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Very High Bypass Ratio Engines for Commercial Transport Propulsion
by

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Abstract

This paper is a feasibility study for the application of advanced turbofan engines to commercial transport aircraft. Performance factors for study engines in the bypass ratio range of 9 to 17.5 are considered along with nacelle installation losses. Trades in engine cycle performance and innovative nacelle configuration options are studied in an attempt to define an optimum engine-nacelle configuration. Mechanical complexity for the various engines is assessed, and economic factors that will ultimately determine the applicability of the engines are presented.

It is concluded that higher bypass ratio (BPR) engine cycles and innovative nacelle configuration concepts can be combined to yield significant improvements in fuel burned. However, other factors such as increased engine manufacturing and maintenance costs due to increased mechanical complexity may adversely affect the economic benefits resulting from the improved engine performance. These factors need to be included in the evaluation of the overall benefits of advanced engine concepts.

Introduction

The application of very high bypass turbofan engines to subsonic transport aircraft requires consideration of many factors. The study to be reported here has been directed primarily at turbofan engines in the range of bypass ratios (BPR) of about 9 to 17.5. Since the ultimate attractiveness of these engines will depend heavily on how they perform relative to engines of both lower and higher BPR, discussions outside of this range will also be presented as needed. Lower BPR engines can be competitive because they represent current technology, and thus lower technical risk, and many relatively mature engines already exist so that development costs have been at least partially defrayed. Engines with BPR higher than the current study level, such as unducted propeller configurations, either direct turbine driven or gear driven, are of interest because of fundamental propulsive efficiency advantages that exceed those in the study range of this paper.

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The factors considered here include engine cycle performance, nacelle drag and internal losses, weight, and mechanical complexity. A summary of results of a previous study (Ref. 1), which considered only engine cycle and nacelle performance factors at Mach 0.80, will be presented. Extension to higher cruise Mach number operation will be discussed, and special attention will be given to a BPR 9.6 engine that represents a compromise power plant that benefits from higher bypass ratio with a minimal increase in mechanical complexity as compared to current technology engines.

Engine Cycle Study

Historically, improved thrust specific fuel consumption (TSFC) through increased bypass ratio has been demonstrated many times; from the inception of the turbojet to the first-generation low-bypass-ratio turbofan engine (BPR ~ 1) to the current BPR = 5 to 6 conventional turbofan. Figure 1 shows that there is still a significant potential improvement in TSFC to be gained by increasing bypass ratio beyond today's standard turbofan. At the high end (BPR ≥ 30), unducted propeller configurations are considered, thereby eliminating the drag and weight penalties associated with extremely large diameter cowling. In the intermediate range of BPR = 10 to 20, ducted fan configurations are required. This paper addresses these intermediate bypass ratio configurations.

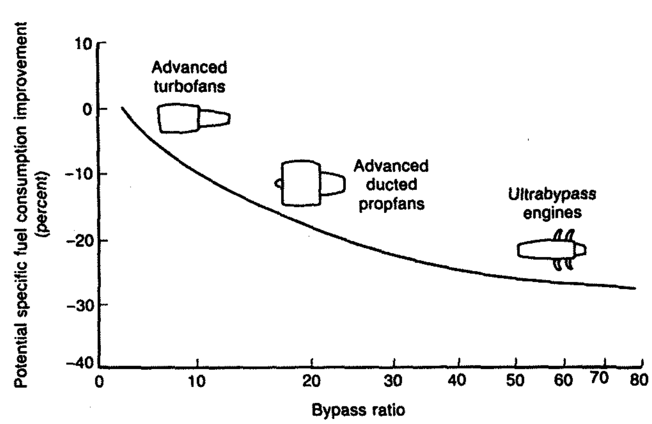

Figure 1. Bypass-Ratio Trends

In Reference 1, it was shown that installed TSFC improvements relative to conventional turbofans ranged from 12% for BPR = 17.5 to 7% for BPR = 9. These improvements were due to increased propulsive efficiency due to higher bypass ratio only, since the other engine thermodynamic cycle parameters (i.e., overall pressure ratio, turbine temperature, and component technology) were held constant. What does differ significantly, however, is the mechanical design of the different engine configurations as bypass ratio is increased. As bypass ratio is increased beyond 10, it is assumed that a gearbox is needed to provide the proper speed for optimum efficiency of the fan without excessive low-pressure turbine stages. In addition, because the higher bypass ratios require a lower fan pressure ratio for minimum TSFC, the fan nozzle will operate unchoked over a significant portion of the operating range. This, in turn, results in large migrations of the fan operating line and will therefore require either variable pitch fan blades and/or a variable fan nozzle area to maintain adequate engine stability. Although there may be a clever way to limit the mechanical complexity with increasing bypass ratio, at this point a more complex engine appears inevitable. This apparent fact prompted a more thorough investigation of the highest bypass ratio considered possible (within reasonable constraints of turbine stages) without incorporating variable geometry features or a reduction gear. The result of this investigation was a 9.6 BPR engine, shown on Figure 2, operating at a fan pressure ratio of 1.45. Although slightly better turbine efficiency could have been obtained by using seven stages, a six-stage low-pressure turbine was finally used as a compromise between weight, parts count, and efficiency.

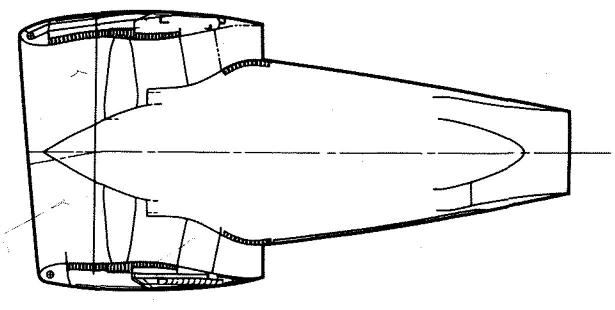

Figure 2. Very High Bypass Ratio Gearless Engine

As bypass ratio increases, nacelle diameter also increases for a given thrust level. For an increase in BPR from 5 to 17.5, the nacelle diameter may increase as much as 50%. To help minimize the increase in nacelle diameter and length, the fan face Mach number can be increased. Figure 3 shows the effect of fan face Mach number on fan stage efficiency for both single and counterrotation designs. As fan face Mach number increases, fan efficiency is reduced for a fixed exit Mach number. This deficiency can be reduced by increasing the stage exit Mach number through the use of annular convergence across the rotor and stator blade rows. As noted in Figure 3, the dual row counterrotation fan stage can maintain high efficiency as fan face Mach number is increased due to reduced blade blockage associated with fewer blades per row. These trades of fan efficiency with increased through flow Mach number can be used to advantage in minimizing cowl drag at higher flight Mach numbers as will be discussed in the next section.

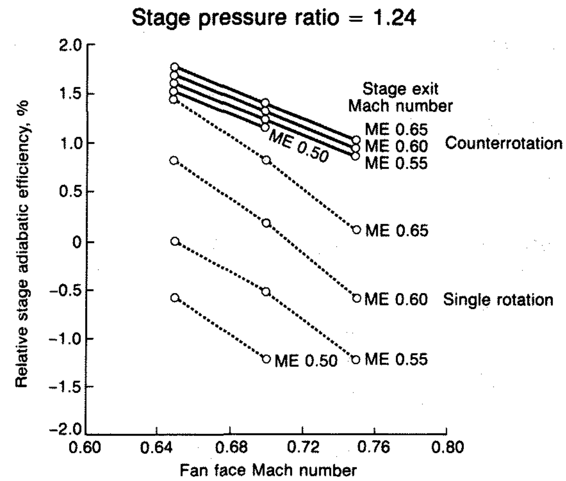

Figure 3. Relative Fan Stage Efficiency as Function of Inlet and Exit Mach Number

Nacelle Design Considerations

Since fan diameters of very high bypass ratio (VHBPR) engines are significantly larger than conventional engines, concerns over nacelle drag, weight and internal losses demand close attention to the design of the nacelle. In the following discussion, results from a previous VHBPR engine study (Ref. 1) will be reviewed and additional results pertaining to higher Mach number operation will be presented.

Inlet

Inlet airflow levels for VHBPR engines are fundamentally higher than for lower BPR engines of the same thrust level. This dictates that the inlet throat must be larger in diameter in order to avoid choking at high power conditions. In addition, engine growth capability is a prime consideration for any new engine. It is therefore necessary to include margin in throat size to accommodate thrust growth to the maximum flow capability of the fan.

Although throat diameter must increase, the results of the study presented in Reference 1 indicate that there is a VHBPR engine characteristic that may permit a reduction in the inlet lip contraction ratio, as compared to current design procedure, needed to ensure satisfactory engine operation at high angle of attack conditions.

This characteristic results from a combination of engine thrust lapse rate and fan flow response to speed and altitude. The takeoff-to-cruise airflow ratios at constant combustor exit temperature and sea level conditions for BPR 5.7 and 17.5 engines are shown on Figure 4 to illustrate the engine flow response differences. As shown on this figure, the higher bypass engine flow decreases more rapidly as freestream Mach number decreases than the lower bypass engine and ends up at a lower fraction of the cruise flow rate at takeoff conditions. Taking advantage of this cycle response and assuming airplane takeoff performance similar to that for a conventional BPR engine, it is possible to operate the VHBPR engine at inlet throat Mach numbers well below that for conventional engines. This allows for reductions in inlet lip contraction ratio which, in turn, allows reductions in inlet highlight diameter and cowl maximum diameter. Figure 5, from Reference 1, illustrates the contraction ratio reduction possible for two different inlet lip separation criteria over a range of bypass ratios. The shortest aerodynamically feasible inlet length was assumed for the Reference 1 study.

The gearless BPR 9.6 engine requires a larger inlet lip contraction ratio than higher BPR engines because of its higher takeoff throat Mach number. The study inlet for this engine, Figure 2, also had a longer inlet diffuser than the higher BPR engines in anticipation of acoustic lining requirements. Advantage was taken of this additional inlet length by reducing the throat diameter so that the contraction ratio effect on inlet highlight radius was minimized.

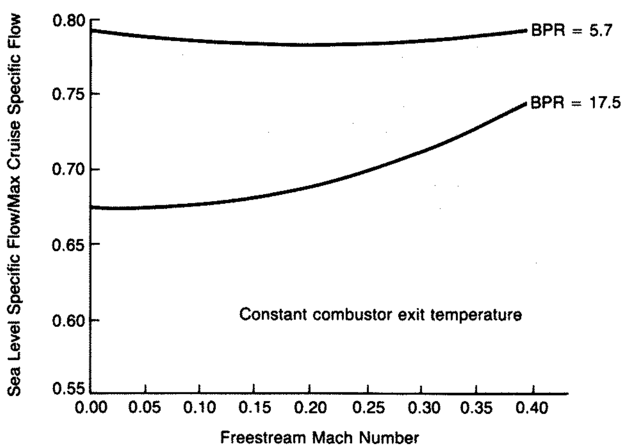

Figure 4. Engine Sea Level Specific Flow Variation With Freestream Mach Number at BPR = 5.7 and 17.5

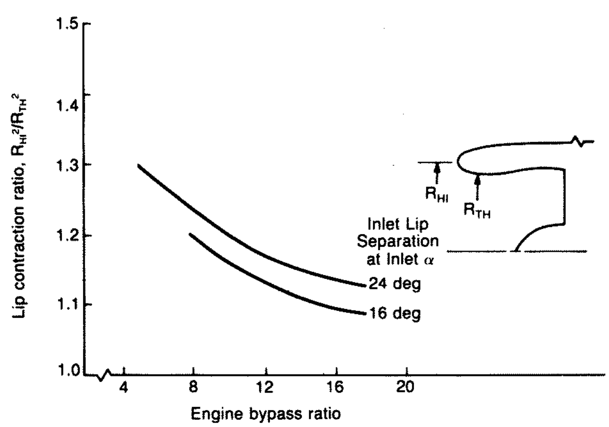

Figure 5. Required Inlet Lip Contraction Ratio as a Function of Engine Bypass Ratio

External Cowl

At cruise conditions, the forward facing area of the external cowl surface of a typical subsonic engine nacelle is subjected to a suction force that tends to balance the captured stream tube total momentum increase that develops as the flow approaches the inlet. The cowl forebody shape must be chosen carefully to avoid shock losses or boundary layer separation if minimum nacelle drag is to be achieved. For the VHBPR engine, it is desired to keep the maximum diameter and length as small as possible to minimize weight, drag, and installation constraints. This objective tends to make the forebody design problem more difficult. In the study of Reference 1, it was found that a short cowl could be used if the trailing-edge radius of the cowl could be increased so that the forward projected area of the cowl external surface covered a larger portion of the total cowl length. This leaves the fan cowl trailing edge (nozzle exit) at a larger radius than would be found by scaling up a conventional cowl, but with the short cowl and a fixed engine length, the resulting increased length available for the fan nozzle afterbody allows an afterbody angle within normal limits.

At higher speeds, the forebody shape becomes more critical because the spilled flow tends to reach higher local Mach numbers for a given amount of spillage and surface curvature. In increasing the freestream Mach number from 0.80 to 0.84, it was found that about a 40% increase in cowl length was needed to avoid drag rise. Figure 6 shows a comparison of a BPR 17.5 engine fan cowl geometry designed to operate at Mach 0.84 with a fan cowl for the same engine optimized for Mach 0.80. Note the significant change in fan cowl length for the 0.84 cowl design, the changes required in the fan nozzle offset and the addition of a primary plug nozzle to allow reasonable fan afterbody angle. A longer fan nozzle afterbody would be a possible alternate to the plug nozzle. Figure 7 shows the drag characteristics for both of the cowls and indicates the serious drag penalty that would be present if the Mach 0.80 cowl were to be operated at Mach 0.84.

The cowls shown on Figure 6 were both designed with the assumption that an inlet boundary layer separation angle of attack of 16 deg would be adequate. This is a more aggressive design than that used for most current engines and would require engine stability studies to verify its acceptability. If a conventional inlet with an inlet lip separation angle of, say, 24 deg is to be used at Mach 0.84, a much longer cowl will be needed to control spillage drag.

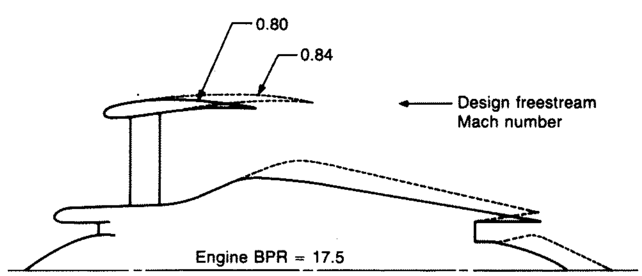

Figure 6. Comparison of VHBRP Fan Cowl Geometry for Design M_∞ = 0.80 and 0.84

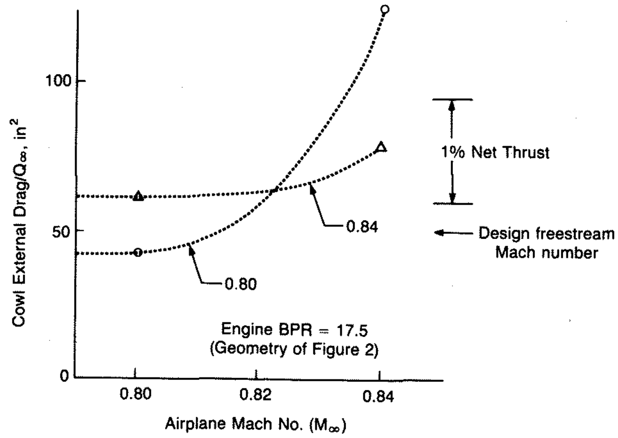

Figure 7. Drag Rise Performance for VHBPR Fan Cowls Designed for M_∞ = 0.80 and 0.84

An engine cycle parameter that could be exploited for higher cruise Mach numbers is the fan face entry Mach number. The higher the fan entry Mach number the greater the inlet stream capture ratio (capture stream tube area over inlet highlight area) will be and the lower the suction loading on the fan cowl forebody. Figure 8 shows a comparison of the Mach 0.80 fan cowl from Figure 6, which was designed for a fan entry Mach of 0.64, and a cowl designed for a fan entry Mach of 0.75. Since the same fan face airflow was assumed in both cases, the fan diameter and the inlet highlight have been reduced for the fan entry Mach 0.75 case, but the same cowl maximum diameter has been retained. Figure 9 illustrates the increase in stream tube capture ratio that results from this change in fan entry Mach number. Figure 10 shows the drag rise results for the two cowls for Mach 0.80 and 0.84. The high flow fan cowl is clearly superior for this case and no increase in fan cowl length is required.

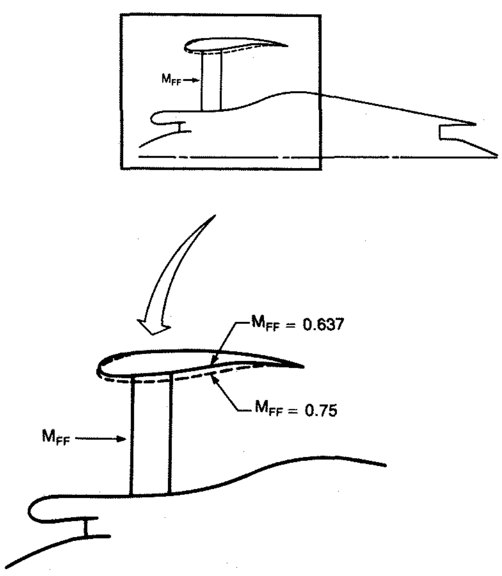

Figure 8. Comparison of Fan Cowl Geometry for Fans With Entry Mach Number = 0.637 and 0.750

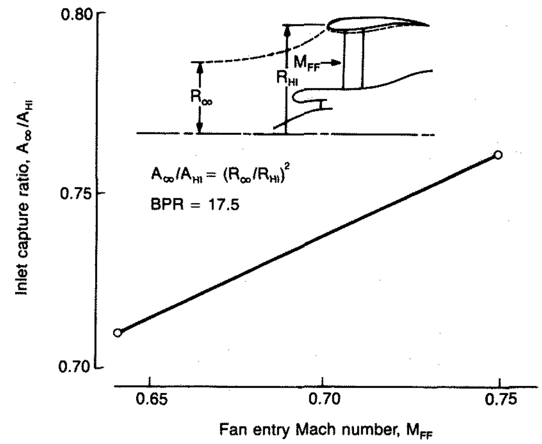

Figure 9. Inlet Capture Stream Tube Area Ratio Variation With Fan Entry Mach Number

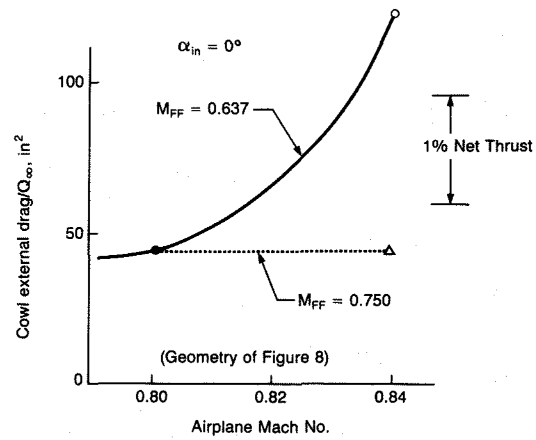

Figure 10. Predicted Drag Rise Characteristics for Cowls Designed for Fans With Entry Mach Number of 0.637 and 0.750

At higher speeds, the cowl forebody design problem becomes even more severe. Figure 11 shows a comparison of a cowl designed for Mach 0.90 compared with an aggressive cowl geometry designed for Mach 0.80. The Mach 0.80 cowl was designed for an inlet lip separation angle of 16 deg and would require improved engine stability for low-speed angle of attack operation. It still results in wave drag at Mach 0.90 of 3.3% of engine net thrust while the Mach 0.90 design has a predicted wave drag of about 0.5%. The Mach 0.90 design cowl has an even thinner inlet lip, however, and a raised core cowl to push the entry stream tube out. Special inlet lip treatment such as variable geometry might well be required for a low-drag Mach 0.90 nacelle.

The external surface for the BPR 9.6 engine cowl is shown on Figure 2. The previously mentioned inlet highlight radius reduction resulting from the assumed diffuser length helps the design of a low-drag external contour. Using cowl trailing-edge radius as a free parameter, an external contour with no wave drag at Mach 0.80 was found easily. Studies for this engine at higher Mach number have not been done, but it is expected that it would require reductions in lip contraction ratio or significantly increased length as was found for the higher BPR engines.

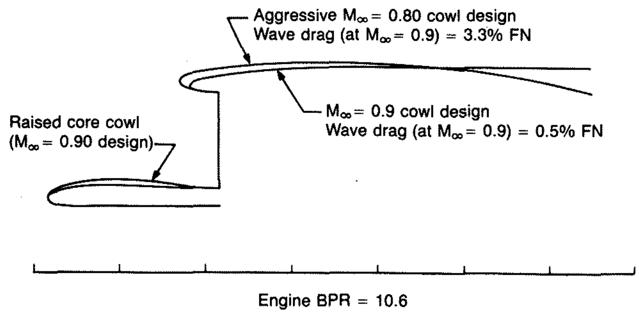

Figure 11. Comparison of Geometry for Aggressive $M_\infty = 0.80$ Cowl and Cowl Designed for $M_\infty = 0.90$

Nozzle

Nozzle losses for VHBPR engines are of increasing importance as BPR increases because, at cruise conditions, higher levels of gross thrust are produced for a given net thrust level for these engines than for lower bypass engines. Using the ratio of actual jet velocity to ideal jet velocity (velocity coefficient or C_v) as a measure of nozzle performance, a 1% reduction in nozzle C_v at BPR 5 gives about a 2% reduction in net thrust while at BPR 17.5 this same reduction in C_v gives approximately a 4.6% reduction in net thrust. Figure 12 presents the variation in fan nozzle C_v influence coefficient over the range of BPRs used in this study.

The highly offset nozzles that are required by the external cowl geometry are a concern for the internal nozzle design. Flow analysis of these nozzles suggests that acceptable upper and lower nozzle contours can be found, but the presence of struts and bifurcations in the flow may generate secondary flows that could increase losses. Current nozzle analysis tools do not treat this problem very accurately, and testing will be needed to fully assess these characteristics as well as verify the calculated nozzle performance.

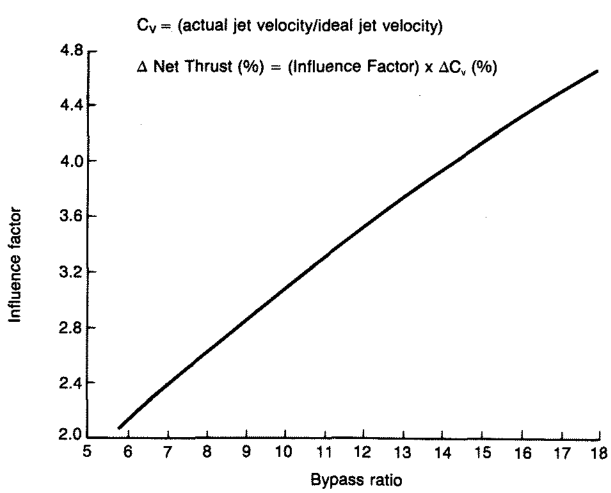

Figure 12. Fan Nozzle C_V Influence Factor on Thrust

Thrust Reverser

Analytical studies reported in Reference 1 indicate that, if variable pitch blades are used for the fan and an auxiliary fan flow path is provided, it may be possible to achieve a significant level of reverse thrust at landing speeds using reverse pitch.

If variable pitch blades are not used, a conventional cascade thrust reverser may be needed. To minimize length, a translating cascade concept would be desirable that incorporates a lower cascade turning angle to maximize the effective flow area of the cascades.

As an example, a preliminary thrust reverser concept for the BPR 9.6 engine, discussed above, was developed which used fan stream only reversing and a translating cascade. It was also desired to minimize the cascade translation distance so that a short fan cowl could be used that would allow core mounted accessories to be serviced without the need for a D-duct system. Relative to a BPR 5 engine of equal thrust, the fan contribution to net thrust for the BPR 9.6 engine will be about 10% greater, and the nonreversed primary contribution to net thrust will be about 10% less. Thus, assuming at least equal efficiency in the reverser flow path for BPR 9.6, it should only be necessary to achieve about 70% of the fan flow thrust reversal that is achieved with the BPR 5 engine to generate the same retarding force. An attractive way to take advantage of this would be to reduce the turning angle for the cascades so that the translation length needed to achieve a given effective flow area is reduced. For the nacelle shown on Figure 2, the conclusion was that 30-deg forward turning would be adequate relative to the 45-deg forward turning used in many reverser cascade designs.

Engine Maintenance Cost

A preliminary maintenance cost assessment has been undertaken to aid in evaluating the economic benefits of increasing turbofan engine bypass ratio. It was assumed that the reliability of each of the candidate engines would be essentially the same when the engines were mature (after about 7 years in service). The assessment technique was directed at estimating the relative cost of repairing mature engines in an airline repair facility. The cost of repairing current large high-bypass-ratio engines was utilized as the base. The data was obtained from airline repair facilities and permitted visibility of the distribution of labor, material, and outside repair costs between engine modules. Fully burdened labor rates were used in the base case and are assumed to be the same for all comparisons.

The design and configuration changes that occur as BPR increases are: the fan diameter increases, the fan blades become longer and larger, the fan containment case and intermediate case dimensions increase and there are associated changes to containment rings, shaft strengths, and bearing loads. To drive the larger fans requires either more turbine stages or a gearbox (transmission). As the BPR increases to about 10, the number of turbine stages can be increased to provide the required fan horsepower. Above a BPR of about 10, the continuing decrease in optimum fan pressure ratio and its accompanying decrease in optimum tip speed results in an excessive number of turbine stages. At this point, either a gearbox (transmission) becomes necessary or operation at nonoptimum power turbine speeds will be required.

Again, as BPR increases above about 10, the need for variable fan blade pitch and/or variable fan nozzle area becomes necessary in order to keep the fan operating line within stability limits. The inlet and fan cowl become larger, and the fan thrust reverser becomes larger. Only the impact of thrust reverser changes from the base engine have been considered.

These configuration changes impact engine maintenance and the general tendency is for maintenance cost to increase as engine complexity increases. Table 1 shows the results of the maintenance cost assessment relative to the standard 5 to 6 BPR engine. In addition to the base engine, data are shown for four classes of engines: those with BPR less than or equal to 10, greater than or equal to 10 with a gearbox (geared), greater than or equal to BPR 10 with a gearbox and variable pitch fan blades, and greater than or equal to 10 with variable area nozzle also. The results are relative to the base 5 to 6 BPR engine of 100%.

The estimated maintenance cost increases from a low of 4% to a maximum of 22% for the geared, variable pitch, variable nozzle, high BPR fan. Some reduction in this maintenance cost level is possible if the thrust reverser can be eliminated through the use of variable pitch fan blades. The use of variable pitch fan blades is estimated to increase the maintenance cost as a result of refurbishing the retention and pitch change features as noted in the lower portion of the table. The variable area nozzle feature includes the incremental cost that might be associated with the larger reverser in the final right hand column.

All of the maintenance cost estimates are identical for the core portion of the engine based on the assumption of constant technology level. While these estimates are preliminary and need to be revised as the configuration matures in design details, we believe it is sufficiently accurate for preliminary screening. The results suggest that increasing the BPR is desirable but only to the point where variable pitch blades or nozzles and gearboxes are required. Radical increases in fuel prices would, of course, suggest that even higher BPRs might be cost effective.

Table 1. Relative Maintenance Cost of Advanced Engines (In Percent)

Item	Base BPR = 5-6	BPR ≤ 10	BPR ≥ 10 Geared	BPR ≥ 10 geared V/pitch	BPR ≥ 10 geared V/nozzle V/pitch
Fan					
Fan case	5	5 to 6	6 to 7	3 to 4	3 to 4
Fan interim					
Case					
LP-compressor	3	3	3	3	3·
HP-compressor	9	9	9	9	
Diffuser case and combustor	10	10	10	10	10
HP-turbine	45	45	45	45	45
LP-turbine	11	14	10	10	10
Accessory G/B	2	2	2	2	2
Controls	2	2	2	2	2
Expendables	13	13	13	13	13
Subtotal (%)	100	103–104	100–101	97–98	97–98
Main G/B	–		8–10	9–10	9–10
V/P blades	–	–	–	4	4
Mech Sys	–	–	–	4	4
V/P control	–	–	–	1–2	1–2
V/A nozzle and control	–	–	–	–	4
Reverser increment	–	1	1–2	1–2	–
Total (%)	100	104–105	109–113	116–120	119–122

Economics

To evaluate the economic merits of the different engine configurations, the current cash direct operating cost (DOC) of a typical twin-engine aircraft using 5 to 6 bypass ratio engines was utilized. Figure 13 shows the distribution of cash operating cost that includes crew (pilots), fuel, maintenance cost for airframe and engines, and the cost of insurance for 500- and 2000-nmi trips.

The thrust specific fuel consumption reduction for increasing .he bypass ratio from the current 5 to 6 range to about 10 is 7%. This would reflect in a trip fuel consumption reduction of 7.1% at 500 nmi and 7.5% at 2000 miles. Increasing the BPR above 10 requires the use of a gearbox and some form of variable geometry but will gain another 5% in thrust specific fuel consumption at BPR = 17.5 for a total of 12% improvement. The greater than 10 BPR engines would reduce the trip fuel consumption about 12.2% at 500 nmi and 12.8% at 2000 nmi. Some of the savings due to reduced fuel consumption will be off-set by increases in maintenance cost. In a simplistic fashion, the improvements and debits can be evaluated as shown below:

> At 500 nmi, the bypass 10 engine has a fuel consumption improvement = 35.3% x 7.1% = 2.5%. Thus, the reduction in fuel consumption = 2.5% in cash DOC.
>
> The increase in maintenance cost is 14.6% x 4.0% = 0.6%. Thus, the increase in maintenance cost = 0.6% in cash DOC.
>
> The net improvement = 2.5% 0.6% = 1.9% in cash DOC.

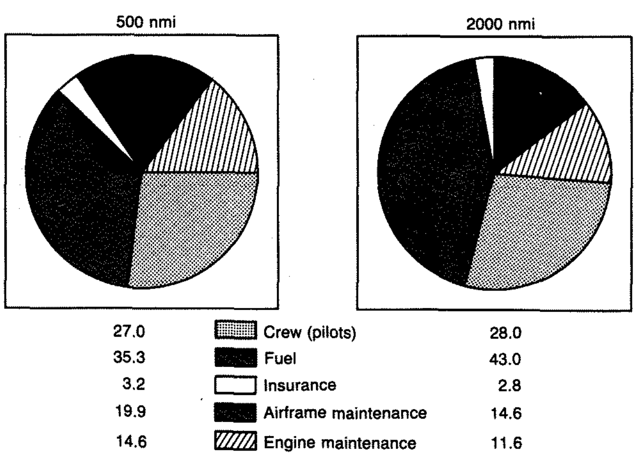

Figure 13. Cash DOC Elements—Twin-Engine Aircraft (In Percent)

Table 2 gives the results of these simplistic calculations using a 4% increase in maintenance cost for the BPR 10 engine and a 10% to 20% increase in maintenance cost for the greater than 10 BPR engine with variable geometry and/or a gearbox. Fuel burn benefit for the variable geometry/gear engine is assumed to vary from 8% to 12.2% at 500-mile range and from 8.5% to 12.8% at 2000-mile range for the BPR 10 and 17.5 engines, respectively.

It can be observed from Table 2 that the economic benefits of improved fuel consumption increase with increasing flight duration. Further, it is seen that the benefits are sensitive to the impact of maintenance cost. Not included in the cost considerations discussed so far is the impact of increased engine price for the more complex although more efficient engines, or the impact, if any, on repair and test facilities. Uncertainty in these parameters suggest the need for more detailed analysis by engine manufacturers. It is clear that there are modest benefits in cash DOC to be achieved by increasing overall engine BPR, particularly at longer ranges. Further efforts are required to determine if the overall benefits to be achieved are worth the investment of resources at this time or whether we must wait for significant increases in world fuel prices or technology advances.

Table 2. Potential Cash DOC Improvements

Range (nmi)	BPR ≈ 10	BPR ≥ 10 (gears/variables)
500	1.9%	1.3 to 1.4*
2000	2.8%	2.4 to 3.2*

*The first number is associated with 10% maintenance cost increase, BPR = 10, and the second with a 20% maintenance cost increase, BPR = 17.5.

Conclusions

It has been shown that, through the use of higher bypass engine cycles and innovative nacelle configuration concepts, substantial reductions in fuel consumption are possible for turbofan engines even with nacelle losses included. Study of the economic factors that must be considered in judging the merit of a new engine installation shows that significant penalties may be present for engines that require higher levels of mechanical complexity. In fact, the economic impact of first cost and maintenance may cancel out fuel burn savings. If competing conventional technology engines in the desired thrust range are available, it will be especially difficult to demonstrate an economic benefit for VHBPR turbofan engines. If a new thrust class of engine is to be designed, the results of this study show that the highest possible BPR engine that retains mechanical simplicity, by avoiding gearboxes and variable pitch, may be the most desirable approach.

References

(1) Colehour, J. L. and Zimbrick, R. A., "Very High Bypass Turbofan Propulsion Systems," AIAA Paper 88-2953, Presented at the 1988 Propulsion Specialist Conference, Boston.