View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by NASA Technical Reports Server

NASA TECHNICAL MEMORANDUM

NASA TM X-67983

NASA TM X-67983

CASE FILE
COPY

VARIABLE GEOMETRY AFT-FAN FOR TAKEOFF QUIETING OR THRUST AUGMENTATION OF A TURBOJET ENGINE

by Richard J. Weber and David G. Evans
Lewis Research Center
Cleveland, Ohio
December, 1971

E-6714

VARIABLE GEOMETRY AFT-FAN FOR TAKEOFF QUIETING OR THRUST AUGMENTATION OF A TURBOJET ENGINE

by Richard J. Weber and David G. Evans

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

ABSTRACT

A concept is presented that combines the low-noise and high-thrust characteristics of a turbofan at takeoff, together with its high efficiency at subsonic flight speeds, with the high efficiency of a turbojet at supersonic cruise. It consists of a free turbine with tip fan mounted behind the turbine of a conventional turbojet engine. Fan air is supplied from blow-in doors or is ducted from the main engine inlet. At high flight speeds where fan augmentation is not desirable, the fan inlet is closed and the free turbine is stopped by adjustment of its variable-camber stators. Estimates of noise, cycle performance, and example configurations are presented for a typical supersonic transport application.

VARIABLE GEOMETRY AFT-FAN FOR TAKEOFF QUIETING OR THRUST AUGMENTATION OF A TURBOJET ENGINE

by Richard J. Weber and David G. Evans

INTRODUCTION

For many airplane applications, the simple turbojet engine is a desirable propulsion system. This is especially the case if considerable amounts of supersonic cruise are required. For example, both the Anglo-French and the proposed Boeing supersonic transports were based on the use of afterburning turbojets. It is often the case, however, that the engines, if sized for best supersonic cruise performance, are underpowered or excessively noisy at takeoff. Enlarging the engines to meet the takeoff constraints then causes some penalty in overall airplane range or payload capability. Another problem has been the inherently lower efficiency of the turbojet than the turbofan when operating at subsonic flight speeds. This paper describes a concept for alleviating both of these difficulties.

The concept consists of a free turbine with tip-mounted fan blades that is installed in the exhaust duct just downstream of the existing compressor-turbine assembly of an otherwise unchanged turbojet (fig.1). The fan compresses a separate stream of air, with the turbine being driven by the hot gas stream emerging from the basic turbojet turbine. At takeoff, the unit thus operates as a turbofan engine. However, following takeoff or subsonic cruise, the rotation of the free-turbine is halted, the airflow through the fan is shut off, and the unit operates as a conventional turbojet engine. To stop the aft-fan from rotating, the free-turbine stator is uncambered by flapping its trailing edges. The low work requirements of the free turbine make it uniquely adaptable to this concept in that the pressure losses across its blading can be minimal when in the stopped condition. It is hoped to thereby obtain the high takeoff thrust, low noise, and good subsonic flight efficiency of a turbofan, together with the good supersonic cruising efficiency of a turbojet, with a minimum of penalties due to added weight, nacelle drag, and internal pressure losses.

This report presents some introductory calculations of thermodynamic performance and a preliminary analysis of how the concept might be implemented. The authors wish to acknowledge that the development of the present concept was stimulated by presentations by Mr. Walter Swan of Boeing, who pointed out the noise problems of the original turbojet engine for the SST and speculated that some sort of adjustable-bypass engine might be beneficial.

It is recognized, of course, that the desirability of variable-bypass engines is common knowledge and that numerous efforts toward this end have been made in the past. Furthermore, there is nothing new about the idea of using aft fans for modifying a turbojet engine to obtain higher thrust, better specific fuel consumption, or lower jet noise. (For example, this scheme was applied by G.E. as early as 1960 in their CJ805-23 engine and was proposed more recently by others for STOL applications.) The contribution of this report lies in the particular mechanical means to implement the concept in terms of a representative supersonic transport application.

SYMBOLS

A	area
BPR	bypass ratio, wt_f/wt_T
D	diameter
f/a	fuel-air ratio
g	gravitational constant
Δh	specific work
J	mechanical equivalent of heat
N	rotative speed
p	static pressure
P	total pressure
Pr	total pressure ratio
r	radius
T	total temperature
U	blade velocity
V	absolute air or gas velocity
wt	weight flow
W	relative air or gas velocity
λ	speed-work parameter, $U_m^2/gJ\Delta h$
η	adiabatic efficiency based on total pressure ratio

Subscripts

amb	ambient
ann	annulus

F	aft-fan
h	blade hub
m	blade mean
t	blade tip
T	free turbine
U	tangential
X	axial

Stations

2	core engine inlet
5.1	core engine turbine exit
6	auxiliary fan inlet
7	auxiliary fan inner-stage
8	auxiliary fan exit

ANALYSIS AND RESULTS

Assumptions

Engine. - As an example of the application of the auxiliary fan, it will be considered in conjunction with an afterburning turbojet engine having characteristics generally similar to the GE/4 that was considered for the Boeing version of a supersonic transport. At sea-level static conditions, the engine was assumed to have an airflow of 633 lb/sec, a turbine-rotor-inlet temperature of 2200°F, and a compressor pressure ratio of 12. The computed turbine-discharge conditions for such an engine are shown in fig. 2 for various takeoff turbine-inlet temperatures. It was assumed in the calculation that the exhaust-nozzle-throat area was varied so as to maintain constant engine airflow during part-power operation. This is desirable for low noise with a simple turbojet (ref. 1), but is not necessarily preferable when the aft fan is added.

In computing takeoff thrust, the nozzle thrust coefficients for both the core engine and the bypass air were taken as 0.97; adiabatic efficiencies for the free turbine and the fan were 0.85; the product of inlet pressure recovery and duct loss for the bypass stream was 0.94.

Noise. - Exhaust-jet noise was computed at the start of takeoff roll measured at a point 1500 feet from the sideline of the runway, using the technique of references 2 and 3. In applying this procedure, the core and fan streams were considered to be separate jets emerging into the atmosphere; possible favorable interactions between the streams were not included in this preliminary study.

Cycle Analysis

Full-power takeoff. - At maximum turbine-inlet temperature without afterburning, the reference turbojet engine generates a takeoff thrust of 50,000 pounds and 121.4 PNdB of noise. If more thrust is required (as it was for the Boeing SST), this could be obtained by afterburning at the expense of still more noise or by enlarging the engine at the expense of greater engine weight. An alternative solution is to extract energy from the exhaust gases in order to compress a separate, bypass airstream with an aft fan. Fig. 3 shows that the total thrust (core plus bypass) is increased by this technique. Total thrust increases with both bypass ratio and fan pressure ratio. There is also some modest degree of quieting obtained (not shown) although fan jet noise becomes significant at the higher fan pressure ratios. Another limiting factor on fan pressure ratio arises from the noise generated internally by the rotating blades. This becomes especially important if more than a single-stage fan is required (fan pressure ratios exceeding 1.7 - 1.8). This internal noise is amenable to suppression, but again at the expense of additional weight.

A limiting factor on bypass ratio, as shown by the scale on the right of fig. 3, is the increase of fan diameter with bypass ratio. Associated with the larger diameter could be a greater nacelle weight, nacelle drag, and fan weight. This becomes especially significant if the fan diameter approaches or exceeds the 90-inch diameter of the basic turbojet nacelle.

Part-power takeoff. - The noise reductions associated with fig. 3 are not adequate to meet recent FAA standards for commercial aircraft. However, if all the additional thrust provided by the fan is not needed, an opportunity exists to further reduce noise by taking off with less than full power. For example, the Boeing SST required the GE/4 engine to produce about 60,000 pounds of thrust at takeoff, which could be provided by the basic engine only with the use of afterburning. This created a noise level of 123 PNdB. Numerous combinations of bypass ratio and fan pressure ratio in fig. 3 produced more than 60,000 pounds of thrust, so in these cases the turbine-inlet temperature can be reduced with a consequent noise reduction. Fig. 4 displays the reduction in noise that results from this situation.

Part-throttle takeoffs are seen to be very effective in reducing engine noise. This could also be accomplished with a conventional turbojet engine, of course, but it would be necessary to increase the engine size in order to obtain the desired takeoff thrust. Determining whether the penalties imposed on airplane performance by a larger engine are greater or lesser than those due to adding an auxiliary fan requires a more detailed study than is presented herein.

If the auxiliary fan approach is adopted and a typical takeoff noise limit of 108 PNdB is imposed, figure 4 shows that a bypass ratio of about 1.5 is required for a fan pressure ratio of 1.7. The fan diameter in this case approaches the 90-inch diameter of the standard turbojet nacelle (fig. 3). Still lower bypass ratios could be used if (1) higher fan pressure ratios were attainable without causing excessive turbomachinery noise, (2) an exhaust-jet noise suppressor were available, or (3) the presence of the annular jet of bypass air causes a reduction in primary jet noise not accounted for in the present noise computations (as suggested in ref. 4).

Fuel consumption. - Another benefit of the auxiliary fan might accrue from an improvement in fuel consumption during takeoff and low-speed subsonic portions of the airplane flight. Several thousands of pounds of fuel are consumed during takeoff. The specific impulse of a low-bypass-ratio turbofan is enough superior to that of an afterburning turbojet to save nearly half of this fuel. Much larger amounts of fuel are consumed by the turbojet (in the non-afterburning mode) during subsonic climb, subsonic cruise, hold, and diversions to an alternate airport (the latter two phases constituting a large part of the fuel reserves). If the fan can be used in these post-takeoff portions of flight, it might be possible to save many more thousands of pounds of fuel (up to 20,000 pounds for the nominal, primarily supersonic mission, and even more if considerable subsonic cruise is required to avoid overland sonic booms).

Supersonic cruise performance. - The preceding discussion concerned engine performance at takeoff and subsonic flight with the auxiliary fan and free turbine operating. During supersonic flight, it is assumed herein that the fan would be shut down. However, the thrust and efficiency of the turbojet may be adversely affected by pressure losses associated with the presence of the non-rotating free turbine in the exhaust gas stream. The effect of various amounts of pressure drop across the free turbine during a typical SST cruising condition is shown in fig. 5. For instance, a pressure drop of 5 percent causes a reduction in specific impulse of 0.8 percent, with a nearly equal reduction in cruise range. This corresponds to only 28 nautical miles at a typical total range of 3500 n.mi.

Engine Design

To illustrate the concept, a preliminary design study was made of a free-turbine and auxiliary aft-fan configuration for a fan bypass ratio of 1 and a pressure ratio of 1.7 during full-power takeoff (turbine-rotor-inlet temperature of 2200°F) for a GE/4-type of turbojet. Some of the detailed component assumptions differ slightly from those of the preceding parametric study.

Aerodynamic design. - The fan tip speed was selected as 1200 ft/sec and was sized on the basis of a takeoff airflow rate of 34 lb/sec per square foot of annulus area. Mean-radius velocity diagrams and approximate blade shapes are pictured in fig. 6. It was assumed that a single-stage fan with two downstream stator rows could provide the overall pressure ratio and axial discharge requirements. Overall efficiency was assumed to be 0.87. The resulting design characteristics of the fan are tabulated in Table I. Fan tip diameter was 81 inches, hub diameter was 60 inches, and rotative speed was 3400 rpm.

The corresponding data for the single-stage free turbine at takeoff conditions are shown in fig. 7 and Table II. The design was for zero exit whirl. The tip and hub diameters were 56 and 34 inches, respectively. Two inches of thickness were allowed for a shroud to separate the fan and core streams and to provide room for fan blade attachments and rotating seals between the two flow streams.

The centrifugal stress for combined turbine and fan blading, assuming a steel turbine and aluminum fan, was determined to be 13,000 psi and 39,000 psi at the hub of the fan and turbine blades, respectively. This was not considered to be excessive because of the considerable reduction of operating time and operating temperature from that of the core engine blading.

The low work requirement for the free turbine ($\lambda = 0.74$) permits a slightly cambered, nearly axially oriented rotor-blade configuration. This fact, coupled with the low gas temperature entering the free turbine (about 1600^{o}F), leads to the concept of aerodynamically stopping the rotor by adjusting the stator blades when fan operation is not required. The type of stator blade variation envisioned is a simple, movable flap. A Coanda slot could be used to help turn the gas flow on the suction side, as indicated in fig. 7(a). Incorporation of a jet flap could also be considered for both the stator and rotor.

Figure 7(b) shows the turbine when in the non-rotating position (stator positioned to establish zero life across the rotor). It is estimated that the pressure loss when in this configuration would be 4 to 5 percent. Note that the amount of stator variation is not extreme. The flap is set at 40^{o} from axial when the turbine is driving the fan and at approximately -15^{o} when not rotating. Turning vanes could be provided behind the turbine to straighten the flow if necessary.

The preceding section on Cycle Analysis suggested that part-throttle takeoffs and higher bypass ratios might be required to lower engine noise. The lower turbojet turbine-inlet temperature yields a lower free-turbine inlet temperature (fig. 2). This is desirable from a materials standpoint but would require a higher free-turbine pressure ratio in order to extract the proper amount of work. This is undesirable aerodynamically, as it would necessitate more highly cambered blades with the likelihood of higher pressure losses across the free turbine when not rotating. Higher bypass ratios are also undesirable, as they would require longer fan blades which increase fan diameter and blade stress.

Example layouts. - No mechanical designs were attempted for the auxiliary fan/turbine concept. However, fig. 8 displays two illustrative configurations. Part (a) shows a close-coupled arrangement layed out to the dimensions noted in Tables I and II. Part (b) shows a variation in which the free turbine is located further downstream of the core engine. A semi-vaneless turbine stator similar to the one described in ref. 5, was used. It both reduced the amount of stator flapping required and reduced the amount of stator flapping required and reduced the hub diameter of the free turbine. As a result, fan tip diameter was reduced about six inches.

Fig. 9 shows how the auxiliary fan might be integrated into the propulsion nacelle. In part (a), air is supplied to the fan at takeoff or at other subsonic operating points by blow-in doors. Part (b) shows an alternative approach where air from the turbojet inlet (enlarged from that of part (a)) is ducted to the fan. This approach more readily allows the use of the fan for thrust augmentation during transonic or supersonic flight and might also help reduce inlet spillage drag losses.

Analogous to the problem of supplying air to the fan when it is running is that of providing for efficient expansion of the compressed air through a nozzle. Both the inlet and exhaust systems selected must cause minimum drag or disturbance to the core turbojet when the fan is not being driven. Perhaps the simplest approach to the exhaust problem is to provide a separate nozzle for the fan stream as shown in fig. 1. A simple, two-position, sonic nozzle (possibly side-mounted) that can be closed when not in use would be adequate. Alternatively, the primary core nozzle (which requires variable throat and exit areas in any event) may be designed to integrate the bypass flow as shown in fig. 9, especially if an ejector-type nozzle is employed.

Weight and drag penalties. - The maximum nacelle diameter of the basic turbojet engine is approximately 90 inches. From fig. 3, it appears that bypass ratios as high as 1.5 can be accommodated within this size of nacelle (ignoring the volume occupied by engine accessories). In this case, there should be no major increases in nacelle drag associated with the auxiliary fan concept. However, an unavoidable penalty would be the weight of the free turbine, fan, bearings, supports, inlet doors and exhaust system. A very crude estimate of added weight for 4 engines is 16,000 pounds. If this weight displaces an equal amount of fuel, the airplane would lose 280 nautical miles in range. However, as previously noted it is possible that a reduction in fuel consumption of this same order of magnitude might result from maximum usage of the better specific impulse of the turbofan mode of operation. It is, therefore, possible that the benefits of the auxiliary fan might be achieved with no penalty in aircraft range. In contrast, simply enlarging the conventional turbojet to allow quieter, part-power takeoff would lose over 1000 miles in range (ref. 6).

The above discussion has been in terms of a nominal, all-supersonic-cruise mission with minimal subsonic operation. In practice, however, an SST may fly considerable distances subsonically (e.g., to avoid over-land sonic booms). The better specific impulse of the turbofan mode of operation would be even more profitable in this case.

CONCLUDING REMARKS

A concept is examined that permits an engine to operate as a turbofan during takeoff and subsonic flight and as a turbojet during high speed flight. In a supersonic airplane like an SST, this permits combining the benefits of the turbojet's generally higher specific impulse during supersonic flight with the turbofan's generally higher thrust and lower noise during takeoff plus higher specific impulse during subsonic flight.

The device consists of a free turbine with a tip-mounted fan that is installed downstream of the basic turbojet engine. With the proper selection of fan pressure ratio and bypass ratio it is possible to obtain large amounts of low-speed thrust augmentation. If the extra thrust is not required, takeoffs with part throttle yield large reductions in exhaust-jet noise.

A preliminary study of turbine aerodynamics indicated that the free turbine can be started or stopped as desired by varying the angle of a trailing-edge flap on the turbine stator. Because the lightly loaded turbine required only moderately cambered blade profiles, the pressure drop across the turbine is estimated to cause only very small airplane range losses during supersonic flight when the turbine is stopped. However, the weight of the auxiliary fan/turbine may cause additional losses in range. Furthermore, the loss would be even worse if the installation requires an increase in nacelle diameter with resultant drag penalties. However, some or all of the range loss may be recovered if the higher specific impulse of the turbofan operation can be sufficiently utilized during low-speed portions of the airplane flight.

A more detailed analysis will be required to determine whether the overall performance of this concept is superior to other techniques for noise alleviation, such as oversized turbojets or jet noise suppressors.

REFERENCES

1. Whitlow, John B., Jr.; Koenig, Robert W.; and Kraft, Gerald A.: Supersonic Transport Airport and Community Jet Noise During Takeoff and Initial Climb. NASA TM X-1452, 1967.

2. Anon.: Jet Noise Prediction. Aerospace Information Report 876, SAE, July 10, 1965.

3. Anon.: Definitions and Procedures for Computing the Perceived Noise Level of Aircraft Noise. Aerospace Recommended Practice 865, SAE, Oct. 15, 1964.

4. Dosanjh, Darshan S.; Abdelhamid, Amr N.; and Yu, James C.: Noise Reduction from Interacting Coaxial Supersonic Jet Flows. Basic Aerodynamic Noise Research. NASA SP-207, 1969, pp. 63-101.

5. Rohlik, Harold E.; Wintucky, William T.; and Moffitt, Thomas P.: Investigation of a 0.6 Hub-Tip Radius-Ratio Transonic Turbine Designed for Secondary-Flow Study. III. - Experimental Performance with Two Stator Configurations Designed to Eliminate Blade Wakes and Secondary-Flow Effects, and Conclusions from Entire Stator Investigation. NACA RM E57G08, 1957.

6. Whitlow, John B., Jr.: Analysis of SST Turbojet Engines Designed for Part-Power Takeoff to Reduce Jet Noise. NASA TM X-52667, 1969.

Table I. - Fan design characteristics (take-off conditions).

(a) Assumptions:

$Pr = 1.7$

$BPR = 1.0$

$wt = 621$ lb/sec

$U_{t,b} = 1200$ ft/sec

$(wt/A_{ann})_6 = 34.0$ $^{lb}/_{sec\text{-}ft^2}$

$\eta = 0.87$

$T6 = 70^{\circ}F$

$P6 = 14.7$ psia

$D_{h,6} = 60$ inches

$V_{x,6} = V_{x,7} = V_{x,8}$

(b) Computed:

$D_{t,6} = 81$ inches

$U_m = 1045$ ft/sec

$N = 3400$ rpm

$\Delta h = 24$ $^{Btu}/_{lb}$

Horsepower = 21,100

$(V_h/V_t) = 0.74$

Hub centrifugal stress = 13,000 psi (aluminum)

$D_{t,8} = 77.7$ inches

$D_{h,8} = 63.3$ inches

Table II. - Free-turbine design characteristics (take-off conditions).

(a) Assumptions:

wt = 603 lb/sec

η = 0.90

N = 3400 rpm

P6 = 50.4 psia

T6 = 1596°F

f/a = 0.0268

D_t = 56 inches

6° inlet whirl

(b) Computed:

D_h = 34 inches

Pr = 1.22

Δh = 24.5 Btu/lb

U_m = 668 ft/sec

$$\lambda = \frac{U^2_m}{\Delta hg\ J} = 0.74$$

V_h/V_t = 0.61

Hub centrifugal stress = 39,000 psi (combined stress of aluminum fan blade supported through steel turbine blade).

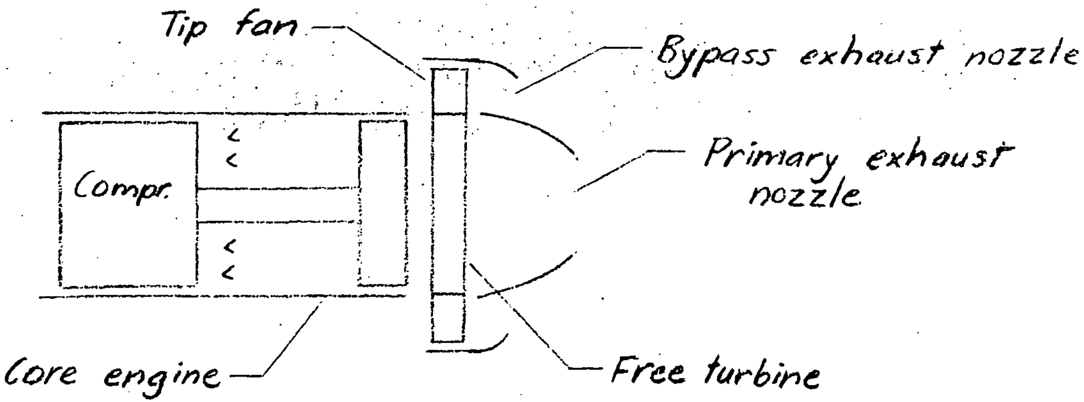


Fig. 1. - Schematic of auxiliary fan/turbine.

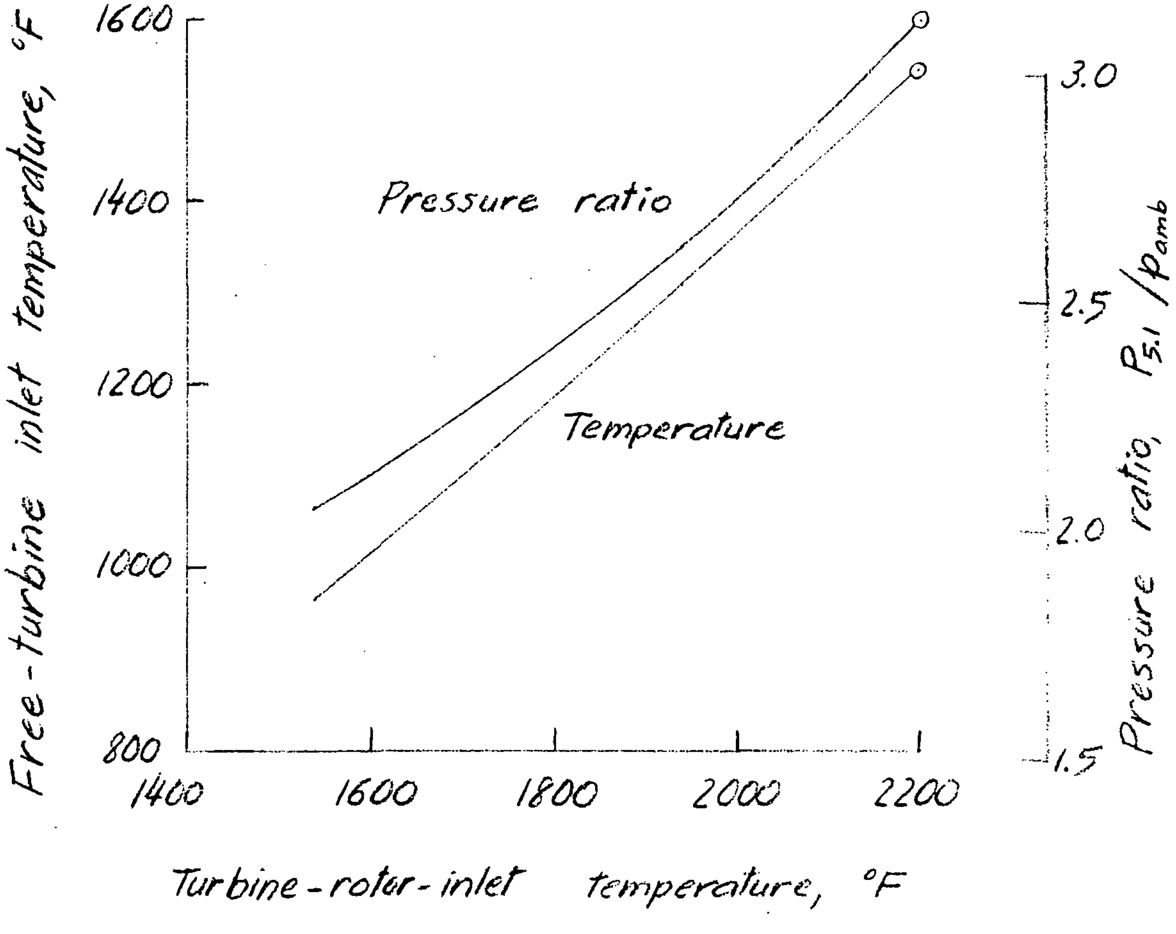


Fig. 2. - Conditions of turbojet-engine exhaust gas before entering free turbine. Sea-level static flight condition.

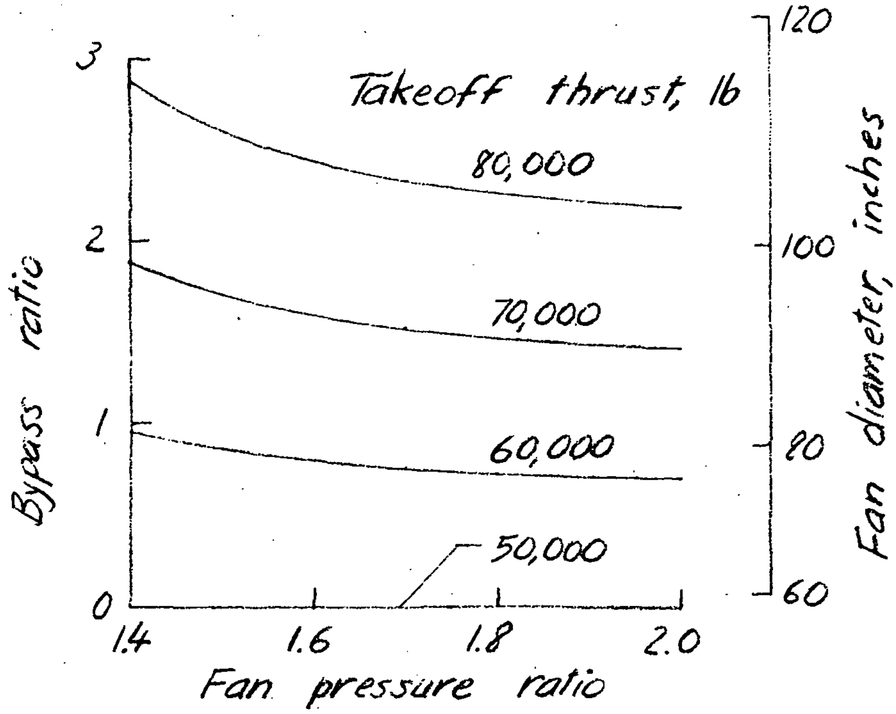


Figure 3.- Thrust augmentation of GE/4 with aft fan. Turbine-rotor-inlet temperature, 2200° F.

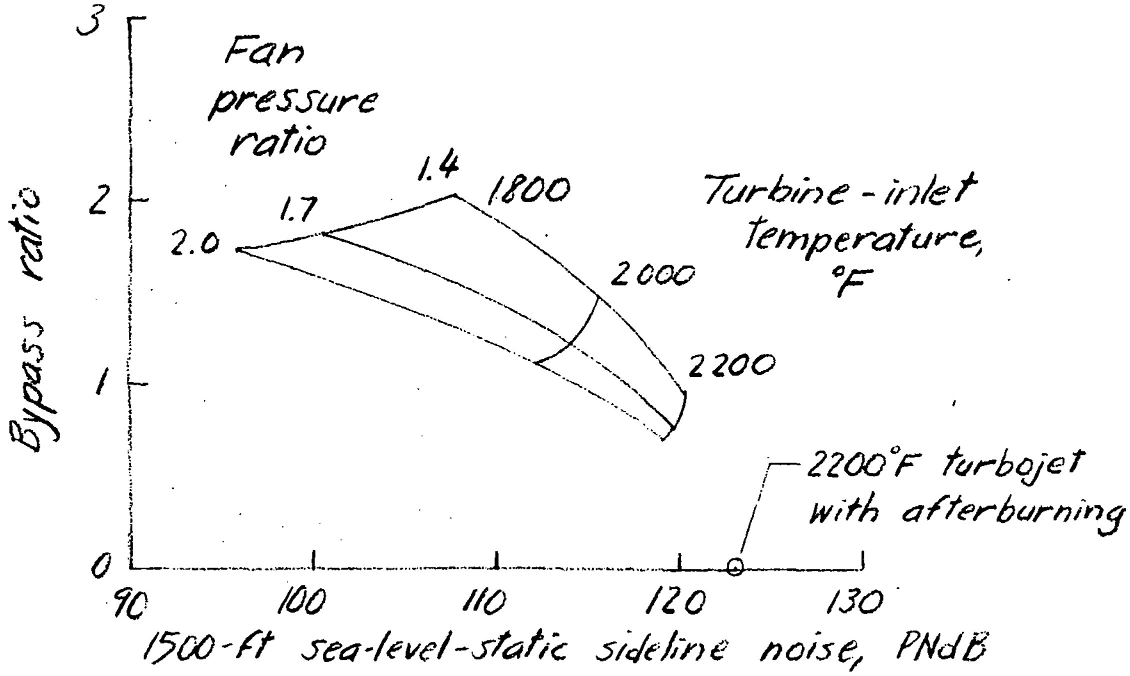


Figure 4.- Exhaust-jet noise during takeoff. Thrust per engine, 60,000 lb.

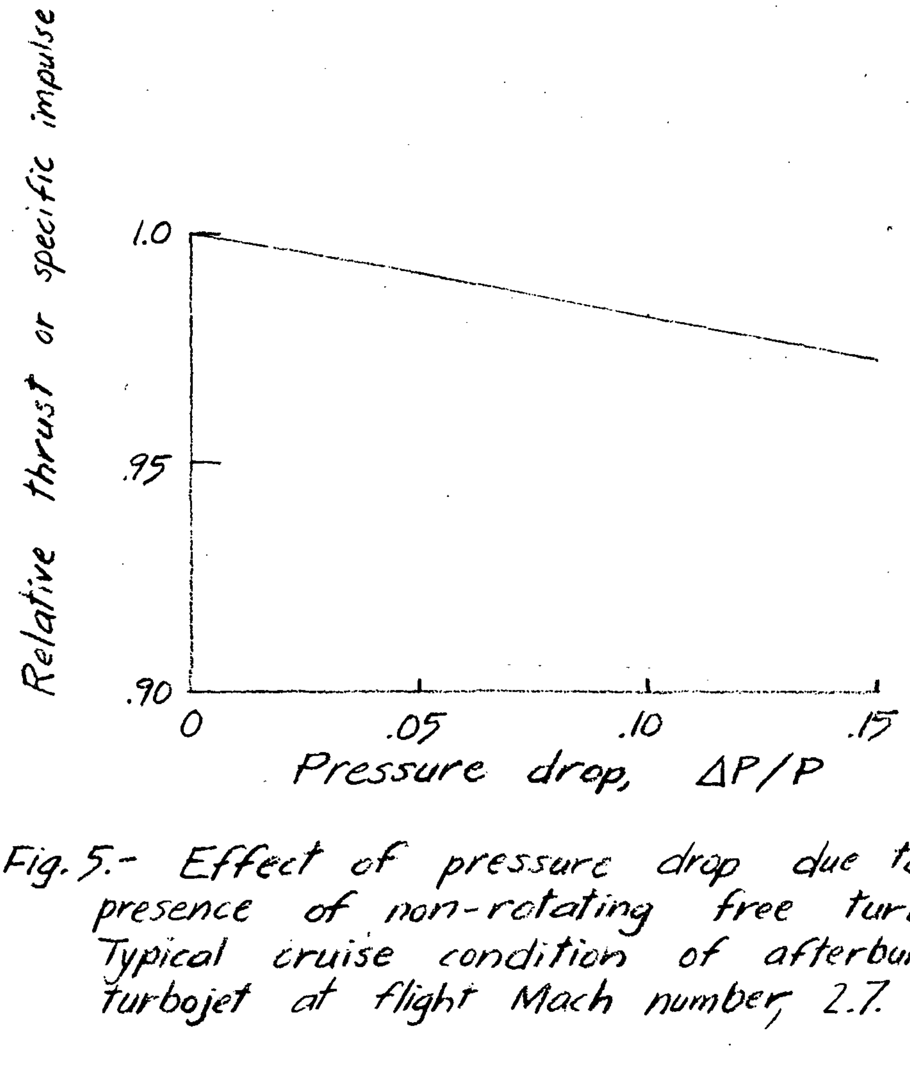


Fig. 5.- Effect of pressure drop due to presence of non-rotating free turbine. Typical cruise condition of afterburning turbojet at flight Mach number, 2.7.

RJW
7/7/71

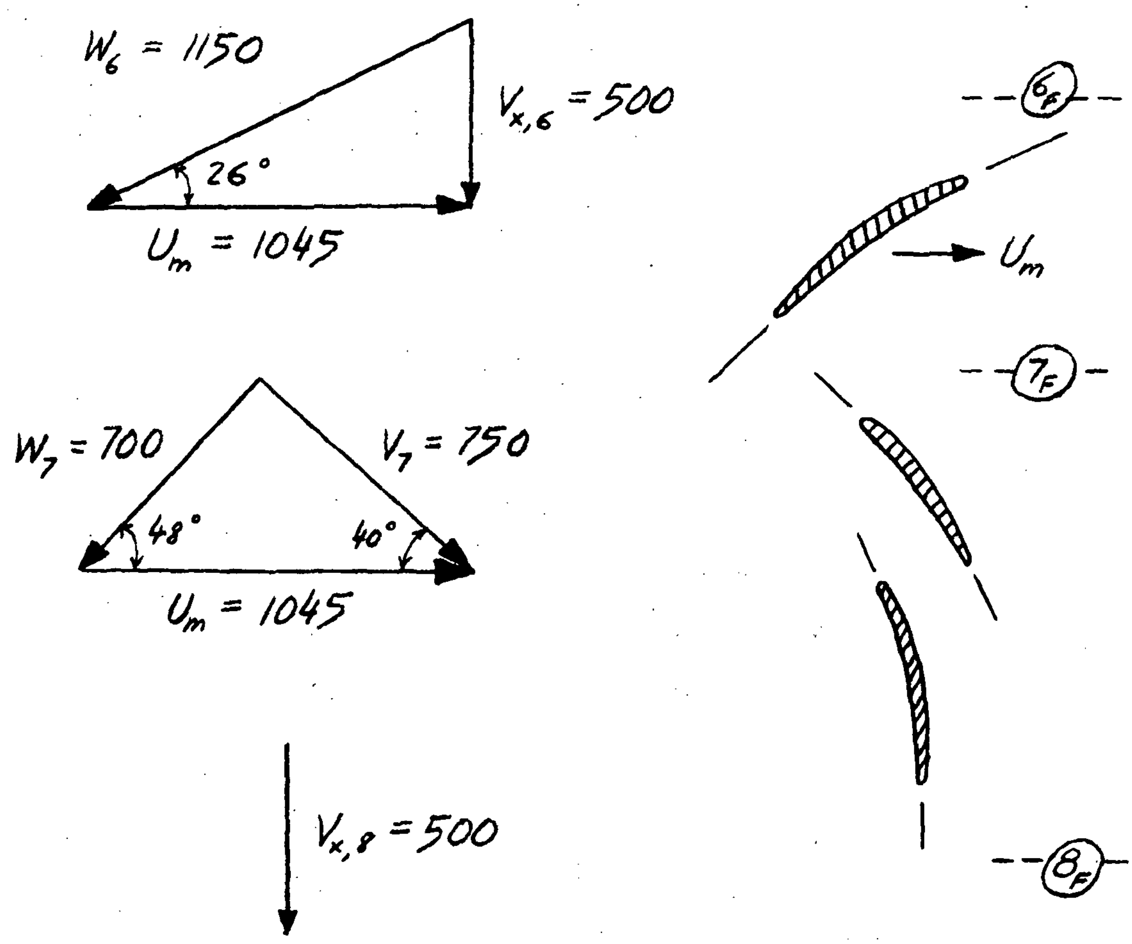
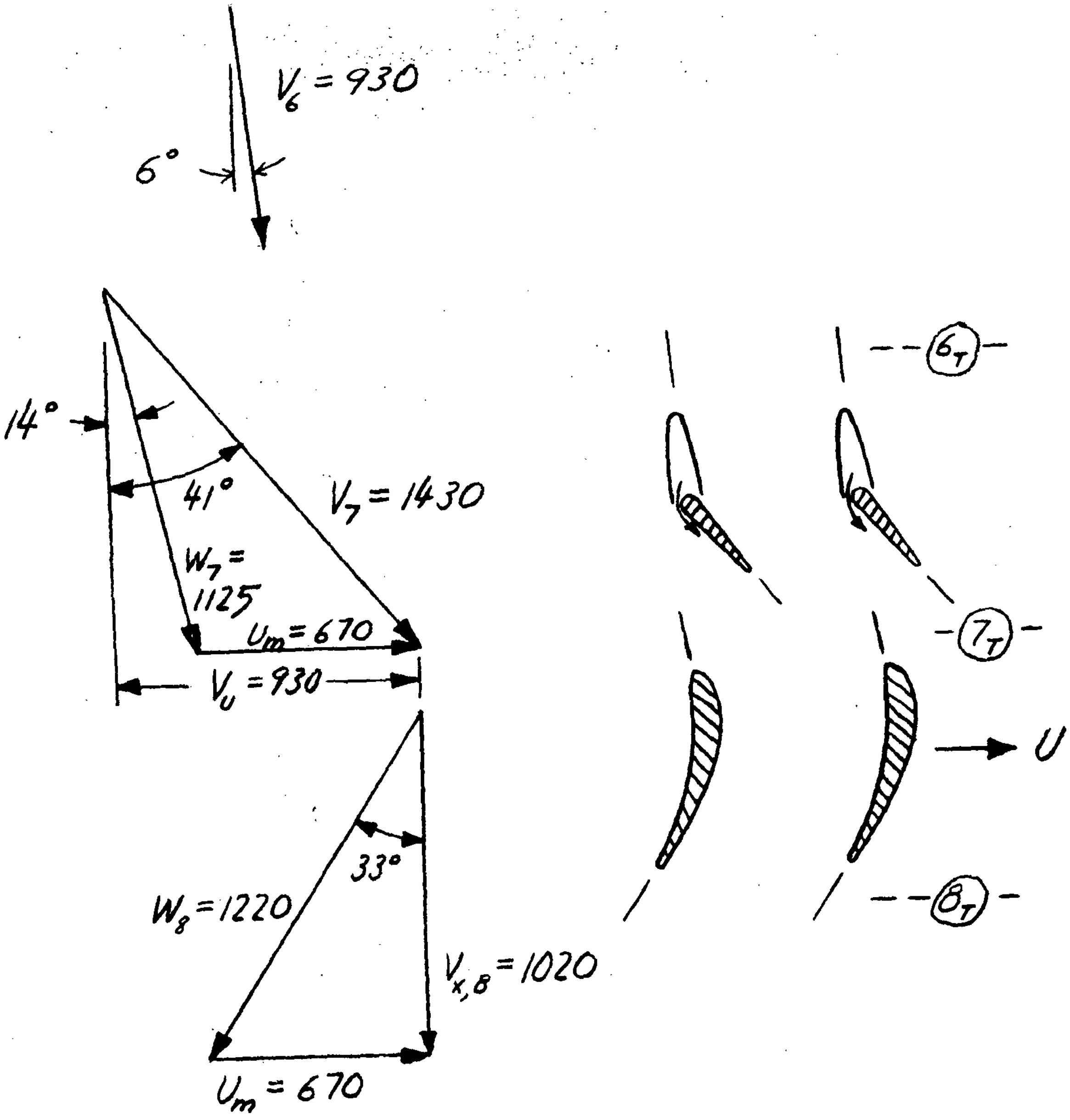
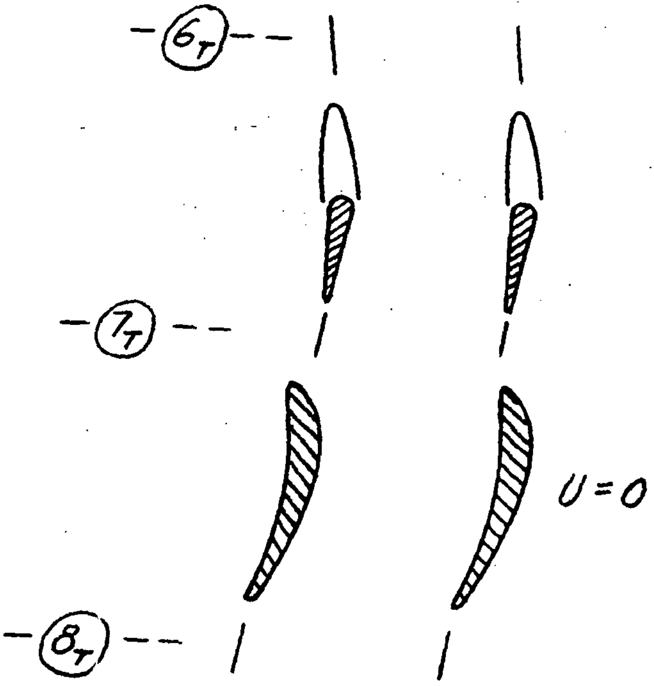


Fig. 6.- Mean-radius velocity diagrams and blade shapes for aft-fan at takeoff conditions (velocities in ft/sec).



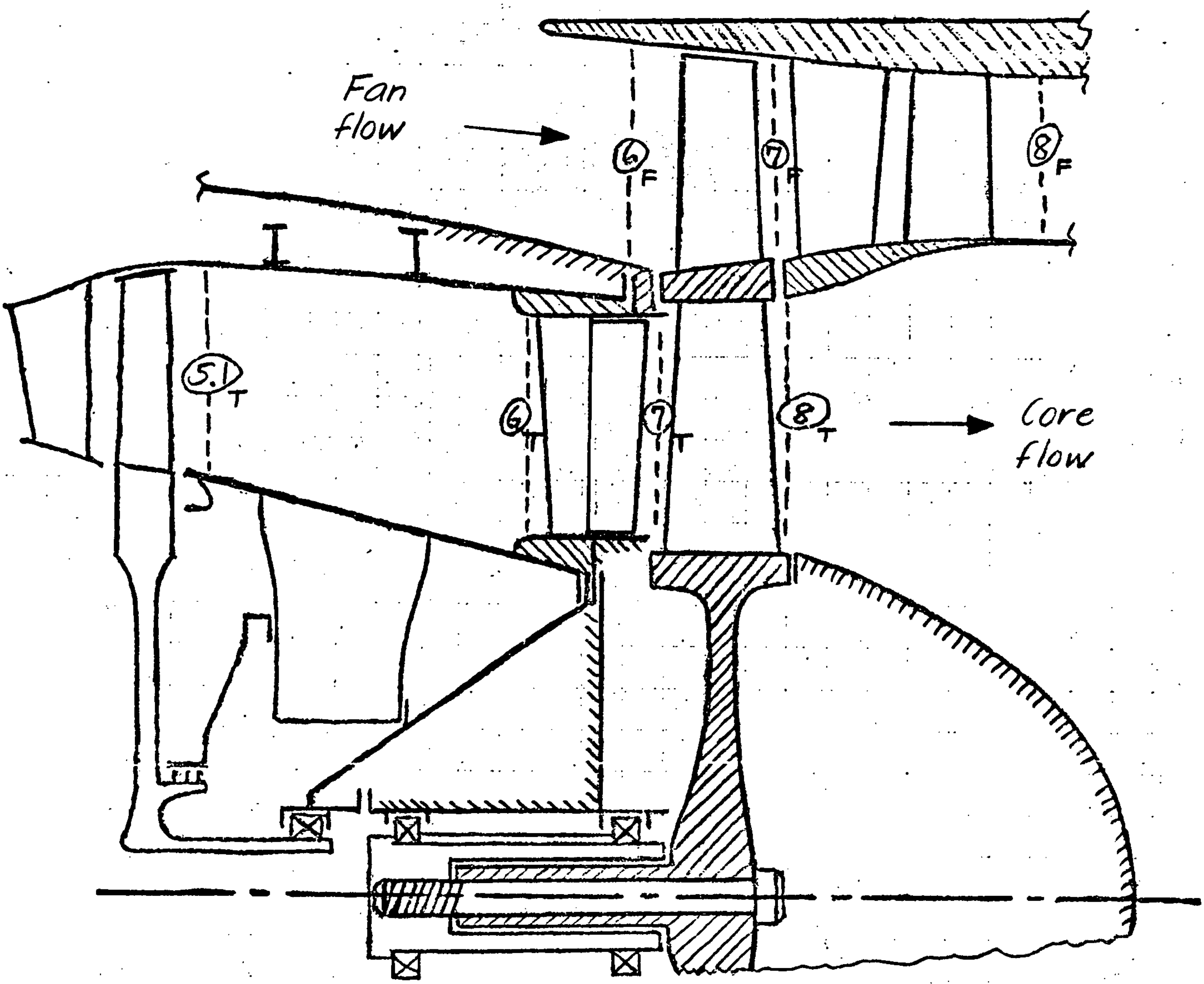
(a) Takeoff

Figure 7.- Mean-radius velocity diagrams and blade shapes for free turbine (velocities in ft/sec).



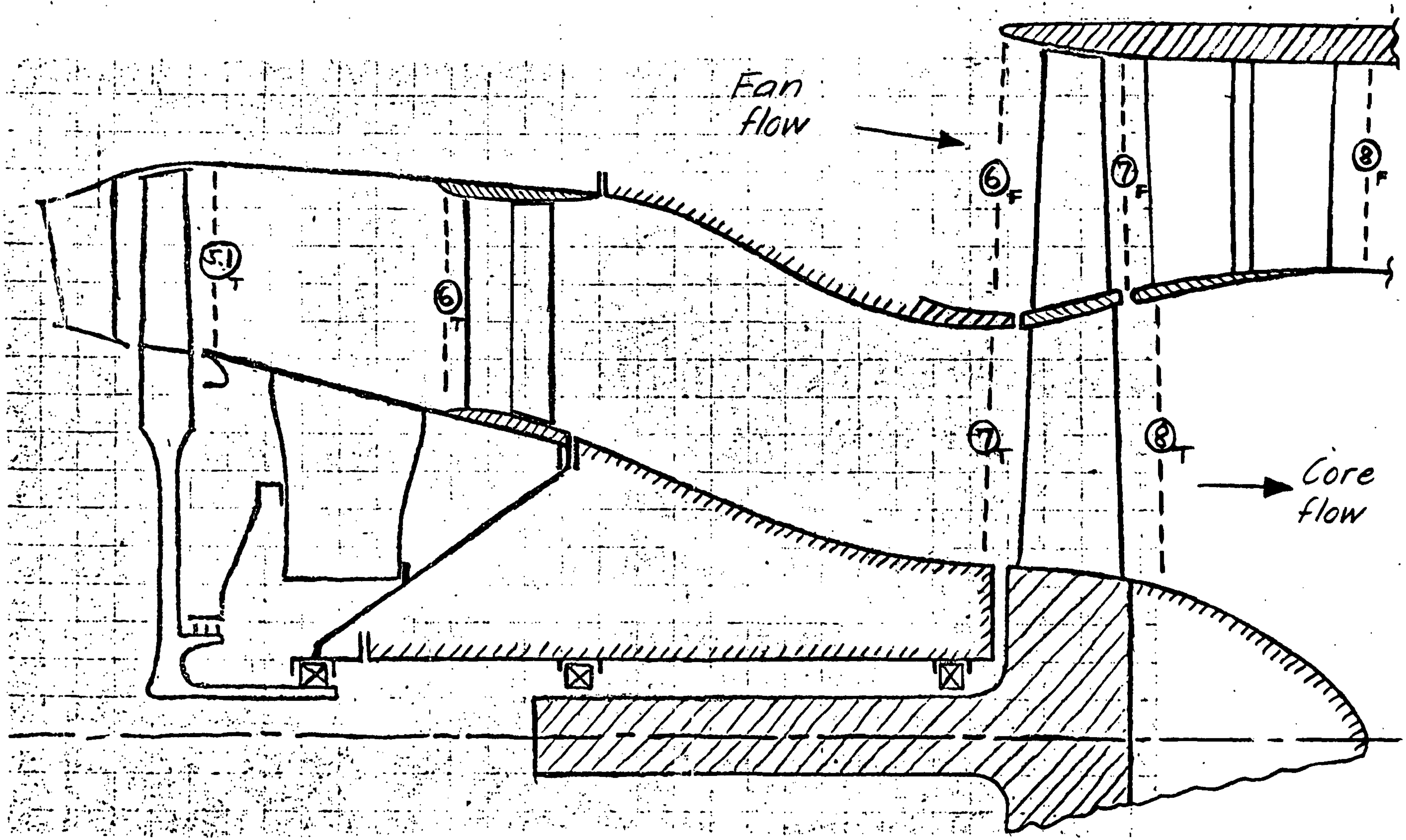
(b) Non-rotating

Figure 7.- Concluded.



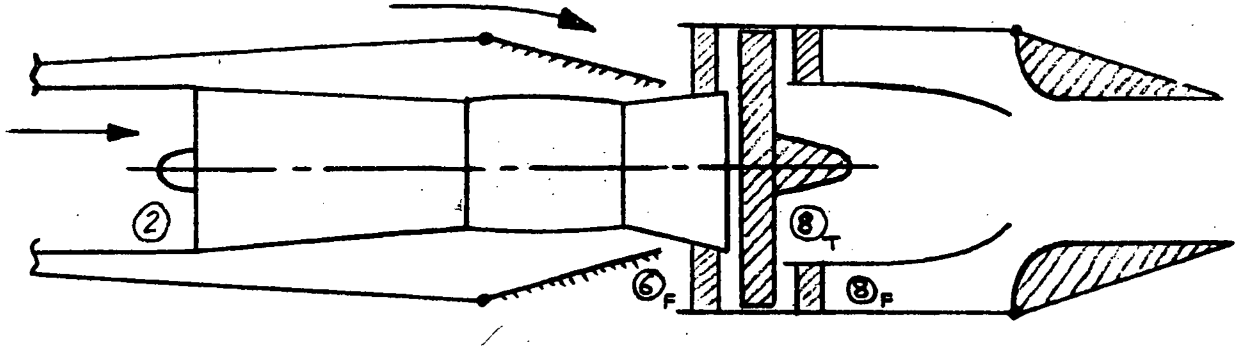
(a) Nominal aft-fan configuration

Fig. 8.- Example layouts of auxiliary fan concept adapted to GE/4 type of engine (new components shown shaded).

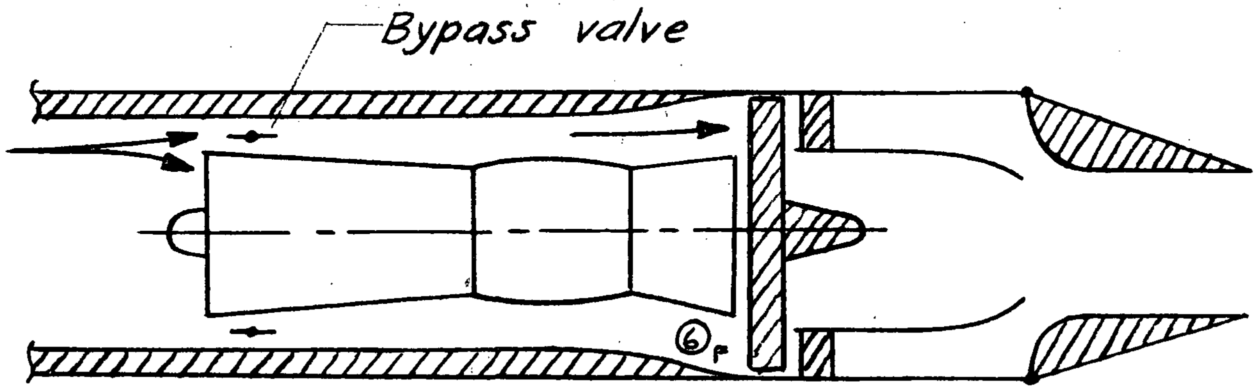


(b) Semi-vaneless free-turbine, aft-fan configuration

Fig. 8. - Concluded.



(a) Supply air to auxiliary fan via blow-in doors



(b) Supply air to auxiliary fan via turbojet inlet

Figure 9. - Example installation of auxiliary fan engine (new components shown shaded).