DESIGNING FOR DURABILITY IN FIGHTER ENGINES

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ABSTRACT

Aircraft fighter engine design is a tradeoff between performance, reliability/durability, weight, and cost. The performance including operability and, more recently, survivability, can largely be determined early in the development program. "Shake and bake" component testing followed by Accelerated Mission Testing (AMT) can go a long way in the development of overall reliability. Engine weight and manufacturing cost can also be determined up front with reasonable certainty. However, durability or life is not readily determined during development and remains a promise to be designed into the engine to achieve the life requirements and reasonable cost of ownership. It can be argued that durability, heavily dependent on the mission duty cycle, is also closely linked to reliability, maintainability, and safety. Designing for durability includes "starting off on the right track" with the initial configuration, the selection of reliable and dependable damage tolerant materials and manufacturing processes, a rigorous structural analyses, and overall attention to detail. This paper describes an art and science "lessons learned" approach developed during the past 25 years to accommodate rapid throttle maneuver transients encountered in the aircraft fighter engines.

INTRODUCTION

In a general sense, engine durability can best be described as the retention of performance throughout the life of the weapon system. Over the years, durability has been a major cost factor in maintaining the large scale peacetime deployment of fighter aircraft in the "ready position." It’s been said that "We measure engine performance on the thrust stand, engine weight on a scale, cost by an accountant — but durability remains a promise." Based on past history, there is, unfortunately, much truth in this statement. Long-term durability has been difficult to evaluate during the development and qualification phases of engine development especially if the user is not certain of the engine requirements. If the "developed" engine does not achieve long term durability, then the average engine may require as many as eight overhauls during its lifetime. However, with built-in durability this can reduce the number of required overhauls by a factor of four, resulting in a significant cost savings. Using results from the Navy sponsored Advanced Technology Engine Studies (ATES, N00019-80-C-0225), it can be shown that durability, or lack thereof, can be a large factor in the overall life cycle cost of a fighter engine.

"Lessons learned" in the art and science of engine design during the past 25 years can be used to both evaluate and enhance engine durability during the relatively short development phase. The implementation of these techniques during engine development of gas turbine engines offers the potential for significantly reducing the long-range cost of ownership of the production fleet. Figure 1 illustrates a durability "road map" that can be applied to the design and development process. The "road map" is circular to represent a repetitive process in the event that the required durability is not achieved on the first pass through the development cycle. Great emphasis and rigorous attention to detail must be placed on all tasks within the roadmap to minimize having to redesign and repeat the process.

Figure 1. Durability Development in Turbine Engines
Durability is achieved during development by providing a well balanced design which is then tested in an environment which attempts to simulate the planned usage in the field. When a part is determined to lack durability through engine testing (usually the result of not understanding the environment of the part), it is redesigned. The degree of difficulty and associated cost of a redesign increases with each step beyond the instrumented test used to verify design intent. The cost of redesign increases dramatically when design deficiencies are discovered during field service.

Past history has repeatedly demonstrated the importance of first understanding the flight envelope and mission requirements in the preliminary design phase. Figure 2 illustrates the flight envelope, mission requirements, and duty cycle for a typical fighter aircraft. The engine design should include features that permit unrestricted steady-state and transient operation within the aircraft flight envelope. The mission requirements define the length of time the engine must operate in various regions of the flight map while the duty cycle signifies how many times the engine must complete the mission before scheduled maintenance is performed. It is the duty cycle, above all other requirements, that exerts the greatest influence on the overall durability requirements for engine components. This is because the life of the parts is determined by the quantity and magnitude of the internal strain ranges of the metal in regions of high local stress. Strains within the material are caused by a combination of mechanical loads and differential thermal expansions. The thermal strains are induced by thermal gradients within the parts and from alternate cyclic and steady-state heating and cooling of the component. The mechanical strains result from the external maneuver loads, internal pressures, and rotational effects. Of these mechanical loads, the centrifugal stresses caused by high rotational speeds predominate. A total strain cycle involves a cold startup, acceleration to full power, stabilization, shutdown, and cool off. This process is usually referred to as a cold-to-hot-to-cold cycle and is defined as one Tactical Air Command (TAC) cycle.

Figure 2. Engine Usage Definition Key in Engine Durability

The duty cycle shown in Figure 2 represents several equivalent TAC cycles because the mission represents more than one throttle movement from cold-to-hot-to-cold due to part power transients. It is essential to account for both part power and start-to-shutdown cycles in the design and development process to evaluate the low cycle fatigue life for each part.

“STARTING OFF ON THE RIGHT TRACK” — CHOOSING THE CONFIGURATION

The key to achieving high engine durability lies in choosing a design configuration that incorporates features which will retain performance by avoiding distress and maximizing life. A poor design configuration is extremely costly as subsequent modifications frequently entail less than balanced solutions and affect total system functioning. As the saying goes, it is usually “patched and crutched but seldom fixed.”

The selection process of a good design configuration must include a balanced tradeoff between:

1. Performance — including operability, observability and emissions
2. Reliability, durability, maintainability, and safety
3. Weight
4. Cost of both acquisition and ownership.

These tradeoff factor categories can be considered as the “Big 4” of fighter engine design and form the basis of all technical design decisions.

In many cases, the tradeoffs are coupled and difficult to separate. For example, a turbomachinery component that deteriorates in performance, such as a fan or compressor, requires an increase in fuel flow to maintain a given thrust level. This causes the engine to run hotter, which increases the potential for deterioration of the combustor and turbine. This in turn creates a requirement for an even greater fuel flow, thus further aggravating the total engine deterioration. Additionally, the hotter running engine increases the strain range of the hot section parts which also decreases their life. To achieve durability, priority must be placed on minimizing deterioration early in the design process. Material selection also plays a coupled role. For hot parts, high modulus materials result in higher stress for the same strain and are less capable of accommodating unequal thermal differential expansion.

Choosing a configuration that minimizes the combined mechanical and thermal strain range of the respective part requires an experienced and knowledgeable approach which takes into account both material characteristics and manufacturing processing. Usually, many iterations and design reviews must occur before the “best configuration” is developed achieving the balanced design tradeoff. Examples of configurations that have demonstrated superior durability by resisting failure and keeping the engine operational are discussed as follows:

THE COMPRESSION SYSTEM

The fan, considered a “cold part,” is usually designed for twice as much life as the hot section. The thermally induced strain within this component is small when compared to the mechanical stresses from rotation, gas pressure and maneuver loads. The performance of the engine is a direct function of the fan component performance. For these reasons, particular design attention should be made to make the part “rugged” to avoid deterioration during usage. Durability highlights for the fan, shown in Figure 3, include three rotor stages incorporating long chord blades which provide both high stall margin and resistance to the effects of inlet distortion and transients. This reduces the number of engine stalls encountered and minimizes performance deterioration. The first stage rotor blades are shrouded at the mid-span to avoid high vibration from separated flow and flutter and also to increase resistance to battle damage. The blade dovetails and shroud interlocks are hard coated for wear resistance and to maintain stiffness. The elimination of dovetails and shroud interlocks provides a “no-shift” assembly, and ensures balance retention for a smoother running engine. The rotor is also straddle mounted in bearings for rigidity and clearance retention during aircraft maneuvers. All stators are shrouded to provide vibratory margin and resistance to foreign object damage. The intermediate case or frame is a close tolerance, one-piece titanium casting providing a rigid lightweight configuration at low cost.
arm to the stem is redundant, in that the arm remains attached even in the event that the clamping bolt is broken or missing. This feature also prevents the vane from disconnecting from the lever and rotating off-schedule. An off-schedule variable vane usually results in a downstream blade airfoil failure from a one-per-revolution excitation.

The compressor is also considered a "cold" part and the same design considerations used in the fan apply. However, in most fighter engines, the compressor mid-to-rear sections operate hot enough to warrant the use of nickel-alloy disks. The compressor shown in Figure 4 also has a welded rotor spool to minimize the number of flanged joints and stress concentrations. The nickel alloy disks are machined from crack resistant material for increased residual life in the presence of manufacturing defects or microcracks. Low aspect ratio airfoils (short span and long chord) are used to provide improved fatigue capability, resistance to battle damage and erosion, and to provide adequate stall margin during transients. All the stators are shrouded for good fatigue strength capability and resistance to impact damage.

The variable vane actuation system shown in Figure 5, in combination with the engine control system, schedules the forward stage compressor variable vanes to match the airflow and physical rotor speed characteristics of the engine as a function of corrected speed and inlet temperature. The presence of a durable actuation system that resists wear and minimizes hysteresis assures the retention of engine performance resulting in reduced maintenance cost. Wear resistant features include high length-to-diameter (L/D) stem bushings and a minimum number of joints. "Compliant" lever arms with torsional flexibility eliminate the need for a uniball bearing. Although this design requires additional actuation force to overcome the torsional spring resistance in the lever arms, it is considered a good tradeoff due to the improved durability and the reduced cost and maintenance achieved. The attachment of the vane

![Figure 3. Modern Engine Fan Durability Features](image)

![Figure 4. Modern Engine Compressor Durability Features](image)

![Figure 5. Modern Engine Compressor Variable Vane System](image)

![Figure 6. Combustor Durability Evolution](image)
However, as turbine temperatures and cyclic usage have increased, a shift to machined ring liners with higher cooling effectiveness has offered improved durability. In this concept, cooling effectiveness is improved by impingement of the cooling air on the lower lip prior to its injection as cooling film. Further, the more tortuous flowpath of the cooling air washes out the individual jets from the cooling air holes and provides a more uniform film which is effective for a longer distance. The designer is also afforded the ability to contour metal thickness to reduce local stress concentrations and to distribute thermal strain.

Combustor configurations are also in development where the inner structure is shielded from the hot gaspath. This dual wall concept promises to eliminate low cycle fatigue as a combustor failure mode. The inner walls are both convectively and film cooled, and may be cast of alloys offering superior oxidation life compared to the wrought materials used in conventional combustors. The dual wall configuration offers further life and durability advantages over the machined ring designs, especially at higher temperatures and increased cyclic usage.

THE TURBINE SYSTEM

The two-stage, high pressure turbine shown in Figure 7 represents a design capable of 8000 TAC cycles life and incorporates 25 years of "lessons learned." The design has a minimum of stress concentrations and an absence of bolt or cooling holes in the load carrying disk web or rim structure. The disk material is crack resistant and capable of operating thousands of TAC cycles in the presence of a defect in a critical location.

![Modern Engine Turbine Durability Features](image)

Figure 7. Modern Engine Turbine Durability Features

Traditionally, turbine rim seals and retainers have been life limited parts because of thermal fatigue. The full ring combination seal and land retainers shown in Figure 7 are interference fit-piloted to the disk rims and held in place by piston ring retainers. The retainers/seals become clamped very tightly by centrifugal forces as the rotor speeds up. This feature results in a durable design by providing low leakage and rim loads. The interstage seal design also eliminates both bolt and air cooling holes to reduce stress concentrations. This seal has four stepped and coated seal teeth to minimize leakage and avoid increased disk rim temperatures from gaspath recirculation. The rotor disks are clamped to the stub shaft using an extended shell with internal flange bolted joint for superior structural rigidity.

The turbine rotor parts are forged using a super plastic forming process to near-net shape for improved material properties and lower cost. Surfaces of the high stressed components are shot peened for increased resistance to fatigue and to minimize the effect of a decrease in material properties at defect areas.

When used with a low pressure ratio, high speed compressor, a single-stage turbine offers an alternate design approach. Generally, for high pressure turbines, there is a tradeoff in that the high speed, single-stage uses less cooling air but has lower efficiency than for a two-stage design. High compressor pressure ratios and moderate (or low) turbine temperatures favor the two-stage turbine because of its higher efficiency. Cooling requirements are kept low in the two-stage turbines with advanced single-crystal blading and improved cooling techniques. Low pressure ratios and high turbine temperatures, combined with higher rotational speeds favor the single-stage. Overloading the single-stage turbine by driving too high a pressure ratio compressor results in poor efficiency and a net loss for the turbine cycle. Single-stage turbines also provide cost/weight advantages associated with shorter engine lengths. These configuration trade-offs must be made up front in choosing the best cycle to achieve durability at reasonable cost.

Figure 8 illustrates the effect of turbine blade materials on allowable metal temperature capability. Choosing a single-crystal blade casting can offer an increase in allowable metal temperature of 125°F (69°C) relative to conventional equiaxed materials. Superior fatigue strength is achieved primarily as a result of the low elastic modulus associated with Directionally Solidified (DS) and single-crystal castings. The lower modulus results in both lower stress and longer life for a given thermal strain. In addition, DS and single-crystal castings offer an advantage in stress rupture life compared to conventional castings due to the absence of transverse grain boundaries that act as rupture initiation sites in equiaxed castings. Because single-crystal materials do not contain grain boundaries, it is possible to eliminate several alloying elements that are normally added as grain boundary strengtheners but which do so at the expense of matrix strength. Most important among these are the elements boron and zirconium which reduce the melting point of the alloy. Elimination of these elements permits higher solution heat treatment temperatures with a proportional increase in creep strength. For modern fighter engines, the somewhat higher cost associated with the single-crystal material usually trades favorably because reduced cooling air and higher durability are achieved.

![Turbine Blade Materials Evolution](image)

Figure 8. Turbine Blade Materials Evolution

THE DESIGN RELEASE

The "final" design involving engineering drawings release to manufacturing is arrived at by an iterative process involving the selected configuration and design analysis. A design analysis involving the "Big 4" tradeoff factors includes a continuing structural analysis to predetermine the critical strain range of each part and its resulting life. Ideally, this is done prior to committing numerous sets of hardware, allowing a practical lead time for "tuneups" along the way.
A rigorous design analysis is essential to either verify or change the selected configuration. The objective of the analysis is to determine the temperature, stress and strain range of every part prior to design release. Practically speaking, very few analyses totally accomplish this objective on the first pass for complex parts because of the difficulty in constructing a near perfect theoretical computer model. All the data that can be classified as assumptions used to construct this analytical model are normally verified by an instrumented test. The analytical model is then refined using these data, usually in the form of vibratory frequency and amplitude, pressure, and temperature range and level. These factors have a major influence in the calculated stress and final strain range absorbed by the part. The actual capability and durability of the part are determined by comparing the calculated strain range to the mechanical and thermal characterization of the material and process.

Figure 9 illustrates how the stress and total strain range are determined in the blade dovetail slot of a turbine rotor disk due to the combined action of centrifugal force and radial differential thermal expansion. In locations of nominally high stress gradients, like a dovetail, the combined mechanical and thermal loadings cause strains beyond yield and into the plastic region during throttle transients. The resultant tensile and compressive stresses are additive and produce a strain range that results in a finite life for most fighter engines that undergo extremely rapid throttle transients. For the dovetail slot shown, the diagram represents the stress strain range during cold-to-hot-to-cold TAC cycles.

Figure 10 shows the relationship of the total strain range to cyclic life as a function of the material properties. These material properties are determined by both heated cyclic testing of specimens with simulated disk stress concentrations as well as actual disk rim tests. For the design configuration illustrated, a life of approximately 9000 TAC cycles is achieved based on the minimum material properties. This might represent a potential life in excess of 15 years for a peacetime deployment and is excellent durability for a fighter engine. The most important and profound lesson learned in the design process is that "we don't know what we don't know." Many of the design problems encountered in the pre-qualification or post-qualification phases can usually be traced to unproven and unverified assumptions. Too often "what we thought" is somehow treated as fact, and this sets the stage for failure. Assumptions must be made during the design phase because all the facts are not always available. However, the important organizing ingredient in the thinking process is to carefully categorize what we know from what we think and proceed to define plans to verify all assumptions.

Figure 10. Relationship of Strain to Cyclic Life

MANUFACTURING

The manufacturing effort involving the material and processing plays a critical role in achieving durability. Figure 11 illustrates the manufacturing processing of a critical rotating part such as a turbine disk. The process represented shows the steps from ingot to the final machined disk. This process involves the melting and atomization of powder particles which are screened for impurities and then blended for the proper alloying composition. The blended powder is then hot compacted, extruded to a super plastic condition, preformed in hot dies and then forged to near-net shape prior to final processing.

The importance of the material and processing can best be shown in Figure 12 where a major improvement in the damage tolerance for nickel superalloy disks has been achieved. The disk crack size as a function of cycles is shown for both the current and improved superalloy. The remaining crack propagation life of a component for the intended mission is referred to as its residual life. For a given initial flaw size as shown in Figure 12, residual life of the improved nickel superalloy disk is twice that of a current part. Extension of rotor residual life results in significant increases in component durability and system life cycle cost. Greater crack propagation life configurations are capable of longer inspection intervals (or reduced weight for the current interval). Additionally, a longer inspection interval enhances the benefit of a Retirement For Cause field maintenance philosophy. Safe inspection intervals with verified inspection techniques allow continued usage beyond the current component retirement limit of minimal material property crack initiation. Such a system minimizes life cycle cost by utilizing each component's confirmed ability to safely complete the next interval of operation.
have in excess of 1500 pieces of instrumentation on a single core engine. Having the major portion of this instrumentation record properly at various operating conditions is essential to obtaining the needed data for an evaluation and possible modification of the numerous component analytical models. After the measurements are recorded, a significant effort is required to reduce the data into a form that can be compared to the analytical predictions. If the instrumented testing does not verify the basic design intent on critical parameters, modifications to achieve this result must be initiated and the tests repeated.

Large lightweight engine frame structures have traditionally been fabricated from strut, ring and shell components using multiwelded joints. This fabrication method requires accurate jiggling and extra material provision at the joints to minimize the loss in strength caused by mismatch and porosity. Recent advances and refinements in casting technology have made one-piece large structural castings practical for both titanium and nickel alloys. As an example, Hot Isostatic Pressing (HIP) is used to both improve ductility and close up internal porosity normally associated with casting processes. The large F100 engine intermediate case shown in Figure 13, is an example of the improved state of the art in one piece castings. Near-net shape sizing is used in areas which require final machining such as precision flange joints and locating surfaces. These one piece cast structures offer improved durability at lower cost since the joints do not have weld defects requiring additional inspection and rework. In addition, larger fillet radii and gussets can be easily incorporated to improve the load path structural rigidity.

Figure 12. Damage Tolerant Disk Material for Improved Durability

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Figure 13. One Piece Cast Frame for Improved Durability and Reduced Cost

VERIFYING THE DESIGN INTENT

Figure 14 illustrates a core engine assembled with both steady-state and dynamic instrumentation to record internal pressures, temperatures, and strains. The core engine inlet is supercharged to represent the compressibility effects of the fan. The number of instrumentation locations is dependent on the physical space limitations of the lead-out wires. For the rotor assembly, the instrumentation lead-out wires must pass through the relatively small shaft diameter at the bearing locations. As a result of having a limited number of instrumentation leads to cover many critical internal parts, the analytical model is used to select the critical regions to be instrumented for both temperature and strain. It is not uncommon to have in excess of 1500 pieces of instrumentation on a single core engine. Having the major portion of this instrumentation record properly at various operating conditions is essential to obtaining the needed data for an evaluation and possible modification of the numerous component analytical models. After the measurements are recorded, a significant effort is required to reduce the data into a form that can be compared to the analytical predictions. If the instrumented testing does not verify the basic design intent on critical parameters, modifications to achieve this result must be initiated and the tests repeated.

Figure 14. Testing to Verify Design

ACCELERATED MISSION TESTING (AMT) AND QUALIFICATION

Accelerated mission testing of the engine shown in Figure 15 has, over the years, proven to be an extremely valuable proof test of the critical components. In particular, the hot section flowpath components can be realistically evaluated for cyclic life because of the relatively quick thermal time response during the abbreviated cold-to-hot-to-cold cycle. The massive structural rotor parts, for example, do not respond as quickly to changes in thermal environment and are not necessarily subjected to the full strain range causing low cycle fatigue. As a result, it is important to generate a severity factor for each part to determine its relative durability based on the AMT test cycle. Past AMT testing has shown that combustors, turbine vanes, shrouds, blades, turbine disk rim, and seals usually have a direct durability correlation with field engine experience. These tests have been able to compress five years of field usage into as little as one month of test time!

Figure 15. Design Verification Accelerated Mission Testing

Figure 16 shows the inspection results of F100 engine singlecrystal high pressure turbine blades and vanes after a severe 3000 cycle AMT test. The parts shown look new as a result of having an advanced state-of-the-art internal impingement and convection combined with surface boundary layer film cooling. Furthermore, the excellent condition and outstanding durability of these critical hot parts result in significantly reduced engine deterioration. Providing excellent performance retention through improved durability will result in reduced cost of ownership for the fleet.
During the past ten years, the development of high temperature composites has made sufficient progress to challenge metal alloys for specific applications. Figure 17 illustrates a comparison in the relative durability between a metal exhaust nozzle seal and one fabricated from a coated carbon-carbon (C/C) material. As shown, the C/C seal has substantially improved durability relative to the metal part. Both parts are uncooled, but the low coefficient of thermal expansion for the C/C part offers a substantial reduction in thermal stress and this significantly aids in improving its durability. The accelerated mission testing incorporating TAC cycles is effective in evaluating the relative durability of new design and material combinations. This testing is particularly cost effective to both evaluate and improve the techniques and methods used to construct the complex analytical models used in the design of composite structures.

![Figure 17. Improved Durability of Composites](https://example.com/figure17)

**FIELD SERVICE EVALUATION**

The last step, in developing the durability roadmap outlined in Figure 1, is to accumulate flight test data on an aircraft, as shown in Figure 18. Performance, including operability, can be evaluated in a relatively short time by traversing the flight map. The predicted and expected durability based on ground testing takes years to verify considering the relatively few flight hours accumulated in fighter aircraft each year. This places the emphasis on the need for perfecting a rigorous development program to demonstrate the basic durability prior to full-scale production. Feedback from early field engines relative to operability and usage is important so that trends not consistent with design intent can be understood and proper action taken. It is the large accumulation of data from the fleet and service shops that has forged an understanding and “lessons learned” approach to achieving significantly higher levels of durability in fighter aircraft engines.

![Figure 18. Air-to-Air Fighter — The Ultimate Durability Test Cell](https://example.com/figure18)

**CONCLUSION**

Durability of fighter engines, has until the past few years, had little chance of becoming more than a promise, without the implementation of an improved, rigorous and disciplined development approach to thoroughly verify the design intent. It was recognized ten years ago that a better approach to achieving durability “up front” was required to reduce support cost. Significant thinking and reassessment throughout the industry was generated by the Air Force’s Engine Structural Integrity Program (ENSIP). This concept has fostered improvements in how to evaluate durability in the development phase and at an affordable cost. ENSIP has also promoted the damage tolerant design concept inspiring, as an example, the development of superior material processing that retards crack growth. Durability of high usage and high cost hot section parts can be demonstrated during development once engine field usage is understood. The current F100(3) high pressure turbine blades and vanes in service are showing lives consistent with accelerated mission testing demonstrated at the factory. As a result of the experience and data base, credibility is high that this superior durability will continue to be repeated in service. Further testing is planned to evaluate the available margin in the event of a potential tradeoff between durability and performance. Programs like ENSIP are being used to determine the most cost effective levels of durability required for a given application.

We need further improvements to bring durability into the realm of the other more readily measurable quantities such as performance, weight and cost. Collectively, experience has shown that more emphasis is needed in the design approach and configuration details in order to achieve durability objectives. Without a heavy emphasis on the initial design, attempts to evaluate and provide durability in the development program would, at the least, add high cost without improving the chances of success. The design examples and approaches illustrated are the result of efforts responding to the past 25 years of “lessons learned” experience. Based on this work and both significant current and future efforts, increased maturity can be applied in the design process to achieve significant improvements in durability for fighter aircraft engines.