High-Bypass Turbofan Cycles for Long-Range Subsonic Transports

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The effects of cycle parameters on engine performance at a typical cruise condition are examined. High-bypass, high-pressure-ratio cycles are shown to have the potential for a large improvement in specific fuel consumption compared to present-day turbofan cycles. An engine and installation concept suitable for bypass ratios in the 5-to-10 range is described. The results of a parametric analysis of engine and installation characteristics are used to compute relative aircraft range as a function of cycle parameters assuming cruise sizing of the engines. With the use of air-cooled turbine temperatures, increases in bypass ratio up to the value of 10 studied and increases in cycle pressure ratio up to the value of 30 studied yield improvements in range. Takeoff requirements are then considered and shown to have little effect upon these trends. It is pointed out that high-bypass engines need not be greatly different from current turbofans in respect to the takeoff to cruise thrust relationship. Technology factors associated with the air-cooled turbine required for a high-bypass engine are discussed briefly.

Introduction

THE first generation of jet-powered subsonic transports used turbojet engines that were essentially the same as engines developed to power various military aircraft. In later models of these aircraft and in new aircraft now going into service, turbofan engines are used. However, these turbofans for the most part are derivatives of the same military engines and are limited to a bypass ratio of 1.5 or less. Nevertheless, they yielded improvements in cruise fuel consumption on the order of 15% plus higher takeoff thrust levels, both contributing to the much improved performance of these aircraft. It is expected that there will be another generation of military and commercial subsonic transports providing greater payloads, longer ranges, and lower operating costs. It is felt that a new engine should be tailored to the requirements of these aircraft. Many studies have been carried out within the General Electric Company pointed at this objective. It has been concluded that a high-bypass turbofan utilizing air-cooled levels of turbine temperature and high cycle pressure ratio is the proper power-plant for these new aircraft. This paper considers the thermodynamic cycles for high-bypass engines.

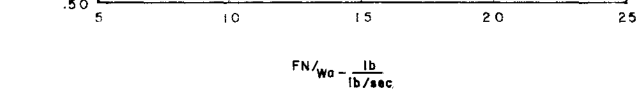

Fig. 1 Effect of cycle parameters on cruise performance (M = 0.8; 36,089 ft). Constant component efficiencies and cooling air. Fan pressure ratio at thermodynamic optimum.

Basic Cycle Effects

Figure 1 shows parametric cycle data at a typical cruise condition for a subsonic transport. Specific fuel consumption (sfc) is plotted vs specific thrust, the latter being an inverse measure of the total engine airflow required to supply a given cruise thrust requirement. Two bypass ratios are shown, 5 on the right and 10 on the left. Increased bypass ratio improves sfc but at the expense of specific thrust. For each bypass ratio, an increase in turbine temperature increases specific thrust with little effect upon sfc for the higher-bypass-ratio case. Since an increase in turbine temperature normally requires an increase in cooling air, the effect of a 3% increase is shown for the 2200°F turbine temperature lines. Note that air cooling of the turbine blades is required for the

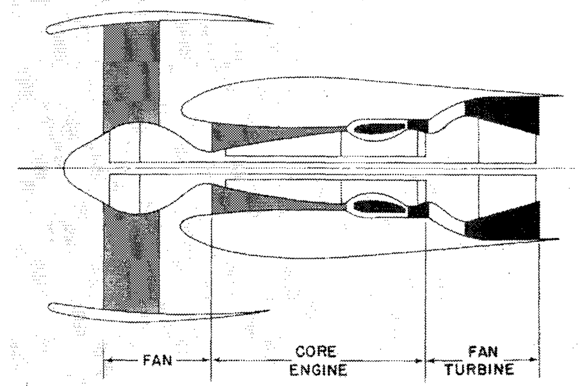

Fig. 2 Schematic high-bypass turbofan.

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range of cruise turbine temperature shown, considering that takeoff will be at a higher temperature level. The effect of an increase in cycle pressure ratio is to improve sfc with a small reduction in specific thrust. It is clear that an installed performance analysis including weight and size effects is required in order to sort out the relative merit of the various cycles.

It is of interest to note that current military and commercial turbofans have minimum cruise sfc levels in the range of 0.75 to 0.8 at the same flight condition shown on Fig. 1 and have specific thrust on the order of 20 at representative cruise conditions. This figure suggests that improvements in sfc on the order of 20 to 30% are possible in a new high-bypass engine without going to specific thrust levels substantially lower than current turbofans.

Engine Design Approach

Figure 2 is a schematic of one approach to high-bypass-engine design. It consists of a core engine on one rotor which is supercharged by the fan on a separate rotor. The fan is direct-driven by a multistage turbine. Engine and aircraft accessories can be located beneath the core engine without affecting normal cowl lines.

The core engine or gas generator is a high-pressure-ratio engine incorporating a variable stator compressor. It is very similar to the J-79 in its operating characteristics, with the primary effect of the fan being to supply air to the core engine at an increased pressure level. The engine control is that required by the core engine, the addition of the low pressure spool not involving any additional functions. Thus, conventional control as used on current commercial turbojet and turbofan engines can be used for the high-bypass engine.

The low-pressure rotor system consists of a low-radius-ratio high-tip-speed fan driven by a multistage fan turbine. The number of fan turbine stages involved depends upon the specific cycle and upon the trade between various design parameters. For example, the number of fan turbine stages can be decreased if the fan turbine diameter is increased, but this adversely affects the installation drag.

An alternate approach to the design of the low-pressure system would be to use a high revolution-per-minute fan turbine with a smaller number of stages driving a fan through a reduction gear set. Although not covered in this paper, this possibility has been studied and the conclusion reached that there is little difference in installed performance, including the effect of weight difference. The direct drive was selected because the development of the additional low-tip-speed, low-temperature turbine stages to an acceptable degree of life, maintainability, and reliability is believed to be more straightforward and assured than the development of the high-speed gear set to transmit the high horsepowers involved.

Installation Approach

Figure 3 illustrates a logical installation approach for a high-bypass engine in an under-the-wing location. The fan is located in the forward cowl behind a conventional subsonic inlet. The core engine, accessories, and fan turbine are located in the mid-cowl. The bypass air is exhausted over the mid-cowl, similar to what is done in some current turbofan installations. The fan-stream thrust reverser may either be a cascade type stowed within the forward cowl or a modified target type stowed within the mid-cowl. The fan turbine exhaust for which thrust reversal may or may not be necessary passes over a final plug nozzle. This arrangement minimizes the nacelle and the duct surface areas with concurrent weight benefits. Although this topic will not be covered in this paper, this arrangement has been shown to be efficient from a drag standpoint for high-bypass engines.

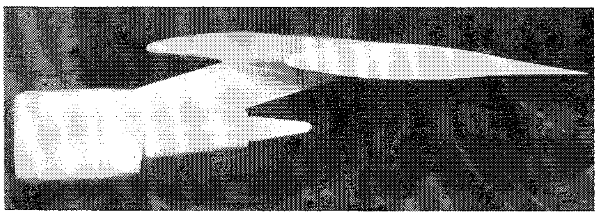

Fig. 3 High-bypass installation.

VARIABLES	-	CYCLE PRESSURE RATIO
		TURBINE TEMP. - SCHEDULED COOLING AIR
		BYPASS RATIO
ENGINE SIZING	-	F_N = CONSTANT AT CRUISE
EVALUATION	-	BREGUET RANGE CALCULATION FOR LONG RANGE TRANSPORT

Fig. 4 Relative range study.

Relative Range Study

In order to determine the merit of the various cycles, a relative range study as indicated on Fig. 4 was carried out. The major cycle parameters were varied over the range of values shown on Fig. 1. The engines were sized for a constant level of cruise thrust, the implications of takeoff being considered later in the paper. The relative range was determined using a typical set of characteristics for a long-range subsonic transport.

The factors taken into account in the relative range study are listed on Fig. 5. Typical amounts of engine bleed and high-pressure extraction for a long-range transport at cruise were used. Engine dimensions and weight were estimated from parametric designs of the basic engine type of Fig. 2 using consistent criteria for the major components. Installation weights including the thrust reverser, nacelle, and pylon were also estimated on a simplified basis. Installation drag was estimated by a simplified but systematic calculation of the various elements of drag as they would be affected by engine dimensions and exhaust velocities.

Figure 6 shows the results of the foregoing procedure applied to variations in cycle pressure ratio. The figure shows the improvements in range associated with increasing the cycle pressure ratio above the base level of 15. The band shown includes the range of cycle parameters shown on Fig. 2, with the higher turbine temperature level showing higher pressure ratio to best advantage. These results clearly show a significant payoff for high-cycle pressure ratio for a long-range subsonic transport engine up to the level of 30 studied. The limitation to the use of high-cycle pressure ratios will be the state of the art of compressor and engine design technology.

ENGINE SFC	-	M = .8, 36,089 FT DATA
BLEED & POWER EFFECTS	-	CONSTANT LB/SEC AND HP
ENGINE DIMENSIONS & WEIGHT	-	PARAMETRIC DESIGNS OF:
		FAN COMPONENT
		GAS GENERATOR
		FAN TURBINE
		JET NOZZLES
INSTALLATION WEIGHT	-	THRUST REVERSER
		NACELLE AND INLET
		PYLON
INSTALLATION DRAG	-	BY INDIVIDUAL ELEMENTS

Fig. 5 Factors used in relative range study.

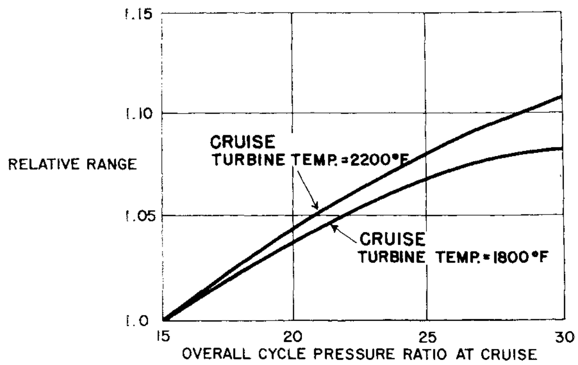

Fig. 6 Effect of cycle pressure ratio on range.

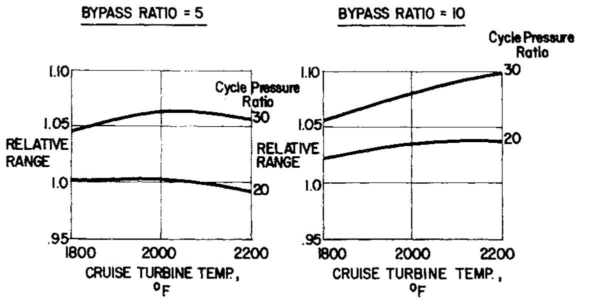

Fig. 7 Effect of turbine temperature on range cruise-sized engines.

Figure 7 summarizes the results of the relative range study as influenced by turbine temperature. Relative range is shown as a function of turbine inlet temperature for two levels of bypass ratio and two levels of cycle pressure ratio. There tends to be an optimum turbine temperature for each cycle combination. This optimum increases somewhat as cycle pressure ratio is increased. It also increases as bypass ratio is increased from 5 to 10. Since bypass ratio and turbine temperature are so closely related, a separate study was made to show the effects of bypass ratio.

Bypass Ratio Study: Cruise Sizing

The next series of studies illustrates the effects of bypass ratio when an appropriate level of turbine temperature is picked at each bypass ratio. Figure 8 shows the schedule of turbine temperature which was picked to provide nearly optimum performance from a range standpoint. The same procedure as shown on Figs. 3 and 4 was used in this study.

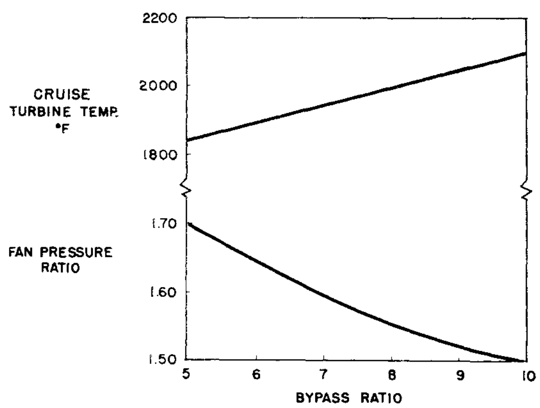

Fig. 8 Bypass ratio study. Selected schedules of turbine temperature and fan pressure ratio (M = 0.8; 36,089 ft; cruise cycle pressure ratio = 25).

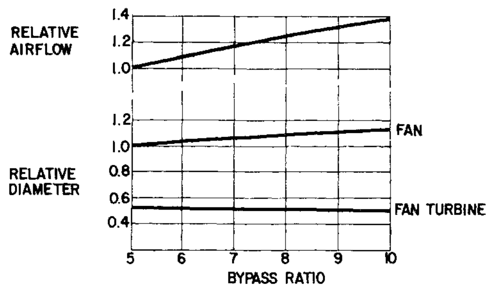

Fig. 9 Bypass ratio study.

The only difference was that the fan pressure ratios on Fig. 8 were selected to provide optimum installed performance in contrast to the data used in Figs. 1, 6, and 7 which involved fan pressures yielding minimum bare engine sfc. For a given combination of other cycle parameters, the optimum installed fan pressure ratio is somewhat lower because of the smaller fan turbine and lower engine weight.

Figure 9 shows the effect of bypass ratio on total air flow and engine diameters for the selected schedule of cycle parameters. There is an increase in fan air flow and fan diameter as bypass ratio is increased, but little change in the fan turbine diameter. For reference, the relative diameters of a current turbofan engine scaled to the same cruise thrust are 0.88 at the fan and 0.64 at the fan turbine, indicating that the physical size of high-bypass engines is quite reasonable.

Figure 10 shows the effect of bypass ratio on relative weight with 5:1 as the base. Increased bypass ratio increases engine weight for cruise-sized engines but to a much smaller extent than would be the case if turbine temperature were not scheduled to show each bypass ratio to advantage. Installation weight also increases with bypass ratio with the variation in total installed weight of the powerplant indicated on the figure. At the higher bypass ratios, it becomes possible, depending upon reverse thrust requirements, to consider a reverser for the fan stream only rather than reversers on both streams. In this study, the change was made above a bypass ratio of six, leading to a change in slope of the installed weight curve.

Figure 11 indicates the installation drag situation. The dotted curve illustrates the variation that would be obtained if drag were proportional to fan frontal area. This assumption has often been made in studies of bypass ratio effects and can result in a significant error. The solid curve shows the summation of the drag elements identified in the sketch. The reasons for the relatively modest increase with bypass ratio is that certain elements of drag, gas generator cowl scrubbing and plug scrubbing, in particular, are relatively unaffected or decrease with bypass ratio.

Figure 12 summarizes the results of this bypass ratio study. The lower curve shows the bare engine sfc. Added to this are the effects of bleed and high-pressure extraction and installation drag which relatively penalize the higher bypass engines a small amount. The last step includes the equivalent effect in terms of sfc of the installed weight difference between engines as it would affect range. In this study, 4% installed engine weight for 1% sfc was used as being typical of a long-range transport. The net result is a reduction in equivalent

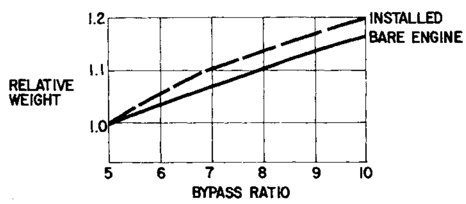

Fig. 10 Bypass ratio study.

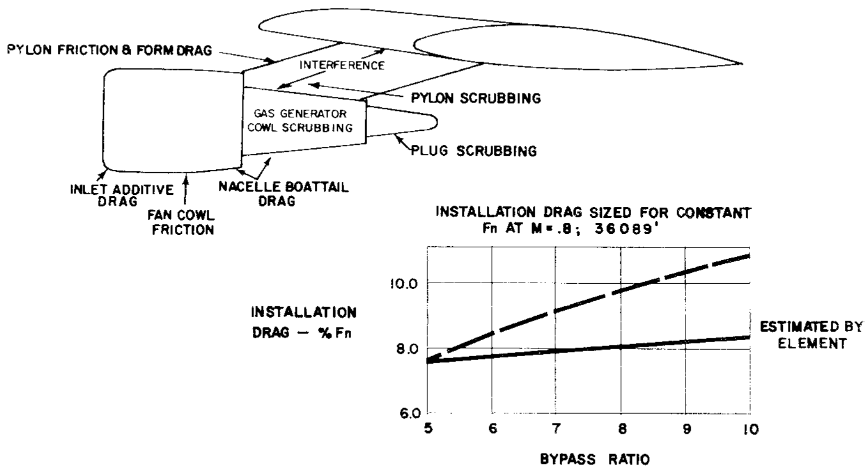

Fig. 11 Bypass ratio study.

sfc, which means an increase in range as bypass ratio increases within the 5-to-10 span studied.

Takeoff to Cruise Relationship

The bypass ratio study just described assumed cruise sizing, but takeoff requirements must also be considered. Figure 13 shows one way of handling this. Shown on the upper portion of the figure are the turbine temperature schedules that result in a given ratio of nominal cruise thrust to takeoff thrust (or lapse rate, as it is sometimes called). Note that a flight Mach number of 0.2 on a 90°F day has been used as representative of the takeoff condition. With this approach, the results of the bypass ratio installed performance study are not changed when takeoff is considered. The particular thrust ratio used in this study was selected as being appropriate for a long-range transport and is within 5% of that of the standard-day takeoff-to-cruise thrust ratio of the turbofan engine powering most current long-range commercial transports.

The turbine temperature difference between cruise and takeoff is reduced as bypass ratio is increased, as shown on the lower portion of Fig. 13. This is accomplished by appropriate scheduling of the rotor speeds at takeoff relative to the cruise values. If it were desired to maintain the same difference in turbine temperature independent of bypass ratio, the higher bypass engines would have relatively greater takeoff thrust and would show to slightly greater advantage in an installed performance study.

If a different relationship were desired between takeoff and cruise thrust of any of the forementioned engines, the turbine temperature difference between takeoff and cruise could be changed to accomplish this. The resulting temperature levels would, of course, be incorporated into the design requirements of the engine. Thus, there is flexibility in the engine design process to match different thrust requirements. On the other hand, the aircraft design can have a substantial effect upon the required takeoff-to-cruise thrust ratio. For example, an increase in wing loading would increase the takeoff thrust required. At the same time, it would lower the cruise altitude for optimum aircraft performance, which, neglecting any restrictions to altitude, would mean a lower corrected cruise thrust requirement. The combined efforts of the engine designer and the airframe designer should certainly result in a good cruise-to-takeoff thrust match.

Cycle Sensitivity

The statement has often been made that the performance of high-bypass-ratio engines is sensitive to changes in various parameters. Figure 14 shows the results of a study that does not support such a statement. One-percent changes in component performance are made, and the resultant changes in takeoff thrust and cruise sfc are shown. Parametric turbofan engines with bypass ratios of 5 to 10 and air-cooled levels of turbine temperature are compared with the J-79 commercial fan engine and with a current turboprop, both having uncooled turbines. The high-bypass engines are somewhat more sensitive to fan and fan turbine efficiency than the J-79 fan engine because of the higher energy involved on these components. There is no significant difference between the turbofans in sensitivity to gas generator components as represented by the compressor and turbine efficiencies and combustor pressure drop. On the other hand, the turbofan engines are much less sensitive to gas generator compressor and turbine efficiencies than is the turboprop. It has been concluded from these data and from other investigations that high-bypass-ratio engines with air-cooled turbine temperatures are not significantly more sensitive to component deviations than are current turbofans.

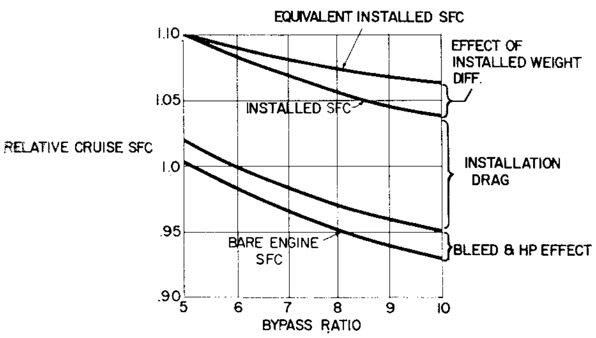

Fig. 12 Bypass ratio study. Installed performance sized for constant *Fn* at $M = 0.8$; 36,089 ft.

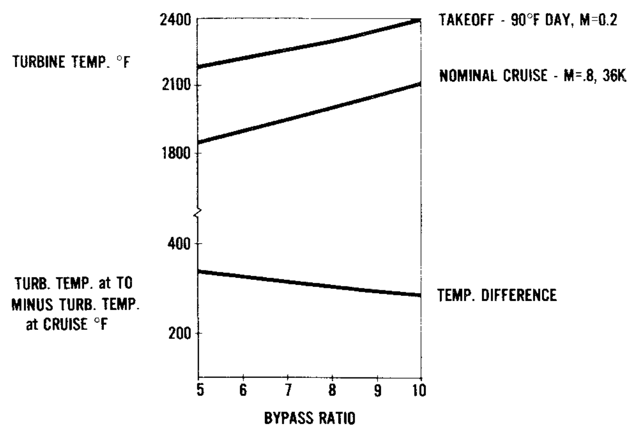

Fig. 13 Bypass ratio study. Turbine temperature schedules for constant ratio of cruise to takeoff *Fn*.

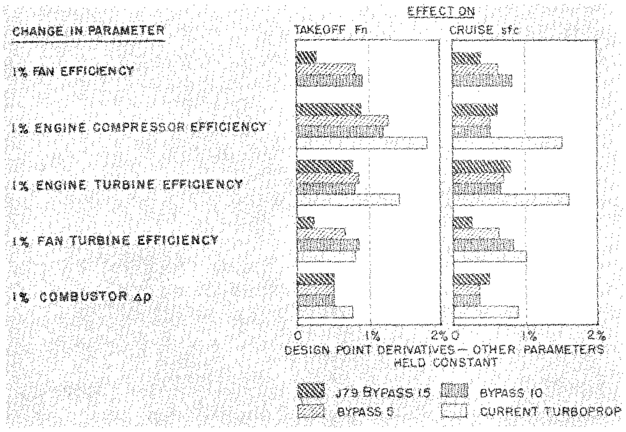

Fig. 14 Effect of bypass ratio on cycle sensitivity.

Turbine Cooling

It has been indicated that turbine temperatures requiring air cooling of turbine blades are a requirement for efficient high-bypass engines. Many current engines, including the J-93, J-58, TF-30, T-56, Conway, Tyne, and Spey, incorporate air-cooled turbine blades of the convection or internally cooled type. It has been established that a combination of film and convection cooling will result in a more effective use of cooling air, and the current study assumes the use of such cooling. It will be noted that most current engines incorporate some form of film cooling on static parts, including, in some cases such as the J-79, film cooling of turbine nozzle blades.

Of the many technical considerations of air-cooled turbines, one of the most important is the control of temperature levels and gradients in the blading. Figure 15 shows data on turbine bucket metal temperatures obtained during engine testing of a commercial J-79 engine with solid buckets and of a high-temperature test engine with air-cooled (film and convection) buckets. The air-cooled test engine was run with a maximum turbine temperature level approximately 400°F higher than that of the non-air-cooled engine. The upper curve shows the leading edge temperature and the lower curve the mid-chord temperature during the important engine transients, starting, acceleration from idle to rated thrust, and throttle chop. Lower metal temperatures are shown for the air-cooled buckets, despite the higher turbine inlet temperature. Air cooling allows the engine designer improved control of metal temperatures to whatever is required to meet creep and stress rupture criteria.

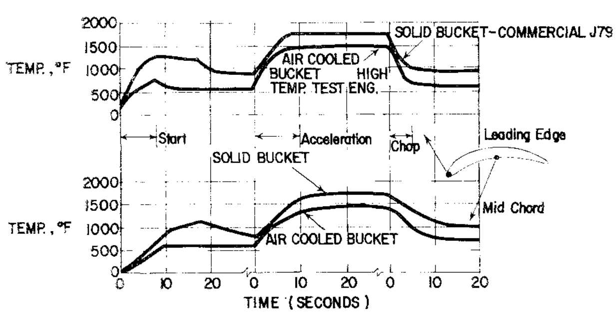

Fig. 15 Measured bucket metal temperatures during engine transients.

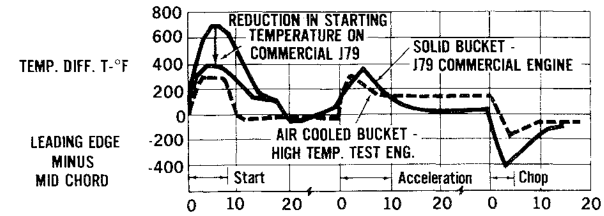

Fig. 16 Measured bucket temperature gradients during engine transients.

Figure 16 shows the same data plotted in the form of the temperature difference between the leading edge and mid-chord. This is an important factor in turbine life, since the primary reason for low-cycle fatigue cracking of turbine blading is the thermal stress associated with various temperature gradients occurring during engine transients. For example, the peak difference shown for the solid bucket during the hot start is severe enough to cause thermal cracking because of low-cycle fatigue. The reduction in gradient indicated for the solid blade has been achieved in current versions of the J-79 commercial engine by changes in bucket design and start schedule and has increased bucket life by a significant factor. Air cooling tends to maintain the edge temperatures closer to that of the body of the blade and to equalize the response of various portions of the bucket during changes in gas conditions. Thus, the engine designer has improved control of metal temperature gradients as well as levels. For these reasons, air-cooled blades are expected to have improved low-cycle fatigue life over that experienced by uncooled blades operating at much lower turbine temperatures.

Conclusions

This paper has covered the concept of high-bypass-ratio cycles for long-range subsonic transports. Improvements in installed performance and range were shown for increases in bypass ratio up to the level of 10 studied and for increases in cycle pressure up to the level of 30 studied. The use of air-cooled turbine temperatures is clearly indicated to achieve these improvements. Current turbofans that were introduced to replace the turbojets in first generation of subsonic transports gave improvements in cruise sfc on the order of 15%. It is believed that the high-bypass-cycle concept described in this paper will provide even greater improvement relative to current turbofan engines in the next generation of subsonic transports

In order to illustrate the advantage that might be achieved with a new high-bypass engine, it will be assumed that an improvement in installed sfc of 20% with no change in installed specific weight is possible compared to an engine based upon current technology. It is estimated that a large transport aircraft designed to carry a given payload 4000 naut miles would be approximately 15% lighter in takeoff gross weight with this new engine than if designed using the same criteria with the present-day engine. The reduction in fuel used and the reduction in air frame costs associated with the lower gross weight are equivalent to a 10% reduction in direct operating cost in commercial service. This large economic benefit certainly seems to provide the incentive to develop and install such engines in the next generation of subsonic transports.