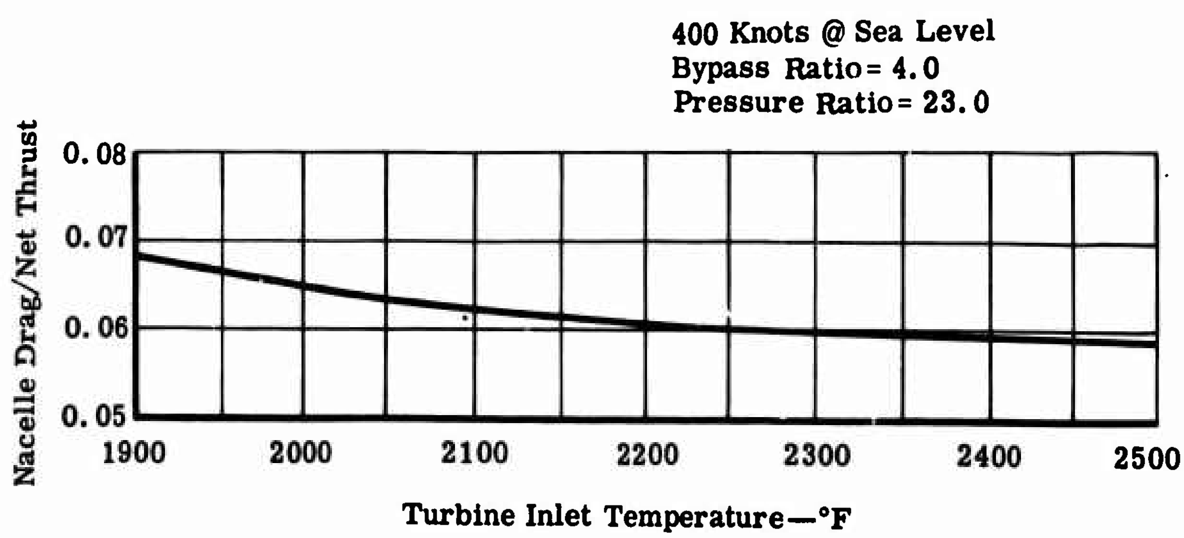


Figure 66. Study Engine Drag Characteristics Versus Turbine Inlet Temperature.

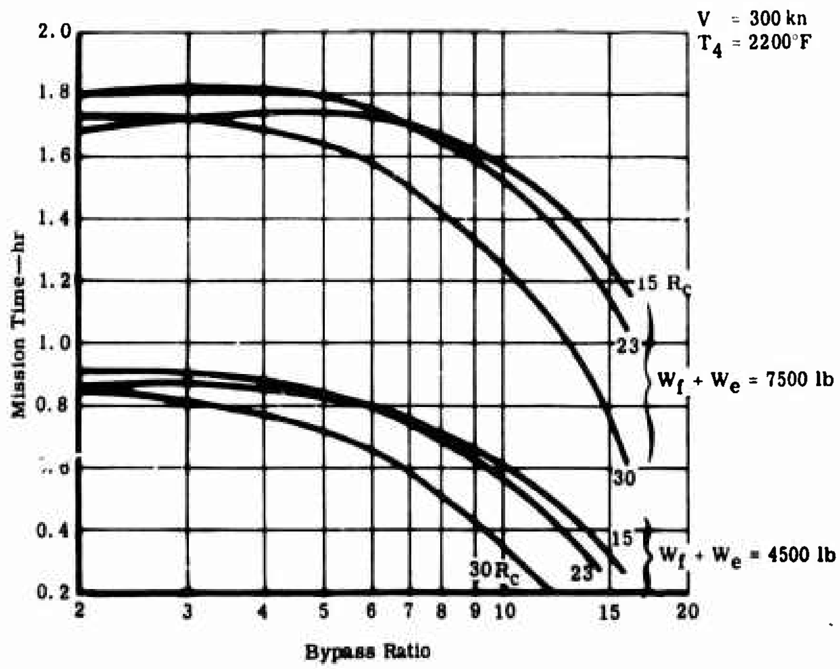


Figure 67. Mission Time Versus Bypass Ratio—2200°F.

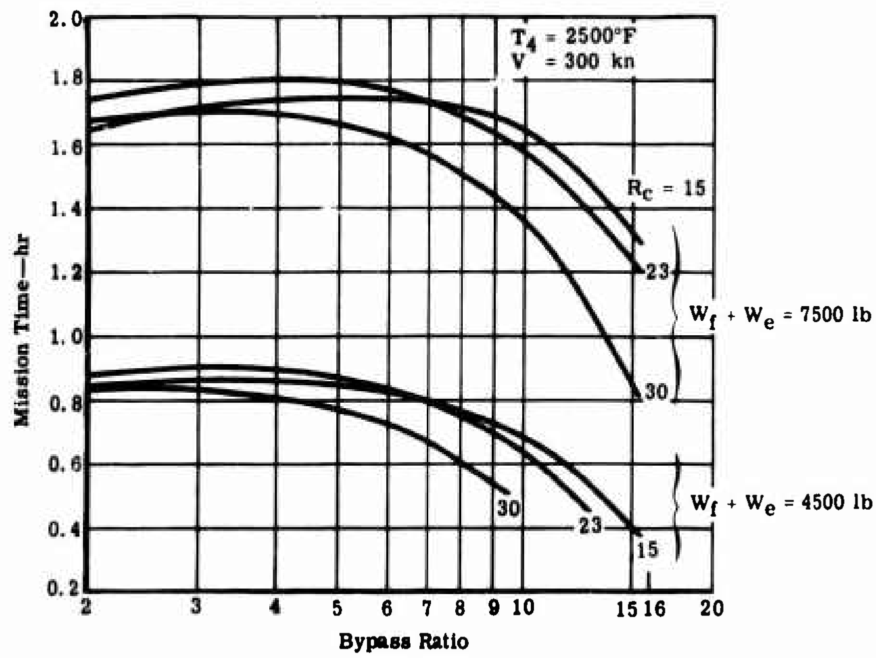


Figure 68. Mission Time Versus Bypass Ratio—2500°F.

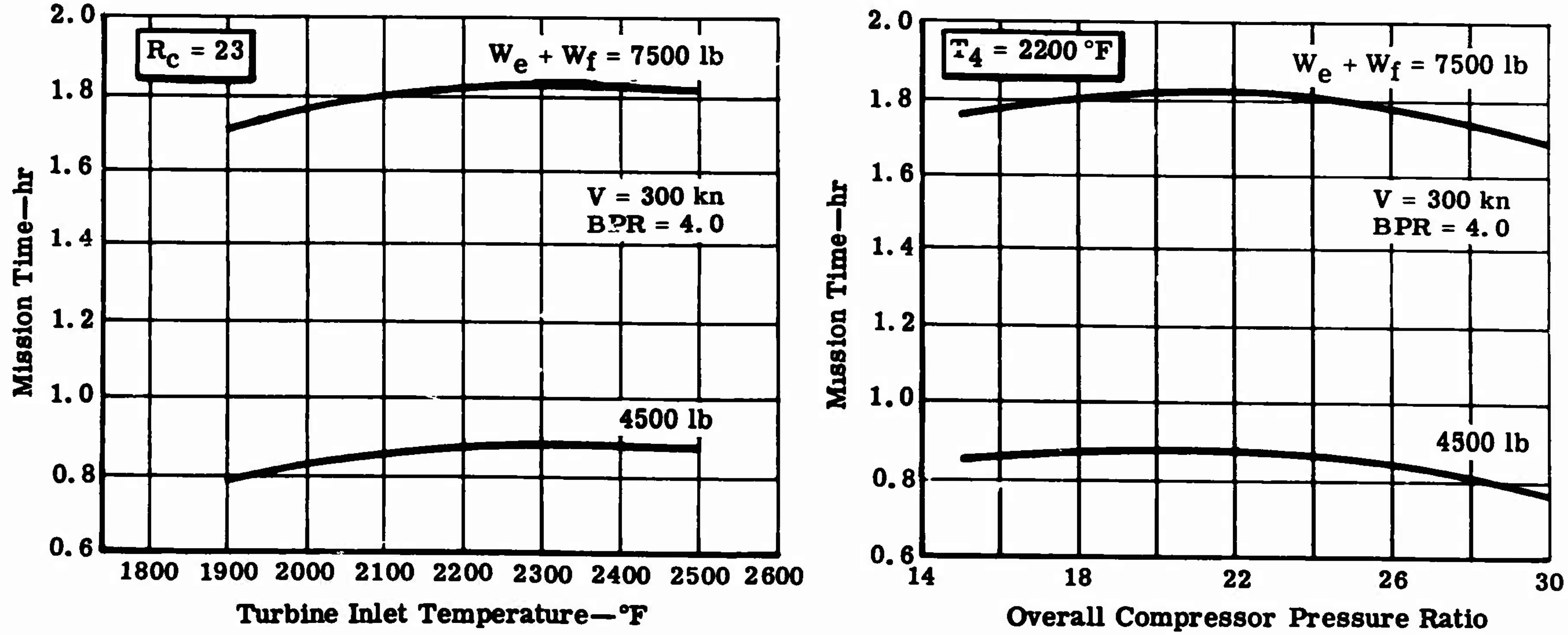


Figure 69. Effect of Turbine Inlet Temperature and Pressure Ratio on Mission Time.

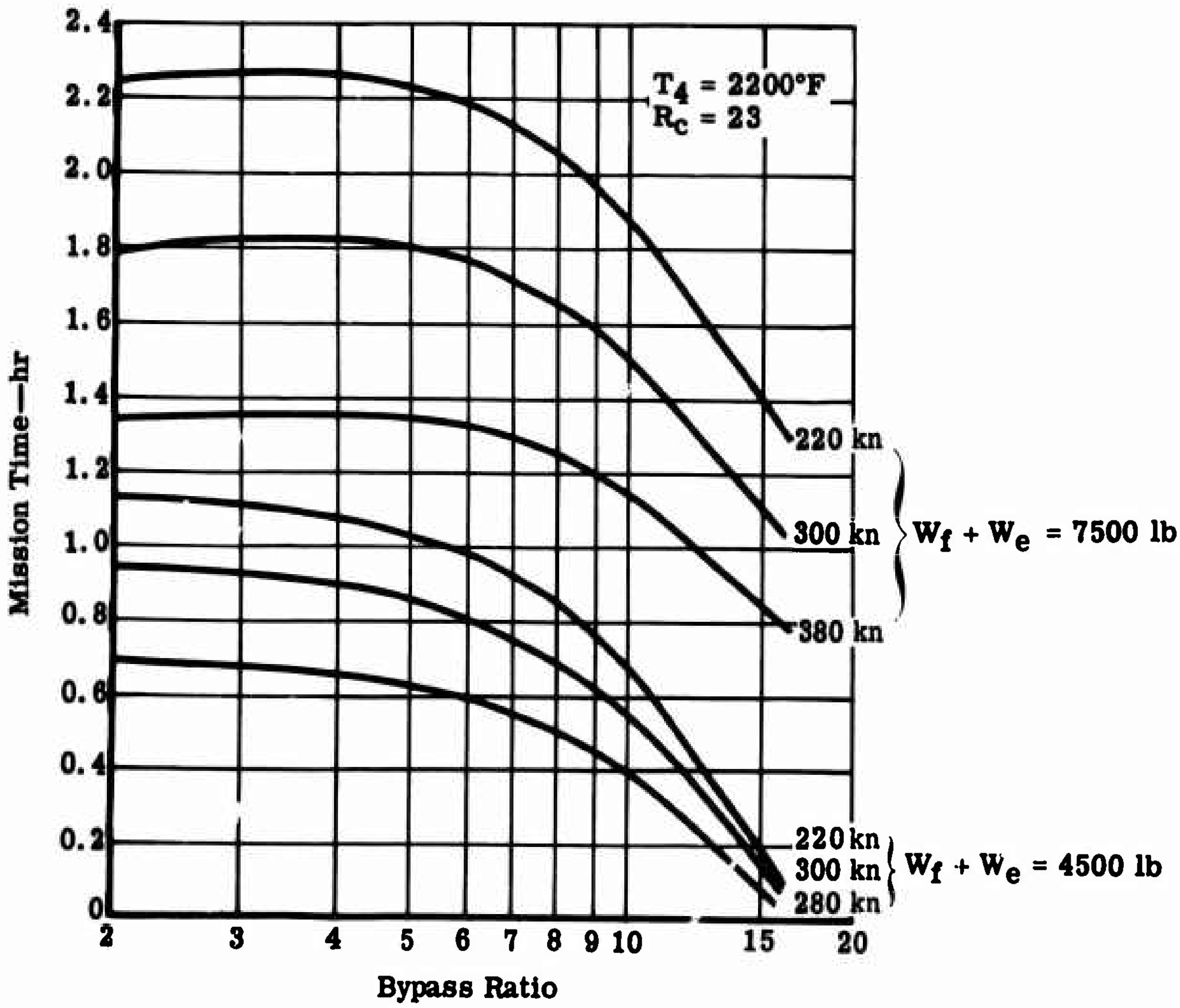


Figure 70. Effect of Cruise Speed on Mission Time.

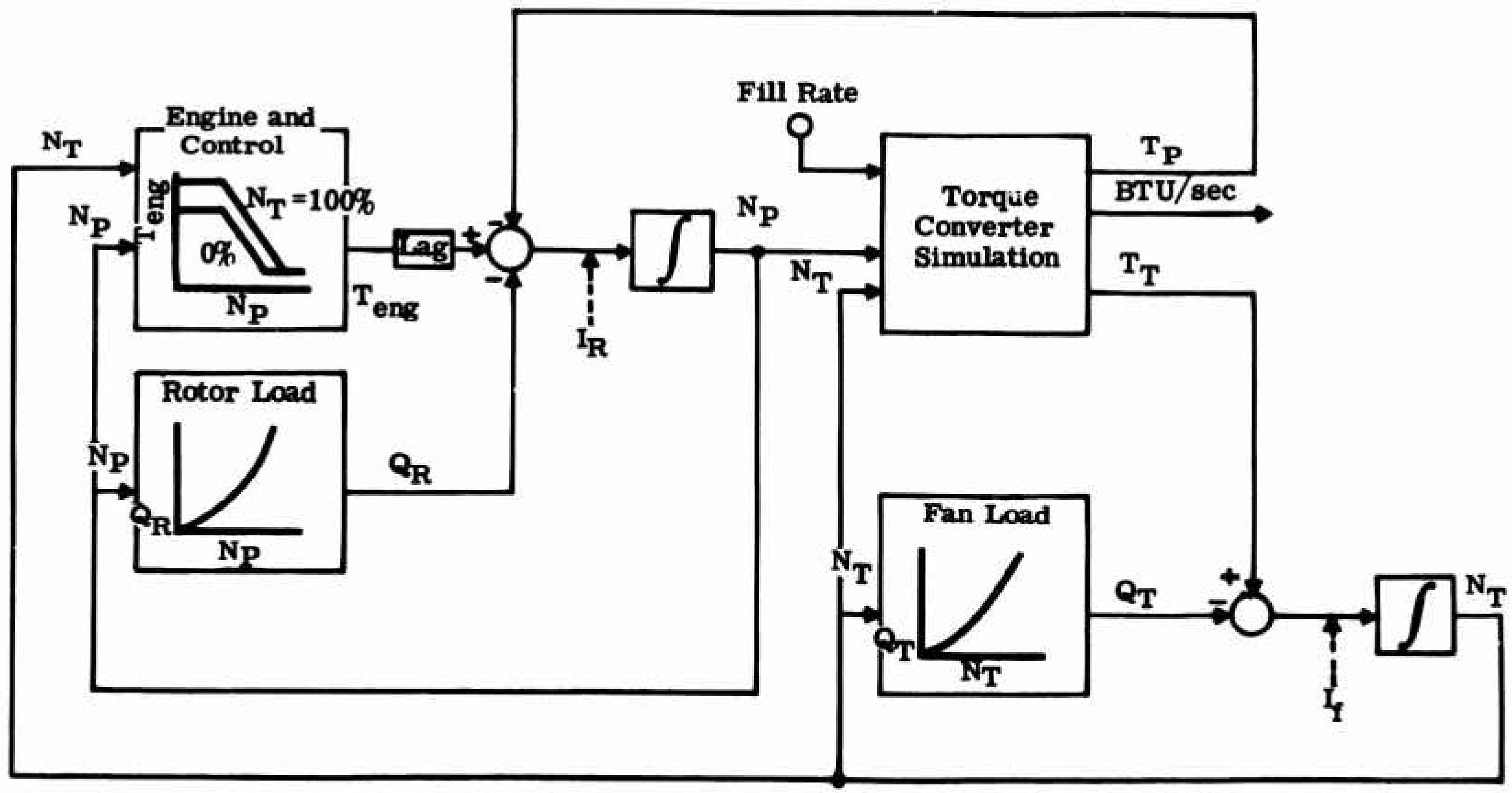
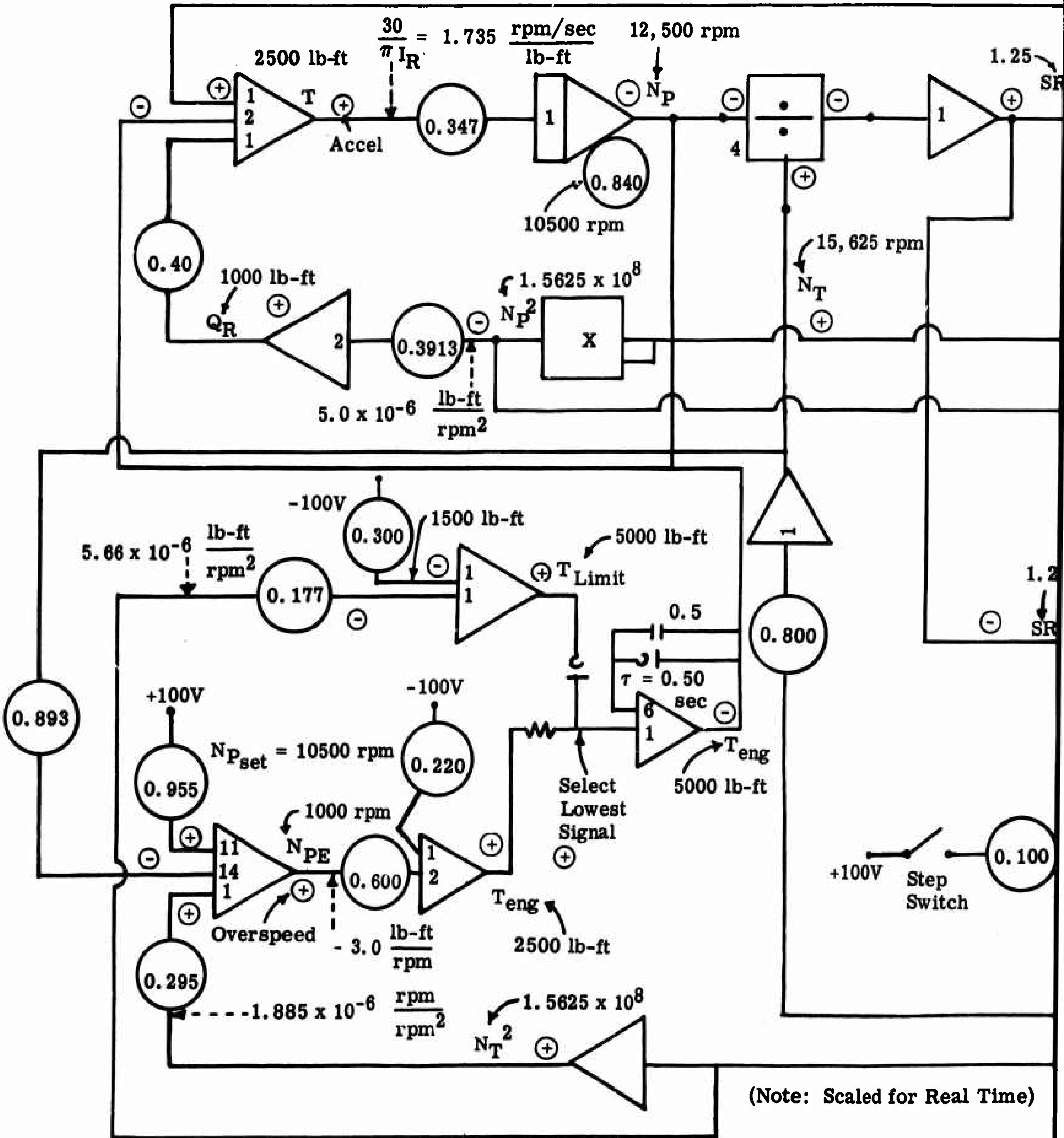
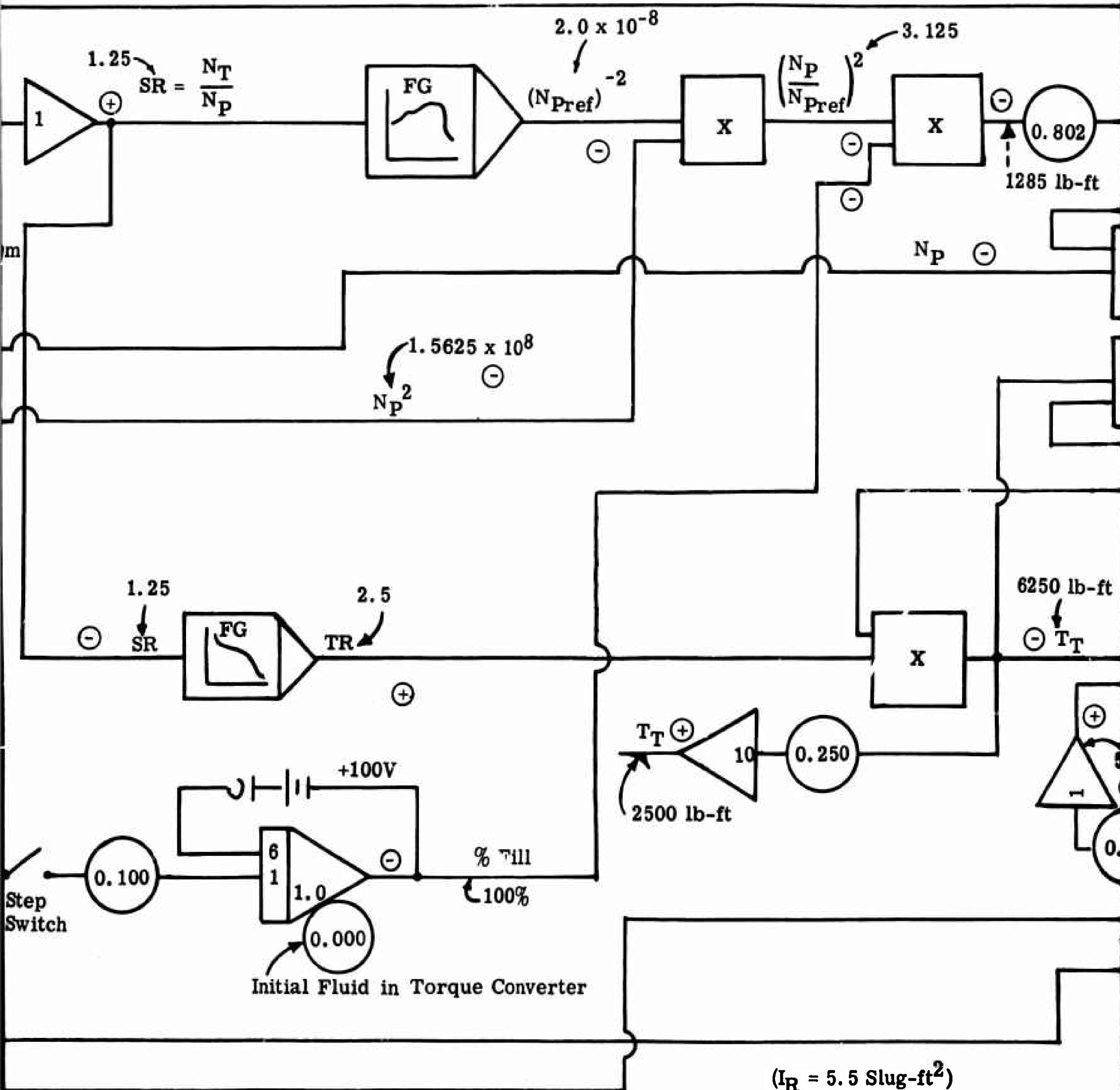


Figure 71. Block Diagram of Convertible Fan/Shaft Engine Simulation.



(Note: Scaled for Real Time)

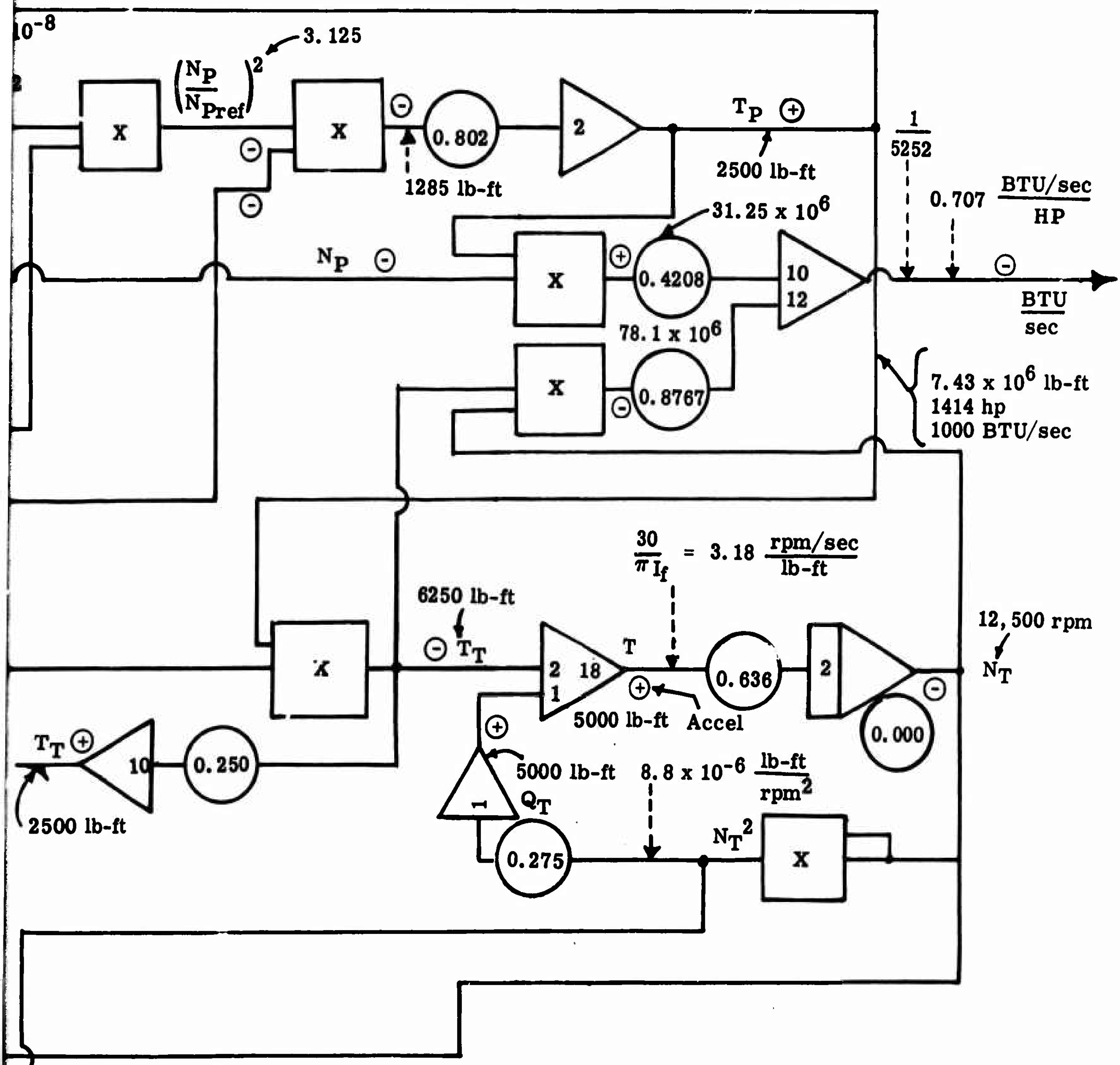
Figure 72. Convertible Fa



r Real Time)

Convertible Fan/Shaft Engine Simulation.

B



(I_R = 5.5 Slug-ft^2)

(I_f = 3.0 Slug-ft^2)

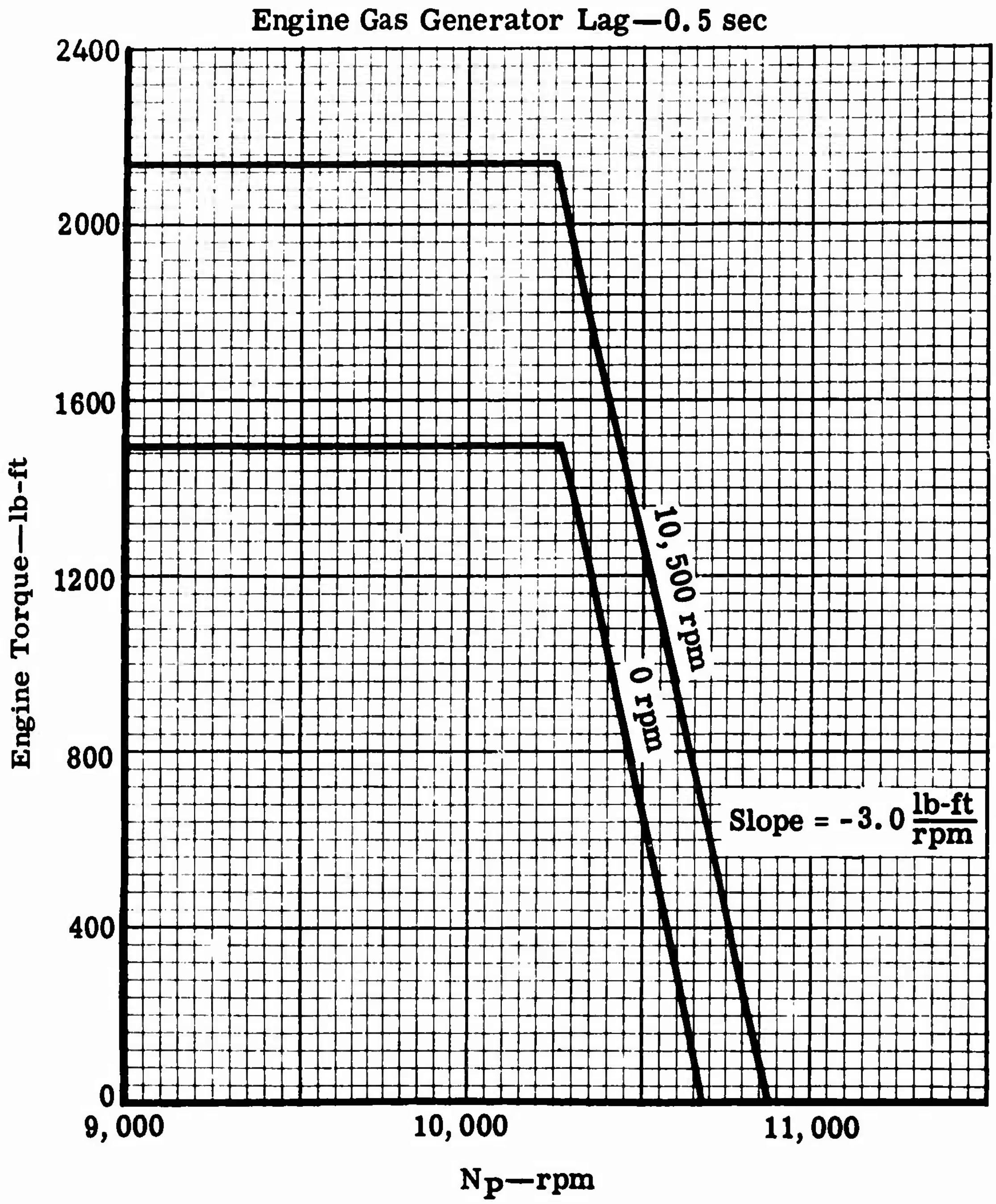


Figure 73. Assumed Engine Governor Characteristics.

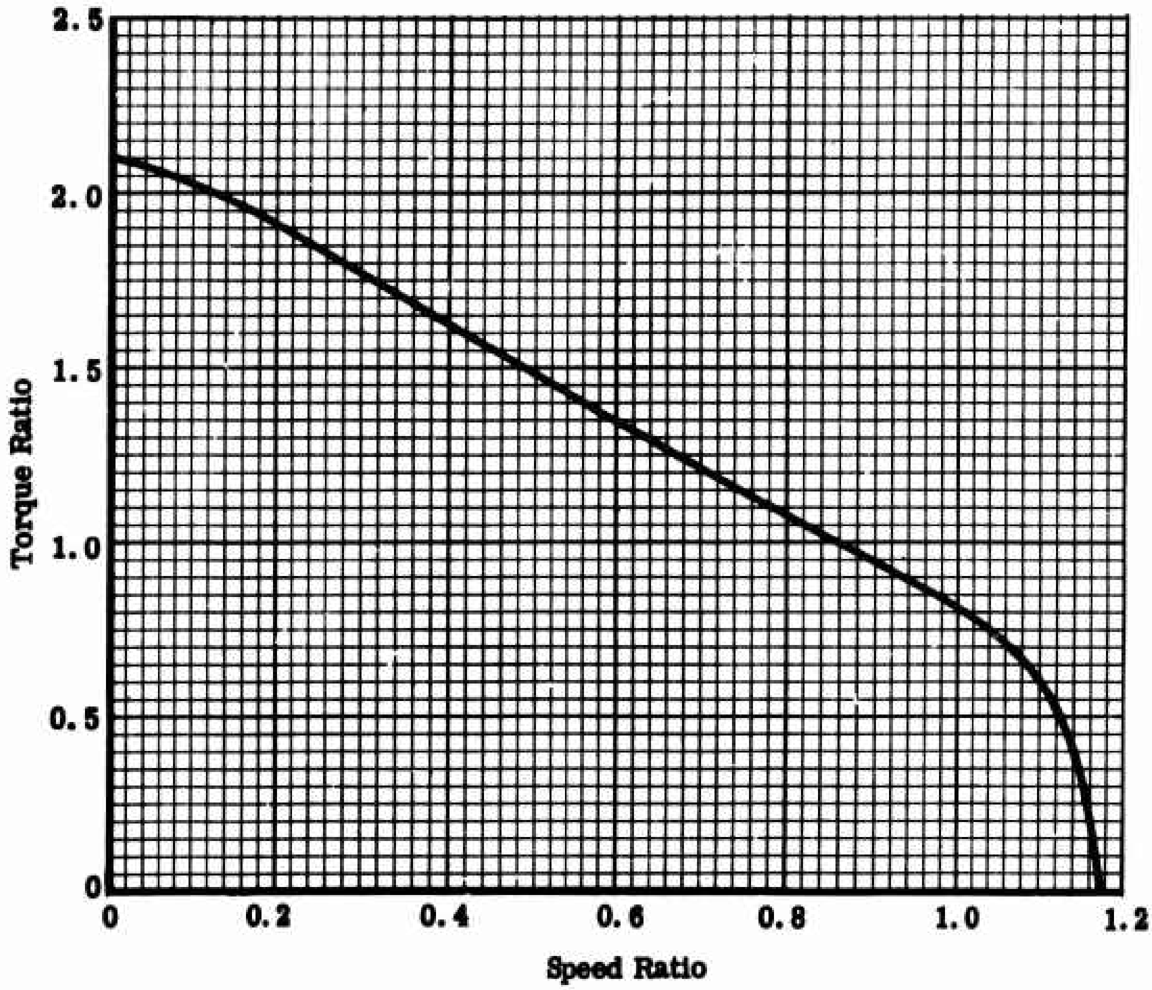


Figure 74. Torque Ratio as a Function of Speed Ratio.

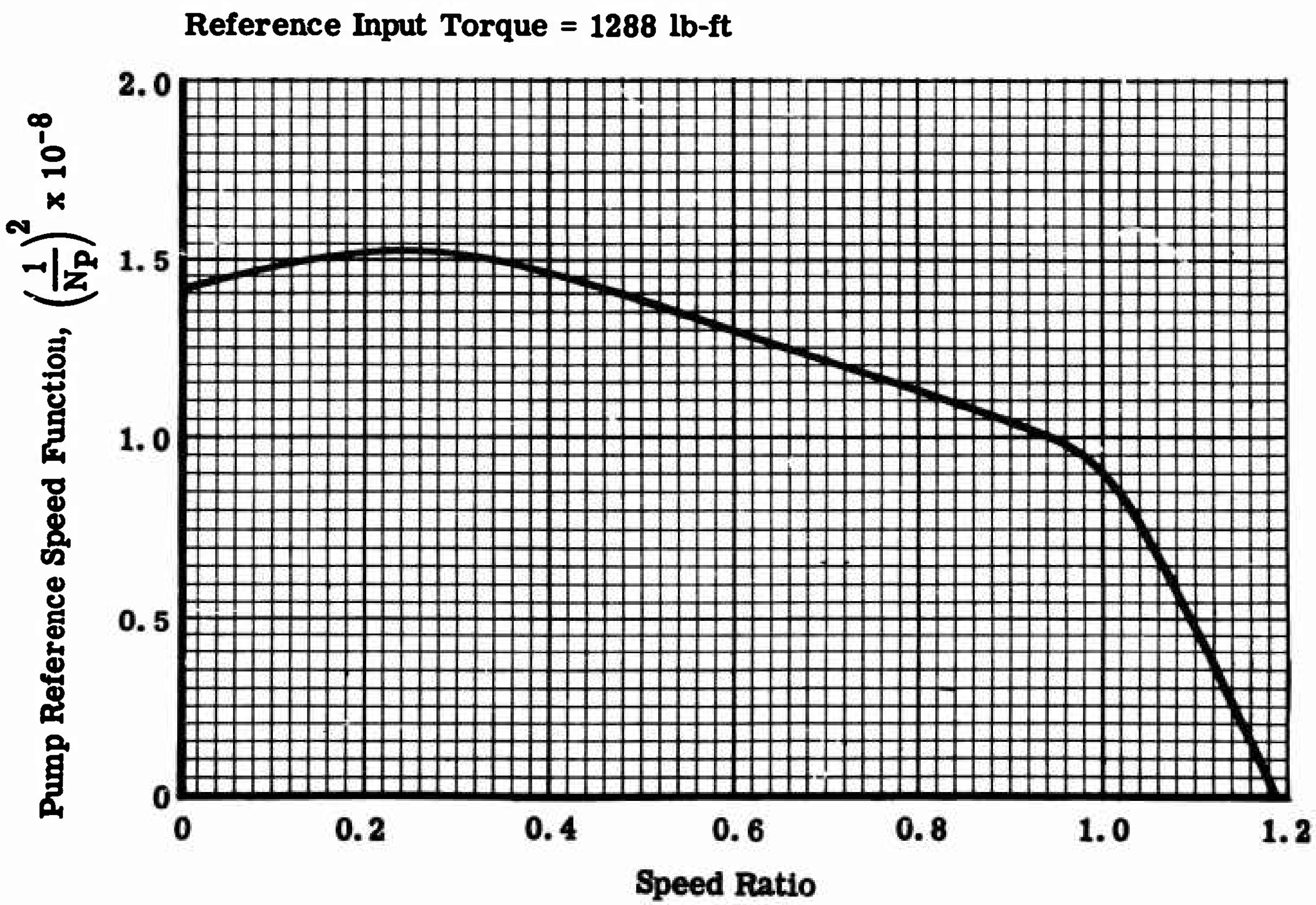


Figure 75. Pump Reference Speed Function Versus Speed Ratio.

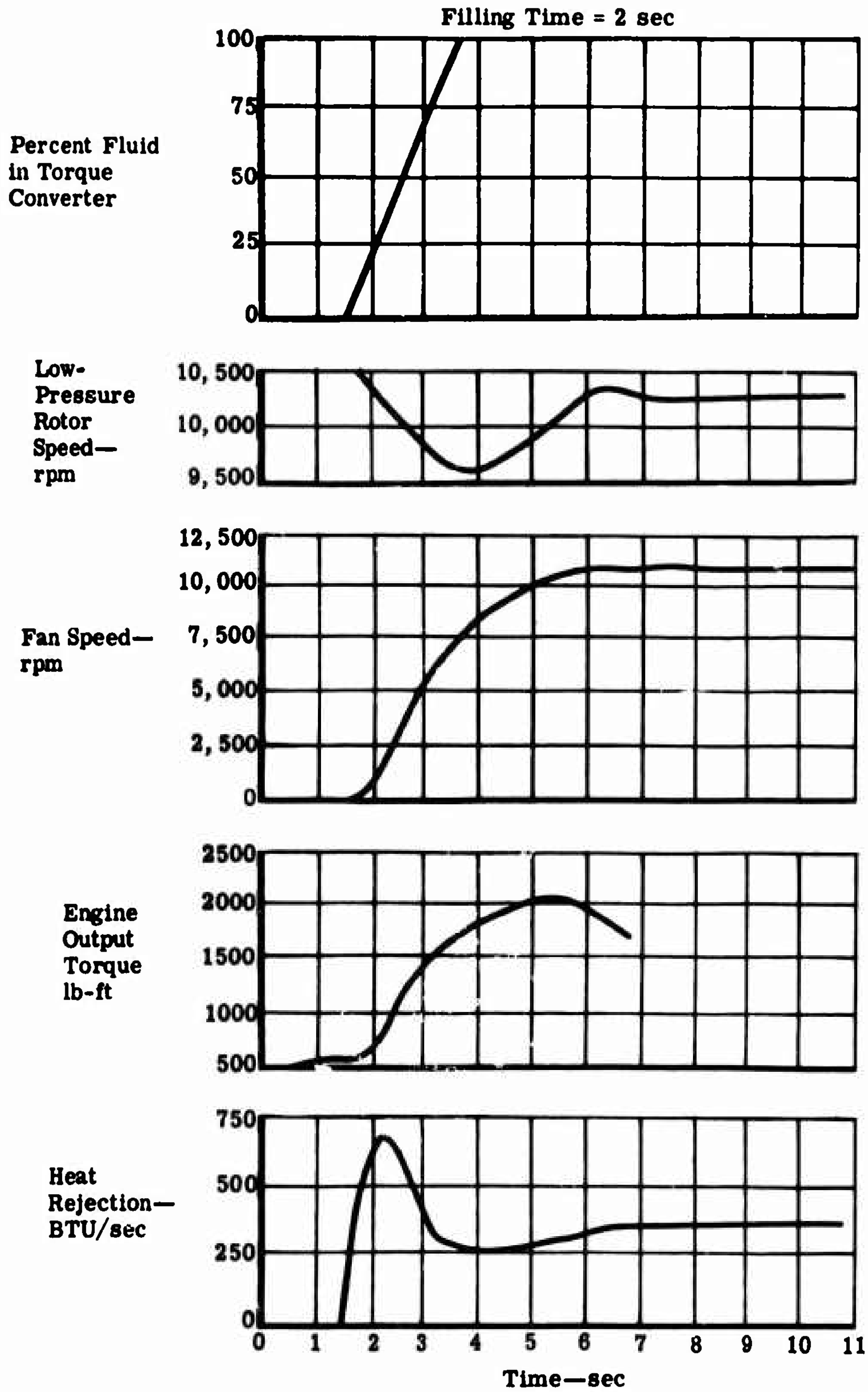


Figure 76. Analog Computer Analysis of Torque Converter—2 Seconds Fill Time.

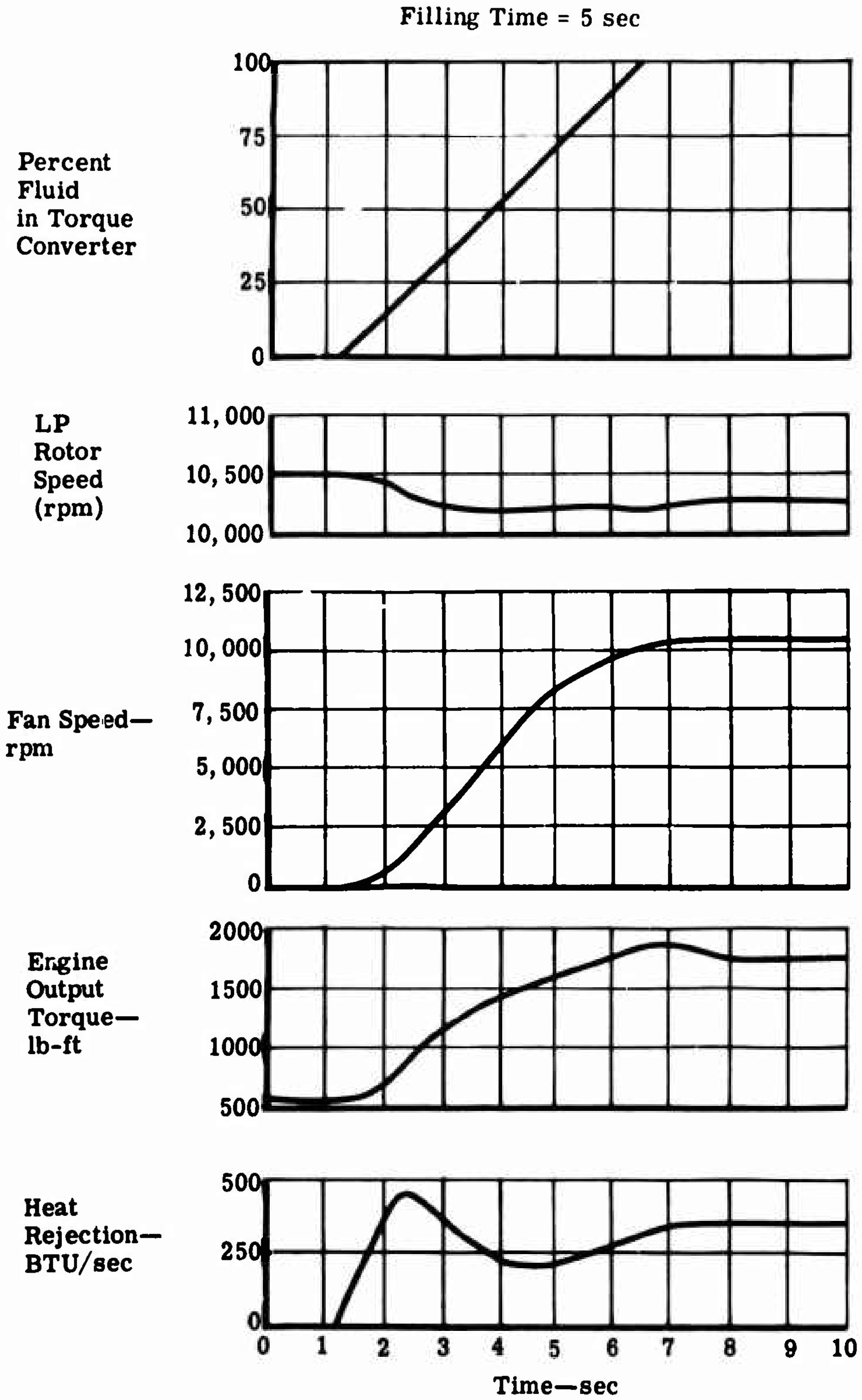


Figure 77. Analog Computer Analysis of Torque Converter—5 Seconds Fill Time.

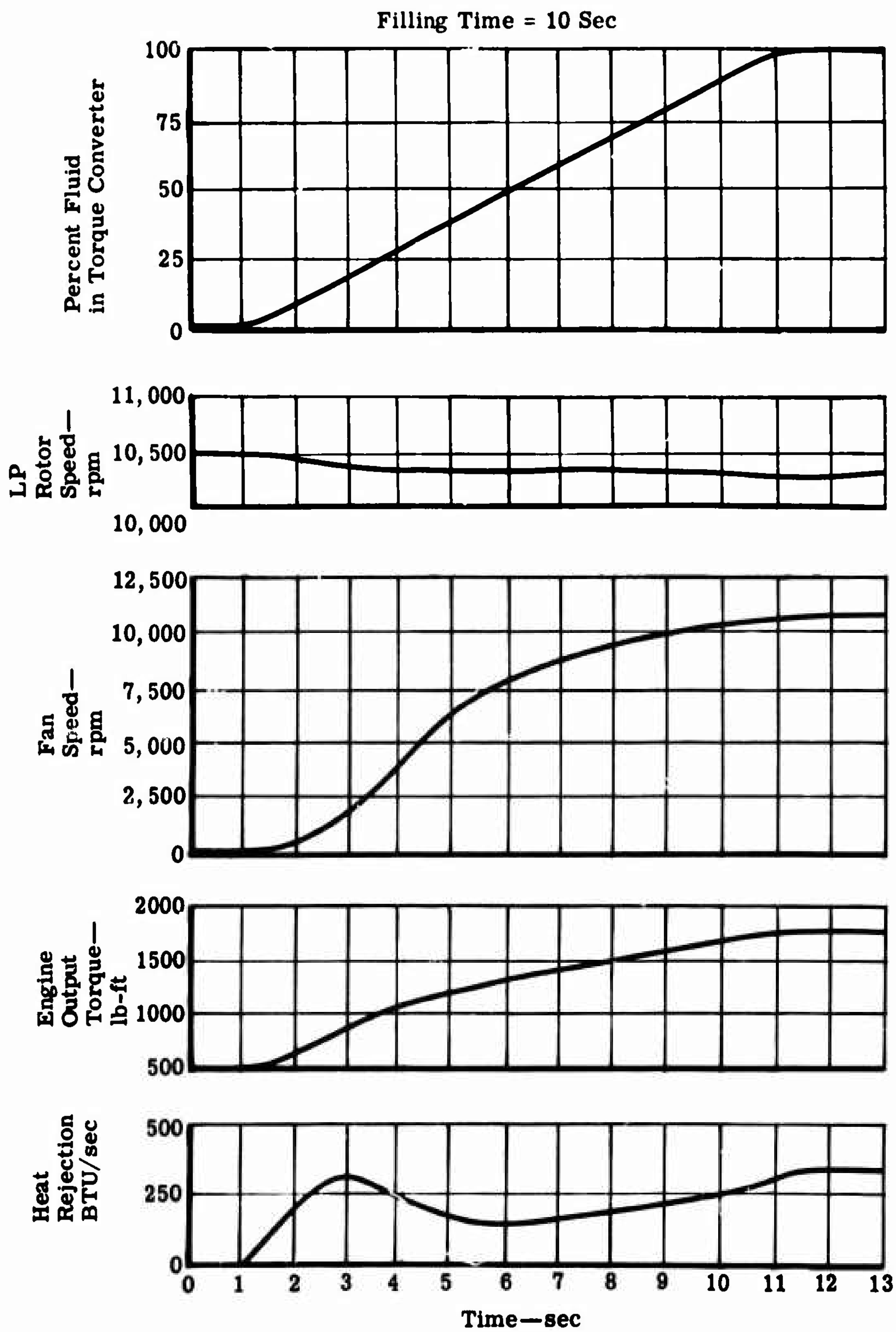


Figure 78. Analog Computer Analysis of Torque Converter—10 Seconds Fill Time.

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13. ABSTRACT

This report presents the results of a study of a large number of conceptual arrangements for a convertible fan/shaft engine applicable to advanced rotary-wing aircraft. Fan/shaft power transfer methods were examined and defined. Various methods of fan unloading to minimize or eliminate thrust at hover and to reduce the parasitic fan power were explored. Engine sizing to meet the dual requirements of shaft power and fan thrust was accomplished, and a control system for coordinating shaft power and fan thrust was defined. Performance is presented for supercharged and nonsupercharged gas generator arrangements with various forms of variable fan geometry and decoupling.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Convertible						
Composite						
Fan/Shaft						
Helicopter						
VTOL						

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Security Classification

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