Regenerative Turbofans: A Comparison with Nonregenerative Units

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A theoretical study was made of the performance of regenerative turbofans. Particular attention was paid to the feasibility of small regenerative turbofans from the aerodynamic drag, mechanical arrangement, and weight viewpoints. It was concluded that, on a thermodynamic and aerodynamic basis, compared with conventional nonregenerative, high pressure ratio, high bypass ratio units regenerative turbofans can have specific fuel consumptions about 17% lower for flight, and up to 24% lower for sea level static, operation. It was assumed that the effective nacelle drag coefficients of regenerative turbofans would not be higher than those of nonregenerative engines provided greater installation complexity is acceptable. The predicted thrust-to-weight ratio of regenerative units is approximately 3.2:1 compared with 6:1 for high pressure-high bypass ratio machines. Typically, assuming that both engine types are suitable alternatives for a particular aircraft, this weight penalty would be counteracted by a fuel saving after about 4 hr flying without reserves. The corresponding figure for small aircraft, for which high pressure ratio turbofans appear to be impractical, is about 2 hr. In the absence of major developments in regenerator technology regenerative turbofans appear to be restricted to relatively low thrust applications.

Nomenclature

B = bypass ratio
C_D = nacelle drag coefficient based on maximum cross-sectional area
D = drag (of aircraft)
L = lift of (aircraft)
$\dot{m}_{FUEL}$ = mass flow of fuel
M_∞ = flight Mach number
P = stagnation pressure, static pressure at stations 7 and 9: $P_7 = P_9 = P_\infty$
P_∞ = ambient pressure
T = stagnation temperature, static temperature at stations 7 and 9
T_∞ = ambient temperature
T_{MAX} = maximum cycle, (stagnation) temperature T_4
W_{FIN} = final weight of aircraft $= W_{INIT}$ − fuel consumed
W_{INIT} = initial weight of aircraft; structure + payload + fuel
η = efficiency, see Table 1
η_R = regenerator thermal ratio (temperature basis) $\{\equiv (T_3 - T_2)/(T_5 - T_2)\}$

Subscripts

1,2,3,4, etc. = locations of cycle state points, see Fig. 1
C = compressor
F = fan
I = intake
M = mechanical
N = nozzle
T = turbine

Introduction

SIMPLE analysis shows that there is considerable difficulty in extending to low thrust levels the performance advantages accruing from the current use in large transport aircraft, of high pressure ratio, high bypass ratio, turbofans. The main difficulties in producing such engines for low thrust applications are problems associated with the small blade sizes, tip clearances, and the fragility of components, etc. This situation is a direct consequence of the relatively small gas passages in the high pressure portions of high pressure ratio, high bypass ratio turbofans.

The basic regenerative turbofan engine arrangement considered in the computerized, variable specific heat analysis is shown diagrammatically in Fig. 1. An aft fan arrangement is shown in Fig. 1; the analysis is equally applicable to either front or aft fan configurations because the fan and compressor polytropic efficiencies were taken to be equal. Table 1 presents a list of the component efficiencies etc. used throughout the work; values were selected from several sources.[1–4] The numbered subscripts appearing in Table 1 correlate with the location numbers appearing in Fig. 1. No attempt was made in the analysis, to establish part load performances or to match static and flight operating parameters for any particular engine.

The major sources of internal losses for regenerative engines, over and above those of nonregenerative units, are duct pressure losses and pressure losses within the regenerator. Under flight conditions the total loss of pressure of 11% between the compressor outlet and gas generator thrust nozzle inlet (see Table 1) comprises, approximately, a

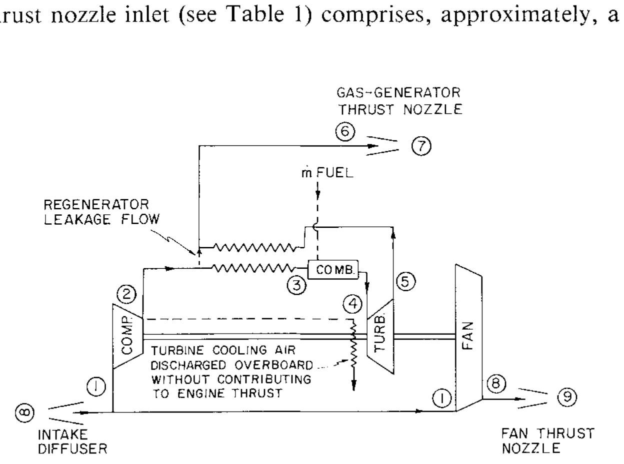

Fig. 1 Schematic diagram of a regenerative turbofan showing state point locations.

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Table 1 Values of constants, etc., used in the analysis

Description	Notation (see Nomenclature)	Values: Regenerative cycles	Values: Nonregenerative cycles
Fan polytropic efficiency	η_F	0.87	0.87
Compressor polytropic efficiency	η_C	0.87	0.87
Turbine polytropic efficiency	η_T	0.85	0.85
Pressure (loss) ratio between turbine inlet and compressor outlet	P_4/P_2	0.93	0.95
Pressure (loss) ratio between exhaust nozzle inlet and turbine outlet	P_6/P_5	0.96	0.99
Fraction of gross power of turbine available for driving compressor and fan (mechanical efficiency)	η_M	0.99	0.99
Fan and gas generator thrust-nozzle isentropic efficiency	η_N	0.98	0.98
Intake isentropic efficiency (static and flight conditions)	η_I	1.00	1.00
Turbine cooling air mass flow	...	$= \dot{m}_{FUEL}$	$= \dot{m}_{FUEL}$
Fraction of compressor delivery mass flow bypassing combustor and turbine (regenerator net carryover)	..	0.03	zero
Effective calorific value of fuel (includes combustion efficiency and heat loss influences)	...	18,000 Btu/1b$_m$	18,000 Btu/1b$_m$
Nacelle drag coefficient based on maximum nacelle cross-sectional area	C_D	0.07	0.07
Static Conditions[a]	...	$T_\infty = 520°$R (60°F)	$T_\infty = 520°$R (60°F)
Flight conditions[a]	...	$T_\infty = 394°$R (—66°F) $M_\infty = 0.9$	$T_\infty = 394°$R (—66F) $M_\infty = 0.9$

[a] Static and flight conditions are defined such as to imply sea level and 35,000 ft altitudes, respectively, when referred to the international standard atmosphere. The ambient pressure does not appear in the analysis as specific thrusts only are evaluated and these are independent of pressure.

3% combustor pressure loss (less than the corresponding 5% loss assumed for nonregenerative engines due to the lower combustor temperature rise in the regenerative case), a total loss of approximately 4% within the regenerator core[3] and the remaining 4% distributed in the interconnecting ducts and turbine exhaust diffuser. Since a typical flow Mach number in the interconnecting ducts is 0.1, this corresponds to a total duct pressure loss of approximately six dynamic heads; however for this allowance to be adequate a turbine exhaust diffuser efficiency of 75-80% is required. This should be attainable in practice given good turbine outflow conditions. For sea level static operation the total pressure drop in the regenerator core is only about 1%[3] and hence the demands on the turbine exhaust diffuser are less stringent.

As can be seen from Table 1, the nacelle drag coefficient based on maximum nacelle cross-sectional area has been taken to be equal for both regenerative and nonregenerative engines. This appears to be physically reasonable provided very great care is taken in the installation of regenerative turbofans.

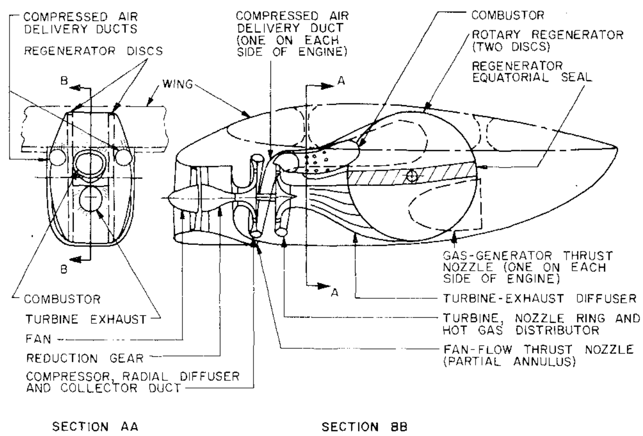

Fig. 2 Nacelle-mounted turbofan with twin rotary regenerator aft of the turbine.

Engine Configuration and Drag

One of the major problems associated with aircraft gas turbines equipped with rotary regenerators relates to the packaging of the power units in such a way that excessive drag is avoided in nacelled installations. Figure 2 shows, to scale with correctly proportioned flow areas, a preliminary arrangement for a small, simple, regenerative turbofan featuring a single turbine and a geared fan. To minimize frontal area the rotary regenerators are located aft of the turbine rather than at the sides of the engine as is the case in most automotive gas turbines incorporating rotary regenerators. Despite the location of the regenerators it can be seen that the configuration shown in Fig. 2 will still have a greater frontal area, and possibly a greater length, than nonregenerative units. However, it would appear that this disadvantage can be wholly or partly eliminated if the nacelle is mounted in contact with, say, the lower surface of the wing as, for example, in the Boeing 737. It should then be possible to reduce the effective frontal area of the nacelle by burying the upper portion of the engine in the wing. It seems that, at the price of this inconvenience, the nacelle drag would be approximately the same as that of a conventional nonregenerative turbofan engine mounted wholly externally, but adjacent, to the wing.

Figure 3 shows a preliminary layout, also to scale with correctly proportioned flow passages, of an alternative scheme, incorporating axial flow turbo-machinery and a two-shaft arrangement, in which the relatively bulky regenerative equipment is buried in the fuselage and the turbo-machinery only is contained in a pylon-mounted external nacelle. The effective drag coefficient of such an arrangement should be equal to or, due to the beneficial effects of energising the boundary layer on the after portion of the fuselage with the cooled gas generator exhaust, conceivably less than that of a corresponding conventional, nonregenerative, pylon-mounted turbofan. Clearly an arrangement as shown in Fig. 3 presents more severe installation problems than that shown in Fig. 2.

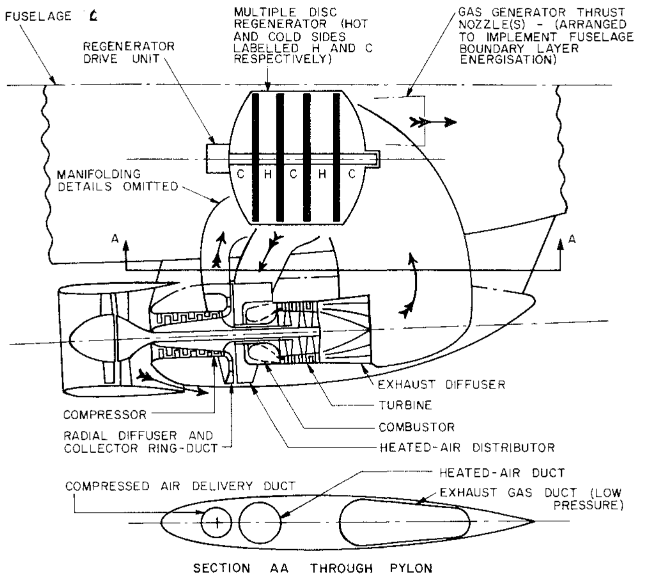

Fig. 3 Pylon-mounted turbofan attached to the rear portion of an aircraft fuselage. Regenerator located within the fuselage cross section.

It would appear that the use of a regenerative turbofan imposes some restrictions on the aircraft designer in the selection of suitable locations for the engines when low nacelle drag is of utmost importance. In the case of a self-contained unit, such as that of Fig. 2, there is a need to bury a portion of the unit within the aircraft to reduce nacelle frontal area. In the case of a "divided" engine such as that shown in Fig. 3 it is desirable to mount the turbo-machinery section as close as possible to the regenerators to reduce the weight and pressure losses, associated with the interconnecting ducts.

Thrust-to-weight Ratio

Several types of nonregenerative, high bypass ratio, turbofans are currently available, operating at pressure ratios of approximately 6:1 or greater, having thrust-to-weight ratios of about 6.5:1.[5] It would, therefore, seem well within the capabilities of current technology to produce a regenerative turbofan, operating at a relatively modest T_{MAX} of 1830°F, with a thrust-to-weight ratio of approximately 7:1 when the weight of the regenerator, regenerator casing and associated ducts is omitted. The advance over the previously quoted value of 6.5:1 can be justified on the basis of the low pressure ratio of about 4:1, which will later be shown to be optimum, of such regenerative engines.

A typical, low coefficient of expansion, ceramic material used for the cores of rotary regenerators weights, with gas passages molded in, 41 lb_f/cu. ft.[3] Current practice with automotive gas turbines is such that approximately 18 lb_f of this material is provided per lb_m/sec of mass flow; this allows a thermal ratio slightly in excess of 0.9 to be attained under sea level static conditions.[6] Analysis showed that a thermai ratio of approximately 0.95 would be obtained under the cruise conditions ($M = 0.9$ at 35,000 ft) adopted for this study although pressure losses in the low pressure path of the regenerator would be relatively high.

A simple design exercise was carried out in which four disks of regenerator material, having a total weight of 180 lb_f (each disk corresponding approximately to the maximum size available commercially), were assumed to be used in a regenerative turbofan. It was found that the approximate weight of, the nickel-chrome alloy steel and titanium regenerator housing, bearings, ducts, etc., was 130 lb_f. On the basis of the previously referred to automotive practice the gas generator mass flow would be 10 lb_m/sec and hence with a 4:1 bypass ratio and a specific thrust of 22.5 lb_fsec/lb_m, values shown later to represent optimum operating conditions, a sea level static thrust of 1125 lb_f would be generated for a total engine weight of 471 lb_f giving a thrust-to-weight ratio of 2.39:1. It would appear that the foregoing engine is sufficiently conservatively designed to set, for all practical purposes, the lower limit of the likely range of thrust-to-weight ratios of regenerative turbofans.

A more advanced design was also considered in an attempt to obtain an indication of the upper limit of the thrust-to-weight ratio range. This unit had the same gas generator mass flow as in the previous case, however the weight of regenerator material was reduced to half that of the former case by reducing the disc thickness. Analysis showed that this would permit a thermal ratio of approximately 0.8 to be achieved under sea level static conditions and 0.9 during cruise without the excessive pressure drop of the previous case. The cycle T_{MAX} was chosen to be 2200°F for which condition it will be later shown that the optimum pressure and bypass ratios are each 5:1. In addition it was assumed more advanced technology would be utilized for the turbo-machinery section, for example the use of nonmetallic fan and compressor blades, such that the previously quoted ratio of 7:1 would be replaced with a ratio of 10:1, a value which appears to be well within the limits of current low pressure-ratio lift-turbofan technology[7] but probably at the limit of, or beyond, current cruise engine technology. Such an engine would produce 1440 lb_f sea level static thrust and weigh 364 lb_f giving a thrust-to-weight ratio of 3.96:1.

On the basis of the foregoing elementary analyses it would appear that small regenerative turbofans can be expected to have thrust-to-weight ratios between 2.4 and 4:1. This corresponds to an average of 3.2:1, a thrust-to-weight ratio attainable with a 2200°F T_{MAX} cycle when the turbo-machinery thrust-to-weight ratio is 7:1 and the weight of regenerative material is approximately 25% greater than for the advanced design. A thrust-to-weight ratio of 3.2:1 was, therefore, assumed to be applicable to regenerative turbofans. The design exercise also implied that difficulties would arise if attempts were made to design, on the basis of current regenerator technology, regenerative turbofans for large thrusts.

Current thrust-to-weight ratios for large nonregenerative high pressure ratio turbofans are within the range from about 4.5 to 6.5:1.[1] Rounding these values upwards in an attempt to accomodate progress due to development suggests that the thrust-to-weight ratio of any regenerative turbofan to be built in the near future should be compared with a value between 5 and 7:1. A thrust-to-weight ratio of 6:1 was, therefore, selected as representative of nonregenerative high pressure ratio units.

Influence of Regenerator Thermal Ratio

In common with most other regenerative gas turbine cycles the regenerative turbofan demonstrates a considerable sensitivity, in terms of specific fuel consumption, to the regenerator thermal ratio η_R. Figure 4 shows specific fuel consumption and specific thrust, for static operation, vs cycle pressure ration, P_2/P_1, for a fan pressure ratio, P_8/P_1, of 1.3 and a bypass ratio of 4.0 with a cycle T_{MAX} of 1830°F. The dotted line to the left marks the lower limiting cycle pressure ratio for which the gas generator exhaust nozzle pressure ratio is unity.

It can be seen from the figure that both the optimum cycle pressure ratio and minimum attainable specific fuel consumption rise rapidly as η_R decreases. The slight difference between the static thrust curves for $\eta_R = 0.6$ and $\eta_R = 0.9$ is due entirely to the relatively cool exhaust from the gas generator associated with high values of η_R. An increase in η_R has the effect of reducing the thrust produced by the gas generator exhaust due to the accompanying decrease in exhaust gas temperature. Naturally this effect is of zero consequence when the gas generator nozzle pressure ratio has the

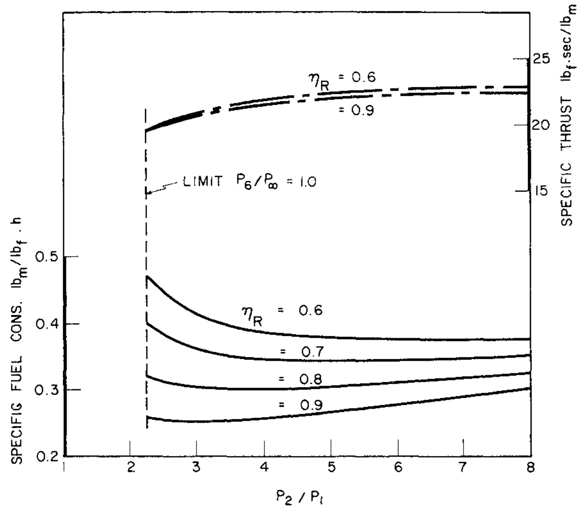

Fig. 4 The influence of regenerator thermal ratio, η_R, on the static performance of regenerative turbofans. Fan pressure ratio, $P_8/P_1 = 1.3, B = 4.0, T_{MAX} = 1830°F$.

limiting value of unity and hence the gas generator thrust is also zero. On the basis of the results displayed in Fig. 4 a representative and feasible value for η_R of 0.9 was selected for the remainder of the study.

It was also noted from Fig. 4 that a cycle pressure ratio of approximately 4.0 appears to be desirable from the viewpoint of obtaining a low specific fuel consumption without a major sacrifice in specific thrust. It can, however, be shown that the constant fan pressure ratio used for the development of Fig. 4 is not necessarily an optimum value. In general the fan pressure ratio should be regarded as a variable to be established by optimization.

Criteria for Optimum Performance

Figures 5 and 6 show predicted static and flight performance characteristics, as a function of bypass ratio, of regenerative turbofans with a pressure ratio of 4.0, $\eta_R = 0.9$ and $T_{MAX} = 1830°F$. It can be seen from the figures that two criteria of merit are implied, one relating to the condition for minimum specific fuel consumption, the other to the condition for maximum specific thrust.

For regenerative engines the condition for minimum specific fuel consumption corresponds to a relatively small power consumption in the fan and, consequently, a relatively high gas temperature, T_5, in the flow leaving the turbine. This, due to the action of the regenerator, implies that a relatively high temperature, T_3, is achieved at the entry to the combustor and hence a comparatively small fuel flow is required to attain the prescribed maximum cycle temperature T_4 ($= T_{MAX}$); hence the specific fuel consumption is relatively low. For the maximum specific thrust case more work is extracted from the turbine and consequently T_5 and hence T_3 are each lower than for the former case. However, the fan is a more effective means of producing thrust than the discharge of a relatively hot, relatively high pressure, flow through the gas generator thrust nozzle. Thus, of the two cases, that for which the fan work is the greater produces the highest specific thrust.

There is no parallel to the foregoing situation for the nonregenerative case. Here, for a prescribed bypass ratio, the fan pressure ratio for minimum specific fuel consumption is automatically that for maximum specific thrust. Figure 7 shows the static and flight performances, as a function of bypass ratio, of conventional non-regenerative turbofans having a representative pressure ratio of 25.0 with a T_{MAX} of 1830°F. It can be seen from Figs. 5-7, that for both regenerative and nonregenerative turbofans under both static

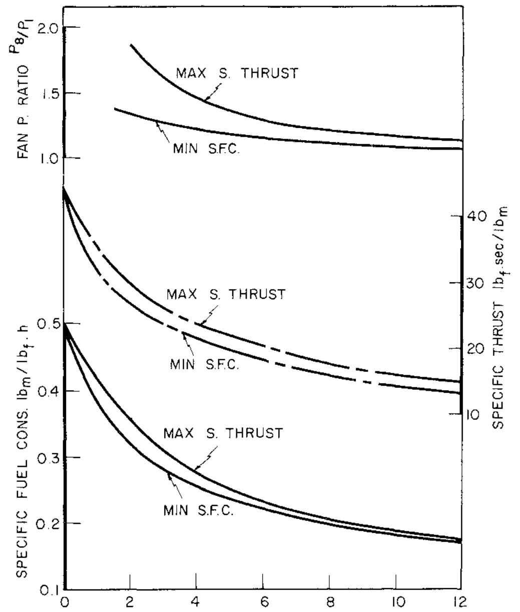

Fig. 5 Influence of bypass ratio, B, on the static performance of regenerative turbofan cycles optimized for minimum S.F.C. and also maximum specific thrust. $P_2/P_1 = 4.0$, $\eta_R = 0.9$, $T_{MAX} = 1830°F$.

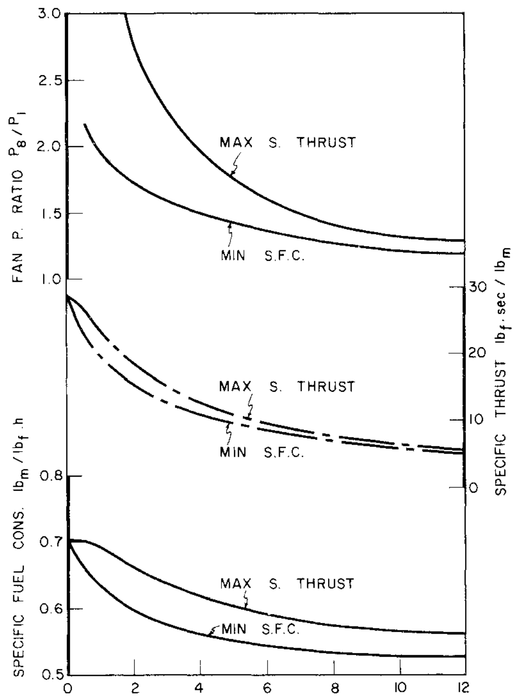

Fig. 6 Influence of bypass ratio, B, on the flight ($M_\infty = 0.9$ at 35,000 ft) performance of regenerative turbofan cycles optimized for minimum S.F.C. and also for maximum specific thrust. $P_2/P_1 = 4.0$.

and flight conditions the specific fuel consumption, specific thrust and optimum fan pressure ratio decrease steadily, over the range investigated, as B increases. To establish realistic optimum bypass ratios account must be taken of nacelle drag.

Selection of Optimum Bypass Ratio

Figure 8 displays net flight performances, based on the data of Figs. 6 and 7, vs bypass ratio when nacelle drag is allowed for. The nacelle drag coefficient based on the maximum

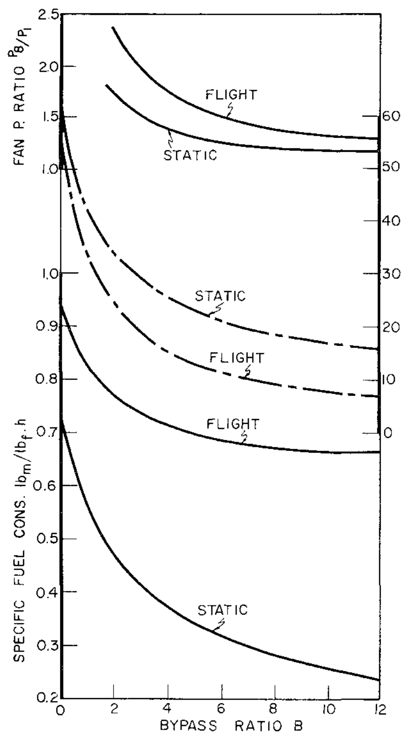

Fig. 7 Influence of bypass ratio, *B*, on the flight (M_∞ = 0.9 at 35,000 ft) performance of regenerative turbofan cycles optimized for minimum S.F.C. and also for maximum specific thrust. $P_2/P_1 = 25.0$, $T_{MAX} = 1830°F$.

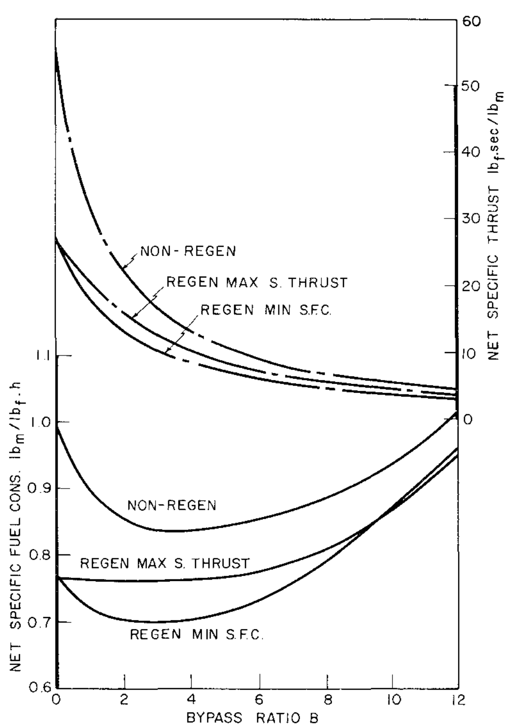

Fig. 8 Net S.F.C. and net specific thrust of regenerative and nonregenerative turbofan cycles with allowance for nacelle drag (M_∞ = 0.09 at 35,000 ft).

nacelle cross-sectional area was taken as 0.07 for both regenerative and nonregenerative engine types. This value was selected from data compiled by Hoerner.[4] Justification for assuming equal drag coefficients for both engine types was given earlier. The maximum nacelle cross-sectional area was assumed to be 1.5 times that of the air inlet, at a station where

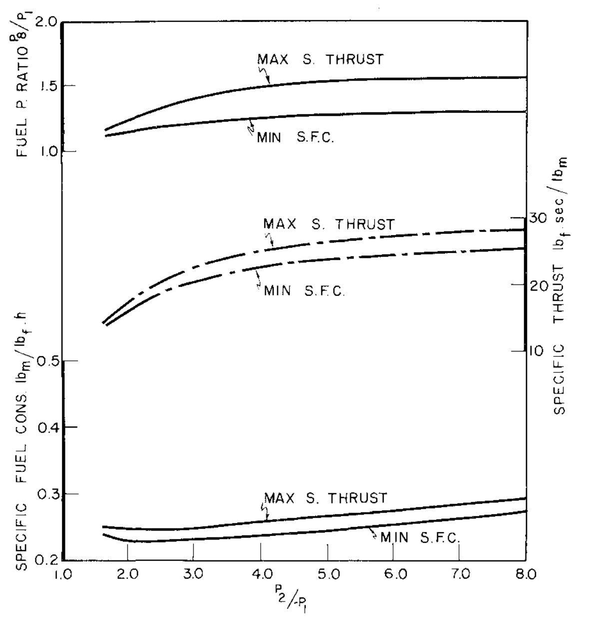

Fig. 9 Optimized minimum S.F.C. and maximum specific thrust of regenerative turbofan engines vs pressure ratio P_2/P_1. Static conditions. $B = 4.0$, $\eta_R = 0.9$, $T_{MAX} = 1830°F$.

the flow Mach number = 0.4, for both regenerative and nonregenerative units. It was also assumed that for both engine types the flow Mach number approaching the fan face (or fan and compressor faces for aft-fan arrangements) was 0.4.

It can be seen from Fig. 8 that for regenerative turbofan designs based on the minimum specific fuel consumption precept the optimum bypass ratio is in the region of 3.0 and for the nonregenerative units it is about 4.0. However, very little loss of performance occurs for either type when bypass ratios of 4.0 and 5.0, respectively, are selected. The advantage of using slightly higher bypass ratios than are indicated from the curves of Fig. 8 is manifest at low flight speeds. Figures 5 and 7 show clearly the advantage of higher than optimum flight-bypass-ratios under static operating conditions.

It can also be seen from Fig. 8 that in the region of the optimum bypass ratio the net specific fuel consumption of a regenerative turbofan engine designed on the basis of the maximum specific thrust criterion is nearly 10% greater than for a design of the minimum specific fuel consumption type. This indicates that under flight conditions the latter design concept is to be preferred from the performance standpoint.

Static and Flight Performances

Figures 9-11 show static and flight performances of regenerative and nonregenerative engines, with a T_{MAX} of 1830°F, as a function of pressure ratio. The bypass ratios were maintained constant at the previously selected values of 4.0 and 5.0 for regenerative and nonregenerative engines respectively. Figures 9 and 10 show that the previously chosen approximate optimum pressure ratio of 4.0 is confirmed as a reasonable compromise from the viewpoint of minimizing specific fuel consumption without significant sacrifice of specific thrust. Likewise Fig. 11 confirms that a pressure ratio of 25.0, chosen as representative of current practice, should probably not be increased without an accompanying increase in maximum cycle temperature. While increasing the compressor pressure ratio without increasing T_{MAX} results in a slight decrease in specific fuel consumption when nacelle drag is neglected, the resultant decrease in specific thrust will probably more than counter this benefit when allowance is made for nacelle drag.

Figures 12-14 show performance characteristics, vs compressor pressure ratio, for the static and flight operation of

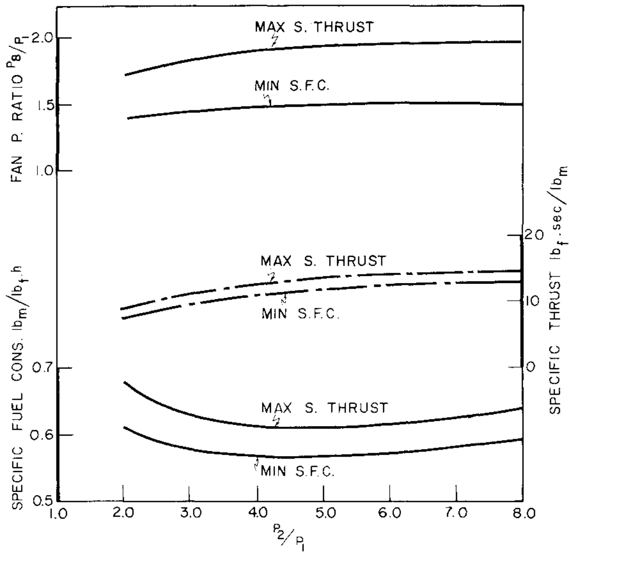

Fig. 10 Optimized minimum S.F.C. and maximum specific thrust of regenerative turbofan engines vs pressure ratio P_2/P_1. Flight conditions (M_∞ =0.9 at 35,000 ft). B=4.0, η_R=0.9, T_{MAX}=1830°F.

advanced regenerative and nonregenerative turbofans having maximum cycle temperatures of 2200°F. The approximate optimum bypass ratios were taken to be 5.0 for the regenerative units and 6.0 for the nonregenerative types. From Figs. 12 and 13 it can be seen that a pressure ratio of approximately 5.0 represents a reasonable compromise on the basis of minimizing specific fuel consumption without incurring a penalty in the form of a significant loss of specific thrust. From Fig. 14 it appears that nonregenerative turbofans will probably be developed to achieve a compressor pressure ratio of about 35.0 but it would not seem worthwhile going above that figure without a further increase in T_{MAX}.

Noise Characteristics and Infrared Signature

It can be shown that, under both static and flight conditions, the gas generator exhaust velocities of optimum regenerative engines designed according to the minimum specific fuel consumption criterion are slightly lower, and for maximum specific thrust designs substantially lower, than those of corresponding optimum high pressure—high bypass ratio nonregenerative units. This implies that the jet noise produced by the gas generators of minimum specific fuel consumption regenerative engines should be approximately the same as that of corresponding nonregenerative units of equal thrust when allowance is made for the higher bypass ratios of the latter. In the case of regenerative engines the presence of the regenerator will probably inhibit partially the direct transmittal of combustor and turbine noise through the gas generator exhaust nozzle; this may be an important factor.[8] The lower fan pressure ratios under both flight and static conditions of minimum specific fuel consumption regenerative engines compared with corresponding, conventional, high pressure—high bypass ratio turbofans should ensure that both the fan noise and the jet noise produced by the fan flow will be less for the former.

The temperature of the gas generator exhausts of optimized regenerative turbofans are substantially cooler, both statically and in flight, than those of nonregenerative optimized units. This will tend to make the former engine type less susceptible to infrared detection through an atmospheric window[9] which should be advantageous for military applications. The exhaust temperature difference in favour of regenerative engines is, of course, considerably smaller when the comparison is based on the mixed fan and gas generator exhausts. The relevant quantitative information is presented in Table 2.

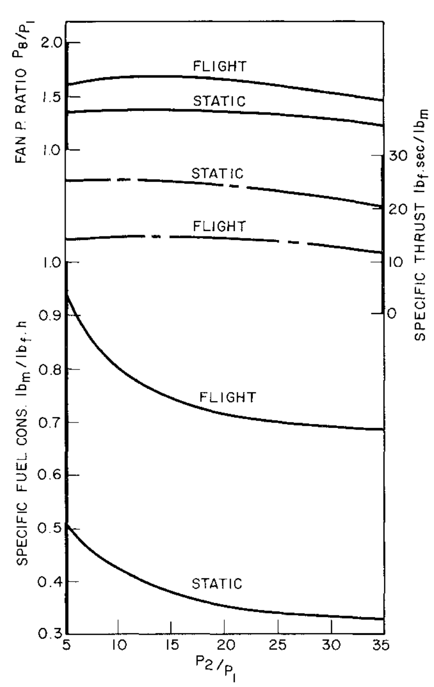

Fig. 11 Optimized performances, vs pressure ratio P_2/P_1, for flight (M_∞ =0.9 at 35,000 ft) and static operation of nonregenerative cycles. B=5.0, T_{MAX}=1830°F.

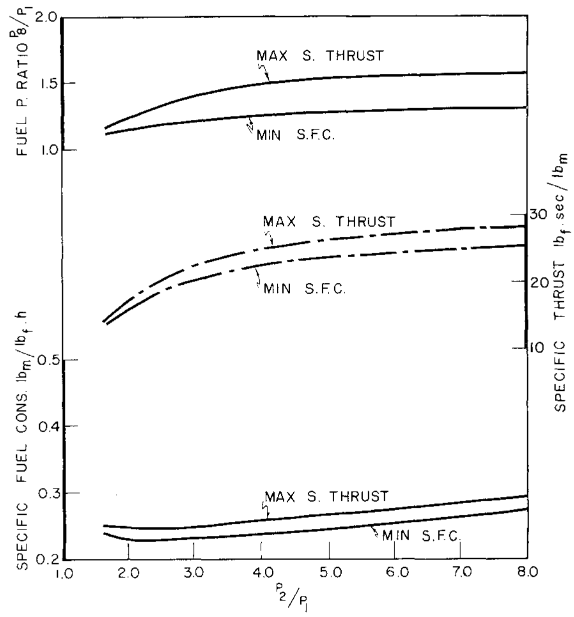

Fig. 12 Optimized minimum S.F.C. and maximum specific thrust of regenerative turbofan cycles vs pressure ratio P_2/P_1. Static conditions. B=5.0, η_R=0.9, T_{MAX}=2200°F.

Influence of Intake Temperature

Figures 15 and 16 display, for regenerative and nonregenerative turbofans respectively, the influence of intake temperature on static performance. It can be seen from Fig. 15 that the reduction of specific thrust due to an increase of intake temperature from 60 to 120° is approximately 4 and 6% for minimum specific fuel consumption and maximum specific thrust designs respectively. Figure 16 shows that the corresponding reduction for nonregenerative turbofans is about 15%. Because the ordinates of Figs. 15 and 16 represent the ratio of specific thrusts, the percentage reductions in

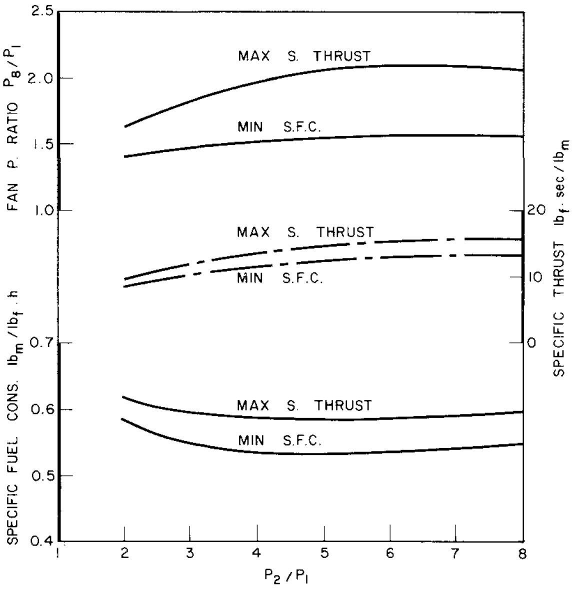

Fig. 13 Optimized minimum S.F.C. and maximum specific thrust of regenerative turbofan cycles vs pressure ratio P_2/P_1. Flight conditions ($M_\infty = 0.9$ at 35,000 ft). $B = 5.0$, $\eta_R = 0.9$, $T_{MAX} = 2200°F$.

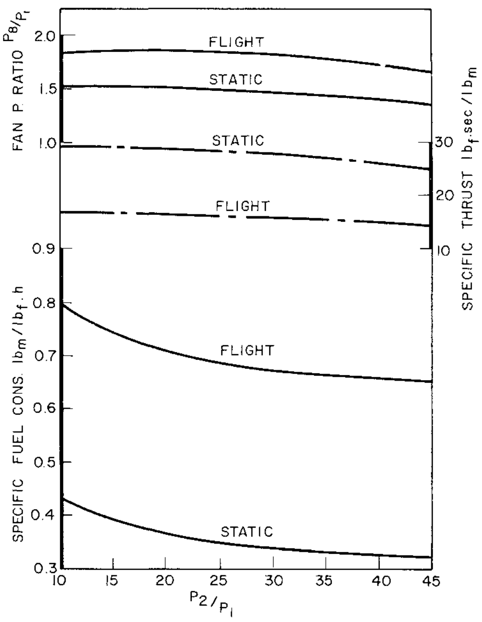

Fig. 14 Optimized performances, vs pressure ratio P_2/P_1, for flight ($M_\infty = 0.9$ at 35,000 ft) and static operation of nonregenerative turbofan cycles. $B = 6.0$, $T_{MAX} = 2200°F$.

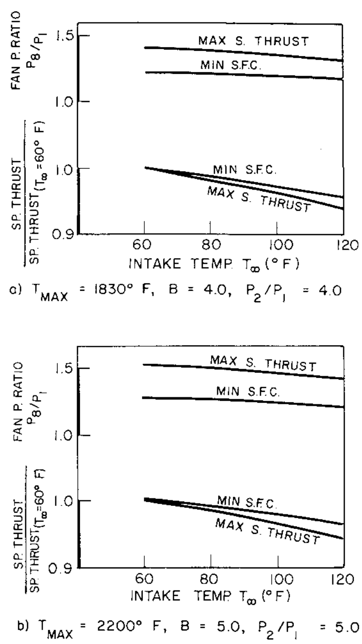

Fig. 15 Influence of intake temperature on the specific thrust at static conditions of moderate and high T_{MAX} regenerative turbofan cycles.

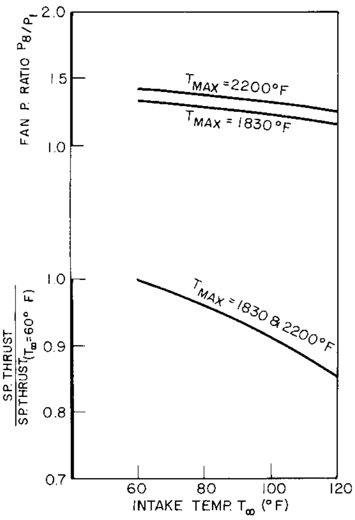

Fig. 16 Influence of intake temperature on the specific thrust at static conditions of nonregenerative turbofan cycles. For $T_{MAX} = 1830°F$; $B = 5.0$, $P_2/P_1 = 25.0$ For $T_{MAX} = 2200°F$; $B = 6.0$, $P_2/P_1 = 35.0$.

overall thrusts are, of course greater than quoted above and, for a prescribed inlet Mach no., are 9, 11, and 19%, respectively.

Endurance

It appears that the thrust lapses, with altitude and speed, of nonregenerative and regenerative high bypass ratio turbofans are approximately equal when allowance is made for the influence of the increase of cycle pressure ratio associated with the cruise condition. Details of the matching process depend, of course, on compressor characteristics, whether or not variable engine geometry is used etc. Accordingly, assuming equal thrust lapses for regenerative and nonregenerative units sea level static thrusts equal to about 30% of the maximum takeoff weight are required for cruise at $M = 0.9$ at 35,000 ft when the average L/D = 12, a value which is inclusive of engine nacelle drag. A simple jet-type Breguet endurance analysis was carried out for aircraft, with an average L/D = 12 including nacelle drag, fitted with both kinds of engine; the results are displayed in Fig. 17. When the nacelle drag coefficients, and nacelle cross-sectional areas per unit mass flow, of regenerative and nonregenerative engines are equal, as assumed here, the L/D value is approximately 1% lower with the regenerative engines: this small effect was ignored. The thrust-to-weight ratios, based on sea level static operation, of regenerative and nonregenerative engines were taken to be 3.2:1 and 6:1, respectively.

On the basis of these values it can be shown that when regenerative engines are compared with high bypass ratio—high pressure ratio nonregenerative units, such as might be used in large aircraft, the extra weight of the regenerative engines is typically counted, ignoring reserves, by

Table 2 Exhaust gas temperature

T_{MAX}(°F)	Engine type	Operation	Exhaust gas temperature (°F)	
			Gas generation exhaust only	Mixed fan and gas generator exhaust
1830	Nonregenerative	Static	778	226
	($B=5.0, P_2/P_1=25.0$)	Flight	748	185
	Regenerative[a]	Static	489	171
	($B=4.0, \eta_R=0.9, P_2/P_1=4.0$)	Flight	400	126
2200	Nonregenerative	Static	908	232
	($B=6.0, P_2/P_1=35.0$)	Flight	844	206
	Regenerative[a]	Static	570	178
	($B=5.0, \eta_R=0.9, P_2/P_1=5.0$)	Flight	473	136

[a]For the regenerative engines, the temperatures quoted are for the minimum S.F.C. optimum conditions.

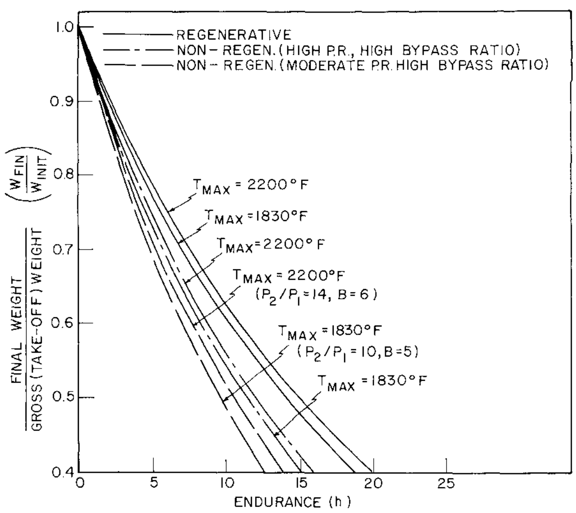

Fig. 17 Flight endurance (for $M_\infty = 0.9$ at 35,000 ft) of aircraft propelled by regenerative, and nonregenerative, turbofans. Based on a jet-type Breguet analysis modified to include initial climb and acceleration; L/D = 12.

a reduction in fuel load after about 4 hr. flying. In other words for a prescribed gross takeoff weight, an aircraft with regenerative engines will be able to carry a greater payload than one equipped with high bypass ratio—high pressure ratio units for missions exceeding 4 hr. duration. This of course is based on the implicit assumption that it is engineeringly feasible to build engines of both types in overlapping thrust ranges or, alternatively, the aircraft can be equipped with either a small number of nonregenerative engines or a larger number of regenerative units.

A more appropriate comparison for small aircraft, for which high bypass—high pressure ratio units appear to be impractical, can be made between regnerative and nonregenerative moderate pressure ratio—high bypass ratio engines: the relevant data are shown in Fig. 17. On the basis of a thrust-to-weight ratio of 6:1 for the latter engine type, the additional weight of a regnerative turbofan is countered by a fuel saving after about 2 hr. flying.

Conclusions

The main conclusions drawn from the work are that regenerative turbofans can make available for small aircraft many of the advantages of the high pressure ratio-high bypass ratio turbofans already in use in large aircraft. In some respects regenerative turbofans can, in principle at least, offer a performance superior to that of the nonregenerative high pressure ratio—high bypass ratio type namely in respect to 1) better fuel economy for both sea level static and flight conditions (up to 24% better at sea level and approximately 17% better under flight conditions when the nacelle drag coefficients, and nacelle cross-sectional areas per unit mass flow, are assumed equal for both engine types and nacelle drag is taken into account separately from that of the remainder of the aircraft), 2) lower potential for noise generation due primarily to the low fan pressure ratio associated with the minimum specific fuel consumption concept, 3) lower gas generator exhaust temperature with, consequently, less likelihood, for military applications, of infrared detection, 4) thrust lapse rate with increasing ambient temperature about half that of a nonregenerative engine. The disadvantages of regenerative turbofans are: 5) poorer thrust-to-weight ratio (approximately 3.2:1 compared with 6:1 for the high pressure—high bypass ratio nonregenerative type). Assuming that comparisons, of both engine types, based on a prescribed aircraft gross takeoff weight are engineeringly feasible, the lower thrust-to-weight ratio of regenetive engines is compensated by a fuel saving for flights exceeding about four hours duration. The corresponding figure when the comparison is with moderate pressure ratio—high bypass ratio engines is 2 hr., 6) greater sensitivity, due to the presence of the regenerator, to foreign body ingestion damage in the gas generator; the risk of ingestion can probably be minimized by shielding the compressor inlet with the fan hub the latter serving,to some extent, as a centrifuge (Figs. 2 and 3), 7) restriction, in the absence of major technological developments in the regenerator field, to relatively low thrust levels only. There are no corresponding thermodynamic or aerodynamic limitations.

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