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A VECTORED THRUST POWERPLANT FOR COMMERCIAL V/STOL OPERATIONS: SYSTEM CONSIDERATIONS AND PRELIMINARY MODEL TESTS

by

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SYSTEM CONSIDERATIONS AND PRELIMINARY MODEL TESTS ON A FORM OF VECTORED THRUST POWERPLANT FOR COMMERCIAL V/STOL OPERATIONS

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Abstract

VTOL capability promises increased potential for commercial short-haul aircraft. A variable bypass ratio lift/thrust engine arrangement is discussed in relation to safety and economic requirements. Some feasibility aspects and possible problem areas have been investigated on a model scaled to produce 700 lb. lift/thrust. The test results relate mainly to fan-drive efficiency at partial admission, and to the use of fan stator adjustment for fast response thrust modulation.

Introduction

The potential advantages of V/STOL aircraft in commercial operations are well known in principle if, as yet, unrealized in practice. The relatively low requirements in size and cost of ground facilities point to the use of V/STOL aircraft both in intercity-centre transportation over short distances in heavily populated super-metropolitan regions, and in supply operations in undeveloped areas where conventional airport expenditures are uneconomic.

In addition to access to new traffic, VTOL capability offers gains in operational safety and economy. Omnidirectional approach and take-off, zero touchdown speed, and reduced sensitivity to gusts imply advantages in all-weather operation(1). The absence of restrictions associated with orthodox take-off and landing requirements allows the use of wing loadings optimized with respect to overall economics(2). In intercity-centre service, opportunities for basic weight saving lie in the adoption of commuter design concepts for passenger accommodation(3,9). Significant time savings accrue from reduced ground manoeuvre, rapid initial acceleration, and steep, omnidirectional approach. The small ground and air spatial requirements for take-off and landing promise less traffic congestion and further improvement in block time through reduced air control delays.

Air congestion is a growing problem at existing airports and the productivity and economy of new, high speed, short-haul aircraft are seriously offset by current delays(4). Reduction in the fraction of available aircraft operating time spent below cruising altitude has an important bearing on short-range aircraft economics and represents, with cruising Mach numbers already in excess of 0.7, a major remaining approach to improved economic efficiency(2).

Thus, at least three potential roles for V/STOL commercial aircraft can be distinguished. In probable order of development, these lie in short-haul operations from existing airports, in supply operations in undeveloped areas, and, ultimately, in intercity-centre passenger transportation.

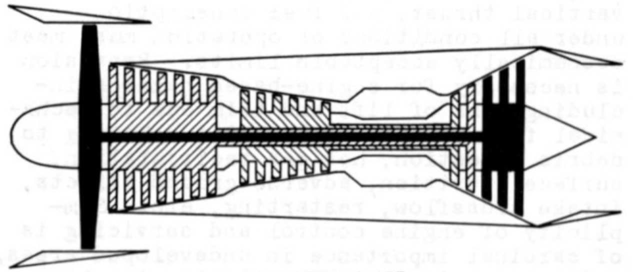
The commercial exploitation of favourable V/STOL vehicle characteristics implies minimum propulsion system requirements relating to installation, economy and safety. Engine installation is effected ideally with no substantial compromise to wing configuration, minimal aerodynamic interference and low external drag. Engine weight and cost penalties associated with vertical thrust, and fuel consumption under all conditions of operation must meet economically acceptable limits. Provision is necessary for engine-based hazards including loss of lift and trim due to mechanical failure and difficulties relating to debris ingestion, hot gas recirculation, surface attrition, adverse ground effects, intake crossflow, restarting, etc. Simplicity of engine control and servicing is of cardinal importance in undeveloped areas, while intercity-centre operation involves difficult requirements with respect to noise.

The accommodation of these requirements in a practicable system presents a complex problem admitting different approaches. Clearly, whatever the approach, a propulsion system for commercially useful aircraft will involve the most advanced technology available from current conventional and V/STOL engine developments.

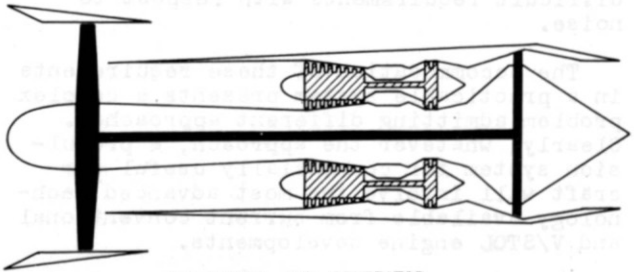
Turbofan Status

In recent years, engine development for conventional transport aircraft has centred on turbofan engines of increasingly large bypass ratios. Progressing from the fractional bypass ratios of early designs, current values are in the range of 4 to 6 with 10 predicted for future arrangements (5). With increasing bypass ratio, aerodynamic design problems arise from the growing disparity in fan and gas generator dimensions. Rotational speed restrictions due to fan size lead to below-optimum blade speeds in compressor and turbine stages on the fan shaft. An additional shaft has been introduced in some designs to free the gas generator compressor system from the slow running fan(6). Further difficulties arise from the conflicting requirements of maximum fan annulus area, a reasonably productive fan root speed, and efficient ducting between the fan and gas generator compressor. These difficulties have led to various proposals for radial grading of the fan work, including the incorporation of a rotating gas generator inlet duct in the fan hub(7).

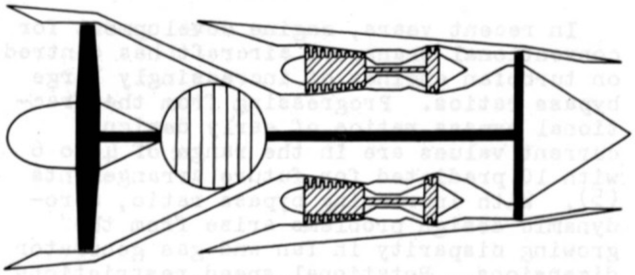
In principle, some relief from the geometrical constraints associated with high bypass ratio is afforded by a shift in layout from the conventional concentric shaft arrangement. A possible system, of say bypass ratio 5, is shown compared with the concentric shaft approach in Figure 1. The gas generator section is subdivided into multiple units disposed around the fan shaft(8,9). The generator units are connected by individual ducts to equal segments of the fan turbine. The turbine dimensions are made compatible with those of the fan for improved turbine blade speed conditions and fewer turbine stages. As a final step, the gas generator units are supplied by individual ram intakes, and the short-cowled fan is provided with separate outlet ducts terminating in reversing nozzles.



CONCENTRIC SHAFT



SUB-DIVIDED GAS GENERATOR



SUB-DIVIDED GAS GENERATOR WITH RAM INTAKES

FIG I SCHEMATIC TURBOFAN CONFIGURATIONS

Applicability to V/STOL Propulsion

The potential usefulness of this form of turbofan lies in its applicability to commercial V/STOL propulsion. In this context, the fan exhaust nozzles are of the rotating lift/thrust type (cf. Bristol Siddeley Pegasus). Since they are subject to similar demands for duration at maximum rating and number of starts, the gas generator units reflect, ideally, the advanced technology stemming from the development of compact, single shaft, lift jets(10). The selection of take-off bypass ratio, as determined by specific mission requirements, is readily accommodated in the main rotor design, including, for example, that resulting in a single fan stage with attendant noise advantages(6). From the safety aspect, gas generator interconnection through the fan drive is inherent to the arrangement. Protection from failure at take-off of a gas generator unit is provided with minimal ducting. The exclusive use, where feasible, of cold vertical jets offers reduced hazards, particularly in operations from natural surfaces. Finally, the arrangement includes the possibility of usefully variable bypass ratio. In particular, thrust reduction by progressive shutdown of gas generator units results in increased operating bypass ratio. Given the technology for continuous turbine operation at partial admission, an additional parameter is admitted to the basic VTOL engine problem of matching take-off and cruise thrust demands.

As a V/STOL transport propulsion system, the arrangement offers some promise of combining the installational advantages of a flexible, forward-facing, integrated lift/thrust engine with inherent safety features, relatively low weight penalty, and acceptable cruising fuel economy. A hypothetical single system, short-haul transport aircraft is shown in Figure 2. Here the wing loading is set by overall mission economics. Wing-tail design and engine placement are governed by considerations of aerodynamic interference, debris ingestion, ground effect, utilizable cabin space, etc. Figure 3 shows a possible four-engined aircraft scheme. In this case provision for a fan rotor failure appears feasible.

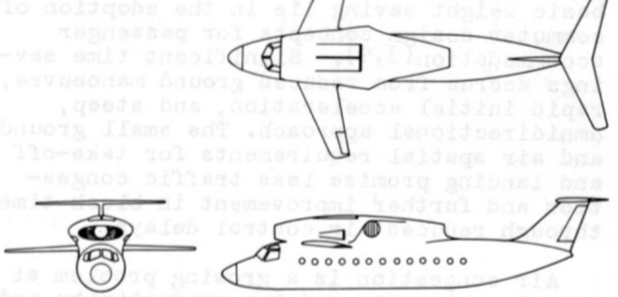


FIG 2 HYPOTHETICAL SINGLE SYSTEM SHORT HAUL V/STOL TRANSPORT AIRCRAFT

Experimental Programme

The V/STOL propulsion system outlined above has received some experimental investigation, using a simple working model operated on the balances of the 10 ft. x 20 ft. N.R.C. V/STOL Propulsion Tunnel. The model design permitted few, if any, inferences to be made concerning the obvious mechanical problems. These involve special considerations of main rotor design redundancies, bearings, mountings, vibration, thermal growth, turbine disc design, etc. However, certain aerothermodynamical implications could be examined in a convenient way. System behaviour under simulated conditions of gas generator shutdown could be assessed directly in terms of fan thrust, bypass ratio, fan drive efficiency and overall economy. The relatively slow response of the high inertia fan rotor system implies an alternative approach to rapid fan thrust modulation in the landing flight phase. The model design incorporated a system of thrust spoiling, preliminary operating data on which could be obtained by direct measurement.

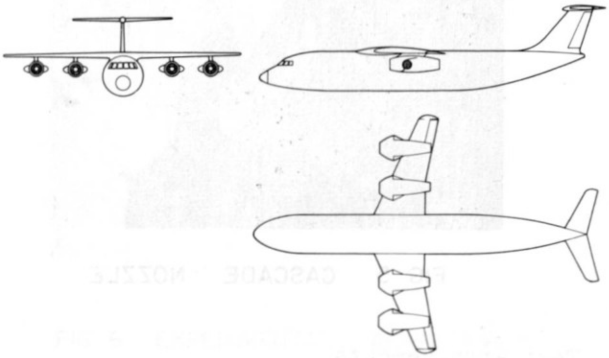


FIG 3 HYPOTHETICAL MULTI-SYSTEM V/STOL AIRCRAFT

Basic Relations

Before entering into a description of the model and experimental results, it might be useful to recall some simplified relations among the system parameters. For convenience, and as representative of the test conditions and vertical flight, the expressions refer to the case of zero forward speed. Fan thrust, F, and total available gas power, G, can be simply related by

$$F^3 = 4\rho kA(\eta\epsilon G)^2 \qquad (1)$$

where η is the overall efficiency of energy transfer from the hot to cold stream. Fan thrust loading, F/A, and ideal fan temperature rise, $\overline{\Delta T}$, vary inversely with bypass ratio, B, according to

$$\frac{F/A}{2\rho k} = gJCp\overline{\Delta T} = \eta\epsilon gS/B \qquad (2)$$

where S is specific available gas power. On the other hand, fan thrust per unit fuel flow, F/W_f, improves with increasing bypass ratio according to

$$F/W_f = Jh_f\eta_G\sqrt{2\eta\epsilon B/gS} \qquad (3)$$

where η_G is gas generator thermal efficiency. If thrust reduction is effected by the shutdown of gas generator units, remaining units operating at equal and unchanged conditions, then both G and W_f are reduced by the factor α, the ratio of the number of active units to the total number in the system. The quantities η_G and S remain unchanged. The fan turbine, however, operates at reduced speed with only a fraction, α, of nozzle arc active. Additional turbine losses contribute to a deterioration of η as α is reduced(11). Expressing the various quantities of interest in terms of the datum values at full admission, and assuming no change in ρk and ϵ with α, then

$$\text{from (1)} \quad \text{Rel}(F) = \alpha^{2/3}\,\text{Rel}(\eta)^{2/3} \qquad (4)$$

$$\text{from (2)} \quad \text{Rel}(B) = \text{Rel}(\eta)\,/\,\text{Rel}(F)$$

$$= \text{Rel}(\eta)^{1/3}\,/\,\alpha^{2/3} \qquad (5)$$

$$\text{from (3)} \quad \text{Rel}(F/W_f) = \text{Rel}(\eta B)^{1/2}$$

$$= \text{Rel}(\eta)^{2/3}\,/\,\alpha^{1/3} \qquad (6)$$

These approximate expressions indicate that fan thrust reduction through α is accompanied by improved economy providing η declines initially more slowly than $\alpha^{1/2}$. The specific fuel consumption based on fan thrust remains below the datum value for as long as Rel(η) remains greater than $\alpha^{1/2}$. A gain in specific fuel consumption reflects an increase in bypass ratio.

This approach to thrust reduction can be compared with the usual throttling procedure. In this case, η can be assumed not to change while S and η_G decline with reduced power. If all gas generator units are throttled in unison to reduce G by the factor β, then

$$\text{from (1)} \quad \text{Rel}(F) = \beta^{2/3} \qquad (7)$$

from (2) and (7)

$$\text{Rel}(B) = \text{Rel}(S)\,/\,\beta^{2/3} \qquad (8)$$

from (3) and (8)

$$\text{Rel}(F/W_f) = \text{Rel}(\eta_G)\,/\,\beta^{1/3} \qquad (9)$$

In general, η_G decreases more rapidly than $\beta^{1/3}$ and thrust reduction by gas generator throttling is accompanied by a progressive increase in specific fuel consumption, while B is substantially constant.

The present system involves certain implications with respect to the allocation of energy between the fan and turbine exhaust jets. In simplified terms, at the datum (take-off) rating,

$$F/m\sqrt{2gS} = \sqrt{\epsilon\eta B} \text{ and } F_T/m\sqrt{2gS} = \sqrt{1-\epsilon} \qquad (10)$$

Maximum take-off lift is given, for fully vectorable hot thrust, by $L/m\sqrt{2gS} = \sqrt{1+\eta B}$, at the fan pressure ratio corresponding to $\epsilon = \eta B/(1 + \eta B)$. Under these conditions, $F/F_T = \eta B$ (or $V/V_T = \eta$), i.e. the contribution of the hot component to vertical thrust is less significant the higher the datum bypass ratio. At sufficiently high bypass ratios the inclusion of the hot component has an adverse effect on engine lift specific weight due to the substantial weight increment represented by the necessary rotating nozzles. For datum bypass ratios greater than about 3-4, it appears advantageous to assign as much take-off power as practicable to the fan, leaving the hot thrust unvectored. This arrangement avoids the use of hot vertical jets. Further, the ratio V/V_T will tend to move towards the optimum value as α is reduced for normal flight, due to the expected increase in ηB. Where circumstances warrant, however, hot thrust deflection, e.g. of the switch-in type(10), could be employed.

Test Model

A general arrangement of the test model is shown in Figure 4. The model design dates from 1960 and was conceived originally as a quarter scale version of a V/STOL propulsion system, for a 10000 lb. A.U.W. aircraft, using what were essentially first generation lift-jets as gas generators. Datum bypass ratio was 4.10. The model was constructed for multi-purpose experimental use and has been employed mainly as a thrusting fan test rig, for example, in the investigation of crossflow generated inflow distortion effects on thrusting fan characteristics(12). With the recent completion of the balance installation in the V/STOL Propulsion Tunnel, direct force measurements became possible and some attention has been directed towards the propulsion system aspect.

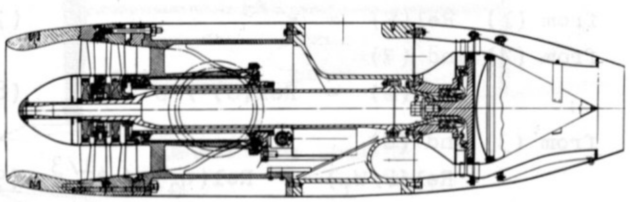


FIG 4 GENERAL ARRANGEMENT OF MODEL

General Description

The model consists essentially of a simple rotor comprising a two-stage fan driven by a single stage turbine supplied from an external source of compressed air. The supply air is led, through a dorsal flange and plenum, to four separate transition ducts each feeding a quarter of the turbine stator annulus. Provision is made for blocking any transition duct to simulate gas generator shutdown. The rotor shaft is supported in a front roller bearing and two rear ball bearings, with oil mist lubrication. The fan delivery duct is bifurcated to side exits equipped with fully rotating vaned nozzles (Figure 5). The nozzles are driven independently by electric motors carried inside the casing with remote control and position indication. Second stage stator blade setting is collectively variable during operation through a ring gear engaging spur gear sectors on each blade root pin.

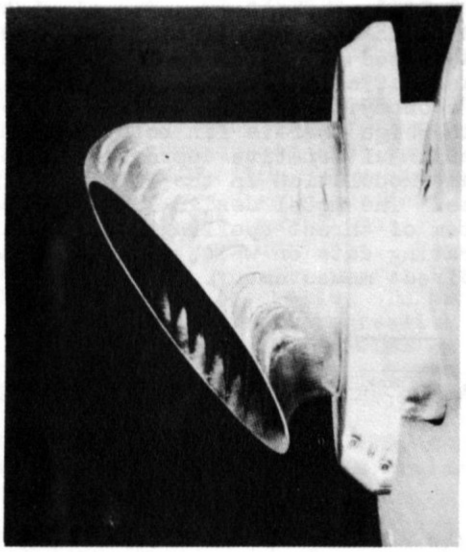


FIG 5 CASCADE NOZZLE

Test Arrangements

The model was suspended horizontally in the 10 ft. x 20 ft. working section of the V/STOL Propulsion Tunnel by bolting the turbine supply flange to the mid-point of a crosspipe connected at each end to an offsite 5000 KW compressor (Figure 6). The crosspipe was supported externally between separate force balances of the weigh beam, automatic null-seeking type. Each balance allowed measurement of vertical and horizontal force. Supply air connection on each side was by means of an air bearing coupling designed to eliminate balance constraints (Figure 7). The arrangement is an adaptation of an air lubricated hydrostatic seal for rotating shafts(13). A spring loaded, bellows mounted bearing face carrying bearing air supply orifices is presented to a vented face of similar dimensions on the model supporting crosspipe. Nominal operating clearance is .0015 in. at a bearing air supply pressure of 50 p.s.i.a. Fan and turbine thrust measurements were separated by rotating the cascade nozzles through 90 degrees, or, alternatively, by rotating the complete model assembly about the crosspipe into the vertical position. All tests were run at essentially zero tunnel speed. Turbine air mass flow was measured by standard orifice in the external line. Rotational speed was determined by magnetic pick-up and electronic counter. Model vibration was monitored by an inertial transducer mounted on the model carcase. Other measurements included total pressure and temperature at appropriate points in the flow system.

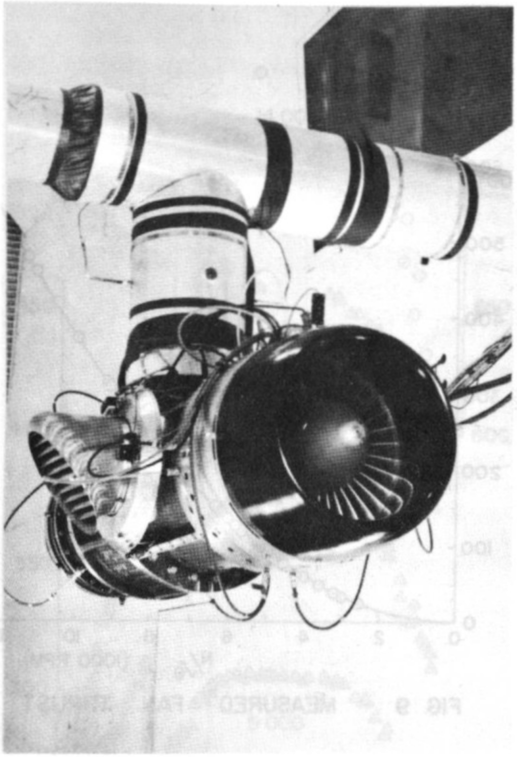


FIG 6 EXPERIMENTAL ARRANGEMENT

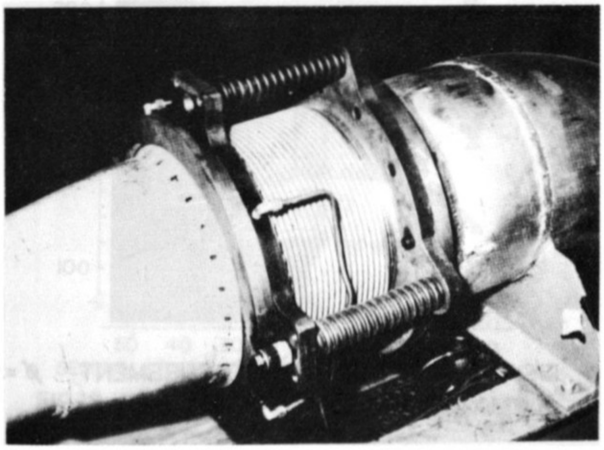


FIG 7 AIR BEARING COUPLING

Aerodynamic Design

The two-stage fan is of the axial inflow type. Entry tip diameter and hub tip ratio are 15.0 in. and 0.5 respectively. The aerodynamic design reflects a conservative approach to blade speed, by current standards. Design fan temperature rise was 20°C per stage, corresponding to a bypass ratio of 4.10 at a modest assumed gas generator performance ($S = 115$ h.p./lb./sec.). Design fan tip speed was 916 ft./sec., (14000 r.p.m.) leading to subsonic tip relative Mach number ($M = .92$). Design load factor of the single stage turbine was correspondingly very high ($\Delta H/U^2 = 2.78$). The use of a transonic fan (tip speed = 1500 ft./sec., say) would have eased the turbine loading considerably, while allowing a smaller turbine disc diameter (12.0 in. on model) or an increased assumed gas generator performance. Turbine design entry total temperature and pressure were 700°C and 2.355 atm., at standard ambient conditions. Design flow was 6.84 lb./sec. for an expected power output of 700 h.p. Corresponding fan air flow was 28.0 lb./sec., for a fan thrust of 735 lb. To further the achievement of design thrust, a conservative approach to fan area was adopted with the use of a relatively low design axial velocity (430 ft./sec., $k = .51$). Design fan thrust loading, based on annulus area, was 800 lb./ft^2.

Experimental Results

In actual operation, the turbine was supplied with unheated compressed air from an outside source. Turbine entry temperature was essentially constant throughout at about 50°C above ambient. The available air supply permitted operation over the complete speed range up to 14000 r.p.m.

Fan Thrust Measurements

Fan characteristics had been determined previously with the rotating nozzles replaced by air flow measuring ducts(12). The approximate operating line with rotating nozzles in place, as determined by measured pressure ratio and rotational speed, is shown in Figure 8. Fan thrust, with the rotating nozzles in the thrust position ($\varphi = 0$), was measured as the difference in horizontal force reading obtained on rotating the nozzles through 90 degrees, at fixed turbine supply conditions. No sensible change in rotor speed occurred during this procedure. The results are shown in Figure 9. Fan thrust with nozzles in the lift position ($\varphi = 90°$), could not be measured directly as a vertical force, due to tunnel constraint effects. In the normal model position, the rotating nozzles were located 7 ft. above the tunnel floor and about 4 ft. from the side walls. The tunnel floor could be raised. At fixed model operating conditions and $\varphi = 90$ degrees, the balance reading of vertical force was found to vary with floor distance. An increased effective floor distance (13 ft.) was obtained by directing the nozzles vertically upward, and, finally, the constraint effect was eliminated by rotating the complete model through 90 degrees and measuring fan thrust directly as horizontal force (Figure 10). Some typical results are shown in Figure 11. Values of fan thrust measured in this way conformed closely with those of Figure 9. Within the limits of the experimental technique, rotating nozzle position appeared to have little, if any, effect on fan thrust.

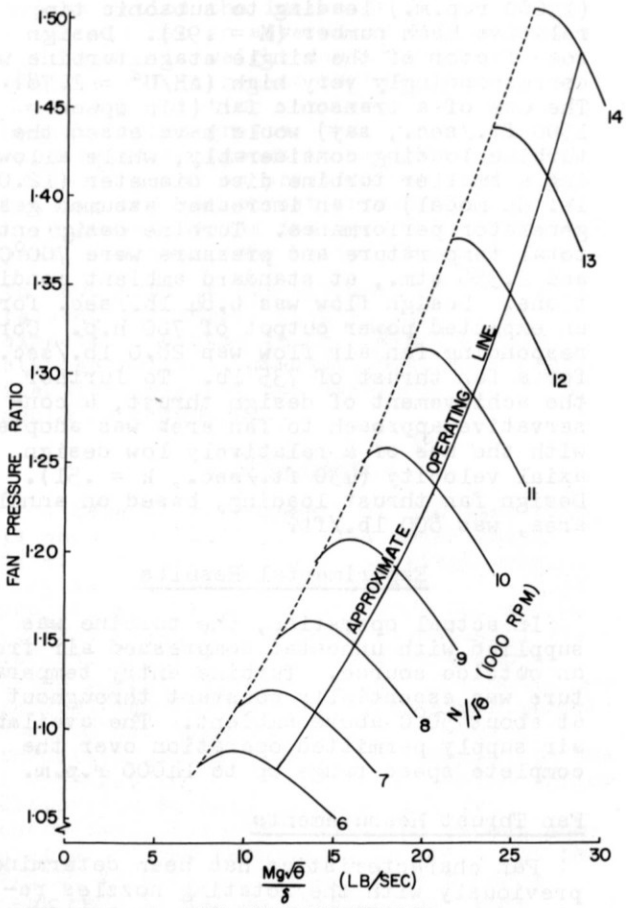


FIG 8 FAN CHARACTERISTICS

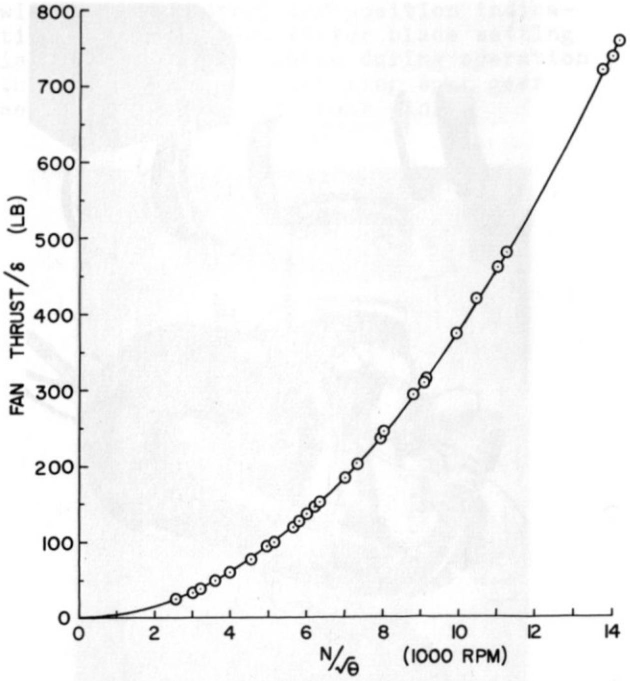


FIG 9 MEASURED FAN THRUST Ø=0°

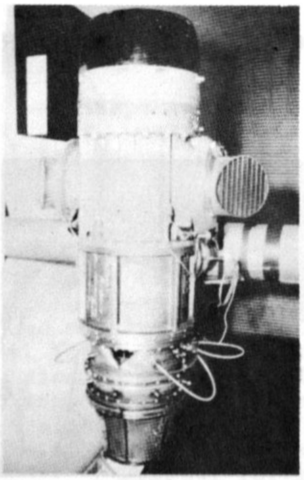


FIG 10 FAN THRUST MEASUREMENT Ø=90°

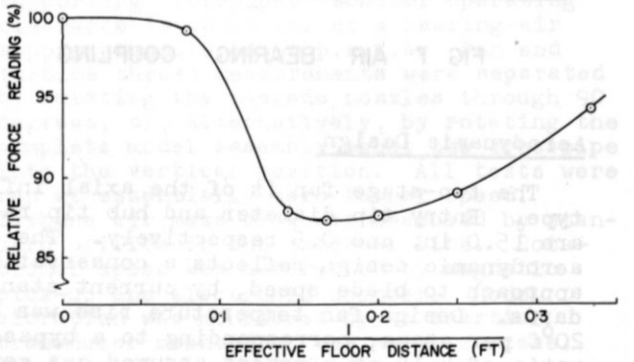


FIG 11 TUNNEL CONSTRAINT EFFECT ON VERTICAL THRUST MEASUREMENT

Thrust Spoiling Results

Further fan thrust measurements were made to secure preliminary data on a possible method of vertical thrust regulation at response rates adequate for controlled landing. Thrust change is effected by collective adjustment of the stator blade setting in the final fan stage, i.e. by direct pressure changes. Essentially no speed change in gas generators or fan rotor is involved.

The present tests were concerned mainly with the variation in steady thrust level as stator setting was changed in either direction from the nominal design value. With the model operating at fixed turbine supply conditions, the stator setting was varied incrementally by remote control and the steady thrust recorded after each adjustment. Mean blade setting was obtained by direct observation of a single stator blade fitted externally with an indicator against a fixed scale, together with prior determination of differences in datum setting and lost motion among the individual blades. The determination of mean absolute stator setting was further complicated by the need to shift the datum setting several times to accommodate a mechanical restriction in the blade drive which limited overall adjustment to 20 degrees.

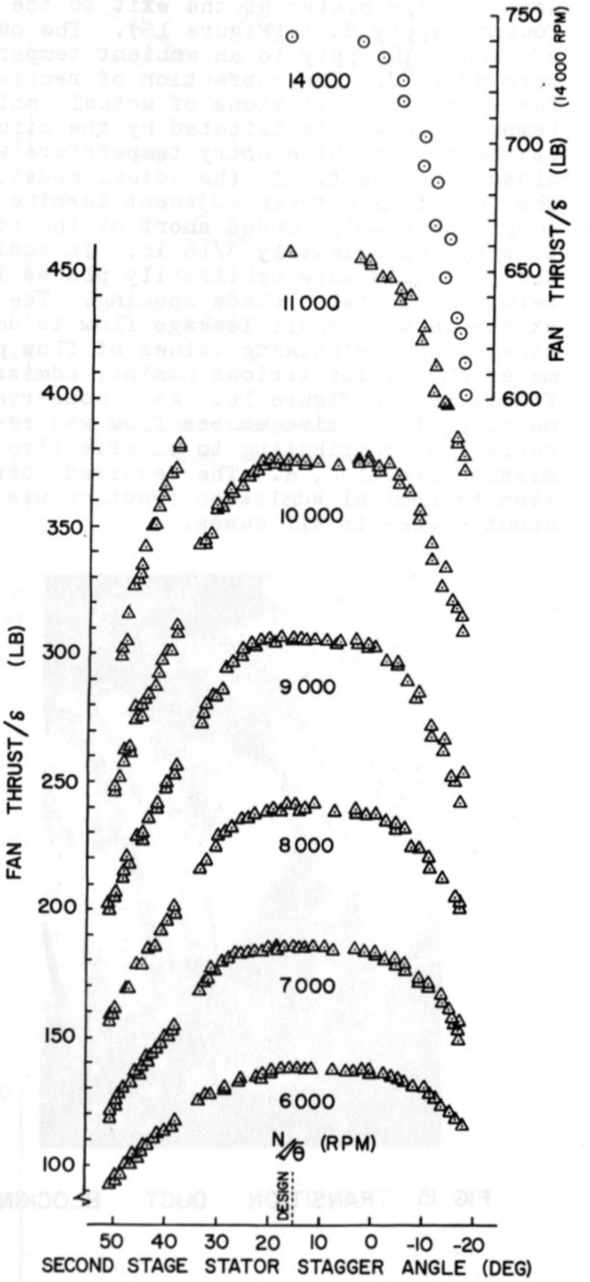


FIG 12 FAN THRUST vs STAGGER ANGLE

The measured results for a range of fan speed up to 10000 r.p.m. are shown in Figure 12. Measurements were also made at 11000 r.p.m. and 14000 r.p.m. over sections of the plotted stagger angle range. A faired curve representing all the data is shown in Figure 13. While referring quantitatively to the specific fan and nozzle combination of the tests, the results exhibit qualitative trends of possibly wider application. Within the limits of accuracy to which absolute stator setting could be established, fan thrust appeared to be uninfluenced by aerodynamic hysteresis effects. The variation of fan thrust with stagger angle was independent of the direction in which angle changes were made. The overall variation was closely symmetrical about a stagger angle near to the nominal design value. Little change of thrust ($<$ 1/2 percent) was observed over a central range of stagger angle of about 20 degrees. As the stagger angle was increased or decreased beyond this range, the thrust fell sharply and, thereafter, declined at an approximately constant rate until the onset of fan stall. For the range of stagger angles investigated, audible fan stall was encountered only at negative incidence. The stalling value of stagger angle exceeded the design setting by about 35 degrees, at 6000 r.p.m., and decreased by about 2 degrees with increase in fan speed to 11000 r.p.m. Corresponding fan thrust was 66-69 percent of the design value. The thrust variation was approximately linear over a stagger angle range of 20 degrees with a gradient of about 1½ percent design thrust per degree. At the relatively slow rate of stagger change available on the model (about 2 degrees per second), the thrust as indicated by the balance display could be cycled repeatedly over this range with no noticeable change in vibration, noise or speed.

In actual landing operations, fan speed would be selected for the necessary lift with the stators at a spoiled setting, allowing a margin of quickly available lift for controlled descent.

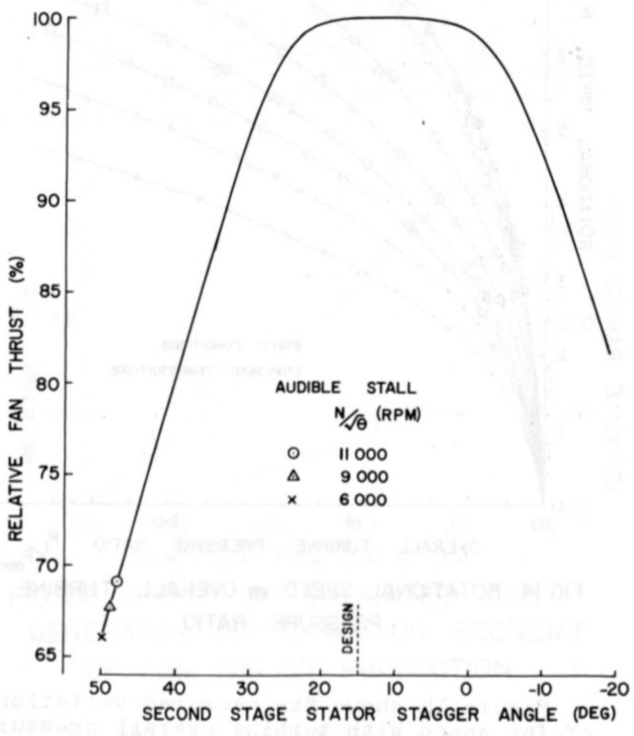


FIG 13 RELATIVE FAN THRUST vs STAGGER ANGLE

Partial Admission Results

Further tests were concerned with system performance under simulated conditions of gas generator shutdown. The turbine was operated at fixed overall total/static pressure ratio, fixed entry temperature and progressively reduced admission fraction. Of particular interest, and implicit in the thrust measurements, was the deterioration of drive efficiency with reduced admission in circumstances involving a parallel drop in turbine speed and increase in turbine loading. As mentioned earlier, the turbine supply air temperature averaged 50°C above ambient. At design pressure ratio and full admission, the turbine load factor was representative of normal practice at about 1.48 (although rotor incidence was 10 degrees negative). These conditions characterized the test turbine datum with which partial admission performance was compared.

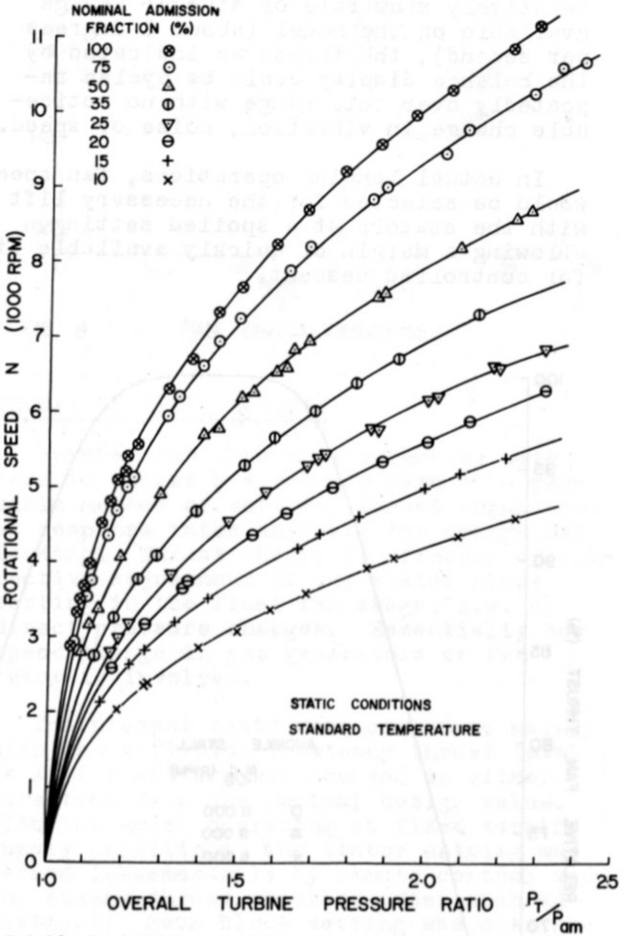


FIG 14 ROTATIONAL SPEED vs OVERALL TURBINE PRESSURE RATIO

Figure 14 shows the measured variation of fan speed with turbine overall pressure ratio, P_T/P_{am}, for a range of nominal admission fraction, $\overline{\alpha}$, from 1.0 to 0.25, obtained by blocking up to three turbine supply ducts. Smaller nominal admission fractions down to 0.10 were included, using baffle plates at the exit to the fourth supply duct (Figure 15). The data of Figure 14 apply to an ambient temperature of 15°C. The correction of recorded fan speed for variations of actual ambient temperature was facilitated by the circumstance that turbine entry temperature was close to ambient. In the actual model, the junctions between adjacent turbine supply duct walls ended short of the stators by approximately 3/16 in. In addition, the junctions were arbitrarily placed in relation to stator blade spacing. The existence of a small leakage flow is demonstrated by the choking values of flow parameter shown, for various nominal admission fractions, in Figure 16. As a conservative measure, the entire excess flow was regarded as contributing to an effective admission fraction, α. The required correction to nominal admission fraction was about + .025 in all cases.

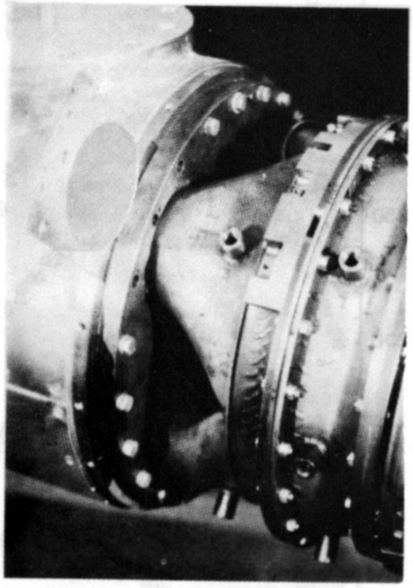


FIG 15 TRANSITION DUCT BLOCKING

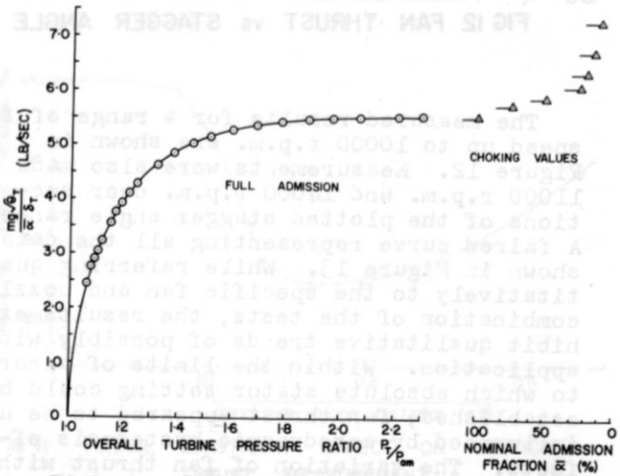


FIG 16 TURBINE FLOW PARAMETER MEASUREMENTS

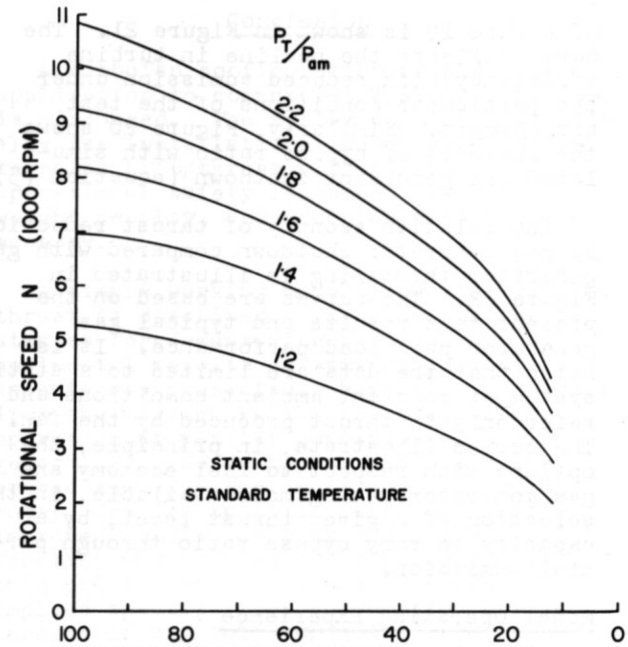


FIG 17 ROTATIONAL SPEED vs EFFECTIVE ADMISSION FRACTION

The data of Figure 14 are shown replotted against effective admission fraction, α, in Figure 17. It is noted that α can be regarded as the ratio of the number of working gas generators to the total number of gas generators in a static system in which all working gas generators are operating at similar conditions. The implied gas power supply, or total fuel flow, is proportional to α. The results of Figure 17, referred to full admission values, are represented closely by the single curve of Figure 18.

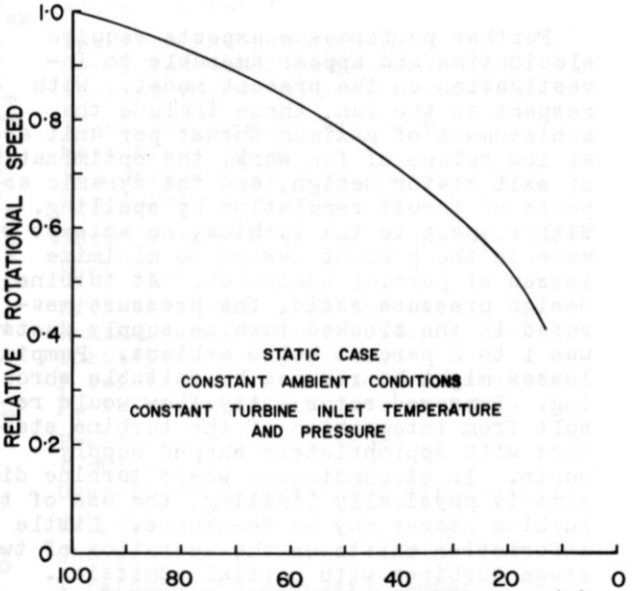


FIG 18 RELATIVE ROTATIONAL SPEED vs EFFECTIVE ADMISSION FRACTION

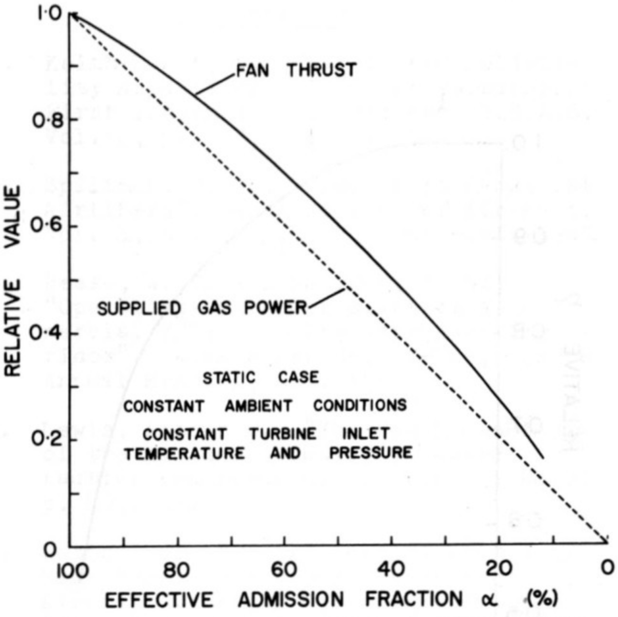


FIG 19 VARIATION OF FAN THRUST AND SUPPLIED GAS POWER WITH ADMISSION FRACTION

Figure 19 shows the corresponding variation of fan thrust (from Figure 9) and supplied power, G, (proportional to α). Finally, the variation of the ratio of fan thrust to supplied power is shown in Figure 20. The economy of thrust production is seen to improve, as α is reduced from unity to values approaching 0.15. The minimum implied specific fuel consumption, based on fan thrust, is 74 percent of the full admission value. The corresponding value of fan thrust is 23 percent of the full admission value.

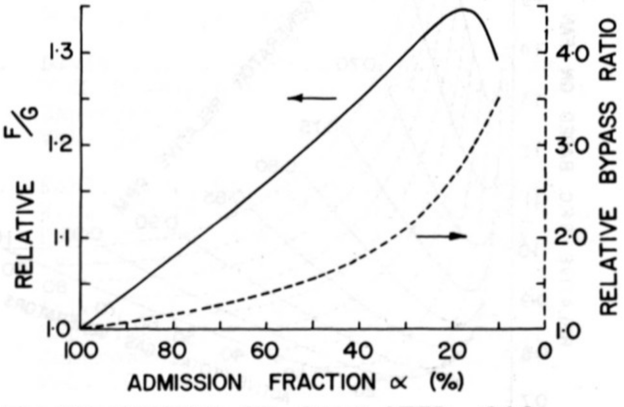


FIG 20 EFFECT OF SIMULATED GAS GENERATOR SHUTDOWN ON ECONOMY OF FAN THRUST PRODUCTION

The results afford some insight into the variation of overall efficiency, η, with α. Within the limitations of the derivation of equation (4), the variation of η implied by the measurement-based data

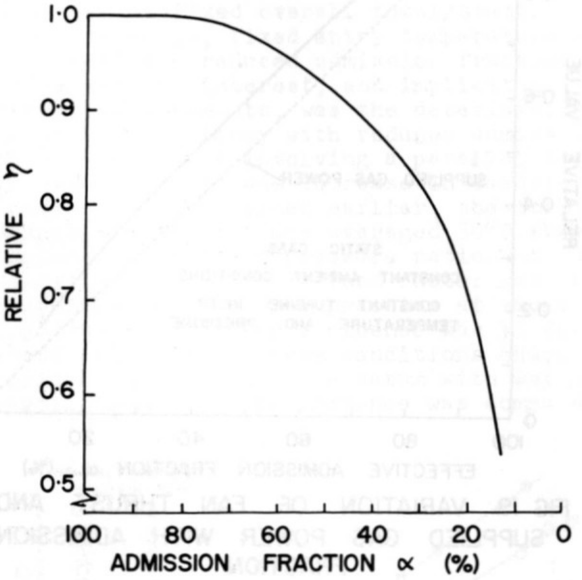


FIG 21 VARIATION OF DERIVED OVERALL ENERGY TRANSFER EFFICIENCY WITH ADMISSION FRACTION

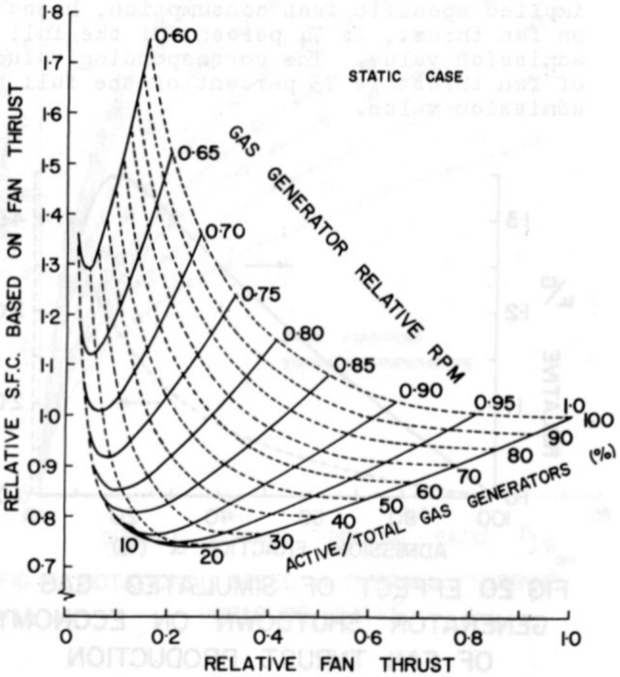


FIG 22 RELATIVE ECONOMY OF THRUST REDUCTION BY GAS GENERATOR THROTTLING AND SHUTDOWN

of Figure 19 is shown in Figure 21. The curve reflects the decline in turbine efficiency with reduced admission under the particular conditions of the test arrangement. Similarly, Figure 20 shows the increase of bypass ratio with simulated gas generator shutdown (equation (5)).

The relative economy of thrust reduction by gas generator shutdown compared with gas generator throttling is illustrated in Figure 22. The curves are based on the present test results and typical gas generator part load performance. It is noted that the data are limited to a static system at constant ambient conditions and refer only to thrust produced by the fan. The curves illustrate, in principle, the options with respect to fuel economy and gas generator rating made available, in the selection of a given thrust level, by a capacity to vary bypass ratio through partial admission.

Model Operating Experience

While the mechanical design is unrepresentative of an aircraft system, approximately 1000 hours of model operation have been accumulated to date. Although much of the running has involved non-standard inlet conditions to fan or turbine, no mechanical difficulties of any kind have been encountered. Maintenance has been limited to precautionary replacement of the standard bearings at intervals of about 300 hours. In the present tests, operation at turbine admission fractions down to 10 percent resulted in no significant change in monitored vibration amplitude. The rotating nozzles were designed, constructed and installed with no further attention. The effectiveness, in practice, of the Pegasus type thrust vectoring system has been noteworthy.

Further performance aspects require elucidation and appear amenable to investigation on the present model. With respect to the fan, these include the achievement of maximum thrust per unit area at low values of fan work, the optimization of exit stator design, and the dynamic aspects of thrust regulation by spoiling. With respect to the turbine, no attempt was made in the present design to minimize losses at partial admission. At turbine design pressure ratio, the pressure measured in the blocked turbine supply ducts was 1 to 2 percent below ambient. Pumping losses might be reduced by suitable shrouding. Improved rotor entry flow would result from integration of the turbine stators with appropriately shaped supply ducts. In circumstances where turbine disc size is physically limiting, the use of two turbine stages may be desirable. Little information exists on the operation of two stage turbines with partial admission. Further uncertainties lie in the design of the turbine exhaust system for minimum losses.

Conclusion

A turbofan configuration of possible application to commercial V/STOL propulsion is discussed. The system combines potentially the installational advantages of integrated lift/thrust with inherent VTOL operational safety features, low VTOL weight penalty, and acceptable cruise economy.

A simple working model producing 700 lb. thrust is described. The model was operated on force-measuring balances and experimental results on some performance aspects are presented. Reduction of thrust from the maximum rating involves turbine operation at partial admission with, in general, increased bypass ratio and improved specific fuel consumption. On the model, implied specific fuel consumption improved continuously as nominal admission fraction was reduced to 15 percent. At this point, fan thrust was 23 percent and implied specific fuel consumption was 74 percent of the full admission values.

Notation

A	Fan inlet annulus area
B	Bypass ratio, M/m
F	Fan stream thrust
F_T	Turbine stream thrust
G	Gas power supplied
ΔH	Turbine enthalpy drop
h_f	Calorific value of fuel
k	V_A/V
L	Engine lift
M	Fan mass flow
m	Total gas generator mass flow
N	Rotational speed
P	Fan inlet total pressure
P_T	Turbine inlet total pressure
P_{am}	Ambient pressure
S	Specific gas power, G/mg
T	Fan inlet total temperature
T_T	Turbine inlet total temperature
$\overline{\Delta T}$	Ideal fan temperature rise
U	Mean blade speed
V	Fan stream efflux velocity, F/M
V_A	Fan inlet axial velocity
V_T	Turbine stream efflux velocity, F_T/m
W_f	Fuel flow
α	Effective admission fraction
$\overline{\alpha}$	Nominal admission fraction
β	Throttled power fraction
δ	P referred to standard pressure
δ_T	P_T referred to standard pressure
ϵ	Fraction of G abstracted by fan turbine
η	Overall energy transfer efficiency, $MV^2/2\epsilon G$
η_G	Gas generator thermal efficiency
θ	T referred to standard temperature
θ_T	T_T referred to standard temperature
ρ	Fan inlet density
ϖ	Nozzle angle from horizontal

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