THE IMPORTANCE OF ENGINE EXTERNAL'S HEALTH*

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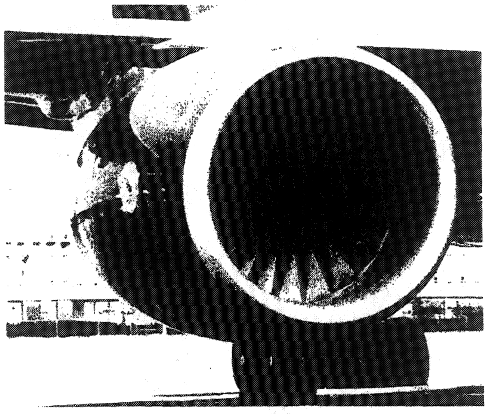
ABSTRACT

Engine external components include all the fluid carrying, electron carrying, and support devices that are needed to operate the propulsion system. These components are varied and include: pumps; valves; actuators; solenoids; sensors; switches; heat exchangers; electrical generators; electrical harnesses; tubes; ducts; clamps and brackets. The failure of any component to perform its intended function will result in a maintenance action, a dispatch delay, or an engine in flight shutdown. The life of each component, in addition to its basic functional design, is closely tied to its thermal and dynamic environment. Therefore, to reach a mature design life, the component's thermal and dynamic environment must be understood and controlled, which can only be accomplished by attention to design analysis and testing. The purpose of this paper is to review analysis and test techniques toward achieving good component health.

Keywords: Engine, External, Components, Thermal, Vibration and Durability

Figure 1. Engine on wing



1. INTRODUCTION

Aircraft engines are not unlike their automotive counterparts in that they are connected with many components such as pumps, tubes, wires, and controls to perform the many operational functions required of aircraft or automobiles in addition to providing propulsion. A look underneath the fan cowl or the core cowl of a modern aircraft gas turbine engine is as bewildering as a look beneath the hood of your car with all the electrical and mechanical gadgets needed for engine control, environmental protection, and passenger comforts. The engine provides power by converting chemical energy from fuel into mechanical and electrical energy for propulsion of the aircraft and control of the many systems beneath the cowls and within the fuselage. Engines produce heat and create vibrations as a result of these energy conversion processes which influence their own design,

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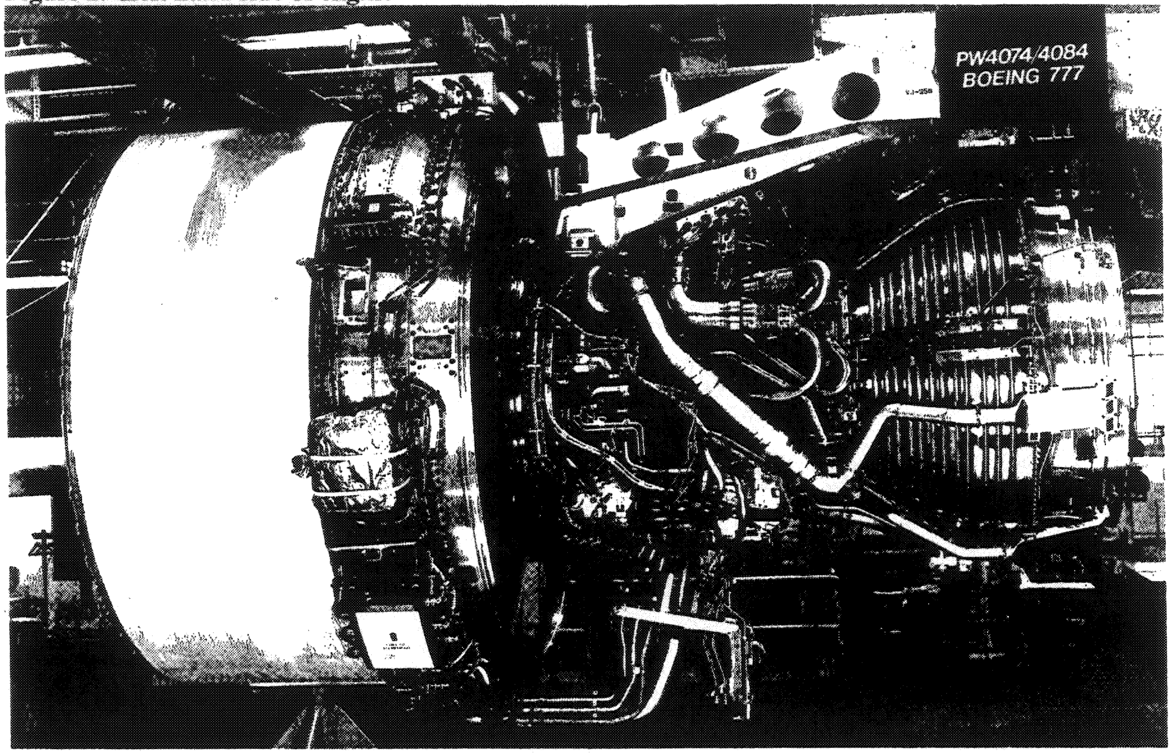
*Paper presented at the Seventh International Symposium on Transport Phenomena and Dynamics of Rotative Machinery (ISROMAC-7) in Honolulu, Hawaii, on Feb. 22-26, 1998.

the design of external components, the design of the aircraft, and the design of the systems needed to accommodate passengers.

The objective of this paper is to address the thermal and dynamic aspects of the external components to achieve acceptable in service component life. Analysis and test techniques will be discussed that have been used successfully by the Nacelles, Externals, and Controls Component Center at Pratt & Whitney (P&W) in designing propulsion systems for modern commercial aircraft. While specific terms are used in the industry to describe components such as the nacelle (inlet, fan cowl, thrust reverser, core cowl, nozzle and plug), engine build up (EBU - components needed to operate systems on the aircraft), and engine externals & controls (components needed to operate the engine), for the purpose of this paper the terms "components" and "externals" will be used as generic terms to describe all the components outside the engine case and within the nacelle. The passenger seldom sees any engine components except the fan blades when looking into the inlet or at the nacelle structure. Figure 1 shows the typical view as seen by the passenger. For a look at the complex externals beneath the cowls, Figure 2 shows the engine's left hand side externals and Figure 3 shows the right hand side prior to nacelle installation.

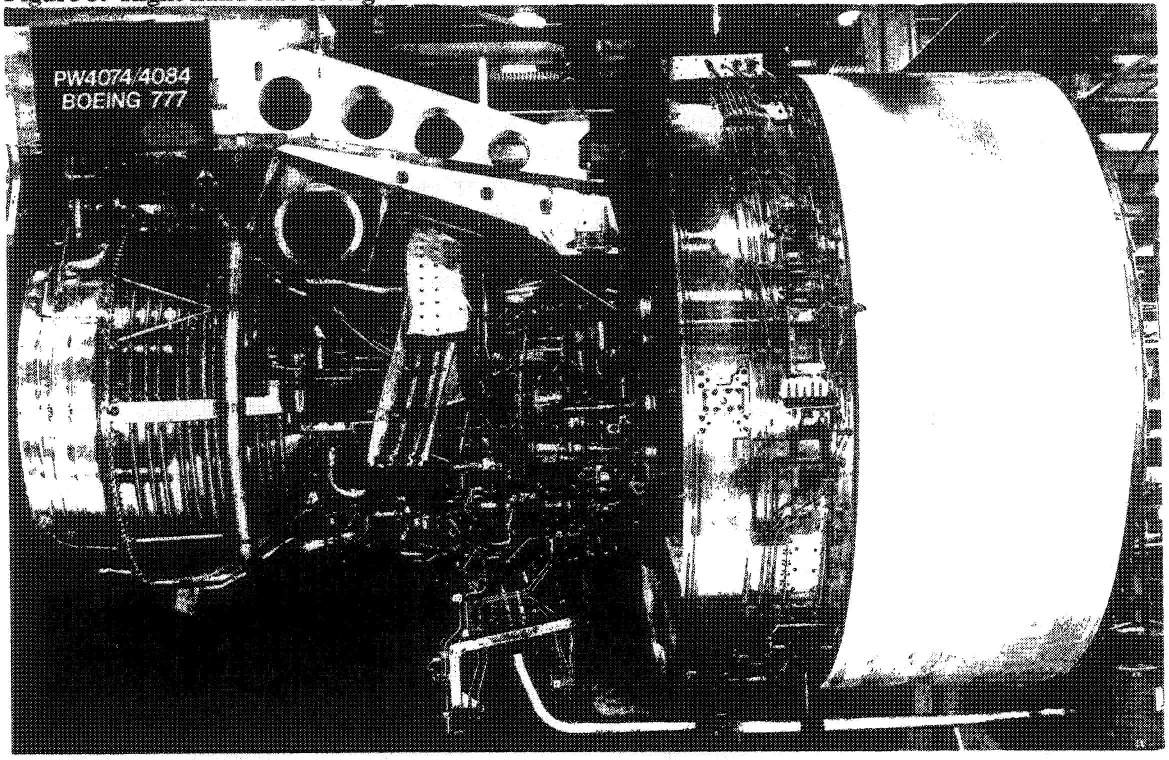
Figure 2. Left hand side of engine



The customer requirement for extended range operation with two-engine airplanes (ETOPS) demands high component reliability. Whenever a commercial twin engine airplane is more than one hour from an adequate airport, FAA regulations require that the aircraft be ETOPS certified. Demonstrated design and in service reliability is necessary to achieve this certification. The most modern twins, like the B777, were designed to achieve ETOPS at "entry into service" (EIS). To earn ETOPS certification at EIS, the FAA imposed Special Conditions which "raised the bar" for component reliability [1,2].

The importance of good externals health is as critical as the health of the engine because the externals and the engine work together to provide the complete propulsion package. Redundancy and/or long life is designed into each critical system and component of the propulsion system. However, some components will fail because of wear or other causes which will result in a maintenance action, a schedule delay, or an in flight engine shutdown. Each of these actions costs time and money to the airline operator and to travelers not to mention the loss of good will. Therefore, it is imperative that the engine and the externals be designed as a completely reliable propulsion package.

Figure 3. Right hand side of engine



2. THERMAL CONSIDERATIONS

Heat transferred through the engine cases is the primary heat source contributing to external component temperatures. The externals receive this heat via each of the three fundamental modes of heat transfer - conduction, convection, and radiation. The engine cases range in temperature from inlet air temperature at the face of the fan to well over 650C in the engine hot section (high speed compressor, burner and turbines). The hot cases transfer heat to the adjacent external air which then transfers heat to the externals. If the components are mounted to the cases or if the components are in close proximity to the cases, heat is readily transferred by conduction and radiation. Typically, the engine hot section cases form the inner boundary for the core compartment which is covered by the core cowl. The fan case provides the inner boundary for the fan compartment which is covered by the fan cowl.

The majority of externals are mounted in the same region as the engine gearbox although many other components are mounted where there is adequate space or near the point of their use to minimize the weight of the installation. The placement of externals can be a complex problem as space is often limited, and hot temperatures often dictate the placement of some components in cooler regions for reliability. Other sources of heat can result from engine flange leakage; from hot oil, air , and fuel tubes; from heat exchanger exhaust; and from electrical heating.

Two primary variables - environmental air conditions and engine power conditions - affect the engine case heating which, in turn, influences the external component temperatures. Environmental air conditions range from extreme cold to hot in the atmospheric transition from ground level to the highest flight altitude. The engine breathes this air to burn the fuel and produce power. To fly the airplane, the engine must produce power to meet the requirements for taxi, take off, climb, cruise,

decent, approach, landing, and stoping(thrust reverse.) During any commercial flight profile or mission, the engine typically experiences two thermal cycles while meeting these power requirements, one for the take off, climb, cruise, and descent, and one for the thrust reverse. Finally, the components are affected by the shutdown phase of the engine when internal heat is transferred outside the engine while cooling, called "soak back."

3. DYNAMIC CONSIDERATIONS

The vibration inputs to the externals result primarily from the engine rotors. Other inputs can result from noise and from fluid mechanics associated with tubes, ducts, inlets, vents, valves and pumps. The engine rotor speed inputs are readily available from the engine performance predictions whereas the other inputs tend to be more subtle. Each of these inputs needs evaluation during the engine and component test phases to assure design accommodation.

Engine rotors are carefully balanced within production acceptance limits prior to shipping. Each engine has vibration pickups to monitor rotor imbalance. This monitored information is sent to the onboard maintenance computers for maintenance evaluation. As the engine operates between start up and the maximum rotor speeds, imbalance will be transmitted as a forced vibration to the external components , which could cause some components to resonate at their natural frequency or other harmonic. The aging of an engine usually increases the dynamic inputs to the externals. For good durability, components must be designed to tolerate rotor imbalance and to have resonance frequencies outside the engine speed range and away from engine rotor harmonics.

4. COMPONENT DESIGN

The careful identification of a component's functional requirements, and the precise execution of its design to meet these requirements are the keys to good component performance and durability. To meet Pratt & Whitney's goals for superior on-wing component performance and durability, P&W has created the generic document, PPS2000 - purchase performance specification - and a second document, the "specific" PPS [3]. Together these documents define the requirements a supplier must meet when producing any component. In addition, the FAA has defined a 36 point checklist that each component must complete to satisfy the airworthiness requirements for certification. The thermal and the dynamic requirements are spelled out in these documents.

The materials selected for a component must accommodate its intended function while taking into consideration the component's environment. For example, if the component's function is to generate electricity, then certain materials common to generators such as winding and bearing materials are likely to be chosen. The housing, on the other hand, may provide a choice from aluminum, titanium, or steel. If the generator uses electronics for control, these devices generally have a limited choice of materials with severe temperature limitations. Electronics typically require special cooling in order to survive the heat generated within the unit, as well as the heat from the environment.

The specific placement of the component on the engine influences the severity of its environment. If the component is placed in a hot region of the engine compartment it may need cooling; however, if a cool region is selected, passive cooling may suffice. So why not place all components in a benign thermal or dynamically quiet region? Although desirable, limited space often prohibits the placing of all components in the same region, and those components requiring mechanical power to operate such as pumps and generators must be mounted on the engine's gearbox. The choice of gearbox location, either on the fan or engine core, is the result of a complex rationalization of aerodynamic, structural, thermal, weight, and cost considerations that will not be discussed here. However the result sets the stage and limits the design choices available for component placement (most P&W installations use the core mounted gearbox).

The thermal preference for component placement is in or near the forward compressor region, away from the hotter turbines, or on the sides or bottom of the engine, away from the hotter top region of the compartment. The dynamic preference is to mount components rigidly to the case; but again space, available attachment points, and thermal considerations may not permit this. To accommodate the need to mount components, many are placed on brackets attached to the limited

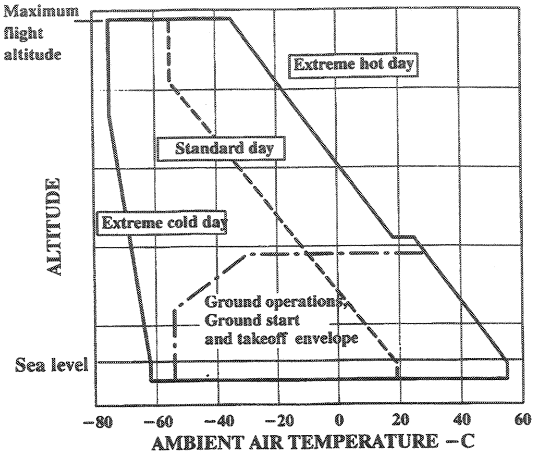
case attachment points. These brackets will separate the component from the hot cases and provide thermal isolation but must be designed with appropriate stiffness to meet the dynamic requirements.

The life requirement for a component is usually specified in the PPS. While it is desirable to have each component last the life of the engine or the airplane, the state of the art in component design has not reached this level for all components and thus life limits are specified for those components. It should be noted that some components can experience early life failures or have infant mortality. This characteristic is totally unacceptable and P&W requires that components be designed and tested and the manufacturing processes demonstrated to avoid this shortfall prior to entry into service.

5. THERMAL REQUIREMENTS AND ANALYSIS

The fundamental environment for an aircraft engine is the atmosphere. An example of the typical atmospheric temperature extremes is shown in Figure 4 as a function of altitude.

Figure 4. Engine operating envelope



A component must operate within these temperature extremes. Since material life/component life is a function of its time exposure to temperature and other loads, the definition of the aircraft flight profile must also be specified.

Figure 5 shows a typical flight profile for a commercial airplane. The engine temperatures and the subsequent component temperatures stem from the

Figure 5. Flight profile

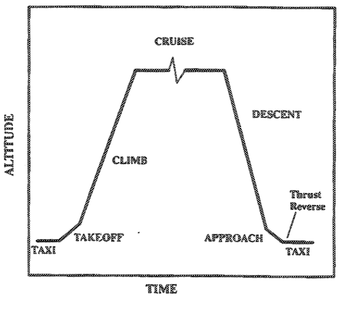
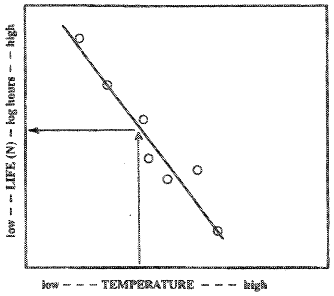


Figure 6. Material life vs Temperature



engine power conditions associated with the aircraft flight profile and the atmospheric conditions. MIL-STD-810C describes generic requirements for addressing a component's high and low temperatures and thermal shock [4]. To satisfy these requirements , the component's temperature environment is calculated according to its physical placement within the engine compartment at each flight segment. These temperature predictions are obtained primarily from test data or calculations as necessary. Since daily temperatures are infinitely variable, a simplified model is used based on an analysis of the atmosphere and the flight profile. Component temperatures are calculated assuming that 85% of the thermal exposure is at standard day atmospheric conditions, 15% at maximum hot day conditions, and 1% at minimum cold day conditions. To complete this time exposure calculation, the time at each flight segment must be determined from the flight profile. This information is then used to determine the component's exposure to temperature. This method of determining a component's temperature exposure is obviously more complex than just identifying the component's maximum temperature - a method that is sometimes used, but insufficient.

For many materials, a life curve can be plotted on a temperature versus time basis to indicate a locus of failure points. These curves are generated by testing the material at temperature and load conditions until the material fails (see Figure 6). Failure of the material is defined according to its use: creep limit, weight loss, tensile strength , dielectric strength and deformation. Since materials in jet engines experience a wide range of temperatures distributed over a flight mission, the cumulative loss of life due to the distributed temperature exposures can be accounted for by application of the linear cumulative damage rule known as Miner's Rule [5]. This rule, which applies to many common aerospace materials, is presented as:

$$R = \sum_{i=1}^{m} \frac{\Im_i}{L_i} \qquad\qquad Life = \frac{\sum \Im_i}{R}$$

R is the portion of life consumed at the conditions (1 is 100%); L_i is the life of the material at temperature i as derived from the life curve (Figure 6), and $\Im_i$ is the time spent at temperature i.

Consider the following example. A part spends 400 hours at 200C and 200 hours at 260C. A life curve for the part material indicates that its life at 200C is 800 hours and its life at 260C is 600 hours. The calculations are shown as :

$$R = \frac{400}{800} + \frac{200}{600} = 0.83 \qquad\qquad Life = \frac{400 + 200}{0.83} = 723\, hours$$

These calculations show that 83% of the life was consumed at the conditions and that the life was 723 hours. If this calculated life does not meet the specified life requirements, then a redesign would be necessary.

This method of accounting for a material's thermal life, which sometimes can be extended to the component itself, has been found to be quite useful [6].

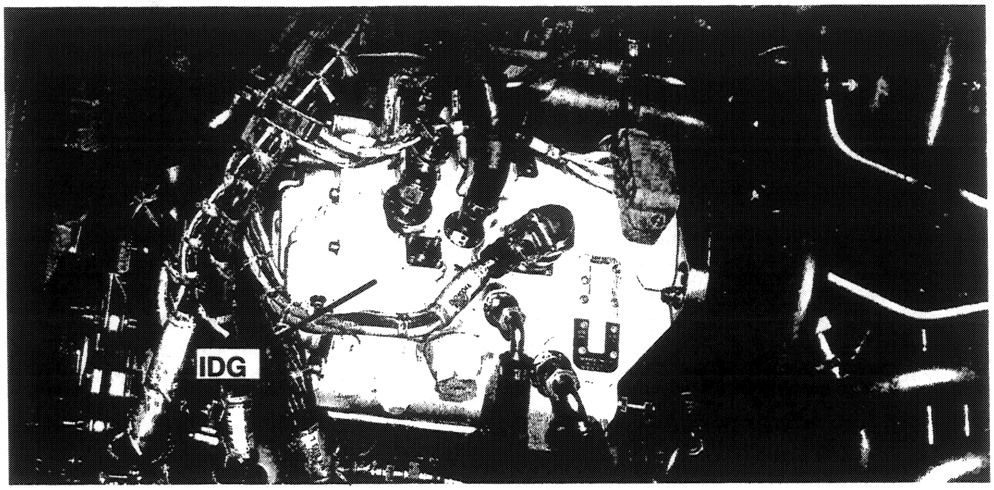
6. DYNAMIC REQUIREMENTS AND ANALYSIS

The vibration environment, used for design and development testing of a component, is also defined in MIL-STD-810C. The component, when exposed to this environment, must survive without structural damage or wear beyond service limits over the component's life. The test item is vibrated along each of the three orthogonal axes at the four most significant resonances found from a resonance search. Resonances are defined as output over input greater than two. The input level at the mounting point is usually 20G at frequencies up to 3000 Hz. The mounting of the component must duplicate the installation on the engine; i.e. brackets, clamps, etc.

Tubes, brackets, and clamps perform seemingly ordinary functions, but the design of these components to withstand the loads and thermals of the aircraft engine can be quite challenging.

These components cannot be designed as separate entities. They must be designed integral to the systems they support meeting the stiffness requirements to avoid resonances within the engine speed range, while avoiding unacceptable thermal stresses yet satisfying fatigue strength requirements, as well as static stress limits.

Figure 7. Generator (IDG) installation on engine



Electrical wires must also be routed and retained to avoid failures due to dynamics, this includies wires external and internal to the component. The best way to clear wire vibration problems is to shake the component in the three orthogonal directions over a range of frequencies and accelerations specified in the PPS and monitor the wires for motion. During the exposure to this environment, the wires must not vibrate in any manner that may lead to eventual damage when extrapolated over the component's life.

7. COMPONENT COOLING REQUIREMENTS

Initially, a component's temperatures are predicted based on an analysis of its environmental conditions or from test measurements for similar installations scaled to the maximum environmental design conditions. Two requirements are then considered when determining if dedicated cooling is needed. The first is the need to meet the component's design life and the second is based on the need to have adequate thermal margin to pass certification flight tests. If the temperatures are predicted within 28C of a passively air cooled component's maximum design temperature, then cooling is applied. Because weak and variable flow fields exist within the core compartment, experience has demonstrated that air cooled component temperatures are often difficult to predict accurately(this is an area where more sophisticated analysis tools are needed) [7]. However, the use of the 28C margin has produced excellent certification results and has resulted in improved component thermal lives. For fuel or oil biased components, the temperature variability is not as great; therefore, an 11C margin is used as the criteria for determining cooling needs. For fan compartment mounted components, where the temperatures are not as hot or variable, an 11C margin is also used as the determining factor for all components.

8. ENGINE TEST VERIFICATION

The successful completion of component rig tests and engine tests is a very important part of the design process. It is this testing that provides the confidence and verification to insure that design requirements for each component have a high probability of being achieved. The component rig test requirements are defined in the PPS and MIL-STD-810C, and the engine test requirements are defined in FARs Parts 25(Certification Flight Test) & 33(Certification Engine Test.) Prior to these certification tests, P&W conducts some very important design tests - the engine shake rig tests and the engine endurance tests.

The engine shake rig is basically an engine case structure that receives input from an electrodynamic exciter [8]. This rig is built with "all" the externals and with accelerometers and strain gauges. The externals are then excited with twice the rotor imbalance throughout the appropriate frequency range. The accelerometers will show whether the component vibration levels are acceptable and the strain gauges will record the stress levels as a result of the vibration. Typically vibratory stress levels below 35 mega Pascals will insure infinite life. Design modifications are employed as necessary.

The engine endurance tests are the most difficult tests and expose the externals to all the engine's characteristics. The engine endurance tests are designed to put time on the externals at the maximum operating conditions - temperature, pressure and rotor speeds. The build of these engines is with all the externals operational. One important dynamic feature P&W adds to these tests is to conduct them with twice the rotor imbalance of the production acceptance limit. The external components are fitted with thermocouples and dynamic probes , but the primary purpose of these tests is to determine if any remaining flaws exist prior to entering certification. To meet the special conditions for ETOPS, the components must also pass a 3000 cycle engine test and a 1000 cycle flight test - a cycle refers to the excursion between idle and high power.

9. FINAL REMARKS

The engine externals encompass a huge number of components that are designed and demonstrated through testing to have the high reliability needed for modern commercial aircraft. Parts counts reach into the hundreds for tubes , hoses (400) and brackets (700). About one hundred control system's components are needed and EBU and nacelle components add a few hundred more. Each of these components are secured with thousands of fasteners. Needless to say, this is a formidable task to design and qualify each of these parts which demands the working together of many aircraft, customer, engine and supplier engineers to achieve the design goals and satisfy the certification requirements.

As a result of this paper, it is hoped that the importance of the external's component reliability, being as critical as that of the engine, is better understood and that the attention to design and test detail is the key to controlling the thermal and dynamic environments needed for high component reliability.

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NOMENCLATURE

R	The fraction of life consumed at the conditions.
$\Im i$	The time spent at temperature i.
Li	The life of the material at temperature i.
i	An individual temperature.
m	The last individual temperature.