Engine Life, Usage, and Cycle Selection

M. L. Roberts*
General Electric Company, Evendale, Ohio

Life-limiting failure modes in aircraft turbine engines are reviewed with examples of how they are considered in the preliminary design process. Creep and rupture life calculations are analyzed in some detail to show their impact and the approximations that go into them. The problem of predicting low-cycle fatigue life is discussed, together with the possibility and desirability of improving present methods.

Introduction

LIFE problems in engines are insidious. We find performance problems as soon as an engine is tested, but life problems often do not appear until years later when hundreds of engines are in the field.

Over the years, almost every manufacturer has had life problems, resulting in strenuous activity by engine companies and sponsoring agencies first to solve the immediate problems and then to improve life prediction methods. A complicating factor in military engines is that the duty cycle actually flown can be quite different from the design duty cycle, because of the need to develop airplane tactics and engine usage after the engine is developed. Components which would have functioned satisfactorily under the design duty cycle develop severe life problems under different duty cycles. Major modifications are needed, costs rise, and vigorous efforts are made to solve a major problem that would have been routine if confronted early in the design cycle. Engine manufacturers devote a large effort to life analysis and prediction as part of the detail design phase. It has been suggested that more emphasis should be placed on life requirements and possible duty cycle changes during preliminary design in order to evaluate their effects on cycle selection and overall system performance. This paper reviews the General Electric Company's approach to this problem, some typical results, and some conclusions that can be drawn from this work.

Mechanical Design Requirements for Gas Turbine Engines

Consider first the major mechanical design requirements that must be satisfied in engine design (Table 1).

Typical strength requirements to avoid rotor burst, contain internal pressure, and transmit thrust force to the airframe are related to limit loads (i.e., the maximum loads that are expected to occur during the life of the engine). As such, these requirements are independent of time and are routinely considered in sizing the engine during preliminary design. They are met by using well-developed elastic analysis methods to calculate the stresses, which are then evaluated against material yield and ultimate strengths. If the yield or ultimate strength is exceeded, the part must be redesigned. By and large, the preliminary design process is accurate enough to size components for strength, and avoid nasty surprises in the final design.

Similarly, the stiffness needed to maintain blade, vane, and seal clearances and to avoid component and system vibration problems are "worst-case" requirements, which are also evaluated during preliminary design with somewhat greater effort. A beam and spring model of the overall engine system is used to evaluate system critical frequencies and move them out of the operating range. It is also used to evaluate relative deflections caused by maneuver and unbalance loads and keep them within bounds. Here again, we are dealing with "worst-case" operating points and, while we are sometimes not as successful in avoiding vibration and deformation problems as we are in avoiding strength problems, the preliminary design work is usually sufficient to allow us to solve them without a major redesign.

The life-limiting failure modes are another story. Being time dependent, they require consideration of the planned engine duty cycle, i.e., the mission mix to be flown. Furthermore, the failure mechanisms are distinctly different and related to different portions of the operating cycle.

High-cycle fatigue can be passed over quickly. This is the classic fatigue failure at 10^5-10^7 cycles of alternating stress. This has been studied for over 100 years. The gross stress is elastic and the driving force is usually a local vibration. The solution to the problem in gas turbines is to eliminate the vibration.

Low-cycle fatigue is a relatively new problem caused by cyclic plastic strain.[1] Failure occurs in less than 10^5 cycles. In this failure mode, component stresses are high enough to cause the material to yield on the loadup part of the operating cycle and then yield in the reverse direction on load removal or reversal. The material is then repeatedly cycled through a sequence of plastic strain reversals. Experimentally, it has been shown that the amplitude of plastic strain reversal correlates well with the number of cycles to failure. In gas turbines, low-cycle fatigue is usually caused by thermal stress induced by temperature gradients. A typical example is the temperature gradient in a turbine disk. During operation, the rim is hotter than the bore, putting the rim into compression and the bore into tension. On shutdown, the rim cools faster than the bore and goes into tension. If the temperature differences between bore and rim are sufficiently large, the rim or bore will yield alternately in tension and compression and fail in low-cycle fatigue.

Table 1 Turbine engine mechanical design requirements

Strength	
	Rotor burst
	Internal pressure
	Thrust
Stiffness	
	Clearances
	Vibration
Life	
	High-cycle fatigue: 10^5-10^7 cycles
	Low-cycle fatigue: up to 10^5 cycles
	Creep and stress rupture
	Crack propagation

Presented as Paper 77-956 at the AIAA/SAE 13th Propulsion Conference, Orlando, Fla., July 11-13, 1977; submitted July 26, 1977; revision received Dec. 2, 1977.

Index categories: Powerplant Design; Airbreathing Propulsion; Structural Durability (including Fatigue and Fracture).

*Manager, Advanced Structural & Life Analysis Methods, Aircraft Engine Group.

The problem is aggravated by stress concentrations, such as bolt holes, dovetails, notches, sharp radii, etc., that mar the otherwise smooth contours of our parts because they are needed to satisfy manufacturing, assembly, maintenance, and other functional requirements. It is this problem area that generates life requirements that have impinged on engine performance by requiring changes in design or operation that reduce thrust and increase weight.

Creep and stress rupture, though time-dependent, are quasistatic phenomena in the sense that, at absolute temperatures on the order of half the melting temperature, metals will deform continuously under a steady load.[2] Failure can occur through excessive deformation, or creep, or actual rupture. Creep problems were recognized in the design of steam turbines and became an early design criterion for gas turbines. In aircraft gas turbines, rapid and frequent changes of temperature and stress complicate the creep problem, but that is beyond the scope of this discussion. The treatment of creep in preliminary design will be discussed again shortly.

Crack propagation was long considered part of the fatigue process, but development of linear fracture mechanics analysis, to the point at which it was possible to predict crack propagation under cyclic loading, made it feasible to divide the fatigue process into crack initiation and crack propagation phases. It also made possible a heated controversy over the feasibility of designing gas turbines for the undetected flaw, that is, the largest flaw that would go undetected with present-day nondestructive inspection (NDI) techniques. This requirement is part of current practice in airframe life analysis. After much study at General Electric, it was concluded that the weight penalty that would have to be paid to meet this requirement would be prohibitive. The rarity of this type of failure in engines can be attributed to the highly refined process control used for gas turbine materials. As a result, at General Electric, crack initiation in rotating parts is considered failure and no life increment is considered for crack growth.

How do these life requirements affect engine cycle selection? Essentially, through three parameters: 1) turbine inlet temperature, T_4, 2) cooling air requirements, and 3) thrust/weight ratio. These parameters, however, are not independent of engine usage, but must be determined within the context of a prescribed mission mix or duty cycle. To the extent that life requirements are not adequately reflected in the choice of these parameters, it may be necessary to pay a thrust penalty by running the engine derated to obtain adequate life.

Cooled Turbine Blade Design

As an example of the treatment of life requirements in the preliminary design process, we can review the design of a cooled turbine blade for an advanced military engine. Figure 1 shows a typical General Electric cooled turbine blade whose complexity is apparent.

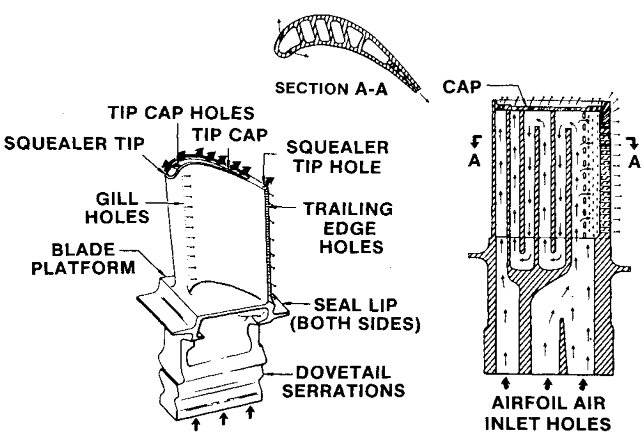


Fig. 1 Stage 1 high-pressure turbine blade.

The design duty cycle for the engine is comprised of the following four missions: 1) long-range (high Mach number, high altitude); 2) short-range (transonic Mach number, low altitude); 3) ferry; and 4) training.

The mission mix that makes up the duty cycle is shown in Table 2. The engine is designed for 4000 h of life against this duty cycle. To simplify the analysis, the duty cycle is broken down into its constituent segments and similar legs are grouped, as shown in the fourth column of Table 3. In this way, we simplify the duty cycle into twelve distinct operating conditions.

The design process for determining the creep life of a cooled turbine blade is summarized in Table 4. The process shown iterates engine cycle cooling air flow, cooling air temperature, blade temperature, and blade creep life until the blade life goal is achieved.[3]

The assumptions made in this analysis reveal its limitations. First, life is defined as either 0.2% plastic creep or rupture, whichever is least. Second, only centrifugal stress is calculated. "Experience factors" are used to account for bending and thermal stress. Third, the cooling effectiveness factor is based on prior experience. Fourth, only average temperatures and stresses on a cross section are used.

How successful is this approach? Excluding radical changes in cooling or structural technology, this approach is quite successful. General Electric has designed a numberof

Table 2 Preliminary duty cycle[a]

	Total time, %
Long-range (high Mach no., high altitude)	20
Short-range (transonic Mach no., low altitude)	10
Training	65
Ferry	5

[a] Study engines are designed to meet 4000 h of life against this duty cycle.

Table 3 Preliminary duty cycle, 4000 h total life

Mach no.	Altitude, 1000 ft	Power setting	Hours	
0	0	ground idle	236	
0.2	0	mil.	47	
0.8	0	mil.	24	
0.9	15	mil.	93	
0.9	25	mil.	93	280
0.9	36	mil.	70	
0.9	36	part load (PC-47)	1989	
0.8	36	max. aug.	24	
1.0	36	max. aug.	25	
1.4	36	max. aug.	3	
2.0	36	max. aug.	8	76
2.0	35	max. aug.	4	
0.9	25	max. aug.	1	
1.6	36	max. aug.	11	
0.9	0	part load (PC-45)	110	
2.0	55	part aug. (PC-60)	353	
1.2	10	part aug. (PC-60)	132	
2.0	55	max. aug.	17	
1.2	10	max. aug.	3	
1.0	36	max. aug.	26	74
0.9	23	max. aug.	14	
1.2	36	max. aug.	14	
1.0	36	mil.	37	
1.2	36	mil.	73	198
0.9	25	mil.	37	
0.8	36	mil.	33	
1.6	36	mil.	18	
0.8	23	flight idle	16	32
0.4	10		16	
0.4	0	part load (PC-35)	473	
			4000	

Table 4 Turbine blade life analysis method

Method of analysis – for given mission
1) Assume cooling flow, run cycle analysis for each mission leg.
2) Assume effectiveness $= (T_{gas} - T_{metal})/(T_{gas} - T_{coolant})$.
3) For chosen reference leg, calculate stress and metal temperature.
4) For every other leg, calculate delta stress and delta temperature.
5) Compute life ratios of each leg (life available/life required).
6) If total of step 5 does not meet required life, adjust metal temperature, repeat steps 3-5.
7) Recalculate effectiveness, compare to assumed value of step 2, iterate steps 2-7 for convergence.
8) For chosen cooling technology, calculate cooling flow required to obtain metal temperature. Compare to step 1 and iterate steps 1-7.

Table 5 Effect of engine duty cycle on turbine blade life

Vary duty cycle assumptions
- Original (baseline)
- Assume all long-range usage
- Assume all short-range usage
- Original mission mix type with only long-range
- Original mission mix type with only short-range

Evaluate impact on cooling flow

Evaluate life for each design against other duty cycles

Table 6 Duty cycle assumptions

	Mission mix, % time				
	Long-range	Short-range	Training	Ferry	Comments
Baseline	20	10	65	5	Original
Alt. 1	100	0	0	0	Increased severity
Alt. 2	0	100	0	0	Increased severity
Alt. 3	30	0	65	5	About same
Alt. 4	0	30	65	5	About same

Table 7 Cooling flow variation[a]

Design mission	Usage mission: Baseline	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Baseline	$(W2)_B$				
Alt. 1		$1.061\,(W2)_B$			
Alt. 2			$0.889\,(W2)_B$		
Alt. 3				$1.003\,(W2)_B$	
Alt. 4					$0.98\,(W2)_B$

[a]Chargeable cooling flow (% $W2$) required to obtain specified turbine blade metal temperatures.

production-type cooled turbine blades within the limits of cooling air flow, blade envelope, and blade weight set in preliminary design. Heroic efforts, sometimes several redesigns, may have been needed, but these involved a reallocation of resources, as the economists say, rather than a greater expenditure of weight or cooling air flow.

Now, where does a low-cycle fatigue (LCF) analysis fit into this process in preliminary design? Looking at Fig. 1, we see an extremely complex geometry and flow path, which clearly experiences large temperature gradients and thermal transients. A complete LCF analysis would require a transient heat transfer analysis and a series of stress analyses that would require more time than is available in preliminary design. How can we ignore low-cycle fatigue? The answer is that, in general, different points on the blade cross section are creep-life limited and LCF limited. For an efficient design, these lives are of the same order of magnitude. We therefore base our new designs on efficient past designs.

Table 8 HPT blade life vs usage mission[a]

	Usage mission: Baseline	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Baseline	1000	395	18,518	909	1760
Alt. 1	2511	1000	56,222	2345	4458
Alt. 2	227	104	1000	212	352
Alt. 3	1104	445	21,847	1000	1936
Alt. 4	567	227	9562	514	1000

[a]Design duty cycle = 1000 h.

Table 9 Disk life analysis

Total disk stress = mechanical + thermal
Mechanical is function only of rpm
Thermal is function of rim/hub delta – temperature:
- a) accel/decel rate
- b) heating/cooling rate
- c) cooling air temperature

Required detailed design of each engine component
For preliminary design must rely on comparative methods (previous designs)
For hardware design, detailed transient analysis must be conducted

Effect of Duty Cycle Change in Turbine Blade Life

What then does this model of the cooled turbine blade tell us of the effect of changing the duty cycle? Tables 5 and 6 show the assumed permutations of the basic duty cycle of Table 2. The relative change in cooling flow required to meet the design life is small but significant for cycle selection (Table 7). It should be noted that these changes are obtained by scaling stresses and temperatures, rather than by repeating the iteration.

Suppose, however, an optimum blade was designed for each of the standard and four alternate duty cycles (Tables 5 and 6). What would the life be if each optimized blade were then operated under each of the other four duty cycles? These lives are shown in Table 8, and the changes in life are drastic. How is this possible when only a relatively small change in cooling air flow is needed if the blade is redesigned for each duty cycle (Table 7)? It is simply that the blade metal temperatures are so high that a change of 50°F is enough to change the creep life by an order of magnitude.

How then are engine duty cycle, required blade life, and engine cycle selection related? First, we should note that engine cycle selection studies have shown that changes in the duty cycle have only a minor effect on the type of engine cycle selected for current state-of-the-art engines. On the other hand, turbine blade life directly affects engine cycle parameters by determining turbine inlet temperature (T_4) and required cooling air flow (W_2). An unrealistic combination of T_4 and design life can require excessive cooling air (W_2), which in turn will increase compressor size, engine weight, and airplane takeoff gross weight. As shown in Table 8, a change in the duty cycle, after the turbine design and cooling flows are set, can severely impact turbine life, whereas the same variation in duty cycle can be accommodated by small changes in either cooling air flow or turbine inlet temperature during the turbine design phase. A systematic study of possible duty cycle variations should, therefore, be part of the turbine and cooling system design process. This could, in turn, affect engine cycle selection indirectly by changing allowable T_4 or minimum required W_2.

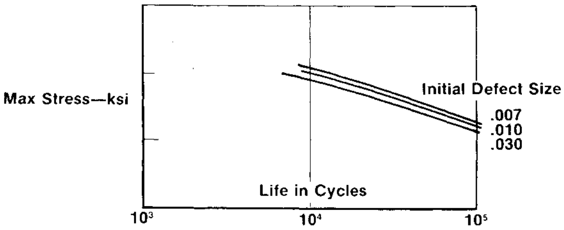
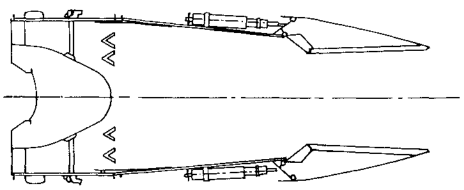


Fig. 2 Titanium disk fracture mechanics analysis.



Component	Failure Mode
Spray Bars	Low Cycle Fatigue
Flameholder	Erosion
Liner	Local Buckling
Nozzle	Rupture & Wear*
Structure	Wear
Bearings	Corrosion (Navy Applications)

* Parts that can be improved by adding weight

Fig. 3 Augmentor failure modes.

As a footnote to blade design, Table 9 summarizes the disk design process. A possible approach[4] to using a fracture mechanics approach to cycle life is shown in Fig. 2 and Table 10. This would require correlating LCF life with a hypothetical initial defect. More work is needed to explore the usefulness of this concept.

Augmentor Design

Augmentor, or afterburner, life requirements establish design and cooling requirements, given the engine operating conditions and duty cycle. Increased severity of the duty cycle can affect engine weight significantly, since augmentor weight can be as much as 25% of the engine weight.

Figure 3 shows a typical augmentor and its potential modes of failure. Here we will review only the effect of nozzle rupture life and wear life on engine weight. The components affected are the nozzle segments and seals (Fig. 4). The design duty cycle and alternates are the same as those used for the turbine blade analysis (Tables 2, 3, 5, and 6). The significant parameters are operating time at and above military power for rupture life and nozzle motion for wear (Table 11). Table 12 breaks down the baseline duty cycle and the four alternate cycles in terms of these two parameters. To assess the effect of duty cycle change on afterburner rupture life and weight, the baseline cycle is compared with each of the alternate duty cycles. Table 13 shows a typical comparison between the baseline and 100% long-range duty cycle. The table shows the Mach number, altitude, power code, and relative maximum wall temperature for the segments that make up both duty cycles. The imposed stress and required life differ for each duty cycle, as does the mode of life degradation. To attain the design life in each duty cycle, the maximum stress must be limited to the normalized stress identified by note b. Nozzle weight is inversely proportional to this stress.

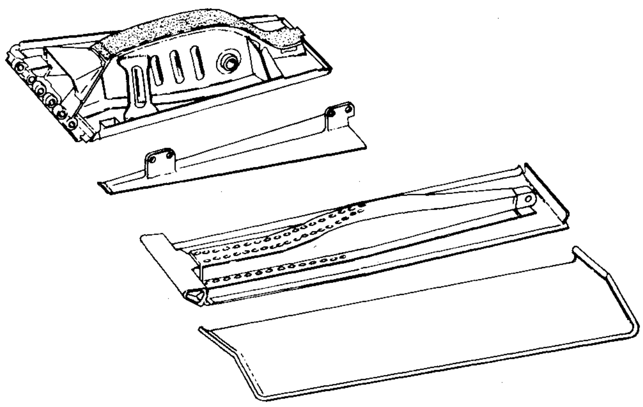


Fig. 4 Typical primary and secondary flap and seal.

This comparison is repeated for all four alternate duty cycles and summarized in Table 14 together with seal rubbing data. The separate percent changes in weight to attain design rupture life and seal wear requirements are shown. Below this are the combined nozzle and overall engine weight changes caused by changes in duty cycle. The 1.8% weight increase shown for the 100% long-range duty cycle would be a severe penalty, if, for example, we were seeking a 10% increase in

Table 10 Fracture mechanics approach to cyclic life[a]

Method of analysis – for given mission
1) Determine number of maximum stress cycles (0 to max. to 0)
2) Assume size and shape of inclusion
3) For stress resulting from standard design practices, evaluate number of cycles required to grow from initial size to critical length
4) Number of stress cycles from step 1 must be less than from step 3

[a] Component: disk or combustor.

Table 11 Augmentor mission comparison

	Missions			
	Long-range	Short-range	Training	Ferry
Operating time, min.				
Military	6.6	11.6	12	6.6
Part R/H	24.8	19.5	7	0
Max. R/H	5.5	1.26	3	0
Total MIL and above	36.9(31%)	32.4(26%)	22(31%)	6.6(28%)
Total mission	117.4	124.1	70.6	297.6
Nozzle motion				
Throttle movements	19	14	25	2
A/B lights	2	2	3	0
Flap/seal wear travel ~ P.L. change, in.	6.5	5.1	7.0	0.82
Flap/seal wear travel ~ control hunting, in.	52.4	45.9	32.6	9.4

Table 12 Augmentor duty cycle comparison

	Baseline	100% long-range	100% short-range	No long-range	No short-range
Long-range missions	408	2044	0	449	0
Hours	800	4000	0	880	0
Percent	20	100	0	22	0
Short-range missions	180	0	1803	0	396
Hours	400	0	4000	0	880
Percent	10	0	100	0	22
Composite training mission	2209	0	0	2481	2481
Hours	2600	0	0	2920	2920
Percent	65	0	0	73	73
Ferry missions	40	0	0	40	40
Hours	200	0	0	200	200
Percent	5	0	0	5	5
Augmentor lights	7800	4000	3600	8300	8200
Military hours	525	225	348	549	576
Max. R/H hours	150	187	37	164	131
Part R/H hours	485	844	586	474	417
Total hours	1160	1256	971	1187	1124
Wear travel, in.					
Due to A/B lights	19,500	13,390	9,250	20,810	19,900
Due to control hunting	99,260	107,510	82,940	101,650	96,250
Total, in.	118,760	120,900	92,190	122,460	116,150

Table 13 Augmentor rupture life

				Baseline			100% long-range		
M	Alt.	P.C.	ΔT_{wall},[a] °F	Max. stress, %	Req'd. life, h	Life used, %	Max. stress, %	Req'd. life, h	Life used, %
0.8	0	50	−779	80.5	24		60[b]	16	
0.8	36	100	−240	24.5	24		18.3	10	
1.0	36	100	−200	31.5	51		23.5	17	
1.4	36	100	−125	45.0	3		33.5	14	
2.0	36	100	0	71.5	8	66.0	53.3	41	71.0
2.0	55	100	0	28.8	21	5.7	21.5	105	15.5
0.9	25	100	−164	44.8	15		...	0	
1.2	36	100	−160	38.5	14		...	0	
1.6	36	100	−285	53.5	11	2.3	...	0	
1.2	10	100	−256	82.0	3	14.8	...	0	
1.2	10	60	−730	85.0[b]	132		...	0	

[a](max. T_{wall}) − (max. T_{wall} @M = 2.0). [b]Max. normalized stress for duty cycle design life.

Table 14 Summary – augmentor life analysis

Mission	Baseline	100% long-range	100% short-range	No long-range	No short-range
Max. rupture stress, %	85.0	60.0	80.0	97.5	100
Seal rubbing, in.	118,760	120,900	92,190	122,460	116,150
Weight adders, %					
Rupture	base	+15	+2	−5	−6
Seal wear strip	base	0	−2	0	0
Total					
Nozzle weight, %	base	+15	0	−5	−6
Weight, %	base	+1.8	0	−0.6	−0.7

thrust/weight ratio in a new engine design. Although the effect on engine life of a change in duty cycle for a fixed augmentor design was not analyzed, it seems likely that the life degradation would be as severe as that shown previously for the cooled turbine blade, as both parts were designed for creep life.

Discussion and Conclusions

From the analyses of the cooled turbine blade and augmentor, we see that a change in duty cycle without a corresponding change in component design can lead to a severe reduction in component life. In an operating environment where the final engine duty cycle is not defined until the engine enters operational service, it would seem prudent to evaluate the life of critical components over as wide a range of duty cycles as possible. The goal would be to reduce engine sensitivity to duty cycle changes. The price would be an increase in cooling air flow and engine weight with the design objective of keeping these increases small. A tradeoff study of engine reliability vs performance might be valuable in clarifying this problem.

We can sum up the life considerations that affect preliminary design and cycle selection as follows:

1) The primary obstacle to carrying out a complete LCF analysis in preliminary design is the extensive time and work needed for transient heat transfer and stress analysis.

2) Low-cycle fatigue requirements are therefore met primarily by relying on previous experience.

3) Life calculations are made primarily for creep and stress rupture.

4) Turbine inlet temperature T_4 and cooling air flow W_2 are the cycle variables most directly affected by life requirements.

5) Creep life requirements directly determine the weight of many of the hot components and, through them, the engine thrust/weight ratio.

6) Changes in the engine duty cycle without corresponding design changes in creep-limited components can reduce component life by an order of magnitude. This results from the extreme sensitivity of creep life to operating temperature.

7) The duty cycle has a minor effect on selecting the type of engine cycle for a weapon system, but it does greatly affect the detailed engine design, particularly T_4 and W_2, to meet life requirements. Thus, it can indirectly put constraints on the engine cycle operating parameters.

8) A wide spectrum of possible duty cycles should be evaluated during the preliminary design process to evaluate engine life sensitivity to duty cycle changes. This should be part of a tradeoff study of engine reliability vs performance and could affect engine cycle operating parameters.

Acknowledgment

The author would like to express his appreciation to J. R. Schwegman, F. J. Zegarski, R. J. Beavers, B. V. Sutherland, and O. T. Castells for their generous assistance in the preparation of this paper.

References

[1] Manson, S. S., *Thermal Stress and Low Cycle Fatigue*, McGraw-Hill, New York, 1966.

[2] Penny, R. K. and Marriott, D. L., *Design for Creep*, McGraw-Hill, New York, 1971, pp. 9-12.

[3] Beglinger, V. and Suter, P., "The Determination of The Life-Time of Cooled and Uncooled Gas Turbine Blades," *Turbo-Forum*, 1st ed., Brown Boveri-Sulzer Ltd., Zurich, Switzerland, May 1971, pp. 35-45.

[4] Sundt, S. A. and Sundt, C. V., "Gas Turbine Engine Disk Cyclic Life Prediction," *Journal of Aircraft*, Vol. 12, April 1975, pp. 361-365.