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Design Considerations for Duty Cycle, Life, and Reliability of Small Limited-Life Engines

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Nomenclature

a	= level of confidence
MTBF	= mean time between failures
R	= reliability
r	= failures
χ	= chi-square distribution

Introduction

DESIGN requirements, design criteria and verification methods related to preliminary design and program planning for small limited life turbine engines have significant differences from other engine technologies. Operating design life of components is defined by development test requirements, rather than mission life requirements. Interpolation between operating mission limits is required to demonstrate operating life for limited life engines rather than extrapolation of accelerated testing required for long life.

Storage life requirements are very stringent. The correlation of reliability prediction vs accelerated verification testing for engines requiring extended dormant storage is being validated.

In this discussion, I have limited this definition of "small limited-life engines" to small gas turbine engines typically applied as emergency power units for flight or ground power generation, target or reconnaissance drone propulsion, or cruise missile propulsion.

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These applications have unique requirements which cause modifications in the usual methods of design, design verification, and reliability prediction used for turbomachinery. The unique requirements are as follows: 1) short operating mission life—the actual mission can be as short as 1 cycle and ½ hour in duration; 2) relatively low cost; 3) long storage life—vehicle may be stored up to 10 years in an adverse environment; 4) minimum storage and preoperational maintenance dictated by life cycle cost considerations; 5) very high starting and operating reliability required after extended storage; 6) very short times required from start initiation to full power. This last requirement applies to cruise missiles launched from a terrain following carrier or an emergency power unit where power interruption is critical.

Each of these requirements leads to variations in the usual engine design criteria.

Operating Design Life

The operating design life for components for this type of engine is not defined by mission length. To establish reasonable design lives, the component should be divided into four categories. These are 1) high cost components; 2) critical components (critical in terms of engine or component performance); 3) parts normally discarded at disassembly (gaskets, seals, etc.); 4) other.

Design life for each of these categories is calculated by obtaining the life requirement based on the following four conditions.

a) Maximum operating time and cycles prior to engine disassembly: This must include the maximum hours accumulated during engine checkout prior to use, as this time may exceed the mission operating life. This value is the minimum applied to all categories of parts.

b) Total operating time and cycles for the design life of the engine: Normally this is the maximum number of overhaul periods multiplied by the value from a. This life is the minimum value to be applied to components in categories 1, 2, and 4.

c) Cost effective life for engine development and qualification testing: This value is calculated by totaling the test hours planned for engine development, also the total time required for qualification and dividing by number of engines assigned to these tasks. These values are used to establish life goals for components in category 1. Conversely, attainable life will determine the number of engines and spares required for development and qualification testing. During the full-scale development phase of F107 family of cruise missile engines, 3157 test hours were run with 14 engines; or 225 hrs per engine. During the qualification phase, 24 engines were built and 387 hrs of testing with 693 starts were accomplished. Therefore the average engine required 16 hrs of operation and 29 starts. Maximum engine time was 20 hrs during qualification. This effort was required to support an actual mission requirement of one start and 5 hrs of operation. The design life for components in this case ranged from 10 to 50 times the mission requirement for economical development and qualification testing. Variation within these limits is determined on a component by component basis based on cost, weight, and anticipated performance loss.

d) The purpose of extended design life on this case is to provide sufficient component usable life to allow reliable performance measurements to evaluate changes which require the use of "back-to-back" test. Small performance or life differences became difficult to evaluate when engine deterioration or build-to-build variations exceed the values being measured. This requirement applied to category 2 (critical) components. A life requirement of three times the mission would allow evaluation of two variables plus a baseline run in one test series requiring an entire mission simulation.

Engine Cost

Figure 1 indicates the relative contribution of development, acquisition, and support costs in the total life cycle cost of the F107-WR-101 engine for a 10-yr life. The preponderance of cost lies in acquisition. This is the case in most applications for short-life engines.

The hierarchy of relative importance of requirements such as fuel consumption, reliability, weight, thrust, etc. must be modified, within the constrains of the ultimate use of the engine, to place acquisition cost near the top.

Storage Requirements

The type of engine under discussion is low cost as compared to other turbomachinery, yet the cost per hour of operation is extremely high. This often implies that the nonoperating time, or storage time, is very long. Figure 2 indicates the variation in support life cycle cost based on different maintenance intervals over a 10-yr operational life for the F107 engine. Assuming little or no acquisition cost increase or reduction in reliability, the obvious conclusion is that the longer the storage interval, the lower the cost. Again referring to Fig. 1, the potential savings in support cost are equal to a substantial portion of the development cost. Therefore a large portion of the development effort should be aimed at improving storage capability rather than the normal total concentration on engine operating characteristics.

For applications which do not require immediate availability, the storage problem can be solved with sealed canisters or other protective methods and the engine designed with adequate shelf life.

For applications requiring full power output in a very short time, the problem can be approached from two different directions. The first is to provide environmental protection with a canister or sealed covers which are rapidly discarded. The second is to design the internal engine components to be resistant to the environment.

In the latter case the environmental conditions include temperature variations, barometric pressure changes, air pollutants, and plant and animal life.

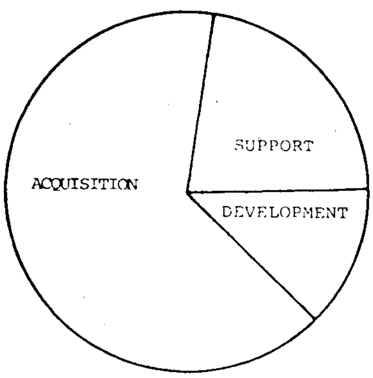

Fig. 1 Relative contributions to life cycle cost for the F107 engine[1].

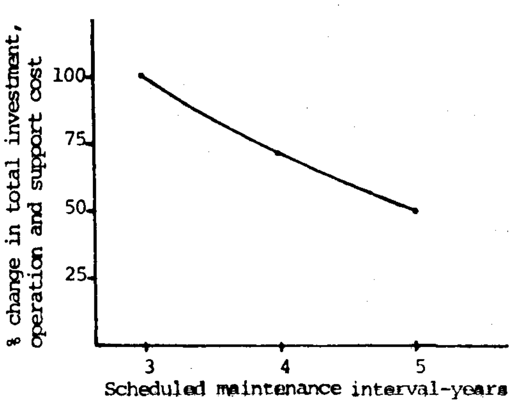

Fig. 2 Percent change in support cost vs maintenance interval.

Limited environmental testing on the F107 engine identified three problems associated with moisture. The first being corrosion, which was controlled by surface protection, mating parts with similar electrical potential and conductive interfaces.

The second was water accumulation where large quantities of water accumulated in low spots. Although not demonstrated by test, the list of potential failure modes is impressive. Examples include damaged components due to freezing, ice clogged control sensors, and even potential surge problems during start due to blockage in the flowpath.

The third problem identified was frozen water droplets on internal surfaces which prevented rotor rotation or delayed rotor rotation so that the required start-to-full-power times could not be met. This problem is not limited to just the blade tips, but could exist in seals, bearings, gears, and accessories.

Based on these problems, the production version of the F107-WR-101 utilizes airframe supplied covers and a desiccant system to provide environmental protection.

Reliability Requirements

The unusual requirements discussed earlier result in difficulties in predicting and verifying system reliability.

For long-life engines, life verification is accomplished by running accelerated engine cycles and elevated temperature cycles to provide a basis to extrapolate engine life. For limited-life engines, the full operating life is run at the corners of the operational envelope and life is interpolated. Expenditures for massive life analysis and experimental data acquisition normally required to extrapolate life for long-life engines must be examined for cost effectiveness when applied to short-life engines.

Storage reliability is a far more challenging situation, as indicated by the following example.

Assume the required engine reliability is to be 0.98 and a 5-yr maintenance period is required. Then,

$$R_{syst} = R_{stor} R_{miss}$$

Assume R_{miss} is 0.99 and can be based on many full mission simulations; therefore the required storage reliability is 0.99.

The mean time between failures is then

$$\text{MTBF} = T/\ell n\, R_{stor} = 497 \text{ yr}$$

Assuming only one failure, 1935 yr of testing would be required to have a 90% confidence level of attaining the required reliability.

$$T = \text{MTBF}/2 \quad \chi(a, 2r+2)\, T = 1935 \text{ yr}$$

Under normal circumstances (and certainly in this example), accumulation of storage data requires an unacceptable amount of time for design and development of an engine. Therefore the approach used to verify storage reliability is to accelerate testing by exaggeration of parameters. This type of test must be of reasonable duration, with exaggerated variations in temperature, humidity, pressure, salt, and other contaminants. Service data for turbomachinery under this type of storage are very limited and difficult to obtain. Data for a meaningful correlation between accelerated testing and actual results are still being accumulated.

To further demonstrate the significance of the storage problem relative to demonstrating mission reliability, assume a mission of 5 h. To calculate the required mission simulation/flight test time we would then use the same calculations as shown above by replacing units of years by hours. Then 1935 h of mission simulation testing, with one failure, would yield the required reliability with a 90% confidence level.

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