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Advanced Concepts in Small Helicopter Engine Air-Cooled Turbine Design

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CONTENTS

Abbreviations and Nomenclature

AMT	Accelerated Mission Test
DS	Directionally Solidified
ES	Electro Stream
L/D	Length to Diameter
OEI	One-Engine-Inoperative
SFC	Specific Fuel Consumption
SHP	Shaft Horsepower
STEM	Shaped Tube Electrode Machining

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Abstract

Traditionally large aircraft gas turbine engines have lead the way to higher operating efficiency by the utilization of higher turbine inlet temperatures. Improved cooling techniques coupled with better materials have enabled today's large commercial turbofan engines to operate at temperatures approaching 2,700°F.

This paper reviews General Electric's experience and approach to advanced small engine turbine design including application of proven large engine cooling technology to its new generation of small engines.

General Electric's success in small engine advanced turbine design is exemplified by the T700/CT7 family of Turboshaft engines. This family has accumulated over 300,000 hours of successful field operation. Design maturity, achieved by extensive factory testing prior to production introduction, has resulted in engine reliability substantially greater than other engines in its class.

The paper also discusses the potential impact on turbine design of new, short duration, one-engine-inoperative ratings being discussed within the industry.

1. Introduction

The basis for aircraft gas turbine performance evolution has been the continued development of more effective, more efficient ways of increasing cycle pressure ratio and temperature. The increase in turbine temperature in turn has depended on an interconnected advance in materials and cooling technology.

2. Driving Factors

To understand how and why hot section design has taken advantage of advancing technology, it is important to understand the factors that drive turbine design. The primary parameter is turbine rotor inlet temperature. (Figure 1).

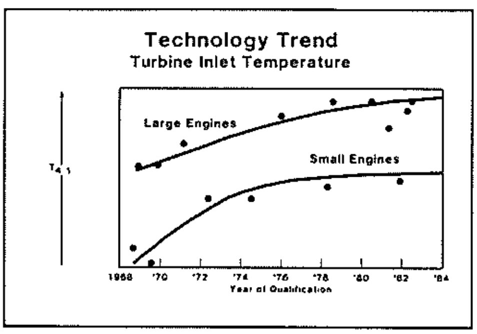


Figure 1.

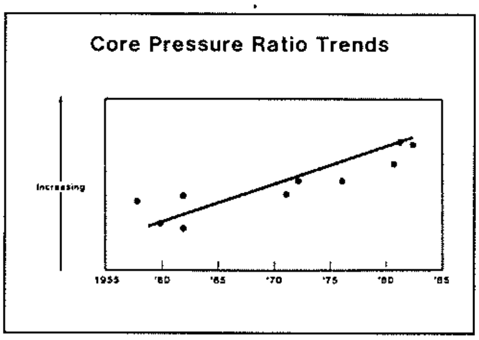


Figure 2.

Since 1950, turbine rotor inlet temperatures have steadily increased from the 1600°F level of the original T58 turboshaft engine to the current 2300°F level of the T700. Core engine pressure ratio has also steadily increased, resulting in increased cooling air temperatures (Figure 2).

The reason for this constant push for higher turbine inlet temperature and higher pressure ratio is that they result in significant cycle performance benefits - both in specific horsepower, SHP/airflow, and specific fuel consumption, fuel flow/SHP (Figure 3). These cycle benefits result in reduced engine size and weight. The reduction in SFC results in reduced life cycle cost. In the 15-1800 SHP size class, achieving the same power with a 250°F hotter turbine inlet temperature saves more than 3% in SFC. This translates to a significant fuel cost savings.

The trend for increased turbine temperature and core pressure ratio has been accompanied by demands for longer life and improved reliability. These factors have led the turbine designer to incorporate improved turbine cooling and improved materials to achieve improved performance with increased life and reliability.

3. Blades and Vanes

The design of the blades and vanes is the key to successful air-cooled turbines. They must be rugged, have high cooling efficiency, and use proven high temperature materials. Blade and vane technology has undergone continued rapid advancement.

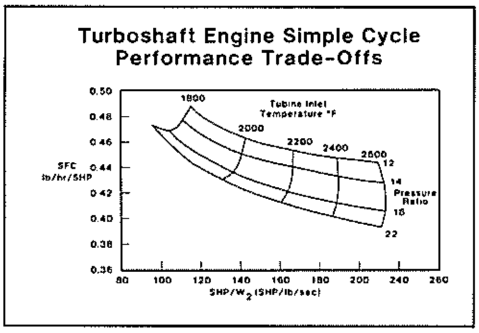


Figure 3.

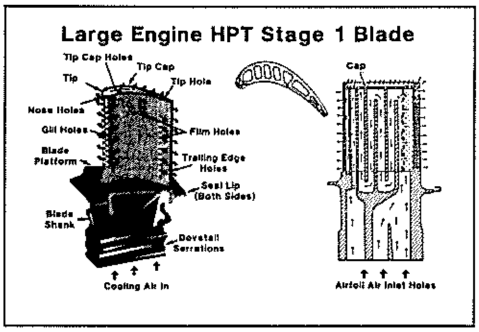


Figure 4.

Most early turbine designs for both large and small engines employed uncooled stage 1 blade designs because cost-effective methods of creating cooling passages were not available. These early designs of the mid-1950s typified by the early models of the General Electric J85, T58, and J79 engines were solid, forged airfoils. In the late '50s and early '60s, casting technology had developed to the point where castings replaced the forged turbine airfoils.

During this time period, General Electric developed the Shaped Tube Electrode Machining (STEM) process and the Electro Stream (ES) drilling process which permitted economical incorporation of straight cooling holes in solid cast airfoils. The T58, T64, TF39 and CF6 adopted this technology to improve performance and increase life.

With the advent of castings, the potential existed to 'cast in' cooling passages and eliminate the cost and time associated with drilling operations. The large engines such as the CF6, CFM56 and F404 have incorporated more complex 'cast-in' cooling designs. The larger airfoil cross-sections of the big engines permitted them to cast intricate cooling designs employing serpentine passages, turbulence promoting ribs, and internal pins to achieve more efficient convective heat transfer. The large airfoils also incorporated internal holes through cavity walls to achieve even more efficient impingement cooling. The addition of film-cooling holes produced by ES drilling, and more recently laser drilling, permits additional cooling of selected areas (Figure 4). As large blade cooling designs improved in efficiency, reduction in cooling flow was made possible. This translates to reduced fuel consumption. (Figure 5)

The TF39, CF6, CFM56 and F404 engines have been employing this type of more complex blade cooling since the late '60s. Collectively, these engines have accumulated many millions of hours of successful operation during that time at turbine temperatures above most small engines.

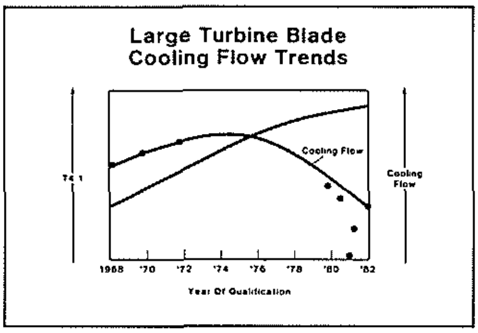


Figure 5.

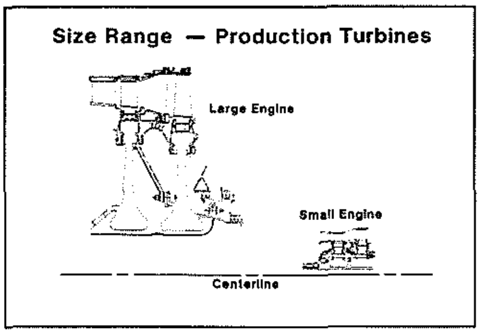


Figure 6.

The large blade features have not been directly applicable to small engines, however, thus preventing them from attaining the higher turbine temperatures of the large engines (Figure 6). Many processing difficulties are encountered when attempting to miniaturize large blade core technology . As blades become smaller, their walls and cores become thinner. The thin cores are fragile and prone to handling damage. Higher length to diameter (L/D) ratios make the cores more susceptible to deformation during casting. Removal of the core material is more difficult since the smaller passages restrict the flow of the leachant. On small blades, tolerances represent a larger percent of the nominal dimensions and die machining accuracy becomes limiting. These factors made incorporation of large blade features unaffordable for small blades (Figure 7).

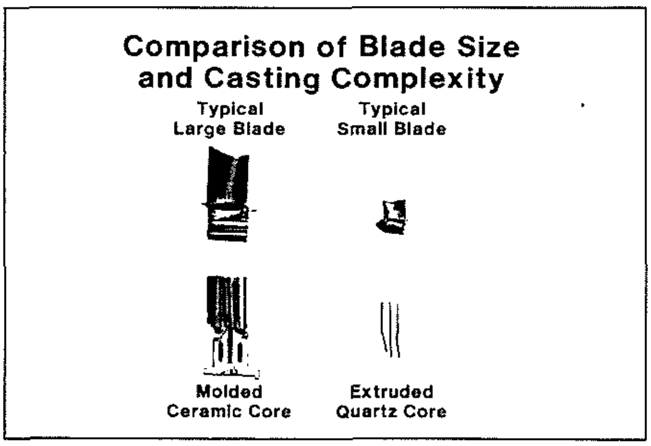


Figure 7.

After much work, the casting industry was successful in developing small diameter extruded quartz rods which could withstand the casting process and economically permit casting in the radial holes that had previously been STEM drilled. Cast radial hole cooling designs have been in production on the TF34, T700, and the late models of the T58 since the early '70s (Figure 8). Over 3000 engines have been delivered with this design and have accumulated more than three million flight hours.

In the late '70s, the addition of turbulence promoting ribs to the small leading edge radial hole of the T700 stage 1 blade was developed to permit higher operating temperature for the -401 model engine. This design was successfully qualified in 1982, and is in production today.

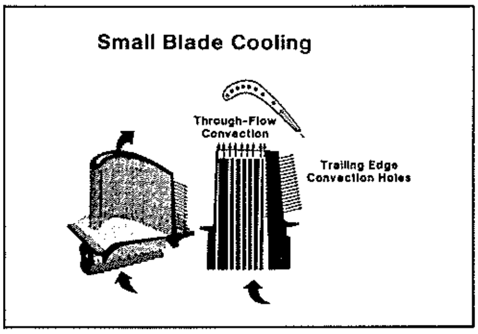


Figure 8.

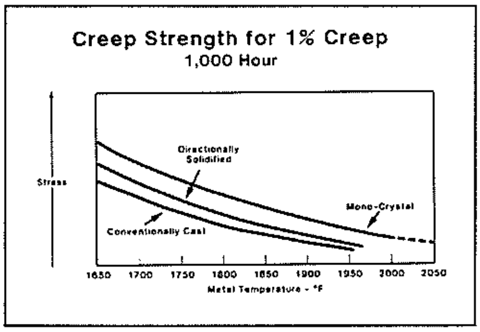


Figure 9.

The evolution of blade cooling technology has been accompanied by the introduction of improved blade materials and casting processes. The early cast nickel base alloys SEL, U500, and U700 led to the development of improved nickel base alloys SEL-15, R77 and R80 in efforts to increase high temperature creep-rupture capability with improved oxidation and corrosion resistance. R80 is currently in production for all major General Electric engines in high and/or low pressure turbine blading and has accumulated many millions of hours of successful operation. R125 was developed following R80. With nearly twice the rupture strength of R80, it has reached the practical limit for a conventionally cast nickel base alloy. It is in production on the T700 and F404 high pressure turbine blading and the F404 low pressure turbine and is performing well with over 400,000 hours of successful operation. To achieve further strength improvements, directionally solidified (DS) and mono-crystal casting processes have been developed. These processes offer significant strength improvements over conventional cast alloys (Figure 9). Uncooled DSR80 has been in production since 1980 on J85 first stage turbine blades, and radial convection-cooled DSR80 blades have been in production on TF34 stage 1 blades since 1982.

The DS and single crystal casting processes require higher molten metal temperatures and slower solidification rates than conventional casting. This results in extended exposure to molten metal for the casting core material. This situation aggravates the problems of incorporating complex cooling designs in small airfoils because the thin cores are more likely to deflect or distort as a result of the greater time-temperature exposure. To counter this, new small engine turbine blade designs will incorporate fewer but thicker airfoils which will permit thicker and, hence, stiffer cores to be used. In this way aerodynamic solidity can be maintained at the same time the higher temperature capability DS and single crystal alloys are used with the more efficient large blade cooling designs at affordable cost.

The evolution of first stage turbine vane design has been similar to that of turbine blades. The impact of airfoil size has not been as significant since the lower solidity and turning requirements for the nozzle permit fewer and larger airfoils. Early vanes were convection-cooled sheetmetal brazed assemblies. These were replaced by hollow castings. Due to the relatively larger size of the vane airfoils compared to the blade airfoils, the small engines were not initially prevented from employing the same cooling designs as the larger engines (Figure 10). During the early '70s, however, the larger engine vanes were successfully introduced to production with impingement cooling inserts in conjunction with leading edge showerhead film cooling. Their larger size readily enabled the placement of an insert within the cast chambers of the airfoil (Figures 11 and 12) The combination of impingement plus leading edge film cooling results in high cooling effectiveness with a minimum of cooling air. The large size and relatively larger distance between adjacent airfoils permitted incorporation of impingement cooling covers for band cooling. The band impingement cooling air also served to film cool the bands.

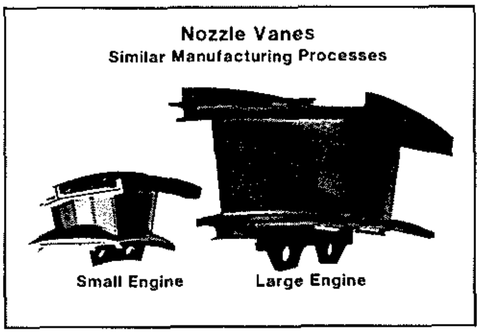


Figure 10.

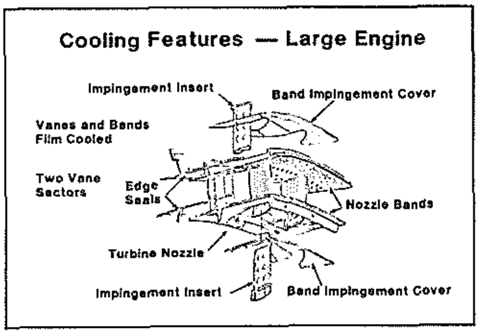


Figure 11.

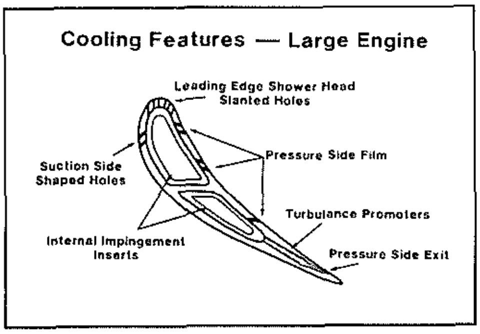


Figure 12.

Small engines like the TF34 and T700, which were being developed during the '70s, incorporated the showerhead film cooling of the larger airfoils. This design has proven itself successful in over 2 million hours of operation. The added complexity of impingement cooling the bands and the double impingement inserts in the airfoil were not incorporated in the TF34 and T700 designs (Figures 13 & 14). The trend toward further increases in turbine temperature will most likely lead designers of new small engine vanes to incorporate the more efficient double impingement insert showerhead film designs of the larger engines.

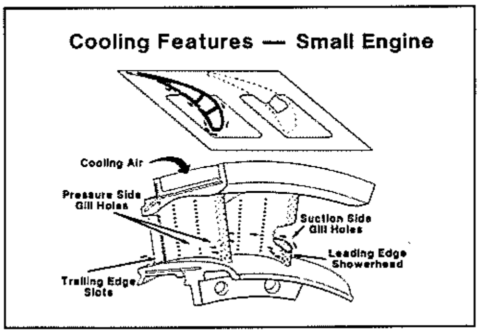


Figure 13.

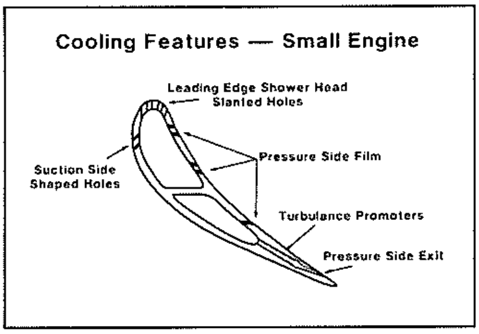
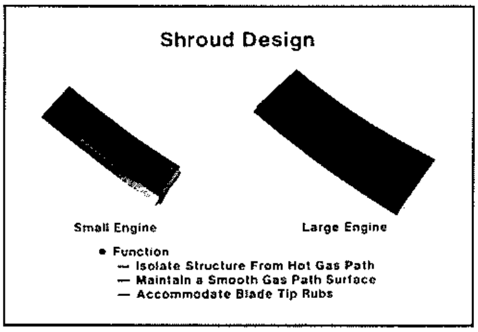


Figure 14.

4. <u>Shrouds</u>

Cooling of the turbine shrouds which form the outer flow path and rub surface for the turbine blade tips is an important feature of air-cooled turbines. Shroud cooling designs are not limited by engine size. Similar features can be incorporated in both large and small engines (Figure 15). The large engines do, however, incorporate more complex cooling designs to meet life requirements at the higher operating temperatures of the larger engines. Their designs incorporate a combination of integral impingement covers and film cooling through the shroud surface. The small engines which operate at lower temperatures incorporate impingement cooling via holes through the support structure and minor film cooling of the forward shroud surface (Figure 16).



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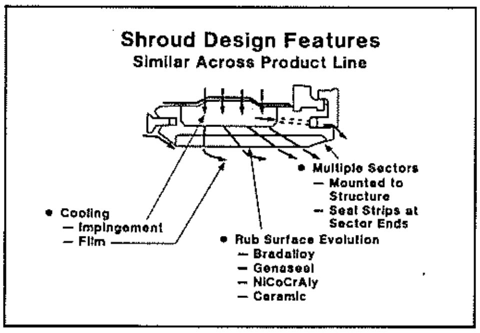


Figure 16.

The evolution of shroud designs has involved the pursuit of better rub surface material. In the late '60s, solid metal surfaces were replaced with porous Bradelloy, a sintered Nickel-Aluminum powder material, for improved thermal fatigue resistance. This material is still the principal shroud rub surface material on most General Electric engines. The need for improvements in environmental resistance and abradability led to the development of Genaseal, a sintered NiCrAlY powder, rub surface material. Genaseal is currently in service on models of the T700, T64 and F404. For lower cost and improved performance, Bradelloy and Genaseal shrouds have been replaced by solid shrouds with a NiCoCrAlY rub surface coating in new production engines like the CF6-80 and CFM56. As turbine temperatures continue to increase, it is expected that NiCoCrAlY will be replaced by ceramic material due to its greater temperature capability.

5. <u>Rotor Cooling Air Management</u>

Management of turbine rotor cooling air is extremely important in advanced air-cooled turbines. Since cooling air has a direct negative impact on cycle performance, it must be used in the most efficient means possible to minimize the impact on performance. Large engines and small engines employ basically the same techniques. To efficiently bring the cooling air on board the rotor, a nozzle accelerates and swirls the air to bring it up to the tangential speed of the rotor. This results in cooler cooling air and reduced pumping losses. Low diameter seals are employed to reduce seal leakage (Figure 17). Blade cooling air is conserved by preventing axial leakage in the blade dovetail and rim areas by means of sealing plates. Rotor cavity temperature is controlled by purge air which prevents hot gas inflow. Where possible the purge air is pre-swirled to reduce losses and lower relative temperature. To minimize rotor cavity heat input, windage covers are employed particularly on large diameter bolt circles, and multiple baffles are employed at the inner flow path rotor to stator interfaces to reduce hot gas ingestion (Figure 18).

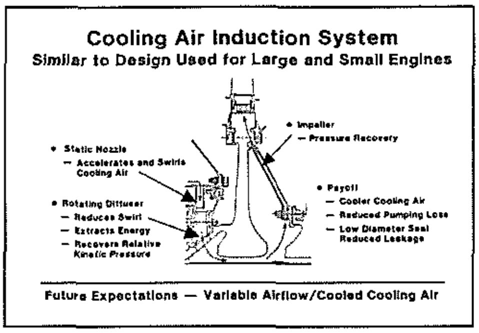


Figure 17.

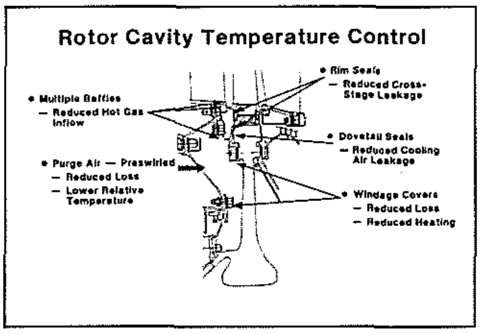


Figure 18.

Future developments in cooling air management will include variable control of cooling air quantity as a function of power level. Emphasis may also be given to reducing the temperature of the cooling air.

6. Combustor

Combustor designs for both large and small engines have evolved as the result of the need to meet the ever increasing combustor life requirements and the need to provide reduced severity exit conditions to ease the task of cooling the turbine vanes and shrouds. These fundamental design requirements impact the cooling design of the combustor. The trend for increased turbine inlet temperatures results in increased combustor temperature rise (Figure 19). The trend for increased cycle pressure ratio results in increases in the temperature of the compressor discharge air that is used to cool the combustor. Reductions in combustor pattern factor have required an increase in dilution air, leaving less air for liner cooling (Figure 20).

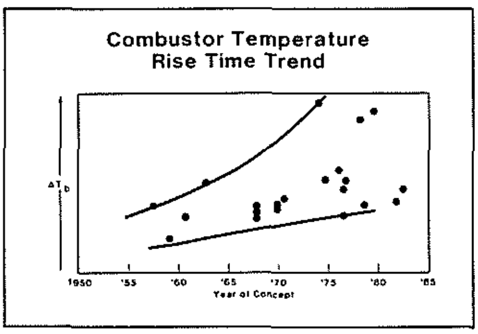


Figure 19.

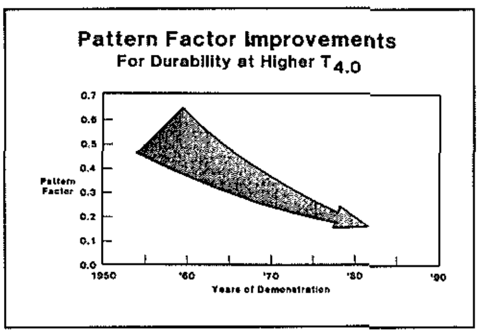
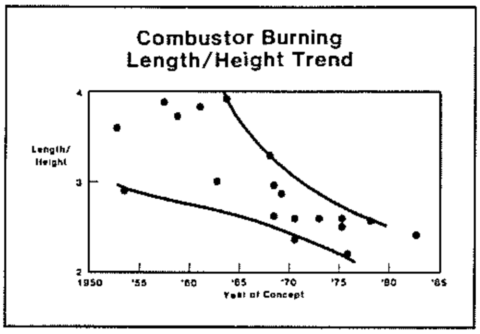


Figure 20.

A significant result of these factors which make combustor cooling more difficult is the trend toward reduced burning length to height ratio. Reduction in this geometric parameter results in less combustor surface area to cool. It also has the added advantage of reducing engine length and weight which can translate to reduced aircraft fuel consumption (Figure 21).



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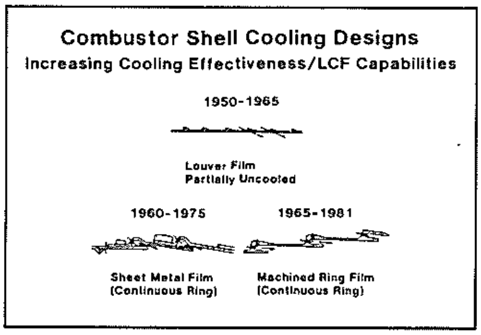

Figure 22.

Early combustor designs of the J85, T58, and J79 engines were brazed and welded sheet metal constructions which employed film-cooling louvers. Subsequent sheet metal designs for the TF39, T64 and CF6 used continuous film cooling. In the late '60s a significant advancement was made with the introduction of combustion liners machined from rolled and welded bar stock rings. The machined ring has greater strength and is much less susceptible to distortion (Figure 22). This results in longer life, more consistent pattern factor control and less deterioration of pattern factor with time/temperature exposure. Cooling is primarily accomplished by film cooling; however, impingement cooling is used in severe exposure areas.

The machined ring combustor has achieved success on many of General Electric's modern engines including the T700, TF34, CF6, F404 and CFM56. The T700 engine machined ring design has demonstrated the equivalent of greater than 5000 mission hours of service in factory testing and has performed flawlessly in over 300,000 hours of field experience (Figure 23).

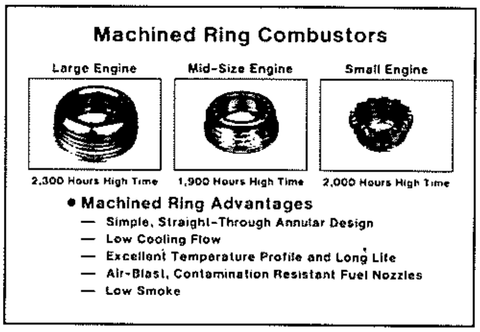

Figure 23.

7. Verification Testing

Verification testing is an integral part of the development of advanced air-cooled turbines at General Electric. Beyond the obvious instrumented engine testing to confirm the design values of stress, temperature, and cooling flow, extensive durability testing is conducted to assure early maturity prior to production. This is accomplished by running Accelerated Mission Testing (AMT). An AMT cycle is defined to exercise the engine in low cycle thermal fatigue and time at temperature in proportion to that which is expected during actual field usage. The AMT cycle is defined with a severity ratio such that one hour of testing equals from 3 to 7 hours of field usage, depending on the component. AMT testing is run on several sets of hardware to verify life requirements. T700 engines, including all hot section hardware, have demonstrated the equivalent of 5000 mission hours of life on several sets of hardware. In addition to AMT, the hot sections are subjected to many 150-hour endurance tests during their development. Turbine inlet temperature for these tests are set at red line to further exercise the turbine. To exercise the rotor structure, engine LCF testing is conducted which puts the engine through repeated zero-idle-max-idle-zero speed cycles.

Environmental testing, including salt corrosion and sand ingestion, are conducted on the engine to verify the capability of the engine to survive extreme exposure to these conditions. The turbine must be capable of operation without adverse plugging of cooling passages and must not experience unacceptable deterioration due to sand or salt corrosion.

The combination of all this testing results in a proven mature hot section design at the time of production. This is evident from the more than 300,000 hours of T700 field experience without a single hot section related durability problem. That experience contains a 2000-hour high time engine, 24 engines with over 1000 hours, and more than 150 engines with over 500 hours of field experience.

8. Certification Requirements

The helicopter industry has recently begun addressing the issues surrounding changes to the categories of engine ratings. Of main interest in both civilian and military arenas is the benefit of a short duration, high power rating for use in an emergency one-engine-inoperative (OEI) situation during takeoff. Current military and civilian rating structures recognize and have established certification requirements for 2 1/2 minute contingency/OEI ratings. These ratings generally provide power levels 5-15% above intermediate/takeoff power. Industry studies are showing that a shorter duration, takeoff OEI power level in the order of 25-35% above intermediate/takeoff power would be of substantial benefit, particularly in payload capability for category A type of operation.

Certification requirements have not been established for very short duration high power ratings by either the civilian or military rating agencies at this time. It is, therefore, worthwhile to consider the implications such a rating would have on turbine design.

Two certification tests establish important design requirements for the turbine; the 150-hour certification test and the overtemperature test. The 150-hour certification test requires operation at the various rating temperatures for specified times. Experience has shown that these tests expose the turbine to significantly greater time-temperature severity than is experienced in the field. The overtemperature test requires five minute operation at a temperature that is a specified amount above the maximum rating temperature. Both of these requirements influence the designer's selection of turbine materials and cooling flow to assure that these tests are completed successfully. The addition of a higher rating to the existing rating structure will place increased importance on turbine cooling and materials. Additional turbine cooling and/or improved materials may be required depending on the rating requirements established for this short duration high power rating.

9. Summary

The benefits of increased turbine inlet temperature and cycle pressure ratio have been, and will continue to be, the important driving forces in the design of advanced air-cooled turbines for both large and small engines. Small engines will continue to incorporate as many of the large engine cooling features as is practical. Since many of the individual turbine components currently incorporate the more efficient cooling designs, increased emphasis is being placed on cooling and leakage flow management to assure that the total chargeable cooling flow is used in the most efficient manner. The incorporation of improved high temperature materials and processes such as single crystal castings permit further increases in turbine inlet temperature. They also offer the opportunity for improved SFC in existing designs by reducing chargeable cooling air.

As further advancements in materials are developed and adapted to turbine designs they will be incorporated in production engines. Materials which show some promise are oxide dispersion strengthened and directionally solidified eutectic alloys. The use of ceramics and carbon-carbon composites are also being explored.

The incorporation of improved cooling designs and improved materials should permit small engine turbine inlet temperatures to approach the levels currently being run in large engines. The key to the successful development of these advances in turbine design is extensive durability testing to assure design maturity prior to production. The advances in turbine technology discussed represent affordable technology that will improve the life cycle costs for new engines as well as existing engines.