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HANDBOOK

ENGINE STRUCTURAL

INTEGRITY PROGRAM (ENSIP)

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FOREWORD

1. This Military Handbook is approved for use by all Departments and Agencies of the Department of Defense (DoD).

2. This handbook is for guidance only. This handbook cannot be cited as a requirement. If it is, the contractor does not have to comply.

3. The purpose of this handbook is to establish structural performance, design development, and verification guidance that should assure structural integrity for engine systems. The guidance contained herein includes the experience and lessons learned achieved during development of USAF engine systems since mid-1940s. Recent experience indicates that superior structural safety and durability, including minimum structural maintenance, can be achieved on an engine system if the guidance contained herein is included and successfully executed during system development. This handbook is intended for use in conjunction Aircraft Turbine Engines (JSSG-2007) on engine development programs or by itself when used for commercial (off-the-shelf) acquisitions.

4. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: ASC/ENSI, 2530 Loop Rd W, Wright-Patterson AFB OH 45433-7101, by using the Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

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1. SCOPE

1.1 Scope.

This handbook establishes structural performance, design development, and verification guidance for turbine engines. This handbook also establishes the need for an Engine Structural Integrity Program (ENSIP). This handbook is for guidance only. This handbook cannot be cited as a requirement. If it is, the contractor does not have to comply.

1.2 Use.

This handbook cannot be used for contractual purposes without supplemental information required for specific application.

1.2.1 Structure.

The supplemental information required is identified by blanks within this handbook.

1.2.2 Instructional handbook.

The instructional handbook, which is contained in the appendix herein, provides the rationale for specific guidance, guidance for inclusion of supplemental information, and a lessons learned depository.

2. APPLICABLE DOCUMENTS

2.1 General.

The documents listed below are not necessarily all of the documents referenced herein, but are the ones that are needed in order to fully understand the information provided by this handbook.

2.2 Government documents

2.2.1 Specifications, standards, and handbooks.

The following specifications, standards, and handbooks form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those listed in the latest issue of the Department of Defense Index of Specifications and Standards (DoDISS) and supplement thereto.

SPECIFICATIONS

Department of
Defense

STANDARDS

Department of
Defense

(Unless otherwise indicated, copies of the above specifications, standards, and handbooks are available from the Defense Automated Printing Service, 700 Robbins Avenue, Building 4D, Philadelphia PA 19111-5094.)

2.3 Order of precedence.

In the event of a conflict between the text of this document and the references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

3. DEFINITIONS AND ACRONYMS

3.1 Definitions.

Definitions applicable to this standard are as follows.

3.1.1 Cold parts.

Parts not in the hot gas path. Those parts not defined as hot parts.

3.1.2 Containment.

The ability of the circumferential case structure of the engine to prevent penetration of failed elements subsequent to specified conditions of primary and secondary failures.

3.1.3 Damage tolerance.

The ability of the engine to resist failure due to the presence of flaws, cracks, or other damage for a specified period of unrepaired usage.

3.1.4 Design service life.

The life duration specified in section 4.3.

3.1.5 Design usage

The usage specified in 4.4.

3.1.6 Deterioration.

The gradual increase in gas temperature and corresponding specific fuel consumption at rated thrust.

3.1.7 Durability.

The ability of the engine to resist cracking (including vibration, corrosion, and hydrogen induced cracking), corrosion, deterioration, thermal degradation, delamination, wear, and the effects of foreign and domestic object damage for a specified period of time.

3.1.8 Durability critical component.

A component whose failure or deterioration will result in a significant maintenance burden, but will not impair flight safety or mission completion.

3.1.9 Engine structure.

All parts of the engine that are designed and sized to meet the structural integrity guidance of this standard. Engine structure includes but is not limited to the following components: ducts, cases, augmentor, nozzle, blades, vanes, disks, spacers, seals, shrouds, plumbing, actuators, gears, shafts, housings, controls and accessories (including pumps, gearboxes, oil tanks, etc.), etc.

3.1.10 Economic life.

The operational life indicated by the results of the durability test program (i.e., test performance interpretation and evaluation in accordance with this standard) to be available with the incorporation of Air Force approved and committed production or retrofit changes and supporting application of the structural maintenance plan in accordance with this standard. In general, production or retrofit changes will be incorporated to correct local design and manufacturing deficiencies disclosed by test. It will be assumed that the economic life of the test article has been attained with the occurrence of widespread damage, which is uneconomical to repair and, if not repaired, could cause functional problems affecting operational readiness. This can generally be characterized by a rapid increase in the number of damage locations or repair costs as a function of cyclic test time.

3.1.11 ENSIP (Engine Structural Integrity Program).

An organized and disciplined approach to the structural design, analysis, qualification, production, and life management of gas turbine engines. The goal of ENSIP is to ensure engine structural safety, durability, reduced life cycle costs, and increased service readiness.

3.1.12 Expendable parts.

Those parts, which are normally replaced at maintenance or overhaul such as, minor hardware, O-rings, and gaskets.

3.1.13 Fracture critical component.

A component whose failure will result in probable loss of the aircraft as a result of noncontainment or power loss preventing sustained flight either due to direct part failure or by causing other progressive part failures or will result in failure to be able to complete the intended mission. Components can be further classified as safety critical or mission critical, if desired.

3.1.14 Hot parts.

Those parts, which are subjected to combustor exit gas flow (such as combustor liner, turbine vanes, blades, and shrouds).

3.1.15 Limit load.

The maximum load a component is expected to encounter when operated for the design service life and design usage. The factor of safety associated with this load is defined as the limit load factor.

3.1.16 Mission critical component.

A fracture critical component whose failure results in inability to complete the intended mission.

3.1.17 Operational life.

That life expected for components when exposed to the operational usage as determined by the component life management actions specified in 4.17.

3.1.18 Operational usage.

The usage the engine is exposed to during actual service operation as determined by the component life management actions specified in 4.17.

3.1.19 Residual strength.

The load carrying capability of a component at any time during the service exposure period considering damage present and accounting for the growth of damage as a function of service exposure time. The intent of the damage tolerance requirement is to provide at least design limit load residual strength capability at all times throughout the service life of the component. The guidance to maintain limit load capability is considered necessary to allow unrestricted operational usage within the flight envelope.

3.1.20 Safety critical component.

A fracture critical component whose failure results in probable loss of engine or power loss preventing sustained flight either due to direct part failure or by causing other progressive part failures.

3.1.21 Ultimate load.

That load obtained by multiplying the limit load, applied singly or in combination except loads due to thermal effects, by a factor of 1.5. In addition, when pressure loads of those components subject to compressor discharge pressure are combined with maneuver loads due to thermal effects, the ultimate load should be based on the most critical condition of two (2) times (X) the maximum operating pressure applied singly or 1.5 X the maximum operating pressure plus maneuver loads plus loads due to thermal effects.

3.1.22 Usable life.

The life required for hot section components prior to reaching distress limits (low cycle fatigue, stress rupture, erosion) that cause replacement due to repair or safety considerations.

3.2 Acronyms.

Acronyms used in this standard are defined as follows:

AMT	Accelerated mission test
DOD	Domestic object damage
ENSIP	Engine structural integrity program
FFR	Full flight release
FOD	Foreign object damage
HCF	High cycle fatigue
IFR	Initial flight relese

ISR	Initial service release
LCF	Low cycle fatigue
NDI	Nondestructive inspection
OCR	Operational capability release

4. GUIDANCE

4.1 Coverage.

The guidance of this document should provide the structural performance criteria for turbine engines. This handbook includes coverage of the following:

a. Engine Structural Integrity Program (ENSIP)

b. Structural performance and design development for turbine engines

4.2 Turbine Engine Structural Integrity Program (ENSIP).

Turbine engine structural integrity requirements should be prepared to assure that the engine has adequate structural characteristics to perform the required missions for the required design service life as specified herein. The ENSIP master plan should be used to define and document the specific requirements.

4.3 Design service life.

The engine should have a design service life of at least _(a)_ when subject to the design usage of 4.4. In addition, the engine should be capable of withstanding __(b)__ hours at any point in the envelope for both hot and cold parts.

4.3.1 Hot parts.

Hot parts should have a usable life of _(a)_ times the design service life specified in 4.3. Hot parts and their lives should be listed in table V.

4.3.2 Cold parts.

Cold parts should have a usable life of _(a)_ times the design service life specified in 4.3. Cold parts and their lives should be listed in table VI.

4.3.3 Expendables.

The minimum life without replacement of all expendable parts and components should be equal to the minimum maintenance-free operating period. Expendable parts, components, and their lives should be listed in table VII.

4.3.4 Bearings.

The mainshaft and gearbox bearings should have B 1.0 lives equal to at least the design service life of the engine. A list of bearings and their lives should be presented in table VIII.

4.3.5 Components.

Engine components should have a usable life of _(a)_ times the design service life specified in 4.3. Engine components and their lives should be listed in table IX.

4.4 Design usage.

The engine structure should be capable of withstanding the design usage specified herein for the design service life specified in 4.3. The design service life and design usage should be specified in terms of mission profiles and mission mix including nonoperating transport of the engine. Important usage parameters should be specified. The flight envelope, mission profiles, mission mix, and environment should be shown.

4.5 Operating envelope.

The engine should meet all the requirements of the document throughout the complete operating envelope without exceeding any limits. The engine operating limits should be specified for the identified environment and displayed with figures 1 and 2 and tables XIII and XIV. If applicable, the thrust augmentation operating envelope should be included on the figures.

4.5.1 Operating attitude and conditions.

The engine operating attitude limits should be shown on figure 3. The engine should meet the requirements of the specification when operating in the normal operation area of the figure, and operate at least _(a)_ seconds continuously in the limited and transient operation areas of figure 3. Operation in the limited operation area should not degrade engine performance or cause any damage. The engine should start, stop, and be stowed in any of the attitudes shown in the normal operation area of figure 3. Engine stowing capability outside of the limited operation area should be specified. The engine should function satisfactorily for at least _(b)_ seconds in negative g and for at least _(c)_ seconds in zero g conditions.

4.5.2 Internal environment.

The engine components should be capable of withstanding the internal thermal and pressure environments that occur during engine operation (steady state and transient conditions).

4.5.3 Externally applied forces.

The engine should function satisfactorily and no deformation should occur during or after exposure to the externally applied forces, which should be indicated in Design Load Diagrams.

4.6 Material characterization.

The materials used in the engine should have adequate structural properties, such as strength, creep, low cycle fatigue, high cycle fatigue, fracture toughness, crack growth rate, stress corrosion cracking, and corrosion resistance; so that component design can be optimized to meet the operational requirements for the design service life and design usage of the engine, or for the life interval required by 4.3 and 4.4.

4.7 Parts classification.

All engine parts, components, controls and externals, and expendables should be classified for criticality.

4.8 Damage tolerance.

Fracture/safety and mission critical engine parts should be capable of maintaining adequate damage tolerance in the presence of material, manufacturing, processing, and handling defects for the design service life and design usage specified in 4.3 and 4.4.

4.8.1 Residual strength.

The residual strength should be equal to the maximum stress that occurs during design usage conditions. Residual strength requirements should be established for all damage tolerant designed parts and components. Associated static and dynamic loading conditions for these parts and components should be included.

4.8.2 Initial flaw size.

Initial flaws should be assumed to exist as a result of material, manufacturing and processing operations. Assumed initial flaw sizes should be based on the intrinsic material defect distribution, manufacturing process, and the NDI methods to be used during manufacture of the component.

4.8.3 In-service inspection flaw size.

The flaw size, which should be presumed to exist in a component after completion of a depot, intermediate, or base level inspection, should be specified.

4.8.4 Inspection intervals.

The frequency of inspection in terms of the required design lifetime should be specified in terms of

a. In-service noninspectable - Once at the end of one design lifetime , or

b. Depot or base level inspectable.

4.8.5 Flaw growth.

The initial flaw sizes specified in 4.8.2 should not grow to critical size and cause failure of the part due to the application of the required residual strength load within two times the specified inspection interval.

4.8.6 Composites.

Composite parts should be damage tolerant with defects resulting from material quality, manufacturing processing, and handling damage.

4.9 Durability/economic life.

The durability/economic life of the engine should not be less than the required design service life when subjected to the design usage.

4.9.1 Low cycle fatigue (LCF) life.

Engine parts should have a minimum LCF life, which is at least equivalent to the design service life of 4.3.

4.9.2 High cycle fatigue (HCF) life.

Engine parts should not fail when subject to the maximum attainable combined steady-state and vibratory stresses.

4.9.3 Life design margin.

A life margin should be applied during design of engine components.

4.9.4 Corrosion prevention and control.

The engine should operate satisfactorily without detrimental material degradation in the environmental conditions specified in 4.5 - 4.5.3 for the design service life.

4.10 Strength.

The engine should meet all the requirements of the specification during and after exposure to limit loads, singly and in combination. The engine should not experience catastrophic failure when subjected to ultimate loads, singly and in combination. In addition, the engine should meet the following strength criteria.

4.10.1 Factors of safety.

Factors of safety should be applied to design usage induced loads to establish limit and ultimate conditions.

4.10.2 Blade and disk deflection.

The blades and disks should not contact any static parts of the engine other than seals and shrouds, during all phases of engine operation including surge and stall occurrences. Seals and clearances should remain effective under all internal and external operational loads.

4.10.3 Containment.

Uncontained failures should not cause fire or catastrophic damage to engine external systems or aircraft systems, or injury to personnel.

4.10.4 Blade out.

Subsequent to a single blade failure, with resulting secondary loss of another blade in the same stage at maximum allowable transient speed, the engine should not experience uncontained fire; catastrophic rotor, bearing, support, or mount failures; overspeed conditions; leakage from flammable fluid lines; or loss of ability to shutdown the engine.

4.10.5 Overspeed/overtemperature.

The engine should meet all the requirements of the specification during and after overspeed and overtemperature conditions.

4.10.6 Disk burst speed.

The minimum loaded disk burst speed of the complete disk assembly should be greater than or equal to the overspeed requirements of 4.10.5.

4.10.7 Output shaft torque limits.

For turboprop and turboshaft engines the maximum allowable steady-state delivered shaft torque (mechanical) limit should be at least __(a)__ percent greater than the rating value.

4.10.8 Output shaft speed limits.

For turboprop and turboshaft engines the maximum allowable steady-state delivered shaft speed (mechanical) limit should be at least __(a)__ percent greater than the rating value. The shaft should be able to operate at this speed for at least __(b)__ and function satisfactorily thereafter. Following loss of load, the output shaft speed should not exceed the maximum shaft speed predicted with the engine at Intermediate power and the output shaft running at the maximum attainable rotor speed.

4.10.9 Pressure vessel/case.

All engine cases and pressure loaded parts and components should withstand the ultimate loading conditions defined in 4.10.1. The cases must remain intact, although permanent deformation and distress, requiring repair or replacement is permitted. Engine cases should not fail due to combustion process burning or erosion.

4.10.10 Pressure balance.

The engine thrust bearings should provide sufficient thrust load to ensure satisfactory bearing operation without skid damage during the design service life.

4.10.11 Gyroscopic moments.

The engine should meet all the requirements of the specification at maximum allowable steady-state engine speeds when subjected to the rotational velocities and accelerations within the flight envelope and the gyroscopic moment conditions.

4.10.12 Main mounts.

The engine mounts should have adequate strength to retain the engine, including retained fluids and externals, at all flight, takeoff and landing, and ground conditions.

4.10.13 Ground handling mounts.

The ground handling mounts should support the engine, including all engine mounted equipment and externals, components, and operating fluids, under the following maximum inertia load conditions, without deformation to the mounts or damage to the engine: __(a)__ axial, (a)__ lateral, and __(a)__ vertical acting in combination at the engine center of gravity.

The locations and descriptions for the individual ground handling mounts should be specified. The arrangement should be compatible with ground handling equipment specified herein by the Using Service.

4.10.14 Engine stiffness.

The estimated stiffness of the engine in resisting loads and moments applied at the outboard end of the output shaft, relative to the engine mounting points, should be specified herein. The first "free-free" lateral and vertical engine bending modes should be specified herein.

4.11 Deterioration.

The engine should be capable of attaining the hot part design life when operating at temperature conditions representing a typical rate of performance deterioration. The temperature margin above the production acceptance engine maximum steady state gas temperature under standard day conditions should be consistent with that required for the engine as stated in the engine specification for the design service life of 4.3.

4.12 Creep.

The engine static and rotating parts should not creep to the extent that acceptable field engine operation is impaired for the operating conditions and the lifetime specified in 4.3. Part creep should not affect disassembly and reassembly of the engine or new part replacement at overhaul throughout the specified life of the engine.

4.13 Vibration.

The engine, external controls, accessories, and hardware should be free of destructive vibration at all engine speeds and thrusts (including steady-state and transient conditions) within the flight and ground envelope.

4.13.1 Vibration limits.

Maximum engine mechanical vibration limits should be established as a function of frequency, engine order, and location and direction of measurement. Maximum engine mechanical vibration limits should be based on setting an acceptable margin of safety for the structural capability.

4.13.2 Critical speeds.

Rotors should be free of detrimental resonance conditions at all speeds in the operating range. Any rotor critical speeds existing above or below the engine operating range should have a factor of safety established on speed to account for the variation in speeds for different operating conditions. Adequate damping and appropriate balancing should be provided so that any critical speed existing below maximum operating speed should be traversed safely with smooth engine operation. The variation in speeds based on operating conditions, etc. should be included. The natural frequencies of the mounting system with the engine installed should have a safety factor established for speeds below idle rotor speed(s) in all detrimental modes of vibration which can be excited by the residual rotor unbalances.

4.13.3 Blade, disk, and static structure vibration.

Blade, disk, and static structure natural frequencies should be such that detrimental resonance should not occur in the engine operating range.

4.13.4 Surge and stall.

The engine should operate satisfactorily without structural degradation in the event of surges and stalls within the flight envelope.

4.14 Noise.

The engine should meet the strength and design service life requirements in the presence of the noise environment produced during installed and uninstalled operation at the flight and ground operating conditions consistent with the design usage conditions.

4.15 Foreign object/domestic object damage (FOD/DOD).

The engine should operate satisfactorily when foreign objects/domestic objects are ingested.

4.16 Structural maintainability.

The engine should be economically maintainable for the design service life and design usage of 4.3. Engine components should fit and function with new components after being operated to the design service life and design usage of 4.3. The function of structural components, elements, and major bearing surfaces should not be degraded by wear, erosion, or corrosion to the extent that performance or structural capability should be impaired. Authorized repairs should be established for critical components that experience detrimental wear, erosion, or corrosion during developmental testing and service operation. The structural life of repaired components specified by the contractor should be equal to or greater than the inspection intervals set forth in 4.8.4. Any repairs must be structurally sound and cost effective.

4.17 Inspectability.

Critical engine components should be inspectable by use of borescope ports and diagnostic methods so that detrimental damage or other deterioration should be detected to facilitate economical repair and to prevent engine failure. A listing of the inspectable components and their methods of inspection should be specified.

4.18 Engine/airframe structural compatibility.

The engine should meet the structural requirements of this document when installed in the airframe. The installed engine should operate satisfactorily in the thermal and aerodynamic environment produced by the engine/airframe configuration. The installed engine should possess flutter margin throughout the engine flight envelope.

4.19 Component life management.

Required maintenance actions (component inspection, repair, or replacement requirements) should be defined to assure adequate structural integrity and operational readiness of each engine for the design service life. Required maintenance actions should be based on duty cycles defined by operational usage of the airframe/engine. Individual component maintenance times should be based on the parameter that causes life degradation.

5. EVALUATIONS

5.1 General.

The evaluation (inspections/analyses/tests) specified herein should verify conformance with the guidance of section 4 herein. All evaluations should be the responsibility of the contractor; the Government reserves the right to witness, or conduct, any evaluation.

5.2 Turbine engine structural integrity evaluation program.

The ENSIP master plan should be used to define and document the specific evaluation tasks.

5.3 Design service life.

The requirements of 4.3 should be evaluated by analysis, inspection, demonstration, and test.

5.3.1 Hot parts.

The requirement of 4.3.1 should be evaluated by analyses and tests.

5.3.2 Cold parts.

The requirement of 4.3.2 should be evaluated by analyses and tests.

5.3.3 Expendables.

The requirement of 4.3.3 should be evaluated by analyses and tests.

5.3.4 Bearings.

The requirement of 4.3.4 should be evaluated by analyses and tests.

5.3.5 Components.

The requirement of 4.3.5 should be evaluated by analyses and tests.

5.4 Design usage.

Evaluation of design usage should be accomplished by analysis, design development tests, and engine tests, in accordance with the ENSIP Master Plan to ensure that the engine and its components meet the design service life and design usage requirements of 4.3 and 4.4. A design duty cycle(s) should be derived from the design service life and design usage specified in 4.3 and 4.4. The design duty cycle should be supplied.

5.5 Operating envelope.

The requirements of 4.5 should be evaluated by analysis, demonstration, and test.

5.5.1 Operating attitude and conditions.

The requirements of 4.5.1 should be evaluated by analysis, demonstration, and test.

5.5.2 Internal environment.

Verification of the capability of the engine components to withstand the internal thermal and pressure environments that occur during engine operation should be evaluated by analysis and test.

5.5.3 Externally applied forces.

Verification of flight and ground externally applied forces should be in accordance with 4.5.3, and should be evaluated by analysis and test.

5.6 Material characterization.

Material structural properties should be established by test.

5.7 Parts classification.

The requirement of 4.7 should be evaluated by analysis, inspection, and test.

5.8 Damage tolerance.

Damage tolerance of fracture critical engine components should be in accordance with 4.8. Verification should be evaluated by analysis and test.

5.8.1 Residual strength.

The requirements of 4.8.1 should be evaluated by analyses and tests.

5.8.2 Initial flaw size.

Material controls, manufacturing process controls, and in-process Nondestructive Inspection (NDI) should be performed on each fracture critical component to ensure that the requirements of 4.8.2 are met.

5.8.3 In-service inspection flaw size.

The requirements of 4.8.3 should be evaluated by analysis, inspection, demonstration, and test.

5.8.4 Inspection intervals.

The requirements of 4.8.4 should be evaluated by analyses and tests.

5.8.5 Flaw growth.

The requirements of 4.8.5 should be evaluated by analyses and tests.

5.8.6 Composites.

The requirements of 4.8.6 should be evaluated by analyses and tests.

5.9 Durability.

The requirements of 4.9 should be evaluated by a strength and life analysis, inspection, demonstration, and part, component, and full-scale engine tests.

5.9.1 Low cycle fatigue (LCF) life.

The requirement of 4.9.1 should be evaluated by analyses and tests.

5.9.1.1 Accelerated mission test (AMT).

An accelerated mission test (AMT) should be performed on the initial flight release (IFR) engine configuration. The test run schedule should simulate the design duty cycle of 5.3. The minimum test duration should be two times the initial flight test usage. This test should be completed prior to first flight.

5.9.1.2 Full-scale development engine.

An AMT should be performed on the full-scale development engine configuration. The test schedule should simulate the design duty cycle of 5.3. The minimum test durations should be one-half the design service life at full flight release (FFR), and one times the design service life at initial service release (ISR).

5.9.1.3 Production tooled engine.

AMT should be performed on a production tooled engine configuration. The test schedule should simulate the design duty cycle of 5.3. The minimum test duration should be one times the design service life at operational capability release (OCR). AMT of any proposed design changes should be conducted to a duration of one times the design service life at OCR.

5.9.1.4 Production tooled engine configuration.

AMT should be performed on a production tooled engine configuration. The test schedule should simulate a service duty cycle that is derived from operational usage data. The minimum test duration should be one times the design service life.

5.9.1.5 Inspections.

Major inspection programs should be conducted as an integral part of the AMT programs.

5.9.1.6 Interpretation and evaluation of test results.

Each structural problem, such as failure, cracking, yielding, wear, and erosion, discovered during inspection of the AMT engines should be analyzed to determine cause, corrective action, and operational implications relative to meeting the design requirements contained in this standard. Specific requirements should be identified.

5.9.2 High cycle fatigue (HCF).

The requirements of 4.9.2 should be evaluated by analysis and test. An up and down stair-step test should be conducted before and after, and throughout the specified engine test(s).

5.9.3 Life design margin.

Attainment of the life design margin should be evaluated by analysis and test.

5.9.4 Corrosion prevention and control.

The corrosion resistance of the engine materials, processes, and protection systems should be evaluated as follows:

5.10 Strength.

The requirements of 4.10 should be evaluated by structural analysis and part, component, and full-scale engine tests.

5.10.1 Factors of safety.

The requirements of 4.10.1 should be evaluated by analyses and tests.

5.10.2 Blade and disk deflection.
The requirements of 4.10.2 should be evaluated by analyses and tests.

5.10.3 Containment.
The requirements of 4.10.3 should be evaluated by analysis and test.

5.10.4 Blade out.
The requirements of 4.10.4 should be evaluated by analysis and test.

5.10.5 Overspeed/overtemperature.
The requirements of 4.10.5 should be evaluated by analysis and test.

5.10.6 Disk burst speed.
The requirements of 4.10.6 should be evaluated by analysis and test.

5.10.7 Output shaft torque limits.
The requirements of 4.10.7 should be evaluated by analysis and test.

5.10.8 Output shaft speed limits.
The requirements of 4.10.8 should be evaluated by analysis and test.

5.10.9 Pressure vessel/case.
The requirements of 4.10.9 should be evaluated by analyses and tests.

5.10.10 Pressure balance.
The requirement of 4.10.10 should be evaluated by analysis and test.

5.10.11 Gyroscopic moments.
The requirements of 4.10.11 should be evaluated by analysis and test.

5.10.12 Main mounts.
The requirements of 4.10.12 should be evaluated by analysis and test.

5.10.13 Ground handling mounts.
The requirements of 4.10.13 should be evaluated by analysis, demonstration, and test.

5.10.14 Engine stiffness.
The requirements of 4.10.14 should be evaluated by analysis, demonstration, and test.

5.11 Deterioration.
Capability of engine components to attain hot section part life under deterioration conditions should be evaluated as follows:

5.11.a Analysis.

Analysis of LCF, creep, stress rupture, and erosion capability accounting for the required temperature margin above maximum steady state gas temperature should be performed.

5.11.b Performance.

Component structural performance during conduct of the several engine tests should be verified.

5.12 Creep.

Creep characteristics of the engine static and rotating parts should be verified per 5.12.a through 5.12.c.

5.12.a Analysis.

An analysis should be performed to demonstrate that sustained stress and temperature combinations should not result in detrimental permanent set/growth for the required design service life and design usage.

5.12.b Test.

A design development test plan and tests for creep evaluation should be developed and performed.

5.12.c Inspection.

Inspection and evaluation of components should be performed subsequent to conduct of the several engine tests required by this standard. These inspections should as a minimum be equivalent to the field and depot inspections.

5.13 Vibration.

Vibration characteristics of the engine should be evaluated per 5.13.a through 5.13.c.

5.13.a Analysis.

Dynamic analysis should be performed to establish component vibrational mode shapes and frequencies. An analytical dynamic model of the engine and accessories should be performed to identify critical system modes, potential forcing functions, and resonance conditions.

5.13.b Test.

A mechanical impedance static test plan and test should be developed and performed on accessories and plumbing when installed on the engine.

5.13.c Engine test.

Instrumented engine tests should be performed to measure vibratory stresses and stability margins including flutter at critical points in the flight envelope. Rotor unbalance, off nominal guide vane schedules, aircraft inlet conditions, stalls, and expected distortions should be evaluated.

5.13.1 Vibration limits.

Verification of vibration limits should be in accordance with 5.13.

5.13.2 Critical speeds.

Verification of critical speeds should be in accordance with 5.13.

5.13.3 Blade, disk, and static structure vibration.

Verification of blade, disk, and static structure vibration should be in accordance with 5.13, and should be evaluated by analyses and tests.

5.13.4 Surge and stall.

Verification of surge and stall should be in accordance with 5.13, and should be evaluated by analyses and tests.

5.14 Noise.

The capability of the engine to meet the strength and durability requirements in the presence of the noise environment generated during engine operation should be verified by test. Specific tests required by this document that will be used to demonstrate compliance with the noise requirement of 4.14 should be identified.

5.15 Foreign object/domestic object damage (FOD/DOD).

Evaluation of the capability of the engine to meet the foreign object/domestic object damage requirements should be by analysis and test.

5.16 Structural maintainability.

Maintainability of the engine should be verified per 5.16.a and 5.16.b.

5.16.a Inspection.

Inspection and evaluation of changes in critical dimensions and finish of components after conduct of the several engine tests required by this standard. A maintainability assessment plan should be developed and implemented.

5.16.b Test.

Structural life of component repair procedures should be verified by test, as required.

5.17 Inspectability.

The ability to accomplish inspection requirements established by 4.17 should be verified during conduct of the engine tests required by this standard.

5.18 Engine/airframe compatibility.

Engine/airframe compatibility should be verified by an instrumented engine test installed in the aircraft. The scope of these tests should be contained in the Interface Control Document.

5.19 Component life management.

Component life management should be defined and implemented by analysis, test, and recording of the operational usage of the engine as follows:

5.19.a Plan.

A structural maintenance plan should be prepared.

5.19.b Data recording.

Engine signals should be provided to the airframe data recording system to record parameters required to establish operational usage duty cycles for the engine. The data recording system should record the following parameters:____________.

5.19.c Counter.

Each engine should contain a counter which should record parameter events that control the structural limits of engine components. The counter should record the following events: ___________.

5.19.d Tracking program.

A critical component tracking program plan should be established. This system should define the analysis procedures, serialization, data collection, and computer programs necessary to establish maintenance times of individual components based on accrual of parameter events.

6. NOTES

(This section contains information of a general or explanatory nature which may be helpful, but is not mandatory.)

6.1 Intended use.

This document should be used as guidance for identifying the structural integrity characteristics of all propulsion systems for military acquisition, which includes the acquisition of commercial off-the-shelf propulsion systems.

6.2 Subject term (key word) listing.

AMT
Durability
Fatigue
Fracture
Life Management
Propulsion

6.3 Changes from previous issue.

Marginal notations are not used in this revision to identify changes with respect to the previous issue due to the extent of the changes.

ENGINE STRUCTURAL INTEGRITY PROGRAM (ENSIP)

A.1. SCOPE

A.1.1. Scope.

This appendix provides propulsion structural integrity rationale, guidance, lessons learned, and instructions necessary to tailor sections 4 and 5 of the basic document (MIL-HDBK-1783) for a specific application.

A.1.2 Purpose.

This appendix provides information to assist the government procuring activity in the use of MIL-HDBK-1783.

A.1.3 Use.

This appendix is designed to assist the project engineer in tailoring MIL-HDBK-1783. This handbook provides guidance on performance requirements to be provided by the procuring activity in the Request for Proposal (RFP) and those verification tasks to be identified by the contractor in response to the RFP.

A.1.4 Format

A.1.4.1 Requirement/verification identity.

Section A.4 and section A.5 of the appendix parallel sections 4 and 5 of the basic handbook; paragraph titles and numbering are in the same sequence. Sections A.4 and A.5 provide each requirement (section A.4) and associated verification (section A.5) as stated in the basic handbook. Both the requirement and verification have sections for rationale, guidance, and lessons learned.

A.1.4.2 Requirement/verification package.

Sections A.4 and A.5 of this appendix have been arranged so that the requirement and associated verification is a complete package to permit addition to or deletion from the criteria as a single requirement. A requirement is not specified without an associated verification.

A.1.5 Responsible engineering office.

The Responsible Engineering Office (REO) for this appendix is ASC/ENFP, Wright-Patterson AFB OH 45433-7101. The individual who has been assigned the responsibility for this handbook is Ms. Sharon I. Vukelich, ASC/ENFP, Bldg. 560, 2530 Loop Rd West, Wright-Patterson AFB OH 45433-7101, DSN 785-8553, Commercial (937) 255-8553.

A.2. REFERENCED DOCUMENTS

A.2.1 General.

Unless otherwise indicated, the documents specified herein are referenced solely to provide supplemental technical data.

A.2.1.1 Government documents

SPECIFICATIONS

Department of Defense

JSSG-2007	Engines, Aircraft, Turbine
AFGS-87233	Support Systems and Equipment

HANDBOOKS

Department of Defense

MIL-HDBK-5	Metallic Materials and Elements for Aerospace Vehicle Structures

(Unless otherwise indicated, copies of the above specifications, standards, and handbooks are available from the Defense Automated Printing Service, 700 Robbins Avenue, Building 4D, Philadelphia PA 19111-5094, phone (215) 697-2179.)

A.2.1.2 Other Government documents, drawings, and publications.

The following other Government documents, drawings, and publications in part form the basis for the requirements and verifications in this handbook.

MCIC-HB-01	Damage Tolerance Design Handbook
AFWAL-TR-81-2045	Damage Tolerant Design for Cold Section Turbine Engine Disks, June 1981
AFWAL-TR-83-2079	Weibull Analysis Handbook
ASD-TR-82-5012	Handbook of Military Aircraft Design Normal Load Factor Exceedance Data
	Scientific Advisory Board (SAB) Special Report on Turbine Engines, January 1976
	Scientific Advisory Board (SAB) Special Report on HCF in Turbine Engines, Oct 1992
	DoD Procurement Management Review, "Aircraft Gas Turbine Engine Acquisition and Logistics Support," February 1976
	GAO Report, "Are Management Problems in the Acquisition of Aircraft Gas Turbine Engines Being Corrected," September 1980

(Application for copies of MCICs should be addressed to Advanced Materials and Process Technology Information (AMPTIAC), 201 Mill Street, Rome NY 13440-6916; TRs should be addressed to National Technical Information Service (NTIS), 5285 Port Royal Rd, Springfield VA 22161-0002; GAO reports should be addressed to GAO Headquarters, 700 4th St., NW, Washington DC 20001-2608.)

A.2.2 Other publications.

The following documents are not referenced in this appendix, but provide supplemental information to the extent specified herein. The issues of the document which are indicated as DOD adopted should be the issue listed in the current DoDISS and the supplement thereto, if applicable.

AFFDL-TR-79-3021 USAF Damage Tolerant Design Handbook: Guidelines for the Analysis and Design Tolerant Aircraft Structures, March 1979

Cowie, W.D., "Turbine Engine Structural Integrity Program (ENSIP)", Journal of Aircraft, Volume 12, Number 4, April 1975, pp. 366-369.

Tiffany, C.F. and Cowie, W.D., "Progress on the ENSIP Approach to Improved Structural Integrity in Gas Turbine Engines/An Overview", The American Society of Mechanical Engineers, 78-WA/GT-13, August 1978.

(Application for copies should be addressed to ASD/ENFP (Sharon I. Vukelich), Bldg. 560, 2530 Loop Rd W, Wright-Patterson AFB OH 45433-7101.)

A.3 DEFINITIONS AND ACRONYMS

The acronyms used in this document are defined as follows:

a. AFWAL - Air Force Wright Aeronautical Laboratory

b. ASIP - Aircraft Structural Integrity Program

c. CDR - Critical Design Review

d. CDRL - Contract Data Requirements List

e. CIP - Component Improvement Program

f. CL - Confidence Level

g. EDM - Electro-Discharge Machining

h. EMD - Engineering and Manufacturing Development

i. FMECA - Failure Mode and Effects Criticality Analysis

j. FPI - Fluorescent Penetrant Inspection

k. FSED - Full Scale Engineering Development

l. HEX - High Energy X-ray

m. HPC - High Pressure Compressor

n. HPT - High Pressure Turbine

o. ICD - Interface Control Document

p. LCC - Life Cycle Cost

q. NDT - Nondestructive Testing

r. OMC - Organic Matrix Composite

s. PLA - Power Lever Angle

t. POD - Probability of Detection

u. REO - Responsible Engineering Office

v. RFP - Request for Proposal

w. RMS - Root Mean Square

x. RPM - Revolutions per Minute

y.	SFC	-	Specific Fuel Consumption
z.	SON	-	Statement of Need
aa.	TOT	-	Total Operating Time
bb.	USA	-	United States Army
cc.	USAF	-	United States Air Force
dd.	USN	-	United States Navy

A.4 GUIDANCE

A.4.1 Coverage.

The guidance of this document should provide the structural performance criteria for turbine engines. This handbook includes coverage of the following:

a. Engine Structural Integrity Program (ENSIP)

b. Structural performance and design development for turbine engines

A.4.1.1 EVALUATION

A.4.1.1.1 General.

The evaluation (inspections/analyses/tests) specified herein should verify conformance with the guidance of section A.4 herein. All evaluations should be the responsibility of the contractor; the Government reserves the right to witness, or conduct, any verification.

A.4.2 Turbine Engine Structural Integrity Program (ENSIP).

Turbine engine structural integrity requirements should be prepared to assure that the engine has adequate structural characteristics to perform the required missions for the required design service life as specified herein. The ENSIP master plan should be used to define and document the specific requirements.

REQUIREMENT RATIONALE (A.4.2)

In past years, numerous structural problems have occurred in USAF turbine engines. Many of these problems resulted in loss of aircraft and an even greater number have affected durability causing a high level of maintenance and modification costs. All of the problems have adversely affected operational readiness. These problems have highlighted the need for a disciplined approach to turbine engine structural development. The need has been identified by no less than 23 studies, assessments, and investigations conducted during 1970 - 1995 to review aircraft engine development, management, and acquisition. The Turbine Engine Structural Integrity Program (ENSIP) is intended to reduce these problems and was established by the Air Force to provide an organized and disciplined approach to the structural design, analysis, qualification, production, and life management of gas turbine engines. ENSIP is organized into five (5) basic tasks as shown in table I and described herein.

(Task I) Design information. Detailed structural design criteria and design usage should be applied during engine material selection and structural design to meet operational needs and requirements. Initial usage definition should be supplied by the procuring activity.

(Task II) Design analyses, material characterization, and development tests. Design analyses should be performed to determine the environments (load, temperature, vibratory, acoustic, and chemical) to which the engine structure should be exposed during operation and transport. Design analyses, material characterization, and development tests should be performed to design and size the components.

(Task III) Component and core engine testing. Component tests should be performed to assess strength, damage tolerance, durability, and dynamic characteristics. Thermal, vibratory, and flutter boundary surveys should be performed during core engine tests.

(Task IV). Ground and flight engine tests. Ground and flight engine tests should be performed to verify the environment in the full-scale engine under steady state and transient conditions and to verify damage tolerance and durability. Types of tests to be performed should include: Ground vibration, temperature, and flutter surveys; external components resonant tests and clearance control tests; and accelerated mission tests. These tests should include measurement of steady state and transient conditions including shutdown and cool down parameters. Installed engine tests should be performed. Telemetry capability should be provided.

(Task V) Engine life management. A data package, monitoring equipment, and analysis methods should be provided so that the Air Force can accomplish the required life management actions. Requirements should include updated strength and life analyses, structural maintenance plan, mission utilization recorder, and critical parts tracking system including individual engine recorder. This task contains basic ENSIP requirements to be performed by the contractor, but unlike Tasks I through IV, should not be for the purpose of providing compliance to the operational requirements. Tasks that are scheduled after full-scale development (FSD) should be identified by the contractor.

The major subtasks or elements contained in each of the five tasks are also shown in table I.

REQUIREMENT GUIDANCE (A.4.2)

The contractor should identify the engine structural integrity requirements tailored to meet the needs of each engine development program. Specific guidance and suggested requirements for identifying supplemental information are contained in this handbook for specific structural requirements. In general, the following guidance should be followed:

1. Design stress spectra, component test spectra, and full-scale engine test spectra should be based on anticipated service usage of the engine.

2. Materials and processes should be thoroughly characterized including fracture properties.

3. It is not realistic to assume defect-free structure in fracture critical components.

4. Cost considerations make it important to extend the useful life of engine components when it can be done without jeopardizing safety. This philosophy is called retirement-for-cause.

5. Critical parts (and part details) and potential failure modes should be identified early and appropriate control measures implemented.

6. Internal thermal and vibratory environments should be identified early in the engine development.

7. Predicted analytical stresses should be verified by test for critical components where practical.

8. Potential engine/airframe structural interactions should be defined and accounted for.

9. Closed loop force management procedures should be defined and implemented. This includes realistic inspection and maintenance requirements, individual engine tracking procedures, deficiency reporting, and updates based on actual usage.

10. Life verification test results should be available to support production decisions.

TABLE I. The ENSIP task.

TASK I	TASK II	TASK III	TASK IV	TASKV
DESIGN INFORMATION	DESIGN ANALYSIS MAT'L CHAR & DEV TESTS	COMP & CORE ENGINE TESTS	GRD & FLT ENGINE TESTS	ENGINE LIFE MANAGEMENT
DEVELOPMENT PLANS • ENSIP Master Plan • Durability & Damage Tol Control Plans • Mat'l Process Charact Plan • Corrosion Prev & Control • Inspect & Diagostics Plan OPERATIONAL RQMTS • Design Service Life & Design Usage • Design Criteria	• Design Duty Cycle • Material Characterization • Design Dev Tests • Analyses - Sensitivity - Critical Parts List - Thermal - Strength - Containment - Vibration/Flutter - Stress/Environment Spectra - Durability - Damage Tolerance - Creep • Installed Engine Inspectability • Manufacturing, Process & Quality Controls - VSR - NDI Demo	COMPONENT TESTS • Strength • Vibration • Durability • Damage Tolerance • Containment CORE ENGINE TESTS • Thermal Survey • Vibration Strain and Flutter Boundary Survey	GROUND ENGINE TESTS • Thermal Survey • Grd Vibration Strain & Flutter Boundary • Unbalanced Rotor Vib • Strength • Impedance • Clearance • Containment • Ingestion • Accelerated Mission Tests (AMT) • Damage Tolerance FLIGHT ENGINE TEST • Fan Strain Survey • Nacelle Temp Survey • Installed Vibration • Deterioration	• Updated Analyses • Engine Structural Maintenance Plan • Operational Usage Survey • Individual Engine Tracking • Durability & Damage Tol Control Actions (Production)

REQUIREMENT LESSONS LEARNED (A.4.2)

A review of structural problems encountered by previous Air Force engine systems highlights the following "lessons learned":

A.5.2 Turbine engine structural integrity verification program.

The ENSIP master plan should be used to define and document the specific verification tasks.

EVALUATION RATIONALE (A.5.2)

Past experience with airframe and engine development programs has demonstrated the usefulness in using plans to show the approach to be used in conducting structural development. As a result the ENSIP uses such plans in several instances as specified herein.

An ENSIP Master Plan is used to define in detail the supplemental information needed in conjunction with this handbook to write a contractual document and to integrate the various analysis and test tasks. Adequacy of the tasks proposed for structural design, development, qualification, and life management of a specific engine system will be evaluated by review of the ENSIP Master Plan.

EVALUATION GUIDANCE (A.5.2)

The ENSIP Master Plan should follow the format of paragraphs A.4 and A.5 of this document. Supplemental information required to make the master plan a contractual document should be developed using guidelines contained in this handbook and through reviews with the procuring activity. The plan should contain the time-phased scheduling and integration of all required ENSIP tasks for design, development, qualification, and life management. The schedules for ENSIP tasks should be integrated with the full-scale development and production decision milestones. ENSIP task milestones are contained in table II relative to the four step full-scale development of Initial Flight Release (IFR), Full Flight Release (FFR), Initial Service Release (ISR) and Operational Capability Release (OCR). The plan should include discussion of unique features, identification of exceptions to the guidelines and requirements of this standard and the associated rationale, and any problems anticipated with execution of the plan. The plan and schedules should be kept current.

EVALUATION LESSONS LEARNED (A.5.2)

Specific lessons learned from past Air Force engine systems are listed in A.4.2 of this handbook.

TABLE II. ENSIP/4 milestone development schedule.

	RFP	CONTRACT AWARD	IFR	FFR	ISR	OCR
• DESIGN INFORMATION						
• ENSIP Master Plan (5.1)		X PLUS PERIODIC UPDATES				
• Design Service Life and Design Usage (5.2)	X					
• Design Duty Cycle (5.2)		X				
• AMT Spectrum (5.6.1)		X				
• Material Characterization Plan (5.3)		X				
• Design Criteria (4.4 through 4.15)	X	X				
• Damage Tolerance and Durability Control Plans (5.5.a & 5.6.1.a)		X PLUS PERIODIC UPDATES				
• Corrosion Prevention and Control Plan (5.6.6.a)		X PLUS PERIODIC UPDATES				
ANALYSES*						
• Thermal (5.4.2.a)			X			
• Damage Tolerance (5.5.b)			X			
• Durability (5.6.1.b)			X			
• Creep/Stress Rupture (5.8.a)			X			
• Strength (5.7.a)			X			
• Dynamic (5.9.a)			X			
• Containment (5.11.a)			X			

*PERIODIC UPDATES REQUIRED PER CDRL TO INCORPORATE RESULTS OF TESTS & USAGE SURVEYS

TABLE II. ENSIP/4 milestone development schedule - Continued.

	RFP	CONTRACT AWARD	IFR	FFR	ISR	OCR
COMPONENT TESTS						
• Damage Tolerance (5.5.c)				X		
• NDI Demonstration (5.5.2)					X	
• Intrinsic Material Defect Distribution (5.5.2)					X	
• Durability (5.6.1.c)				X		
• Strength (5.7.b)			X			
• Creep/Stress Rupture (5.8.b)			X			
• Containment (5.11.b)			X			
CORE ENGINE TESTS						
• Thermal (5.4.2.b)			X-------	--------	-------X	
• Strength (5.7.c)			X			
• Aeromechanical (5.9.c)			X-------	--------	-------X	
• Containment (5.11.b)			X-------	--------	-------X	
ENGINE LIFE MANAGEMENT						
• Interpretation and Evaluation of Test Results (5.6.1.i)			X	X	X	X
• Structural Maintenance Plan (5.16.a)					X---	---X
• Engine Usage Recording System (5.16.b)		X-------	--------	--------	-------X	
• Individual Engine Tracking System (5.16.c)		X-------	--------	--------	-------X	
• Component Tracking System (5.16.d)		X-------	--------	--------	-------X	

TABLE II. ENSIP/4 milestone development schedule - Continued.

	RFP	CONTRACT AWARD	IFR	FFR	ISR	OCR
FULL-SCALE ENGINE TESTS						
• Thermal (5.4.2.b)			X------	------------	--X	
• AMT (5.6.1.d)			X			
(5.6.1.e)				X	X	
(5.6.1.f)						X
(5.6.1.g)						
• Strength (5.7.c)			X			
• Mechanical Impedance (5.9.b)			X			
• Aeromechanical (5.9.c)			X------	------------	--X	
• Noise (5.10)			X------	------------	--X	
• Containment (5.11.b)			X------	------------	--X	
• FOD/DOD (5.12)			X------	------------	--X	
• Engine/Airframe Compatibility (5.15)			X------	---X		

A.4.3 Design service life.

The engine should have a design service life of at least __(a)__ when subject to the design usage of 4.4. In addition, the engine should be capable of withstanding __(b)__ hours at any point in the envelope for both hot and cold parts.

REQUIREMENT RATIONALE (A.4.3)

The service life must be established since it is one of the primary design goals.

REQUIREMENT GUIDANCE (A.4.3)

The following should be used to tailor the handbook paragraph:

(a): The design service life should be determined by the Using Service based on the mission need statement. The units (e.g., cycles, mission hours, flight hours, etc.) for design service life should be determined by the Using Service. The information in table III should be used as a guide to determine the design service life.

(b): A value of ten (10)

TABLE III. Guide to determining design service life.

		Service Life			
System Category	Parts	Flight (hours)	Ground Run (hours)	Flight (missions)	Ground Runs (missions)
Fighter/Attack	Cold Parts	4,000	400	3,000	200
	Hot Parts	2,000	200	1,500	100
Bomber	Cold Parts	10,000	1,000	2,500	200
	Hot Parts	4,000	500	1,250	100
Cargo	Cold Parts	30,000	3,000	9,000	1,000
	Hot Parts	15,000	1,500	4,500	500
Trainer	Cold Parts	18,000	5,400	13,500	1,500
	Hot Parts	9,000	2,700	6,750	750
Helicopter	Cold Parts	6,000	400	3,000	750
	Hot Parts	6,000	400	3,000	750

REQUIREMENT LESSONS LEARNED (A.4.3)

Structural life requirements are the most difficult primary design goals to fulfill. This was the case on many past engine development programs due to a lack of adequate usage parameter definitions. Although requirements for mission profiles, mission mix, and flight hours have often been defined accurately, the important usage parameters that govern cyclic life (major throttle cycles other than the start-stop excursion, time at or above Intermediate power, dwell times, etc.) have not been accurately defined. As a result, operational data has revealed usage parameters not accounted for in design and has resulted in significant reduction in life limits for critical parts and the associated need for redesign and spare parts. Therefore, it is important that realistic design usage information be identified at the outset of the development program for use in design, analysis, and test. The information in table IV presents design service life requirements that have been used in the past.

TABLE IV. Past design service life requirements.

		Service Life			
System Category	Parts	Flight (hours)	Ground Run (hours)	Flight (missions)	Ground Run (missions)
Fighter: F-22 (F119)	Cold Parts	4,000	1,350	2,938	35
	Hot Parts	2,000	675	1,469	18
Bomber: B-2 (F118)	Cold Parts	10,000	N/A	1/	1/
	Hot Parts	4,000	TBD	1/	1/
Cargo: C-17 (F117)	Cold Parts	30,000	TBD	8,516	TBD
	Hot Parts	15,000	TBD	4,258	TBD
Trainer: T-1A (JT15D-5)	Cold Parts	9,000	12,600	2,760	TBD
	Hot Parts	4,500	6,300	1,380	TBD
Turboshaft T800	Cold Parts	6,000	N/A	N/A	N/A
	Hot Parts	6,000	N/A	N/A	N/A

1/ Information classified.

A.5.3 Design service life.

The requirements of 4.3 should be evaluated by analysis, inspection, demonstration, and test.

EVALUATION RATIONALE (A.5.3)

Design service life requirements must be evaluated to ensure the desired levels of damage tolerance, durability, functional capability, operability, performance, reliability, and strength are attained.

EVALUATION GUIDANCE (A.5.3)

Evaluation is generally accomplished by analysis and test. The process of conducting an evaluation program is the responsibility of the contractor and should be an integral part of the tailored integrity program.

EVALUATION LESSONS LEARNED (A.5.3)

None.

A.4.3.1 Hot parts.

Hot parts should have a usable life of __(a)__ times the design service life specified in 4.3. Hot parts and their lives should be listed in table V.

TABLE V. Hot parts.

REQUIREMENT RATIONALE (A.4.3.1)

Hot parts life must be specified in order to achieve logistic and economic effectiveness.

REQUIREMENT GUIDANCE (A.4.3.1)

The following should be used to tailor the specification paragraph:

(a): A value between one-half (1/2) and one (1) times.

A tabular listing of hot parts and their lives should be provided by the engine manufacturer. Hot parts include all parts exposed to the hot gas stream such as the combustor liner, turbine blades and vanes, and exhaust nozzle.

Helicopters designed to operate in environments with minimum maintenance facilities available should require longer hot parts lives for readiness purposes, and be equal to cold parts life.

REQUIREMENT LESSONS LEARNED (A.4.3.1)

In the past, time to cracking did not necessarily become the life limit for a hot part, therefore, the design of hot section parts has been based on evaluation of wear, LCF, creep, stress rupture, oxidation/erosion, and sulphidation.

Cooled turbine vanes were designed such that cooling air would outflow in the presence of cracking or other distress that extends through the thickness. Dual compartment positive outflow design has been needed to minimize erosion rates subsequent to the occurrence of thermal mechanical fatigue cracks thereby maximizing total usable life of the airfoil.

Turbine vanes have also been designed for positive retention so that vane segments would not fall into the gas flow path and cause secondary damage subsequent to total burn-through or severance of an airfoil.

A.5.3.1 Hot parts.

The requirement of A.4.3.1 should be evaluated by analyses and tests.

EVALUATION RATIONALE (A.5.3.1)

Hot parts life must be evaluated to ensure compliance with the requirement of A.4.3.1.

EVALUATION GUIDANCE (A.5.3.1)

A sensitivity analysis should be conducted (on selected hot parts) to identify the effect on parts lives resulting from a range of usage parameters (above and below the design points).

Failure modes (e.g., LCF, creep, stress rupture, etc.) analyses should be conducted by the contractor to establish design stress levels and lives for engine hot parts based on the design usage.

Usage parameters to be considered in the sensitivity analysis should include airspeed, altitude, ambient temperature, partial throttle cycles, and dwell times at minimum and maximum power levels.

Evaluation of hot part lives should be attained as part of the required mission endurance testing. Evaluation of hot parts lives should also be accomplished via the other evaluations conducted in A.4.8 through A.4.15. Pass/fail criteria (i.e., allowable post-test part condition) should be established for all hot parts life testing. Pass/fail criteria for hot parts life testing should be quantified by defining the post-test condition in terms of dimensional tolerances and wear limits.

EVALUATION LESSONS LEARNED (A.5.3.1)

Improper definition of allowable post-test condition of hot parts has been a shortfall in most engine development programs.

A.4.3.2 Cold parts.

Cold parts should have a usable life of _(a)_ times the design service life specified in 4.3. Cold parts and their lives should be listed in table VI.

TABLE VI. Cold parts.

REQUIREMENT RATIONALE (A.4.3.2)

Cold parts life must be specified in order to achieve logistic and economic effectiveness.

REQUIREMENT GUIDANCE (A.4.3.2)

The following should be used to tailor the specification paragraph:

(a): A value of at least one, minimum.

A tabular listing of cold parts and their lives must be provided by the engine manufacturer.

Parts not listed as hot parts in A.4.3.1 are considered to be cold parts.

HCF problems affect those parts that are subjected to aero-induced and vibratory loading. All rotating parts that contact static and/or other rotating parts are susceptible to wear. Although creep is a phenomenon that is typically associated with hot parts, cold and hot section disks have been known to creep due to high centrifugal stresses and the thermal environment.

REQUIREMENT LESSONS LEARNED (A.4.3.2)

Cold parts have been typically designed to an LCF requirement that assured cracking would not occur prior to reaching the required durability limit. The incidence of LCF failures has been reduced after many years of emphasis on designing against LCF. However, other failure modes have become increasingly bothersome (e.g., HCF, wear, and creep).

A.5.3.2 Cold parts.

The requirement of 4.3.2 should be evaluated by analyses and tests.

EVALUATION RATIONALE (A.5.3.2)

Cold parts lives must be evaluated to ensure compliance with the requirement.

EVALUATION GUIDANCE (A.5.3.2)

A sensitivity analysis should be conducted (on selected cold parts) to identify the effect on parts lives resulting from a range of usage parameters (above and below the design points).

Failure modes (e.g., LCF, HCF, creep, etc.) analyses should be conducted by the contractor to establish design stress levels and lives for engine cold parts based on the design usage.

Usage parameters to be considered in the sensitivity analysis should include airspeed, altitude, ambient temperature, partial throttle cycles, and dwell times at minimum and maximum power levels.

Evaluation of cold part lives can be attained as part of the required mission endurance testing. Evaluation of cold parts lives should also be accomplished via the other evaluations conducted in A.4.8 through A.4.15. Pass/fail criteria (i.e., allowable post-test part condition) should be established for all cold parts life testing. Pass/fail criteria for cold parts life testing should be quantified by defining the post-test condition in terms of dimensional tolerances and wear limits.

EVALUATION LESSONS LEARNED (A.5.3.2)

Improper definition of allowable post-test condition of cold parts has been a shortfall in most engine development programs.

A.4.3.3 Expendables.

The minimum life without replacement of all expendable parts and components should be equal to the minimum maintenance-free operating period. Expendable parts, components, and their lives should be listed in table VII.

TABLE VII. Expendable parts.

REQUIREMENT RATIONALE (A.4.3.3)

It is necessary to specify the minimum life of expendable parts and components since their failure or degradation will affect life cycle cost, maintainability, and functional readiness of the engine and subsystems.

REQUIREMENT GUIDANCE (A.4.3.3)

The contractor should provide a tabular listing of expendables with their respective functional lives.

Expendable parts are those normally replaced at maintenance or overhaul, such as minor hardware, O-rings, and gaskets. Expendable components include starters and ignitors.

REQUIREMENT LESSONS LEARNED (A.4.3.3)

None.

A.5.3.3 Expendables.

The requirement of 4.3.3 should be evaluated by analyses and tests.

EVALUATION RATIONALE (A.5.3.3)

Functional life of expendables must be evaluated to insure practical and economical maintenance intervals.

EVALUATION GUIDANCE (A.5.3.3)

Evaluation of expendable parts and components lives can be attained as part of the durability test program. Expendables will typically be replaced during an AMT.

Analyses are not always a practical means of evaluating the required lives of expendables.

EVALUATION LESSONS LEARNED (A.5.3.3)

None.

A.4.3.4 Bearings.

The mainshaft and gearbox bearings should have B 1.0 lives equal to at least the design service life of the engine. A list of bearings and their lives should be presented in table VIII.

TABLE VIII. Bearing lives.

Bearing	Type (Roller or Ball)	Life (Hours)

REQUIREMENT RATIONALE (A.4.3.4)

Main shaft and engine gearbox bearings life must be specified to ensure that the bearings meet engine durability requirements.

REQUIREMENT GUIDANCE (A.4.3.4)

The contractor should provide a tabular listing of the bearings with their respective lives.

Special attention to life testing should be taken when specifying high DN (diameter x rpm) (2.5×10^6) or unusual mounting configuration bearings, e.g., outer race rotating bearings or in shaft bearings in which both races rotate.

REQUIREMENT LESSONS LEARNED (A.4.3.4)

Predictions of bearing performance and/or life have not always been reliable, especially those bearings whose operating conditions exceed recent engine experience or whose designs are unusual. For example, bearing performance analytical models and limited life tests did not have the capability to predict or reveal roller dynamic instability which occurred in some high DN engine roller bearings. More extensive life testing may have uncovered this potentially catastrophic bearing failure mode.

A.5.3.4 Bearings.

The requirement of 4.3.4 should be evaluated by analyses and tests.

EVALUATION RATIONALE (A.5.3.4)

Analyses and tests are required to determine the lives of the engine bearings.

EVALUATION GUIDANCE (A.5.3.4)

A bearing life analysis and bearing tests should be conducted.

The bearing life presentation should clearly identify whether the Weibull slope in the analysis is assumed or whether it is the slope acquired from rig testing. Evaluation should be accomplished early enough in the program to allow for redesign and requalification tests and to make the necessary inputs into the spares provisioning programs.

It is critical that analytical and empirical evaluation of rotor thrust balance occur in IFR and FFR milestones. Rotor thrust balance reports should show agreement between analytical and test data. Rotor thrust evaluation tests should be conducted on appropriate configurations. The intent of the test and analysis is twofold, (1) to ensure peak thrust loads are consistent with thrust bearing life requirements, and (2) to ensure rotor thrust crossovers occur only transiently and in the absence of significant radial loads. The latter is needed to preclude skidding damage to ball bearings.

EVALUATION LESSONS LEARNED (A.5.3.4)

None.

A.4.3.5 Components.

Engine components should have a usable life of (a) times the design service life specified in 4.3. Engine components and their lives should be listed in table IX.

TABLE IX. Components.

REQUIREMENT RATIONALE (A.4.3.5)

Engine components life must be specified in order to achieve logistic and economic effectiveness.

REQUIREMENT GUIDANCE (A.4.3.5)

The value inserted should be:

(a): A value of one, minimum.

A tabular listing of engine components and their lives must be provided by the engine manufacturer. Engine components include: fuel pumps, engine controls, jet nozzle and actuators, anti-icing valves, and the temperature sensing system.

REQUIREMENT LESSONS LEARNED (A.4.3.5)

Air Force engine related mishap data from 1976-1987 shows a high incidence of failure/malfunction of engine components and externals. During that time period, engine component and external failures/malfunctions accounted for no less than 35% of the total engine related mishaps.

A.5.3.5 Components.

The requirement of 4.3.5 should be evaluated by analyses and tests.

EVALUATION RATIONALE (A.5.3.5)

Engine components lives must be evaluated to ensure compliance with the requirement.

EVALUATION GUIDANCE (A.5.3.5)

Failure modes analyses should be conducted by the contractor to establish design lives and stress levels when subject to the design usage. Evaluation of engine component lives can be attained as part of the required mission endurance testing. Evaluation of engine component lives should also be accomplished via other evaluations in this specification.

EVALUATION LESSONS LEARNED (A.5.3.5)

Insufficient qualification testing (methods and duration) has resulted in the fielding of engine components that were not capable of meeting the desired operational life.

A.4.4 Design usage.

The engine structure should be capable of withstanding the design usage specified herein for the design service life specified in 4.3. The design service life and design usage should be specified in terms of mission profiles and mission mix including nonoperating transport of the engine. Important usage parameters should be specified. The flight envelope, mission profiles, mission mix, and environment should be shown.

REQUIREMENT RATIONALE (A.4.4)

One of the major shortcomings in past Air Force airframe and engine development programs has been inadequate definition of the operational usage parameters critical to the durability of engine components. Although requirements for mission profiles, mission mix, and flight hours have often been defined accurately, the important usage parameters that govern cyclic life (major throttle cycles other than the start-stop excursion, time at or above intermediate power, dwell times, etc.) have not been accurately defined as part of design information on many systems. As a result, operational data has revealed usage parameters not accounted for in design and has resulted in significant reduction in life limits for critical parts and the associated need for redesign and spare parts. Therefore, it is important that realistic design usage information be identified at the outset of full-scale development for use in design, analysis, and test of the engine. This rationale applies to A.4.4.1 through A.4.4.8.

REQUIREMENT GUIDANCE (A.4.4)

The design service life and design usage will be supplied by the procuring activity as part of the request for proposal. The contractors should identify any recommended changes based on their experience to the procuring activity for consideration. It is recommended that the contractors conduct trade studies to establish cost (Life Cycle Cost (LCC), Weight, Performance, etc.) as a function of structural life (inspection intervals, economic life, etc.). The results of these trade studies should be presented to the procuring activity for consideration to establish a preferred engine design service life.

If specific design usage requirements are not specified by the procuring activity, the contractor should convert the airframe mission profile information supplied by the procuring activity to engine usage profiles as required (i.e., to convert airplane thrust requirements for profile segments into engine power settings). The design service life and design usage should be included as part of the contract specifications (Prime Item Development Specification and the ENSIP Master Plan).

a. The design usage should include:

(1) Missions and Mission Mix

(2) Usage parameters

(3) Externally applied forces

(4) Operating envelope

(5) Engine attitude limits

(6) Ambient temperature extremes

(7) Icing environment conditions

(8) Corrosive atmosphere conditions

(9) Noise environment conditions

(10) Customer bleed air extraction, loaded accessory pads and power take-off usage

(11) Engine performance retention characteristics

Table X contains engine usage parameters that are critical to structural design as a function of aircraft type. These data should be used as guidance in early design efforts (i.e., advanced engine programs and preliminary design).

TABLE X. Guidance data for early design efforts.

System Category	Parts Classification	Type I Cycles	Type III Cycles	Type IV Cycles	Augmentor Lights or Thrust Reversing	Augment Time or Vector Cycles (hrs)	Time at IRP and Above (hrs)
		0-max-0	Idle-max-Idle	Cruise-Int-Cruise			
Fighter	Cold Parts	3,200	20,000	24,000	17,000	200	800
	Hot Parts	1,600	10,000	12,000	8,500	100	400
Bomber	Cold Parts	2,700	30,000	30,000	16,000	250	1,80
	Hot Parts	1,350	15,000	15,000	8,000	15	90
Cargo	Cold Parts	10,000	14,000	TBD	N/A	N/A	6,300
	Hot Parts	5,000	7,000	TBD	N/A	N/A	3,000
Trainer	Cold Parts	15,000	150K	150K	TBD	TBD	3,600
	Hot Parts	7,500	75,000	75,000	TBD	TBD	1,800
Helicopter	Cold Parts	15,000	N/A	N/A	0	0	N/A
	Hot Parts	15,000	N/A	N/A	0	0	N/A

Typical total flight hours as a function of aircraft type are listed in table X. Total flight hours includes all the time spent at power from the onset of takeoff roll to touchdown at landing. It is the intent that the total flight hours specified for the engine system be consistent (equal to) that specified for the airframe weapon system. If a total flight hour requirement is identified in the

Statement of Need (SON) by the using command, this requirement should be contained in the table.

Total operating time (TOT) includes mission time from engine start through taxi, engine flight time as defined above and taxi after landing to engine shutdown. Past data shows that ground operation during a mission is approximately 0.75-1.00 hours and can be added to engine flight hours per mission to derive TOT per mission.

Typical ground run hours as a function of aircraft type are listed in table X. Engine ground run hours pertain to time spent on the ground running for functional checks such as trim checks and system equipment checks. Past data indicates these ground run hours (excluding taxi time) can be approximately 5-10 percent of total flight hours. Surveys and reviews of past engine usage should be taken periodically to establish ground run time for specific aircraft weapon systems.

Typical number of flight and ground runs as a function of aircraft type are listed in table X. The number of runs is a derived value dependent on the total flight and ground run hours and the length of each type of flight mission and the ground run. The length of each mission type can vary significantly depending on the aircraft type. For example, a fighter aircraft mission flight time can be 1.0-1.5 hours duration while a bomber aircraft mission flight time can be 4.0 hours duration. The number of flight and ground runs should be explicitly stated since it establishes the number of 0-immediate/max-0 throttle excursions.

Typical values for the number and type of throttle excursions as a function of aircraft type are listed in table X. Throttle excursions principally drive the low cycle fatigue failure mode and dictate component crack growth lives and inspection periods in a turbine engine and must be taken into account in design. Therefore, the structural design of a turbine engine should take into account all transients which will produce fatigue damage and/or crack growth from the selected initial flaw. As a minimum, the 0-intermediate/max-0 cycles, idle-intermediate/max-idle cycles and cruise-intermediate/max-cruise cycles should be taken into account. In some cases, it may be necessary to include other types of cycles such as, throttle reburst cycles. A throttle reburst particularly occurs in a system which experiences air-to-air combat or air-to-ground usage. This type of cycle occurs when an idle dwell follows a period of sustained maximum power and the idle dwell is sufficient in duration to achieve thermal reversal on the components (usually a turbine disk and attached blade retainers). Thermal reversals are also possible in the compressor after shutdown and during refueling after high altitude, high mach number operation. A throttle reburst at this point will add mechanical stress to the already present thermal stress. Numerous throttle activities of this type can significantly affect life and should be taken into account in design where appropriate. Hold times at idle power after a sustained period at intermediate/maximum power must be defined and used in design on new engine development programs. Recorded data is now available or becoming available on operational usage of several weapon systems (F-15, F-16, B-1 Flight Test, etc.). These data have been used to establish distribution of dwell times as a function of aircraft type and mission type. It is the intent that these distributions and results for other usage parameters be placed in this appendix as soon as possible.

Typical values of "hot time" as a function of aircraft type are listed in table X. Aircraft drag, gross weight, and mission altitude requirements affect climb time which is usually accomplished at maximum or intermediate power settings and therefore are large drivers in the structural design of engine components subject to creep and stress rupture failure modes. It is suggested that a conservative approach be taken for design purposes in deriving time at or above intermediate power since all past systems historically have had higher drag, and gross weight than originally predicted. Further, in certain cases, system flight tactics may evolve which will require maximum power for extended purposes not foreseen in the construction of early mission profiles. Time at high mach number must be thoroughly investigated since this flight condition usually accelerates creep and stress rupture of some engine components. It is suggested that a sensitivity analysis be accomplished on components critical in creep and stress rupture to all those variables mentioned above. Although time at or above intermediate power is a derived value dependent on the mission profiles, mission mix, and specific duty cycles, it should be stated as an explicit value since it drives creep and stress rupture life for many engine components. It is recommended that time at or above intermediate power not be less than 20 percent of the total flight hour requirement in table X.

Typical values for number of augmentor lights and time spent in augmentation as a function of aircraft type are listed in table X. Careful analysis of mission profiles and mix should be accomplished to determine augmentor usage in terms of number of lights and time spent in augmentation. The number of augmentor lights will affect the thermal low cycle fatigue life of the augmentor liner as well as erosion capability. It is recommended that margins be provided in design for more severe usage of the augmentor than indicated in the mission profiles. Many engine programs in the past have had augmentor durability problems requiring extensive field repair. It is recommended that the time spent in augmentation not be less than 5 percent of the total flight hour requirement in table X. It is recommended that the number of augmentor lights not be less than 50 percent of the total number of throttle excursions contained in table X.

Although time spent at key points in the flight envelope is a derived value dependent on the mission profiles, mission mix, and specific duty cycles, it should be stated as an explicit design requirement since it drives creep, stress rupture, and flutter for many engine components. Also, specific times at flight envelope extremities should be stated as an explicit design requirement in addition to values derived from the duty cycles to assure engine capability to meet future usage requirements of the airframe weapon system.

High mach number/altitude design requirements (flight envelope points and duration) should be established between the procuring activity and the using command for a particular engine and aircraft weapon system, and these requirements should be contained in A.4.4.

The design usage should include, but not be limited to, the defined missions and mission mix, design duty cycle, usage parameters, nozzle usage, environmental (external, internal, and installation) conditions, unique flight conditions, and the non-operating environment. The internal environment is specified in A.4.5.2. The engine operating envelope is determined by the engine contractor. The missions and mission mix of A.4.4 are presented in table XI. Unique flight conditions are discussed in A.4.5 - A.4.5.1 and presented on figure 1. Vibration and dynamic response characteristics are specified in A.4.13 - A.4.13.1. Design usage should also include the external environmental conditions specified in A.4.5, A.4.5.1, and A.4.5.3, which covers atmospheric conditions and engine ingestion capability such as bird, ice, water, steam, sand, and dust.

The typical rate of performance deterioration should be based on the performance program and performance deterioration model. The contractor should address deteriorated engine conditions as part of the design practice and account for it in the life predictions.

Engines with control systems that maintain minimum thrust levels, by increasing engine temperature and speed, will decrease the potential parts lives by exposing the engine to increased thermal and mechanical stresses.

The ability of engine hot parts to meet design life requirements can be significantly reduced due to engine uptrim or other conditions that result in hot gas stream temperatures higher than that of a production engine. To account for the impact on hot parts life, by operation at increased temperatures, margins of 30°F to 70°F above production acceptance (non-degraded) maximum steady-state gas temperature have been imposed by the procuring activity during the design of hot parts to assure that design life goals will be met. AIA PC Project 338-2A members made a consensus recommendation in 1982, that the procuring activity not establish a specific temperature margin since this number will vary with engine type and application. For analysis purposes, the F100-PW-229 was designed for 1/3 life at nominal production performance and 2/3 life at full deterioration levels in order to provide full life, even with deteriorated engines.

REQUIREMENT LESSONS LEARNED (A.4.4)

One of the major shortcomings in past engine development programs has been inadequate definition of the design usage parameters critical to engine durability. Although requirements for mission profiles, mission mix, and flight hours have often been defined accurately, the important usage parameters that govern cyclic life (major throttle cycles other than the start-stop excursion, time at or above Intermediate power, dwell times, etc.) have not been accurately defined. As a result, operational data has revealed usage parameters not accounted for in design and has resulted in significant reduction in life limits for critical parts and the associated need for redesign and spare parts. Therefore, it is important that realistic design usage information be identified at the outset of the development program for use in design, analysis, and test.

TABLE XI. Design duty cycle summary.

Cold Parts									
	Time (hrs)	TAIAA (hrs)	Type I cycles	Type III cycles	Type IV cycles	A/B lts	A/B time (hrs)	Vector cyles	Other cycles
Flight operations									
Ground operations									
Test cell trouble-shooting etc.									
TOTAL									

TAC = Type I + Type III/4 + Type IV/40 + Kx (other cycles)

Hot Parts									
	Time (hrs)	TAIAA (hrs)	Type I cycles	Type III cycles	Type IV cycles	A/B lts	A/B time (hrs)	Vector cyles	Other cycles
Flight operations									
Ground operations									
Test cell trouble-shooting etc.									
TOTAL									

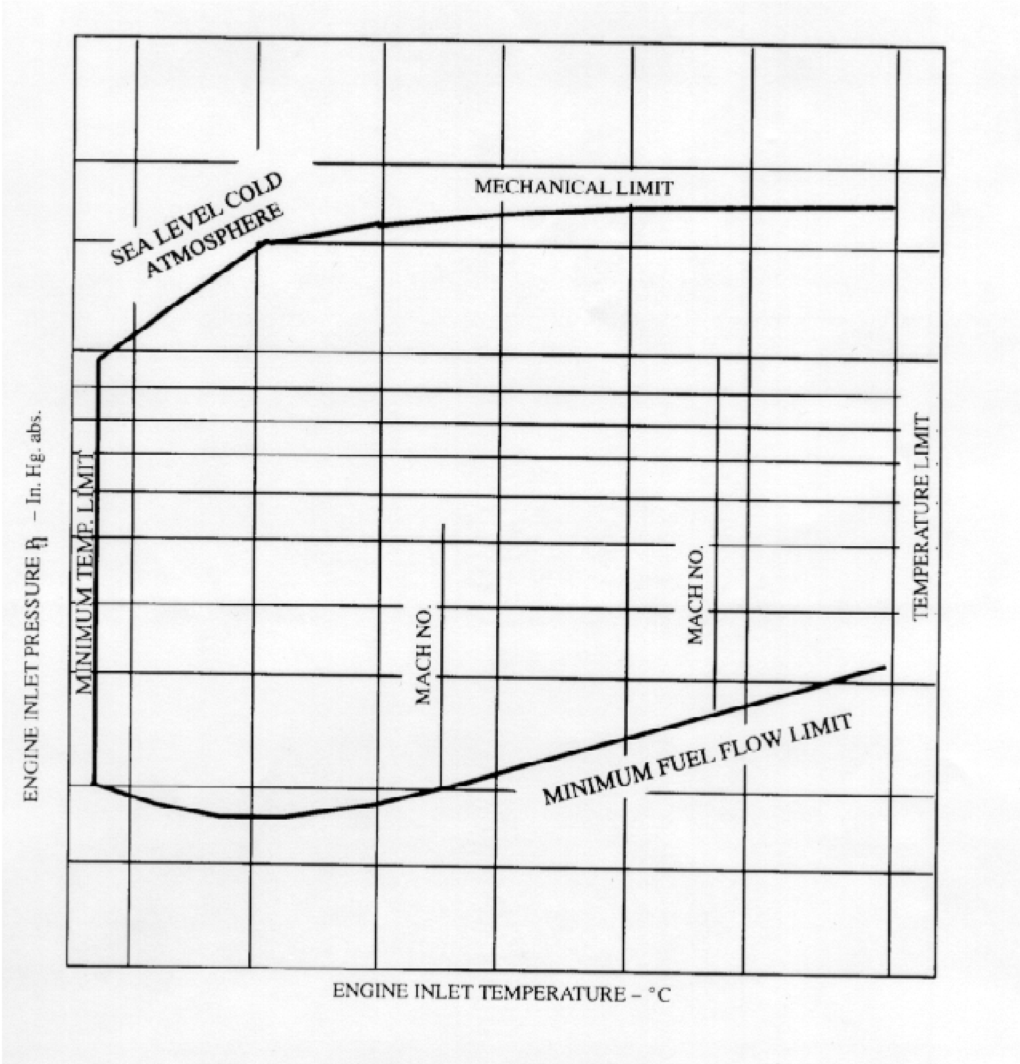


FIGURE 1. Operating limits.

Past program specific usage parameters are specified in table XII.

TABLE XII. Past program specific usage parameters.

System Category	Parts Classification	Type I Cycles	Type III Cycles	Type IV Cycles	Augmentor Lights or Thrust Reversing	Augment Time or Vector Cycles (hrs)	Time at IRP and Above (hrs)
		0-max-0	Idle-max-Idle	Cruise-Int-Cruise			
Fighter F-22 (F119)	Cold Parts	2,973	20,503	22,074	20,239	186 (109)	684
	Hot Parts	1,487	10,252	11,037	10,165	93 (54)	342
Bomber B-2 (F118)	Cold Parts	2,371	7,113	N/A	N/A	N/A	TBD
	Hot Parts	948	2,844	N/A	N/A	N/A	TBD
Cargo C-17 (F117)	Cold Parts	8,516	25,840	17,178	12,700	N/A	TBD
	Hot Parts	4,258	12,920	8,589	6,350	N/A	TBD
Trainer T-1A JT15D-5	Cold Parts	28,000	20,288	3,817	N/A	N/A	885
	Hot Parts	14,000	10,140	1,909	N/A	N/A	443
Helicopter	Cold Parts	15,000	TBD	TBD	0	0	TBD
	Hot Parts	15,000	TBD	TBD	0	0	TBD

A.5.4 Design usage.

Verification of design usage should be accomplished by analysis, design development tests, and engine tests, in accordance with the ENSIP Master Plan to ensure that the engine and its components meet the design service life and design usage requirements of 4.3 and 4.4. A design duty cycle(s) should be derived from the design service life and design usage specified in 4.3 and 4.4. The design duty cycle should be supplied.

EVALUATION RATIONALE (A.5.4)

Usage requirements of A.4.4 will entail multiple mission profiles each with separate speed, altitude, and throttle excursions as a function of time. It is not practical to analyze and test each of these discrete profiles with appropriate mission mix throughout the various development tasks. Therefore, a minimum number of design duty cycles must be derived early in the development phase (as early as contract award) for use in all subsequent analysis and test tasks. These design duty cycles may be provided by the procuring activity as part of the Request for Proposal (RFP).

EVALUATION GUIDANCE (A.5.4)

Sensitivity analysis should be conducted on selected components to identify the effect of probable ranges in usage variables on engine life limits. The results of the sensitivity analysis should be used to condense the design service life and design usage of A.4.4 into a minimum number of design duty cycles. Important parameters to be considered in the sensitivity analysis include airspeed, altitude, partial throttle cycles (cruise to intermediate, idle to cruise, etc.), and dwell time at min and max power levels. The procuring activity will identify in the request for proposal the applicable requirement for sensitivity analysis.

EVALUATION LESSONS LEARNED (A.5.4)

See A.4.4.

A.4.5 Operating envelope.

The engine should meet all the requirements of the document throughout the complete operating envelope without exceeding any limits. The engine operating limits should be specified for the identified environment and displayed with figures 1 and 2 and tables XIII and XIV. If applicable, the thrust augmentation operating envelope should be included on the figures.

REQUIREMENT RATIONALE (A.4.5)

This requirement defines the operating envelope within which the engine must meet its functional, performance, and durability requirements (aerothermodynamic and mechanical limitations). The engine air mass flow inlet conditions in terms of pressure and temperature will be different and more severe than sea level static standard day values during much of its operation. The engine must be able to operate in these expected environments and component durability must not be degraded such that the design life requirements are not attained.

REQUIREMENT GUIDANCE (A.4.5)

If the referenced figures are insufficient to describe the operating envelope, either the Using Service or contractor can add a table.

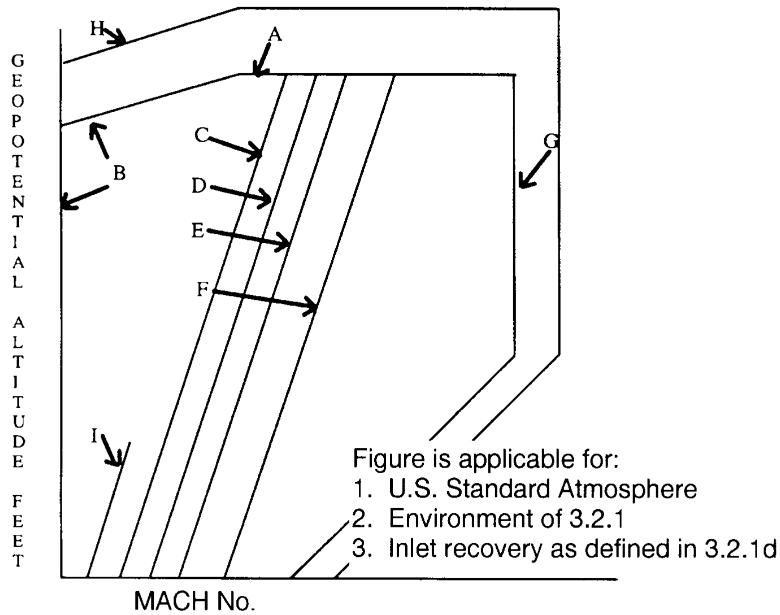
The specified limits should be predicated on the most critical parameters and characteristics of the engine. The absolute altitude of the engine and the range of Mach numbers applicable at standard day, cold, tropical, and hot atmospheric conditions should be specified on a figure. A figure should represent the operating envelope for pressure/temperature. It is recommended that aerodynamic/thermodynamic limits (total pressure-P vs. total temperature-T), the flight envelope (altitude vs. flight mach number), and the ambient temperature distribution be diplayed on figures and be included as a design requirement. Specific values for these curves should be selected to be consistent with the intended application and the primary specification.

Both transient and steady-state operations should be specified. The engine operating envelopes should meet or exceed the envelope requirements of all current and anticipated aircraft applications for the engine.

Design requirements are set by envelope extremes, such as the maximum inlet pressure, which helps define the combustor case maximum pressure requirements and blade aero-elastic requirements for blade vibration. Low inlet pressure and temperatures impose design requirements on the combustor and augmentor performance parameters. Altitude and Mach number extremes will impact the cooling requirements of the engine lubrication system. Bearing loads need to be quantified throughout the engine envelope. In summary, most parts of the engine are, in some way, impacted by the engine envelope requirements.

REQUIREMENT LESSONS LEARNED (A.4.5)

In-service engines have operated outside of the operating envelope. The aircraft envelope is normally within the engine envelope.



NOTES:
A. Maximum starting altitude.
B. Minimum Mach No. for starter assisted starting.
C. Minimum Mach No. starting without starter assist, no customer power extraction, no customer bleed air extraction.
D. Minimum Mach No. for starting without starter assist, Maximum customer power extraction, no customer bleed air extraction.
E. Minimum Mach No. for starting without starter assist, no customer power extraction, Maximum customer bleed air extraction.
F. Minimum Mach No. for starting without starter assist, Maximum customer power extraction. Maximum customer bleed air extraction.
G. Maximum Mach No. for starting air extraction.
H. Operating envelope.
I. Post-loiter starting point.

FIGURE 2. Operating envelope.

TABLE XIIIa. Performance of standard day, 15°C (59°F), sea level, static conditions1/ with _____ nozzle.

Power Setting2/	Minimum Thrust N (lbf)		Maximum SFC (lbm/hr/lbf)		Max Engine Rotor Speed (rpm)		Maximum Gas Temp3/ °C°F)		Maximum Measured Temp4/ °C(°F)		Total Airflow5/ +/- ___% (lbm/sec)	
	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/
Max. Aug. (if applicable)												
Min. Aug. (if applicable)												
Int.												
90% Int.												
75% Int.												
Idle	(Max)	(Max)	6/	6/	(Min)	(Min)						

NOTES:
1/ The engine performance values shown should be from the engine performance computer program of 3.2.1.1
2/ Power settings and columns should be added or deleted as required by the Using Service (e.g., customer bleed air/power extraction).
3/ Defined at the first stage turbine rotor inlet location (Contractor should parenthetically insert, in column heading, the station designation).
4/ Contractor should parenthetically insert, in column heading, the measurement plane station designation.
5/ Total engine airflow.
6/ Maximum fuel consumption - lbm/hr.
7/ Deteriorated engine performance is specified for _________ TACs (or hours) of use.

TABLE XIIIb. Performance at non-standard hot ambient, sea level, static conditions1/ with _____ nozzle.

Power Setting2/	Minimum Thrust N (lbf)		Maximum SFC (lbm/hr/lbf)		Max Engine Rotor Speed (rpm)		Maximum Gas Temp3/ °C(°F)		Maximum Measured Temp4/ °C(°F)		Total Airflow5/ +/- ___% (lbm/sec)	
	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/
Max. Aug. (if applicable)												
Min. Aug. (if applicable)												
Int.												
90% Int.												
75% Int.												
Idle	(Max)	(Max)	6/	6/	(Min)	(Min)						

NOTES:
1/ The engine performance values shown should be from the engine performance computer program of 3.2.1.1
2/ Power settings and columns should be added or deleted as required by the Using Service (e.g., customer bleed air/power extraction).
3/ Defined at the first stage turbine rotor inlet location (Contractor should parenthetically insert, in column heading, the station designation).
4/ Contractor should parenthetically insert, in column heading, the measurement plane station designation.
5/ Total engine airflow.
6/ Maximum fuel consumption - lbm/hr.
7/ Deteriorated engine performance is specified for _________ TACs (or hours) of use.

TABLE XIIIc. Performance at non-standard cold ambient, sea level, static conditions1/ with _____ nozzle.

Power Setting2/	Minimum Thrust N (lbf)		Maximum SFC (lbm/hr/lbf)		Max Engine Rotor Speed (rpm)		Maximum Gas Temp3/ °C(°F)		Maximum Measured Temp4/ °C(°F)		Total Airflow5/ +/- ___% (lbm/sec)	
	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/
Max. Aug. (if applicable)												
Min. Aug. (if applicable)												
Int.												
90% Int.												
75% Int.												
Idle	(Max)	(Max)	6/	6/	(Min)	(Min)						

NOTES:
1/ The engine performance values shown should be from the engine performance computer program of 3.2.1.1
2/ Power settings and columns should be added or deleted as required by the Using Service (e.g., customer bleed air/power extraction).
3/ Defined at the first stage turbine rotor inlet location (Contractor should parenthetically insert, in column heading, the station designation).
4/ Contractor should parenthetically insert, in column heading, the measurement plane station designation.
5/ Total engine airflow.
6/ Maximum fuel consumption - lbm/hr.
7/ Deteriorated engine performance is specified for _________ TACs (or hours) of use.

TABLE XIIIa. Turboprop/turboshaft engine performance at standard day, 15°C (59°F), sea level, static conditions6/ with _____ nozzle.

Power Setting1/	Max. gas generator speed(s) (rpm)		Max. gas temp. 2/ (°C(°F))		Max. measured temp. 3/ (°C(°F))		Total Airflow4/ +/- ___% (lb/sec)		Max. SFC (lbm/hr/kw)		Min. shaft power kw (shp)		Output torque N-m (lb-ft)		Min. output shaft speed (rpm)		Resid. Jet thrust N (lbf)	
	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/
Contingency (if applicable)																		
Maximum (if applicable)																		
Intermediate																		
Maximum Continuous																		
90% Maximum Continuous																		
No load (if applicable)																		
Idle	Min	Min							5/	5/	Max	Max						

NOTES:
1/ Parameters and columns should be added or deleted as required by the Using Service (e.g., customer bleed air).
2/ Defined at the first stage high pressure turbine rotor inlet location (contractor should parenthetically insert, in column heading, the station designation).
3/ Contractor should parenthetically insert, in column heading, the measurement plane station designation.
4/ Total engine airflow.
5/ Maximum fuel consumption - lb/hr.
6/ The engine performance values shown should be from the engine performance computer program of 3.2.1.1.
7/ Deteriorated engine performance is specified for _____ TACs (or hours) of use.

TABLE XIIIb. Turboprop/turboshaft engine performance at non-standard hot ambient sea level, static conditions6/ with _____ nozzle.

Power Setting1/	Max. gas generator speed(s) (rpm)		Max. gas temp. 2/ (°C(°F))		Max. measured temp. 3/ (°C(°F))		Total Airflow 4/ +/- ___% (lb/sec)		Max. SFC (lbm/hr/kw)		Min. shaft power kw (shp)		Output torque N-m (lb-ft)		Min. output shaft speed (rpm)		Resid. Jet thrust N (lbf)	
	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/	New	Det.7/
Contingency (if applicable)																		
Maximum (if applicable)																		
Intermediate																		
Maximum Continuous																		
90% Maximum Continuous																		
No load (if applicable)																		
Idle	Min	Min							5/	5/	Max	Max						

NOTES:
1/ Parameters and columns should be added or deleted as required by the Using Service (e.g., customer bleed air).
2/ Defined at the first stage high pressure turbine rotor inlet location (contractor should parenthetically insert, in column heading, the station designation).
3/ Contractor should parenthetically insert, in column heading, the measurement plane station designation.
4/ Total engine airflow.
5/ Maximum fuel consumption - lb/hr.
6/ The engine performance values shown should be from the engine performance computer program of 3.2.1.1.
7/ Deteriorated engine performance is specified for _____ TACs (or hours) of use.

TABLE XIIIc. Turboprop/turboshaft engine performance at non-standard cold ambient sea level, static conditions 6/ with _____ nozzle.

Power Setting 1/	Max. gas generator speed(s) (rpm)		Max. gas temp. 2/ (°C(°F))		Max. measured temp. 3/ (°C(°F))		Total Airflow 4/ +/- ___% (lb/sec)		Max. SFC (lbm/hr/kw)		Min. shaft power kw (shp)		Output torque N-m (lb-ft)		Min. output shaft speed (rpm)		Resid. Jet thrust N (lbf)	
	New	Det. 7/	New	Det. 7/	New	Det. 7/	New	Det. 7/	New	Det. 7/	New	Det. 7/	New	Det. 7/	New	Det. 7/	New	Det. 7/
Contingency (if applicable)																		
Maximum (if applicable)																		
Intermediate																		
Maximum Continuous																		
90% Maximum Continuous																		
No load (if applicable)																		
Idle	Min	Min							5/	5/	Max	Max						

NOTES:

1/ Parameters and columns should be added or deleted as required by the Using Service (e.g., customer bleed air).

2/ Defined at the first stage high pressure turbine rotor inlet location (contractor should parenthetically insert, in column heading, the station designation).

3/ Contractor should parenthetically insert, in column heading, the measurement plane station designation.

4/ Total engine airflow.

5/ Maximum fuel consumption - lb/hr.

6/ The engine performance values shown should be from the engine performance computer program of 3.2.1.1.

7/ Deteriorated engine performance is specified for _____ TACs (or hours) of use.

TABLE XIV. Performance at altitude conditions 4/ with _____ nozzle.

Power Setting 1/	Alt. (ft)	Amb. Temp.	Mach num.	Minimum net thrust N (lbf)		Maximum SFC (lb/hr/lb)		Maximum engine rotor speed (rpm)		Maximum gas temp 2/ (°C(°F))		Maximum measured temp 3/ (°C(°F))		Total airflow (lb/sec) +/- __%		Cust. Bld. air	Cust. Pwr. Ext.
				New	Det 5/	New	Det 5/	New	Det 5/	New	Det 5/	New	Det 5/	New	Det 5/		

NOTES:

1/ Power settings should be as required by the Using Service to cover the operating envelope and to be compatible with mission requirements.

2/ Defined at the first stage turbine rotor inlet location (contractor should parenthetically insert, in column heading, the station designation).

3/ Contractor should parenthetically insert, in column heading, the measurement plane station designation.

4/ The engine performance values shown should be from the engine computer program of 3.2.1.1.

5/ Deteriorated engine performance is specified for _____ TACs (or hours) or use.

A.5.5 Operating envelope.

The requirements of 4.5 should be evaluated by analysis, demonstration, and test.

EVALUATION RATIONALE (A.5.5)

Engine testing in ground test facilities is required to demonstrate satisfactory engine operation and performance throughout the operating envelope of the engine.

EVALUATION GUIDANCE (A.5.5)

Engine testing should be conducted to demonstrate that the engine can meet the functional, performance, and durability requirements of this specification throughout the operating envelope. All the sea level and altitude tests specified should be used to demonstrate satisfactory operation throughout the operating envelope. Test demonstration figures should show both the operating envelope and demonstration points. The Using Service and contractor should negotiate the test points, and the testing should be accomplished in an altitude test facility.

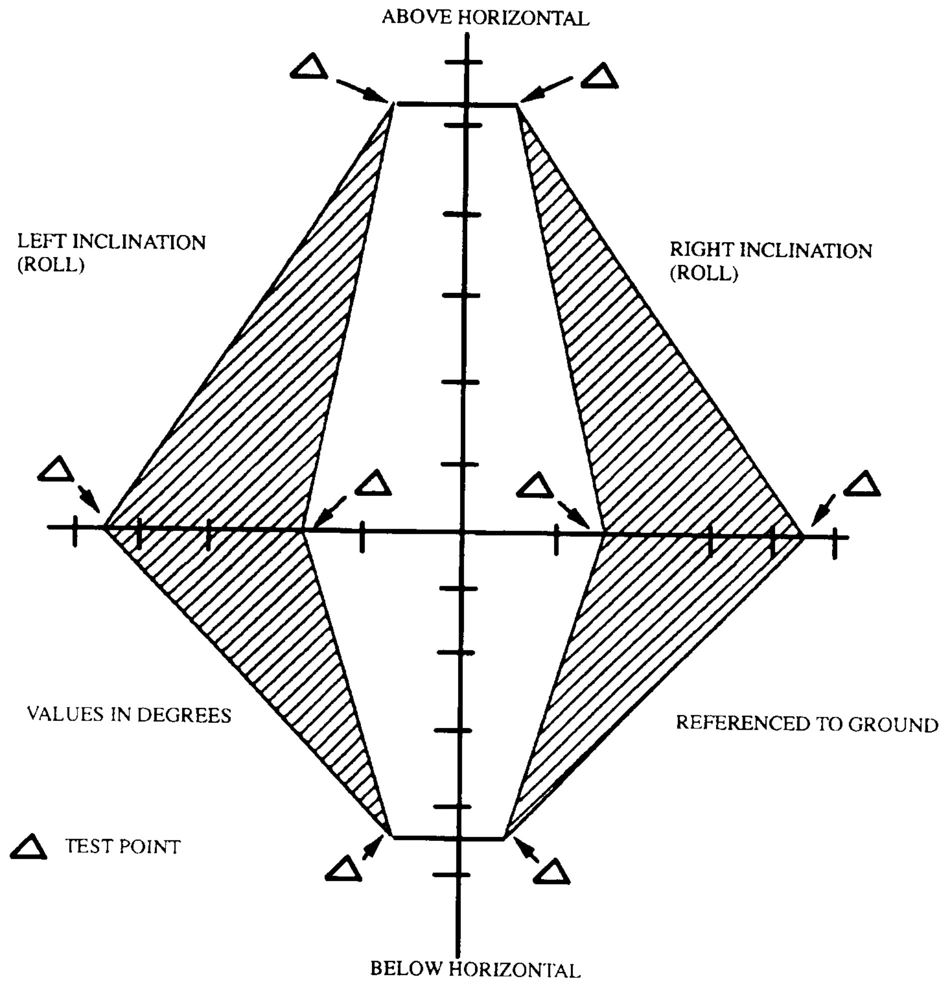
Characteristics of the engine which should be evaluated around the envelope include: steady-state and transient performance, engine stability, starting, internal stresses and temperatures, augmentor operation, lubrication system operation, control system operation, and inlet distortion tolerance.

EVALUATION LESSONS LEARNED (A.5.5)

Thorough testing of the engine around the envelope extremes in an altitude test facility has been a cost effective method of reducing the possibility of encountering engine problems during flight testing and deployment of the weapon system. Early identification of engine problems and demonstration of corrective changes around the engine envelope has been accomplished with this testing. Experience has shown that augmentors on afterburning engines should be tested for stable combustion in the upper left hand corner of the envelope as well as at maximum Mach number conditions. Maximum inlet pressure conditions on the exhaust nozzles have caused buckling of nozzle components. This test is, therefore, of particular importance to engines with variable geometry exhaust nozzles. There have been cases where oil hiding has been observed in the engine gearbox at high inlet pressure. Therefore, the behavior of lubrication and fuel systems should be carefully monitored at flight envelope extremes and during altitude starts.

A.4.5.1 Operating attitude and conditions.

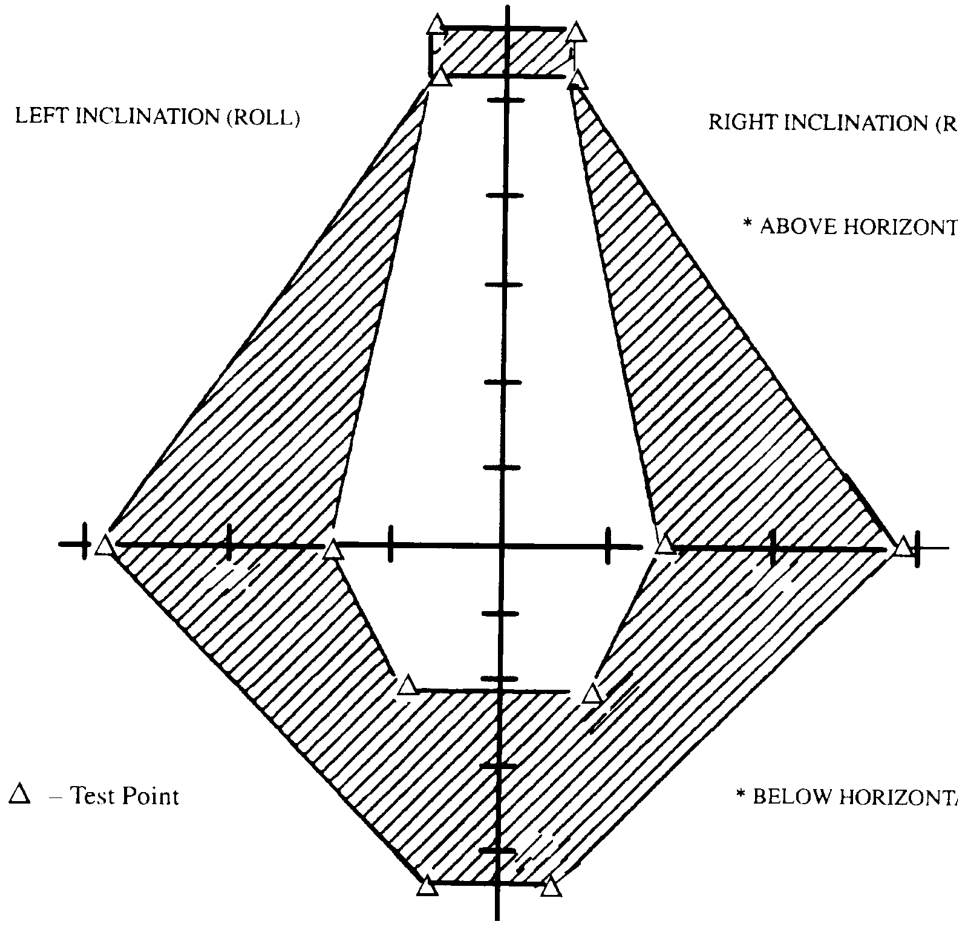
The engine operating attitude limits should be shown on figure 3a, b, and c. The engine should meet the requirements of the specification when operating in the normal operation area of the figure, and operate at least _(a)_ seconds continuously in the limited and transient operation areas of figure 3a, b, and c. Operation in the limited operation area should not degrade engine performance or cause any damage. The engine should start, stop, and be stowed in any of the attitudes shown in the normal operation area of figure 3a, b, and c. Engine stowing capability outside of the limited operation area should be specified. The engine should function satisfactorily for at least _(b)_ seconds in negative g and for at least _(c)_ seconds in zero g conditions.



NOTES:

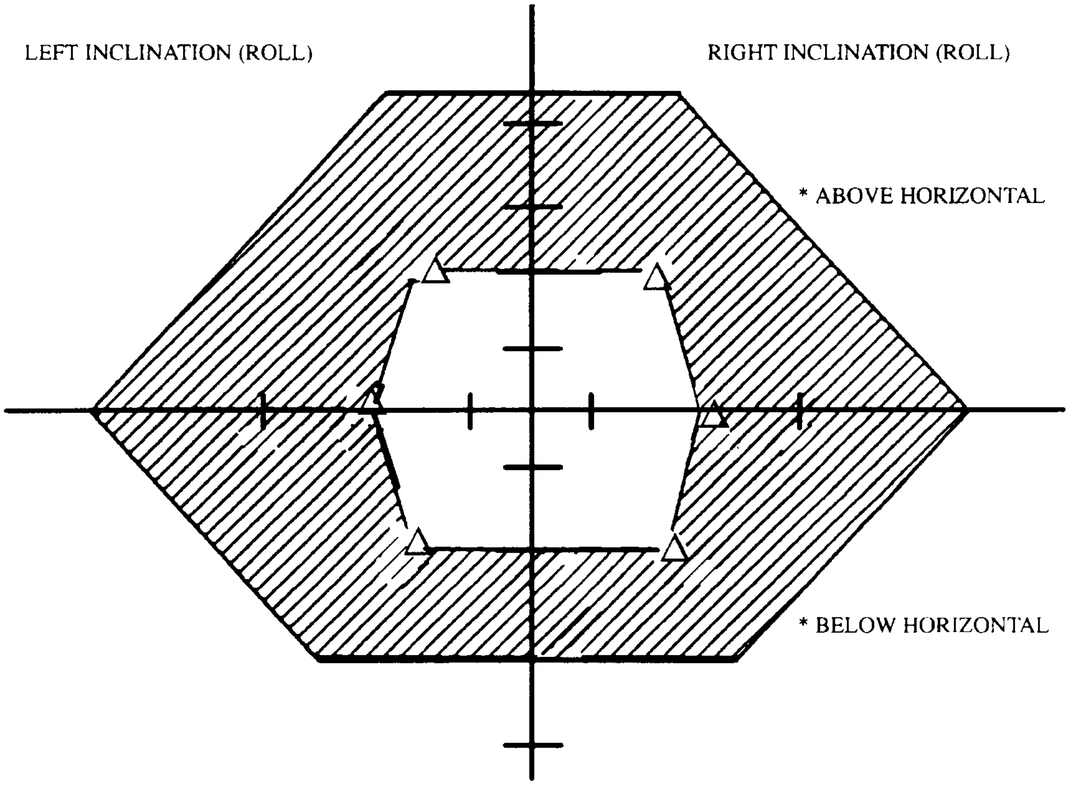
1. The engine shall be capable of operating at all possible acceleration conditions; however, for the purpose of defining the direction of acceleration vector from the engine CG, the figure assumes no acceleration other than gravity.
2. Engine centerline perpendicular to plane of paper.
3. Continuous operation in clear area
4. ________ second operation in shaded area.

FIGURE 3a. Engine attitude limits (fixed wing aircraft).



NOTES:
1. The engine shall be capable of operating at all possible acceleration conditions; however, for the purpose of defining the direction of acceleration vector from the engine CG, the figure assumes no acceleration other than gravity.
2. *_____ referenced to ground.
3. Engine centerline perpendicular to plane of paper.
4. Continuous operation in clear area.
5. _____ second operation in shaded area.

FIGURE 3b. Engine attitude limits (VSTOL aircraft engines).



NOTES:
1. For the purpose of defining the direction of the acceleration vector from the engine CG, the figure assumes no acceleration other than gravity; however, the engine shall be capable of operating at all possible acceleration conditions.
2. * ____ referenced to ground.
3. Engine centerline perpendicular to plane of paper.
4. Continuous operation in clear area
5. ____ second operation in shaded area.
6. Symbol Δ indicates points for test.

FIGURE 3c. Engine attitude limits (rotary wing aircraft engines).

REQUIREMENT RATIONALE (A.4.5.1)

The engine is required to operate throughout the attitudes imposed by the aircraft, such as takeoff, climb, inverted flight, air combat maneuvers, stowage, and terrain following. Time duration of these factors is a significant consideration to the engine design.

REQUIREMENT GUIDANCE(A.4.5.1)

The following should be used to tailor the specification paragraph:

(a): A value of at least 30 seconds.

(b): A value of at least 60 seconds.

(c): A value of at least 30 seconds.

Background:

For Army V/STOL aircraft requiring engine attitude changes, the starting and stopping attitude limits should be not less than 105 degrees nose up, 20 degrees nose down, and 30 degrees roll to each side. Above 6 km, continuous operation is not required at nose up attitudes greater than 45 degrees.

REQUIREMENT LESSONS LEARNED (A.4.5.1)

Extended flight operation in zero or negative "g" conditions resulted in oil system malfunctions, such as oil starvation, bearing sump flooding, gearbox flooding, oil foaming problems, and seal leaks. Special provisions, such as an auxiliary lube system may be necessary in the lubrication system for extended inverted flight operation.

A.5.5.1 Operating attitude and conditions.

The requirements of 4.5.1 should be evaluated by analysis, demonstration, and test.

EVALUATION RATIONALE (A.5.5.1)

Testing is required to demonstrate satisfactory engine functional capability under a variety of attitude and maneuvering conditions.

EVALUATION GUIDANCE (A.5.5.1)

The engine should be subjected to an attitude test to meet the requirements of A.4.5.1. Engine capability to operate for 60 seconds at negative "g" and 30 seconds at zero "g" conditions should be evaluated by analysis or by a rig test of the lubrication oil system. The engine should be started and operated at intermediate thrust/power demand position, for at least 30 minutes, at each of the test points shown in the normal operation area of figure 3a, b, and c. The engine should also be operated at intermediate thrust/power demand position for at least 30 seconds at each of the test points shown in the limited operation area of figure 3a, b, and c. This test should be considered completed when the engine starts satisfactorily, remains within all operating limits, and there is no evidence of mechanical damage.

The qualification test program should have a strong foundation of component tests, especially in the oil system component area. Oil tanks, oil pumps, scavenge pumps, gearboxes, deareators, and bearing compartments should all be component tested in various simulated flight conditions. It may be possible to test complete small engines at various attitudes.

Figure 3a, b, and c should define engine attitude limits (roll and pitch) under static ground test stand conditions and should not be construed as necessarily defining engine attitude limits during flight (engine attitude capability is usually limited by lubrication system design). The forces generated during maneuvering flight may have a combined or resultant effect that permits engine pitch and roll attitudes that exceed the limits of figure 3a, b, and c without encountering an engine limiting condition.

EVALUATION LESSONS LEARNED (A.5.5.1)

None.

A.4.5.2 Internal environment.

The engine components should be capable of withstanding the internal thermal and pressure environments that occur during engine operation (steady state and transient conditions).

REQUIREMENT RATIONALE (A.4.5.2)

Thermal and pressure conditions change significantly throughout the engine rotor stages and must be accounted for in design and analysis to assure that life requirements are attained.

REQUIREMENT GUIDANCE (A.4.5.2)

The internal environment of the engine should be characterized for both steady state and transient conditions for each critical point in the flight envelope. Conditions to be considered should include shutdown and cool down effects, stratification affecting rotor bow and subsequent starts as well as installed engine outer case temperature and temperature variations, thermal, pressure, vibration, and dynamic loading. The internal environment should be specified at various radial and axial locations, as necessary, to completely characterize engine operating conditions. The probable variations in radial profiles and pattern factors between combustor systems which may occur due to fabrication and assembly tolerances should be established. Transient conditions should be evaluated to identify critical thermal stresses that can occur during acceleration, deceleration, dwell, and shutdown.

REQUIREMENT LESSONS LEARNED (A.4.5.2)

Inadequate characterization of the internal environment has been a shortcoming of many engine programs.

A.5.5.2 Internal environment.

Evaluation of the capability of the engine components to withstand the internal thermal and pressure environments that occur during engine operation should be evaluated by analysis and test.

EVALUATION RATIONALE (A.5.5.2)

Analysis and tests should be performed early to establish component internal temperature distributions and interstage pressure distributions to support initial design of structural components. Recorded data during engine operation is required to establish confidence in the thermal heat transfer model and predicted pressure distributions.

EVALUATION GUIDANCE (A.5.5.2)

A thermal heat transfer model should be generated for the engine static and rotating structures. The model should have the capability to predict component nodal temperatures as a function of flight conditions via the engine performance deck. Particular care should be taken in analyzing the internal engine aerodynamics and establishing the convective boundary conditions (recovery temperatures and film coefficient distributions) for the internal structures. Radiation effects should be accounted for where appropriate (i.e., the combustor). The conduction model should have sufficient detail to establish critical temperatures and gradients for steady state and transient conditions. The thermal heat transfer model should be correlated with data obtained from the instrumented engine tests required by A.4.5.2.

Instrumented engine tests should be performed for both steady state and transient conditions to measure internal gas stream, cooling flow cavities, and metal temperatures; pressure distributions; external temperatures for the installed configuration; and temperatures and pressures at other engine locations as required. The contractor should schedule internal environment thermal and pressure surveys as early as possible in the development phase. Both core and full-scale engines should be utilized as appropriate. Engine run conditions should include (1) stabilized idle to snap/acceleration to stabilized maximum power to chop/deceleration to stabilized idle; (2) shutdown and cool down; and (3) the planned AMT power sequence. Thermocouple and pressure measurements should be made throughout the engine modules. Cavity pressures should be measured. Thermocouples should be located at radial locations on disks and on critical seals/spacers to establish gradient data. The scope and plan for the thermal survey program should be identified in the appendix to this specification or in the ENSIP Master Plan.

EVALUATION LESSONS LEARNED (A.5.5.2)

None.

A.4.5.3 Externally applied forces.

The engine should function satisfactorily and no deformation should occur during or after exposure to the externally applied forces, which should be indicated in Design Load Diagrams.

REQUIREMENT RATIONALE (A.4.5.3)

The engine and its components in service use are subject to externally applied forces due to accelerations, decelerations, angular velocities, external airloads, and gyroscopic moments resulting from operation and maneuvering of the aircraft. These forces have an impact on design life.

REQUIREMENT GUIDANCE (A.4.5.3)

Externally applied forces include: loads produced by take-off, landing, in-flight maneuvers, gusts, vibration, installation, and crash conditions. The limit loads should be based on a weight factor consisting of the dry weight of the engine increased by the specified weight allowed for all engine mounted components and operating fluids. In installations where airframe components are supported by the engine, the weight of these components will also be included in the weight factor.

Load factors specified should be sufficient to meet all ground, flight, and landing operations for the installed engine in the intended aircraft application. Loads due to flexure of the mounts, vibration, "g" factors, engine airloads, or crash conditions should be considered in establishing engine strength and life requirements. Aircraft used on carriers are exposed to significant "g" loads resulting from catapult launch or carrier arrest landings. The "g" forces presented on the design load diagrams may be too severe for some given applications. A judgement must be made whether to reduce the requirements for a particular less severe application. The diagrams should consider the extremes for all manned aircraft.

Typical aircraft load factor spectra applicable to cargo, fighter/attack, and trainer classes of aircraft are contained in ASD-TR-82-5012. Applicable aircraft vertical load factor spectra in conjunction with the pitch and yaw velocities of one radian per second should be used to establish repeated loads for engine design.

REQUIREMENTS LESSONS LEARNED (A.4.5.3)

Aircraft such as the F-6, A-4, A-6, A-7, F-4, and F-8 have recorded load factors up to 7g's, and F-16s go up to 9g's. Aircraft maneuver requirements have increased so that particular weapon systems must now be capable of 8 to 10 g's.

The F404-GE-400 engine model specification CP45K006 of 15 November 1975 used a maneuver load spectrum which showed various values of positive and negative "g's" and cycles per 1000 hours for each "g" value. The maximum static load requirement was reduced to 1.4 times the landing loads rather than the 1.5 times requirement.

A.5.5.3 Externally applied forces.

Verification of flight and ground externally applied forces should be in accordance with 4.5.3, and should be evaluated by analysis and test.

EVALUATION RATIONALE (A.5.5.3)

There is a need to evaluate the engine by analysis and test its capability to withstand the external forces to which it may be subjected due to flight maneuvers, landings, and takeoffs.

EVALUATION GUIDANCE (A.5.5.3)

Stress and deflection data should be obtained at critical locations as determined by analysis and preliminary stress coating tests. Engine cases and mounts should be subjected to a static rig test. The static rig test, utilizing the applicable engine static structure, should be conducted to demonstrate the capability of the engine and its supports to withstand maximum externally applied forces specified in A.4.5.3 without permanent deformation of any component and 1.5 times those forces without failure of any component. The loads should be applied separately and in combination.

EVALUATION LESSONS LEARNED (A.5.5.3)

None.

A.4.6 Material characterization.

The materials used in the engine should have adequate structural properties, such as strength, creep, low cycle fatigue, high cycle fatigue, fracture toughness, crack growth rate, stress corrosion cracking, and corrosion resistance; so that component design can be optimized to meet the operational requirements for the design service life and design usage of the engine, or for the life interval required by 4.3 and 4.4.

REQUIREMENT RATIONALE (A.4.6)

Material structural properties must be quantified during detail design so that materials selection and operating stress levels can be established which provide a high degree of confidence that operational requirements will be met. Early generation of sufficient data for use in preliminary and detail design is emphasized since downstream surprises relative to structural properties will have a significant impact on redesign, substantiation and replacement needs, and weapon system availability.

REQUIREMENT GUIDANCE (A.4.6)

Structural properties used in design (design allowables) should be based on minimum material capability. The intent is to base material properties including elongation on minus three sigma (-3σ) values with a fifty percent (50%) confidence level or minus two sigma (-2σ) values with a ninety-five percent (95%) confidence level. An alternative is to state that material properties will be based on B 0.1 values. The confidence level for B 0.1 is fifty percent (50%). Another alternative is "A Basis" from MIL-HDBK-5, which uses properties for 99% exceedance with 95% confidence (equivalent to 3.129 sigma properties). Typical, B 50 properties may be used to characterize fracture toughness and crack growth rate. Also, design allowables should be justified by the contractor's experience base and design methodology. Specimens fabricated from "as produced" parts should be tested to evaluate properties relative to different locations within the part (i.e., locations that receive different amounts of work during manufacture such as the bore, web, and rim regions of disks).

REQUIREMENT LESSONS LEARNED (A.4.6)

Premature structural failures have occurred prior to design service life (based on average material properties) and have been attributable to components with minimum material capability.

A.5.6 Material characterization.

Material structural properties should be established by test.

EVALUATION RATIONALE (A.5.6)

Material properties must be established by test and must be based on specimens fabricated from "as produced" parts since critical structural properties are dependent upon the manufacturing processes.

EVALUATION GUIDANCE (A.5.6)

A material characterization plan should be prepared and existing data should be presented. Final definition of structural capability should be based on the testing of specimens fabricated for "as produced" parts. The contractor should review existing data on proposed materials and processes and develop a material characterization plan that identifies and schedules each of the tasks and interfaces in design, material selection, and testing. The tasks to be identified in the plan should include:

a. Correlation of the operating envelope conditions to which each material will be subjected (i.e., temperature, loading frequency, max and min cyclic stresses, steady and vibratory stresses, etc.).

b. A parts listing with the corresponding materials and manufacturing processes.

c. Identification of mechanical properties that must be generated for each material/part.

d. Test specimen configuration.

e. The source of the material data.

f. Number of tests to be conducted for each material property curve needed for each part.

g. Quality control actions or vendor substantiation test requirements that will be utilized to assure minimum mechanical properties will be attained in finished parts through the production run.

h. Risk assessment for use of any advanced materials and processes.

Existing data obtained through earlier tests can be used during initial design only when the manufacturing processes are similar (i.e., same methods of producing billets, forgings, heat treat processes, machining, etc.). However, final definition of structural capability should be based on material property curves generated by testing specimens fabricated from the "as produced" parts to evaluate material properties relative to different locations on the part.

Material properties should be defined for each material/part source (i.e. material and manufacturing vendor).

The number of tests conducted for each curve or condition must be adequate to establish minimum material properties used in design or to establish the correlation between the data obtained from specimens cut from parts and the data base within the calibrated design methodology.

EVALUATION LESSONS LEARNED (A.5.6)

Many durability problems can be traced to the selection of unsuitable materials. The need to reduce engine weight has forced gas turbine engine contractors to make compromises in the selection of materials or higher risk designs. Characterization and choice of materials should be closely monitored by the procuring activity. Material selection should be reviewed under a risk assessment or management plan.

The contract specifications (i.e., CDRL or elsewhere as appropriate) should require that all data generated be supplied to AFRL for inclusion into the Damage Tolerance Handbook (MCIC-HB-01).

A.4.7 Parts classification.

All engine parts, components, controls and externals and expendables should be classified for criticality.

REQUIREMENT RATIONALE (A.4.7)

Parts, components, and expendables must be classified to assure the appropriate design requirements are applied.

REQUIREMENT GUIDANCE (A.4.7)

For all applications, the classifications should be fracture critical, durability critical, and durability non-critical. Fracture critical parts may be further classified as safety and mission critical. The engine manufacturer should provide the classification summary.

A failure mode and effects criticality analysis (FMECA), a safety/hazard assessment, or other engineering analysis should provide the basis for classification.

The intent is to apply damage tolerance requirements only to fracture critical components. Damage tolerance requirements should not, in general, be applied to components in which structural cracking will result in a maintenance burden but not cause inability to sustain flight, or complete the mission, i.e. durability critical parts. However, damage tolerance requirements should be applied to durability critical parts to (1) identify components that are sensitive to manufacturing variables and pre-damage which could cause noneconomical maintenance (e.g., blades), or (2) aid in establishing economic repair time or other maintenance actions.

Component classification may be affected by aircraft/engine configuration, i.e., single engine or dual engine. For dual engine systems, components will only be classified as fracture critical if failure would likely cause aircraft loss or if the mission could not be completed. For single engine systems, components should also be classified as fracture critical if failure would result in inability to maintain sustained power. An example is a large blade that would be contained but due to progressive damage the engine sustained power capability would not be sufficient to maintain flight. Controls and accessories should be included in evaluating and classifying components as fracture critical. Historical records and experience gained during development tests should be used to classify components. Component classification should be established early and should be identified in the contract specifications. The fracture critical parts list should be updated as required during the development phase based on experience gained during analysis, engine test, and/or flight operations.

REQUIREMENT LESSONS LEARNED (A.4.7)

It has been difficult to determine, in advance, engine parts or components whose failure would have resulted in secondary failure which would have lead to loss of aircraft or essential mission capability. Therefore, continued evaluation has been required as the subsystem was being defined. An example is the high pressure hydraulic or pneumatic pressure vessel, which by itself, may not be safety-of-flight critical, but if located on or close to primary airframe structure could precipitate a failure of the airframe, if it were to fail.

The number of critical parts can be significantly larger for an engine model used in a single engine configuration as opposed to a dual engine configuration. For example, the number of critical parts for the F100 engine in the F-15 and F-16 is 45 and 70, respectively excluding externals.

A.5.7 Parts classification.

The requirement of 4.7 should be evaluated by analysis, inspection, and test.

EVALUATION RATIONALE (A.5.7)

Evaluation of classification is necessary to ensure the appropriate design requirements are applied.

EVALUATION GUIDANCE (A.5.7)

A Failure Modes and Effects Criticality Analysis (FMECA), in addition to other engineering analyses, could be conducted to evaluate the results. Parts should be classified as fracture critical, safety critical, mission critical, durability critical, or durability non-critical, depending on the application (USA, USAF, USN). The parts classification summary for the same engine may vary with application or use. For example, single engine vs multi-engine aircraft will have different lists.

EVALUATION LESSONS LEARNED (A.5.7)

None.

A.4.8 Damage tolerance.

Fracture/safety and mission critical engine parts should be capable of maintaining adequate damage tolerance in the presence of material, manufacturing, processing, and handling defects for the design service life and design usage specified in 4.3 and 4.4.

REQUIREMENT RATIONALE (A.4.8)

The requirement protects fracture, safety, and mission critical parts from potentially degrading effects of handling damage and/or material, manufacturing, and processing anomalies which could result in premature engine failures and loss of aircraft. This process ensures proper material choices, control of operating stress levels, use of fracture resistant design concepts, manufacturing and process controls, and the use of reliable inspection methods during production and in-service maintenance. Attainment of engine damage tolerance is achieved through application of detail requirements in the functional areas of design, materials selections, manufacturing control, and inspections.

REQUIREMENT GUIDANCE (A.4.8)

Damage tolerance should be achieved by proper material selection and control, control of stress levels, use of fracture resistant design concepts, manufacturing and processing controls, and the use of reliable inspection methods. The design objective should be to qualify components as in-service noninspectable to eliminate the need for depot inspections prior to achieving one design lifetime. As a minimum, components should be qualified as depot or base level inspectable structure for the minimum interval.

Damage tolerance can be achieved by performing crack growth evaluation as an integral part of detail design of fracture critical engine components. Initial flaws (sharp cracks) should be assumed in highly stressed locations such as edges, fillets, holes and blade slots. Imbedded defects (sharp cracks) should also be assumed at large volume locations such as live rim and bore. Growth of these assumed initial flaws as a function of imposed stress cycles should be calculated. Total growth period from initial flaw size to component failure (i.e., the safety limit) is thus derived. Trade studies on (1) inspection methods and assumed initial flaw size, (2) stress levels, (3) material choice, and (4) structural geometry can be made until the safety limit is sufficiently large such that the need for in-service inspection is eliminated or minimized. Damage tolerance design procedures that account for distribution of variables that affect growth of imbedded defects are permitted (e.g., probability of imbedded defects associated with the specific material and manufacturing processes). Specific requirements on initial flaw sizes, residual strength, critical stress intensities, inspection intervals, damage growth limits, and verification are contained elsewhere in this document.

Damage tolerance requirements may be applied to durability critical parts to (1) identify components that are sensitive to manufacturing variables and pre-damage which could cause non-economical maintenance (e.g., blades), or (2) aid in establishing economic repair time or other maintenance actions.

A Damage Tolerance Control Plan should be prepared to identify and schedule each of the tasks and interfaces in the functional areas of design, material selection, manufacturing control, and inspection of fracture, safety, and mission critical parts. The tasks to be identified in the plan include:

a. Design concepts/material/weight/performance/cost trade studies.

b. Damage tolerance analysis, development testing, and proof of compliance testing tasks.

c. Parts list that identifies fracture, safety and mission critical parts, locations and special controls required to meet damage tolerance requirements (e.g., material specification controls, quality assurance requirements, etc.).

d. Zoning of drawings for fracture, safety and mission critical parts to identify critical locations and associated quality control requirements, defect locations, orientation, inspection method, and acceptance standards. The use of alternate procedures for identification of critical locations, etc., on drawings may be proposed.

e. Basic materials fracture data (e.g., K_{IC}, K_C, K_{ISCC}, da/dn).

f. Identification and control of fracture toughness and crack growth rate properties in the material procurement and manufacturing process specifications.

g. Traceability requirements on all tiers of procurement, processing, fabrication, and assembly for fracture critical components. Serialization or time coding requirements for tracking operational exposure of individual components.

h. Quality control requirements during component manufacture. Identification of procedures for certifying and monitoring subcontractor, vendor, and supplier inspection and quality control. Nondestructive inspection requirements for use during depot and base level inspections including supporting manuals (technical orders) and equipment needs.

An example of damage tolerant design principles (criteria, design, analysis, and substantiation) is contained in AFWAL-TR-81-2045.

REQUIREMENT LESSONS LEARNED (A.4.8)

There have been numerous Class A incidents on Air Force aircraft and engines due to structural failures caused by material defects, manufacturing defects, or fatigue induced cracks. These defects grew in size due to repetitive cycles of maneuvers or throttle excursions until such time as the residual strength of the component became less than the applied load and failure occurred. Causes have been: (1) use of high strength low fracture toughness materials, (2) improper detail designs resulting in high stress levels and structural discontinuities, and (3) lack of adequate quality control requirements (both in production and depot maintenance). Also, past review of commercial engine experience reveals noncontained failures of blades, disks, and spacers due to structural cracking. When compared against the total number of parts and flying hours, these occurrences are low. However, the demonstrated consequences of failure on Air Force systems has been high in terms of loss of aircraft and crew members. Many of the incidents could have been avoided by proper material selection, control of stress levels, use of fracture resistant design concepts, manufacturing and process controls, and use of reliable inspection methods during production and in-service maintenance.

Recent examples of optimized part designs following the ENSIP/DTD guidelines include the F109-GA-100, F100-PW-220 ILC, F100-PW-229 IPE, F110-GE-129 IPE, and F119-PW-100 ATF engine designs. These design configurations have shown that damage tolerance requirements can be met with small or modest increases in overall engine weight, will have little impact on engine performance, and will provide greatly improved engine durability while significantly reducing weapon system life cycle cost.

Most of the tasks to be contained in the Damage Tolerance Control Plan have been accomplished by engine manufacturers in past development and production programs. However, the durability and damage tolerance requirements established here impose tighter controls and more interface involvement between the functional areas.

A.5.8 Damage tolerance.

Damage tolerance of fracture critical engine components should be in accordance with 4.8. Verification should be evaluated by analysis and test.

EVALUATION RATIONALE (A.5.8)

Damage tolerance analyses are needed to support damage tolerance design concepts, material selection, maintenance requirements, performance, cost, and weight impacts. Damage tolerance tests are required to support material selection and trade studies, obtain early evaluation of allowable stress levels and chemical/thermal environment spectra, and to verify analysis procedures and damage tolerance characteristics.

EVALUATION GUIDANCE (A.5.8)

Early analysis will enable identification of structural sensitive areas which do not meet the desired crack growth intervals and design changes can be introduced early with minimum impact. Emphasis on conducting early analysis will minimize occurrence of deficiencies in later development and proof of compliance testing and facilitate meeting important Engineering and Manufacturing Development (EMD) test milestones.

Attainment of damage tolerant parts is achieved through application of detail requirements in the functional areas of design, materials selections, manufacturing control, and inspections. Most of the tasks to be contained in the damage tolerance control plan have been accomplished by engine manufacturers in past development and production programs. However, the damage tolerance requirement established by this standard imposes the need for new tasks as well as tighter controls and more interface involvement between the functional areas.

Damage tolerance analysis should be conducted on each component classified as fracture critical by A.4.7 of this document. Each location of the component should be surveyed to determine the most critical locations for the assumed initial flaw considering such features as edges, fillets, holes, blade slots, and other high stressed areas. Stress/environment spectra should be developed for each component and location to be analyzed. Imbedded defects should be assumed to exist within large volume locations such as live rims and bores. Damage tolerance analysis that addresses imbedded defects can be based on probabilistic methods that account for the distribution of variables. Interactions between assumed initial flaws at different locations on a component need not be considered. Average (B 50) fracture mechanics properties can be used in the crack growth and residual strength calculations. Stress intensity should be based on the structural geometry and assumed flaw geometry. The critical stress intensity should be based on the required residual strength load level and temperature conditions that exist at the component location being analyzed. Limiting stress intensity should include consideration of the allowable stress intensity accounting for the effect of vibratory stresses. Certain minimum levels of vibratory stress, e.g., 10 Ksi, should be assumed to exist on each fracture critical part to identify sensitive components. The requirement for a damage tolerance analysis and the associated schedule should be contained in the contract specifications.

Early testing should include tests of simple specimens, small elements, and subscale components that represent critical structural details and materials, and full-scale components such as disks. Evaluation of component damage tolerance characteristics during full-scale engine test may be required to demonstrate proof of compliance under realistic environments.

Specimen and element tests should be conducted on representative structural details and materials. Representative fracture critical components should be selected for evaluation by test. These components will either be preflawed or contain natural flaws and will be cycled to evaluate flaw growth characteristics. Preflaws should be sharpened via precycling, vibration, scratching with razor blade or other sharp instrument, etching, electro-discharge machining (EDM), or tackwelding of the surface, or other means to assure flaw growth for evaluation/correlation of analyses. Some cycling of parts may be required to "grow" the preflaw to the necessary size prior to actual testing. Electro-discharged machined preflaws are "clean" (sharply defined). Tackweld preflaws are "dirty" (difficult to determine crack length and to differentiate crack lines from thermal cracks).

Components previously cycled to evaluate low cycle fatigue should be used for damage tolerance testing. Test results should be correlated with predictions of crack growth intervals and critical flaw sizes. The damage tolerance test program should be of sufficient scope to verify fracture critical parts. Deletion of verification of certain fracture critical parts can be proposed based on similarity of materials and structural configurations and demonstrated knowledge of the applied stresses. The scope of the damage tolerance design development test program and associated schedule should be contained in the ENSIP Master Plan or contract specifications. After contract award, the test plan should be finalized and submitted to the Air Force for approval. The test plan will be revised and maintained up to date during full-scale development. Information such as rationale for selection of scope of tests, description of test procedures, loads, and duration of tests should be included in the test plan. Sufficient tests to evaluate allowable stress levels and to support material selection should be scheduled for completion prior to the Critical Design Review (CDR). Component tests will be scheduled for completion prior to Initial Service Release (ISR) decision

The amount of full-scale engine damage tolerance testing that is required is dependent on the extent damage tolerance is demonstrated by earlier component tests and other full-scale testing (i.e., number of cracking incidents and subsequent crack growth occurring during accelerated mission tests).

EVALUATION LESSONS LEARNED (A.5.8)

None.

A.4.8.1 Residual strength.

The residual strength should be equal to the maximum stress that occurs during design usage conditions. Residual strength requirements should be established for all damage tolerant designed parts and components. Associated static and dynamic loading conditions for these parts and components should be included.

REQUIREMENT RATIONALE (A.4.8.1)

The load carrying capability of fracture, safety, and mission critical parts, with "damage" present, must remain above some minimum value during part design service lives and unrepaired service usage.

REQUIREMENT GUIDANCE (A.4.8.1)

The static and dynamic loading conditions which should be considered are:

a. Maximum limit maneuver loading

b. Maximum pressure loading

c. Maximum speed loading

d. Maximum temperature effects

The engine contractor should provide the residual strength requirements for all parts. The minimum residual strength for each part (and location) should be equal to the maximum stress that occurs during design usage conditions. Normal or expected control system overspeed (e.g., 105%) and engine deterioration should be included. Burst margin overspeed conditions should be excluded.

Analytical studies have shown that not every part location will be limited by a crack growing to a calculated critical stress intensity equal to the material's fracture toughness. Some part locations will in fact be life limited by cracks growing to a predicted vibratory threshold DK_{th} HCF.

Where $K_{max\ allowable}$ LCF = ΔK_{th} HCF/(1 - R)

and $R = (\sigma_{steady} - \sigma_{vibratory}) / (\sigma_{steady} + \sigma_{vibratory})$

σ_{steady} = maximum operating stress neglecting vibratory stress

$\sigma_{vibratory}$ = peak to peak vibratory stress and ΔK_{th} HCF = f(R, temp)

Overspeed residual strength requirements need not be considered for those part locations limited by cracks reaching a calculated vibratory threshold. One overspeed cycle occurring at a crack size equal to the vibratory threshold creates less damage (change in crack size) than additional LCF/HCF crack growth from the vibratory threshold to a maximum stress intensity (K_{CRIT}) defined by the material fracture toughness.

For those locations not limited by vibratory stress concerns, the part's maximum allowable crack size should be limited to a size that will survive the maximum design stress that occurs on the last cycle of the calculated safety limit.

REQUIREMENT LESSONS LEARNED (A.4.8.1)

None.

A.5.8.1 Residual strength.

The requirements of 4.8.1 should be evaluated by analyses and tests.

EVALUATION RATIONALE (A.5.8.1)

Evaluation of residual strength by analyses and tests is required to ensure less than critical size flaws will not grow and cause failure due to the application of the required residual strength load.

EVALUATION GUIDANCE (A.5.8.1)

Analyses should assume the presence of flaws in the most unfavorable location with regard to geometry stress and material properties and should show that at the end of the required damage tolerance operational period, the strength requirement can be met for this flaw configuration and the required load.

The testing should be conducted in accordance with A.4.8.

EVALUATION LESSONS LEARNED (A.5.8.1)

None.

A.4.8.2 Initial flaw size.

Initial flaws should be assumed to exist as a result of material, manufacturing, and processing operations. Assumed initial flaw sizes should be based on the intrinsic material defect distribution, manufacturing process, and the NDI methods to be used during manufacture of the component.

REQUIREMENT RATIONALE (A.4.8.2)

This requirement is necessary to establish the probable flaw size that can exist in a part after manufacture. Damage tolerance, as applied in ENSIP, assumes the presence of a flaw in each fracture, safety, and mission critical part, at the highest stressed location with an orientation most unfavorable with respect to the stress field. Tolerance to these initial flaws must be designed into the part.

REQUIREMENT GUIDANCE (A.4.8.2)

Flaw sizes are intended to represent the maximum damage that can exist in a part after manufacture. Assumed initial surface flaw sizes can be based on the NDI methods to be used during manufacture. Assumed initial imbedded flaw sizes will be based on the intrinsic material defect distribution or the NDI methods to be used during manufacture. The initial flaw sizes are used to determine the safe crack growth period (i.e., safety limit). Initial flaw sizes should be proposed by the manufacturer and subject to approval by the Using Service. Demonstration of flaw size detection reliability should be required.

Assuming an NDI method reliability of 90% Probability of Detection (POD)/95% Confidence Level (CL), the minimum initial flaw sizes for crack growth analysis should be as listed in tables XV and XVI.

TABLE XV. Minimum initial flaw sizes for crack growth analysis with NDI method reliability of 90%POD/95%CL.

Inspection Method	Material	Flaw Type	Flaw Size (depth X length)
Manual	All	Surface	0.035 X 0.070 inches
Manual	All	Corner	0.035 X 0.035 inches
Manual	All	Imbedded	0.035 inch diameter
Semi-Auto	All	Surface	0.020 X 0.040 inches
Semi-Auto	All	Corner	0.020 X 0.020 inches
Semi-Auto	All	Imbedded	0.035 inch diameter
Automated	Ti	Surface	0.010 X 0.020 inches
Automated	Ni	Surface	0.007 X 0.014 inches
Automated	Ti	Corner	0.010 X 0.010 inches
Automated	Ni	Corner	0.007 X 0.007 inches
Automated	Ti	Imbedded	0.025 inch diameter
Automated	Ni	Imbedded	0.032 inch diameter

Assuming an NDI method reliability of 90%POD/50%CL, the minimum initial flaw sizes for crack growth analysis should be:

TABLE XVI. Minimum initial flaw sizes for crack growth analysis with NDI method reliability of 90%POD/50%CL.

Inspection Method	Material	Flaw Type	Flaw Size (depth X length)
Automated	Ti	Surface	0.010 X 0.020 inches
Automated	Ni	Surface	0.005 X 0.010 inches
Automated	Ti	Corner	0.010 X 0.010 inches
Automated	Ni	Corner	0.005 X 0.005 inches
Automated	Ti	Imbedded	0.017 inch diameter
Automated	Ni	Imbedded	0.020 inch diameter

The initial flaw size detectability requirement of 90%POD/95%CL should be used for all manual and semi-automated NDI methods. The 90%POD/50%CL requirement can be used for some automated NDI methods based on the NDI process being in control. The 90%POD/95%CL was originally used because manual Fluorescent Penetrant Inspection (FPI) was the most common method of inspection and was highly operator dependent. Operator variability is the most influential single variable on reliability demonstrations/testing. With the introduction of enhanced automated eddy current inspection systems, the POD/CL requirement was changed to 90%POD/50%CL to reflect the reduced/removed operator variability. However, demonstration of flaw size detection reliability should be required to ensure the system is a controlled process.

For detectability requirements of 90%POD/95%CL, there may be a larger test matrix, more specimens, and thus higher cost necessary to achieve the statistical 95%CL.

It is recommended that initial design and sizing of components be based on .040 inch surface flaws or .020 inch by .020 inch corner cracks. The basis for this recommendation is two fold: (1) to establish an initial flaw size that will support use of fluorescent penetrant inspection as the standard NDI method at production and depot and (2) to provide capability for application of upgraded NDI methods at a few locations when full-scale development results indicate the need due to higher than anticipated stresses/usage.

Initial design should also account for (.020 in) diameter imbedded flaws in large surface areas. The imbedded flaws in weldments should have a diameter equal to 20% of the thickness of the weld. These initial flaw assumptions provide some margin when analysis and test results indicate that stresses are higher than anticipated.

REQUIREMENT LESSONS LEARNED (A.4.8.2)

A review of aircraft and engine experience reveals that premature unexpected cracking occurs at high stressed areas. Initial conditions have included material and manufacturing defects (voids, inclusions, machining marks, scratches, sharp cracks, etc.).

Flaw detection capabilities of the various nondestructive testing (NDT) methods are affected by a wide variety of variables. Key to high reliability in NDT methods is high proficiency of the inspection personnel. Also important is the availability of recorded inspection data for evaluation of the characteristics of various sources of initial damage. Redundant inspections also improve the reliability of detecting flaws, i.e., independent applications of the same NDT method or use of different methods. Experience has identified preferred processing methods or key processing parameters as indicated below:

Fluorescent Penetrant Inspection (FPI) - The preferred process utilizes a high sensitivity post emulsified penetrant with a hydrophilic (water soluble) emulsifier. A nonaqueous or water soluble developer is preferred over the dry powder or wet suspendable type of developer. Surface preparation is very important and should include an etch to remove smeared metal, dirt, combustion products, etc. In process FPI preceded by a heavy etch that removes considerable surface material (.001 to .002 inches) is recommended for each fracture critical rotating component. Etch of the finished component prior to FPI is also recommended for each fracture critical component. However, the selection of an etchant for the finished component must be thoroughly evaluated to assure no detrimental life effects are caused when adequate surface material removal is achieved (.0001 to .0002 inches).

Fluorescent Penetrant Inspection

Principle:	Liquid penetrant is drawn into surface flaws by capillary action. Flaws are revealed by a dye.
Applications:	Surface cracks, laps, porosity, shrinkage areas, laminations, etc., that are open to surface.
Advantages:	Inexpensive, portable, and sensitive. Not dependent on magnetic or electrical properties of a material.
Disadvantages:	Flaws on the surface of the part. Not usable on porous and rough surfaces.

Eddy Current Inspection - The preferred process uses automated scanning and automated data recording, and special fixturing when necessary.

Eddy Current

Principle:	Coil induces a current in a metal then detects the resulting current that fluctuates with a change in electrical property of the part.
Applications:	Surface cracks, laps, porosity, shrinkage areas, laminations, etc., that are open to surface. Detects variations in the metal and microstructure of parts.
Advantages:	Very sensitive. Not necessary to contact part.
Disadvantages:	Often too sensitive to unimportant properties.

Ultrasonic Inspection - The preferred process uses automated scanning and may use more than one mode (i.e., longitudinal, shear, surface, lamb, etc.) where appropriate.

Ultrasonic

Principle:	Sound waves are transmitted through material and reflected by flaws.
Applications:	Subsurface flaws such as cracks, laminations, and bonds with principle plane perpendicular to sound source.
Advantages:	Capable of detecting flaws that exist deep in a material. The capability to produce images of the flaw exists.
Disadvantages:	Flaws that are parallel to source of sound are undetectable. Inspection must be performed by trained personnel.

Radiographic Inspection - The preferred process requires selection of proper kilovoltage and exposure geometry.

Radiographic

Principle:	X-rays and gamma rays are sent through the metal and strike a film. The existence of flaws is seen as dark shadows on the film.
Applications:	Subsurface flaws in castings and weldments with the principle plane of flaw parallel to radiation beam.
Advantages:	Flaws are detectable at any depth.
Disadvantages:	Flaws perpendicular to radiation beam are undetectable. Inspection may be hazardous and must be performed by trained personnel. Inspection is expensive.

Magnetic Particle Inspection - The preferred process provides that insecure adequate magnetic field strengths are introduced in the part and at critical locations in the part.

Magnetic Particle

Principle:	Discontinuities distort an applied magnetic field causing leakage fields that attract iron powder.
Applications:	Cracks, inclusions, and other discontinuities on or near the surface of parts.
Advantages:	Inexpensive. Suitable for extremely large objects.
Disadvantages:	Limited by depth of flaw and coatings. Personnel performing inspections must be trained to interpret results.

A.5.8.2 Initial flaw size.

Material controls, manufacturing process controls, and in-process Nondestructive Inspection (NDI) should be performed on each fracture critical component to ensure that the requirements of 4.8.2 are met.

EVALUATION RATIONALE (A.5.8.2)

Initial defect sizes depend on the detail NDI method and/or manufacturing process controls to be employed in production and particular values selected for design have significance only when evaluated by demonstration programs. Evaluation of the initial flaw sizes is necessary to ensure that flaw sizes greater than the those sizes assumed do not exist in finished parts.

EVALUATION GUIDANCE (A.5.8.2)

Controls and inspection methods should be established through the damage tolerance control plan. Damage tolerance of many parts is achieved by providing minimum flaw growth intervals based on initial flaw sizes. The initial flaw size values selected for design only have significance when production NDI capability is confirmed by the demonstration programs. Demonstration programs, in the absence of existing data, should be performed to ensure that flaws greater than the design flaws of A.4.8.2 will not occur in finished components. Subsequent to successful completion of these demonstration programs, the selected inspection methods and processes should become a part of the production requirements and may not be changed without approval of the procuring activity.

It is recommended that initial flaw size based on NDI methods be demonstrated to have a probability of detection and confidence level of 90%/95%.

EVALUATION LESSONS LEARNED (A.5.8.2)

In past programs, inspection capabilities have been quoted, for generic areas and processes with no real basis in reality. For example, an eddy current capability was quoted as .010 x .020 inch for Titanium broach slots. However, eddy current couldn't detect this or any reasonable flaw size within .100 inches of the edge of the broach slot due to the geometry signal. Today, detection of flaws in edges is possible with certain probes, but the inspection time is three times slower than an inspection which does not include the edge. This was only discovered with an NDI demonstration program.

A.4.8.3 In-service inspection flaw size.

The flaw size which should be presumed to exist in a component after completion of a depot, intermediate, or base level inspection should be specified.

REQUIREMENT RATIONALE (A.4.8.3)

This requirement is necessary to establish the probable flaw sizes that can exist in a part after a depot, intermediate, or base level inspection. In-service inspection flaw sizes must be specified to establish part life limitations, and the maintenance capability requirements.

REQUIREMENT GUIDANCE (A.4.8.3)

Although this paragraph establishes a requirement that applies to a post-EMD activity, the information (given up-front) is relative to the logistic requirements for the engine. The probable flaw sizes assumed to exist in a part after completion of a depot, intermediate, or base level inspection must be consistent with nondestructive inspection (NDI) capability used during in-service inspections. It is not essential for the assumed flaw sizes following depot, intermediate, or base level inspections to be the same as those following production inspections as long as inspectability is insured. However, in-service inspection flaw sizes should be larger than or equal to those flaw sizes detectable through current NDI methods. Flaw sizes for in-service inspectable flaws and in-service noninspectable flaws should be based on the NDI methods incorporated into the life management plan. The reoccurring inspection interval will be based on the assumed flaw size after completion of the initial depot, intermediate, or base level inspection.

Flaw size detection capability vs. inspection method should be the same as that specified in A.4.8.2 provided the component is removed from the engine and completely inspected with procedures providing the same degree of confidence and sensitivity as those performed during production. Where etching or other necessary surface preparation is not practical or possible on in-service components, FPI should not be used.

REQUIREMENT LESSONS LEARNED (A.4.8.3)

See Lessons Learned of A.4.8.2.

A.5.8.3 In-service inspection flaw size.

The requirements of 4.8.3 should be evaluated by analysis, inspection, demonstration, and test.

EVALUATION RATIONALE (A.5.8.3)

This requirement is necessary to establish the probable flaw sizes that can exist in a part after a depot, intermediate, or base level inspection. In-service inspection flaw sizes must be specified to establish part life limitations, and the maintenance capability requirements.

EVALUATION GUIDANCE (A.5.8.3)

The Using Service should be able to demonstrate the necessary NDI reliability. The NDI reliability should provide for a Probability of Detection (POD) at the lower bound Confidence Level (CL) consistent with A.4.8.3. Although this evaluation paragraph seems to apply only to a post-EMD activity, it actually provides information (up-front) relative to logistic requirements. In-service inspection flaw sizes should be larger than or equal to those flaw sizes detectable through current NDI methods. The engine contractor should include the in-service inspection requirements (methods and intervals) in the life management plan. Logisticians may not be able to provision for detection of unreasonable flaw size values (smaller than current NDI capability).

In-service inspection flaw size detection capability should be demonstrated on parts with a significant amount of prior engine operation time. This will provide a better understanding of in-service inspection flaw size capability.

It is recommended that initial flaw size based on NDI methods be demonstrated to have a probability of detection and confidence level of 90%/95%.

EVALUATION LESSONS LEARNED (A.5.8.3)

Reliability assessment methodologies can provide very different POD results based on the same data sets. Proposed (DRAFT) MIL-STD-1823 provides a reliability assessment procedure for establishing POD and should be used for all POD and process quality control assessments. In order to standardize POD calculations, software developed under contract with the University of Dayton Research Institute has been programmed based on this MIL-STD and should be used for POD calculations.

A.4.8.4 Inspection intervals.

The frequency of inspection in terms of the required design lifetime should be specified in terms of (1) in-service noninspectable-once at the end of one design lifetime or (2) depot or base level inspectable.

REQUIREMENT RATIONALE (A.4.8.4)

The design objective is to eliminate the need for in-service inspections to achieve damage tolerance. However, the weight penalty incurred to achieve a safety-limit or damage growth interval sufficiently large to preclude the need for in-service inspections may be prohibitive on some components. Therefore, in-service inspections will be allowed on some parts subject to justification.

These requirements are intended to provide the minimum information necessary to show that basic maintenance functions have been considered in the design of the engine.

REQUIREMENT GUIDANCE (A.4.8.4)

Inspection intervals should be compatible with the overall weapon system maintenance plan. The inspection intervals may be proposed by the contractor and approved by the Using Service. The in-service noninspectable period should be at least one times the design service life specified in A.4.3. The minimum depot, intermediate, or base level inspection interval should be equal to the hot parts life of A.4.3.1. The inspection intervals, when accepted by the Using Service, should be contained in the contract specification.

Parts are usually designated "in-service noninspectable" because (1) inspection capability precludes detection of flaws (i.e., parts contain imbedded flaws or unaccessible flaw regions) or (2) the part is not intended to be inspected during its design life. Parts designated as depot, intermediate, or base level inspectable are classified as such because inspection capability exists such that they can be readily inspected (i.e., surface flaw inspection).

REQUIREMENT LESSONS LEARNED (A.4.8.4)

The design objective of damage tolerance is to qualify parts as "in-service noninspectable". However, the weight penalty incurred to achieve a flaw growth interval sufficiently large to preclude the need for in-service inspections may be prohibitive on some parts.

A.5.8.4 Inspection intervals.

The requirements of 4.8.4 should be evaluated by analyses and tests.

EVALUATION RATIONALE (A.5.8.4)

Evaluation of inspection intervals is required to ensure the flaw growth interval of A.4.8.5 is of sufficient duration to preclude failure between inspections.

EVALUATION GUIDANCE (A.5.8.4)

The test should be conducted in accordance with A.4.8.

Inspections after engine testing should provide data that substantiates the flaw growth interval of A.4.8.5. This data should be compared to the time between inspections to ensure that the appropriate inspection interval has been chosen.

EVALUATION LESSONS LEARNED (A.5.8.4)

None.

A.4.8.5 Flaw growth.

The initial flaw sizes specified in 4.8.2 should not grow to critical size and cause failure of the part due to the application of the required residual strength load within two times the specified inspection interval.

REQUIREMENT RATIONALE (A.4.8.5)

The flaw growth interval (i.e., safety limit) must be specified to ensure the assumed initial flaw will not grow as a function of usage to critical size that would cause unstable growth and fail due to application of the required residual strength load.

REQUIREMENT GUIDANCE (A.4.8.5)

The flaw growth interval is also known as the safety limit. It is recommended that the flaw growth intervals be twice the inspection intervals specified in A.4.8.4. Flaw growth interval margins, other than two, can be used when individual assessments of variables (i.e., initial flaw size, da/dN, K_{IC}, etc.) that affect flaw growth can be made (e.g., to account for observed scatter in crack growth during testing). In treating variables which can affect the calculation of the flaw growth interval, the following should be considered:

a. The beneficial effects of interference fasteners, cold expanded holes, shot peening, overload spinning, and other stress enhancement procedures may be used in achieving compliance with the flaw growth requirements. These beneficial effects must be verified and the extent of life "crediting" must be approved by the procuring activity.

b. Damage in a primary structure may result in load increases in the secondary structure. The analysis of such secondary structures should account for this.

c. Continuing damage should be assumed at critical locations where the initial damage assumption does not result in failure of the part (e.g., the case of a free surface at a bolthole). The following assumptions of initial damage and location should be considered with the limiting condition used to establish safety limits and inspection intervals:

(1) When the primary crack and subsequent growth terminates prior to component failure, an initial flaw equal to or greater than .015 inch surface length should be assumed to exist at the opposite location after the primary crack has terminated. The stress gradient assumed at the opposite location should be based on the boundary conditions that exist when crack growth has terminated at the primary location. The safety limit for this condition should be the sum of the crack growth at the primary location and at the opposite location.

(2) Growth of an assumed initial flaw at the location opposite the primary location should be evaluated as an initial condition.

d. The effects of vibratory stress on unstable crack growth should be accounted for in establishing the safety limit. Threshold crack size should be established at each individual sustained power condition (Idle, Cruise, Intermediate) using the appropriate values of steady stress and vibratory stress. The smallest threshold crack size should be used as a limiting value in calculating the safety limit if it is less than the critical crack size associated with the material fracture toughness. An analytical approach to defining the effects of vibratory stress is based on a maximum stress intensity allowable, $K_{max\ allowable}$ LCF, which is predicted from appropriate material high cycle fatigue vibratory threshold DK_{th} HCF properties at steady-state operating conditions. This relationship is as follows:

Assume $K_{max\ allowable}$ LCF = ΔK_{th} HCF/(1 - R)

where, $R = (\sigma_{steady} - \sigma_{vibratory}) / (\sigma_{steady} + \sigma_{vibratory})$

σ_{steady} = maximum operating stress neglecting vibratory stress

$\sigma_{vibratory}$ = peak to peak vibratory stress

and ΔK_{th} HCF = f(R, temp)

ΔK_{th} HCF vs R-ratio material property curves used in this evaluation at various temperatures should be developed during material characterization as necessary.

e. Galling/fretting limits (i.e., permissible depth of surface damage) for fan/compressor blade-to-disk contact surfaces should be defined based on $K_{max\ allowable}$ LCF.

REQUIREMENT LESSONS LEARNED (A.4.8.5)

Since average fracture properties have been used in analysis, parts made from materials with scatter factors greater than two have failed prior to their inspection interval. Thus, for materials with large scatter factors (i.e., greater than two), factors of safety greater than two, on residual life, should be considered.

A.5.8.5 Flaw growth.

The requirements of 4.8.5 should be evaluated by analyses and tests.

EVALUATION RATIONALE (A.5.8.5)

Evaluation of flaw growth is necessary to ensure that initial flaws will not grow to critical size and cause failure due to the application of the required residual strength load.

EVALUATION GUIDANCE (A.5.8.5)

The test should be conducted in accordance with A.4.8.

Analyses should demonstrate that the assumed initial flaws will not grow to critical size for the usage, environment, and required damage tolerance operational period. The analyses should account for repeated and sustained stresses, environments, temperatures, and should include the effects of load interactions. Analysis methods should be evaluated by test, utilizing engine and rig testing.

EVALUATION LESSONS LEARNED (A.5.8.5)

None.

A.4.8.6 Composites.

Composite parts should be damage tolerant with defects resulting from material quality, manufacturing processing, and handling damage.

REQUIREMENT RATIONALE (A.4.8.6)

Damage tolerance of composites must be specified since they are a special type of fracture, mission, and safety critical part. This paragraph is needed to establish a means for composites to comply with damage tolerance requirements.

REQUIREMENT GUIDANCE (A.4.8.6)

Damage tolerant design of organic matrix composite (OMC) parts is extremely complex. Composites exhibit near-linear stress-strain characteristics up to failure, while most metals display some ductile deformation. Hence, composites are less tolerant to overload than metals. Composites generally exhibit good resistance to tension fatigue and are susceptible to local delaminations resulting from compression fatigue.

Because of the multi-phase nature of the materials used in composites, a substantially higher number of defects may exist in a composite part than would occur in a metallic part.

Handling damage to composites includes scratches, gouges, delamination, and fiber breakage. In these instances, delaminations and fiber breakage are usually the result of impact damage.

The extent and type of damage resulting from impact on composites depends on the energy involved in the impact.

Defects in composites due to manufacture are usually of two types: (1) those produced during the preparation and production of the composite and (2) those produced during machining, processing, and assembly of the final component.

Some composite materials are known to absorb moisture and lose strength over time.

REQUIREMENT LESSONS LEARNED (A.4.8.6)

Damage tolerance requirements for composite parts have been derived from the work done for the Aircraft Structural Integrity Program (ASIP).

A.5.8.6 Composites.

The requirements of 4.8.6 should be evaluated by analyses and tests.

EVALUATION RATIONALE (A.5.8.6)

Tests and analyses must be performed to evaluate the damage tolerance of fiber composites.

EVALUATION GUIDANCE (A.5.8.6)

The following should be transferred verbatim into the specification paragraph: Composite parts should be subjected to impact damage equivalent to 100 ft-lbs (74 N-m), using a one inch (2.54 cm) diameter spherical impactor, then operated for the periods specified in A.4.8.4.

Composite parts should be subjected to impact damage to evaluate damage tolerance to handling/ maintenance induced impact damage. The contractor should propose other means of evaluating the damage tolerance of OMC parts.

EVALUATION LESSONS LEARNED (A.5.8.6)

Methods for evaluation of damage tolerance of composites is derived from the work done for the Aircraft Structural Integrity Program (ASIP).

A.4.9 Durability/economic life.

The durability/economic life of the engine should not be less than the required design service life when subjected to the design usage.

REQUIREMENT RATIONALE (A.4.9)

Durability requirements must be applied since engine durability is a primary design requirement. Durability requirements must be applied to minimize cracking or other structural or material degradation which could result in functional impairment or excessive in-service maintenance problems and costs.

REQUIREMENT GUIDANCE (A.4.9)

Durability of engine components should be obtained by proper material selection and control, control of stress levels, detail design, and use of protection systems. A durability control plan should be prepared to identify and schedule each of the tasks and interfaces in the functional areas of design, material selection, manufacturing control, and inspection of engine parts and components. The tasks to be identified in the plan should include:

a. Design concepts/material/weight/performance/cost trade studies.

b. Life analysis, development testing, and proof of compliance testing tasks.

c. List that identifies parts, locations, and special controls required to meet life requirements (e.g., material specification controls, quality assurance requirements, etc.).

d. Zoning of drawings for parts to identify critical locations and associated quality control requirements, defect locations, orientation, inspection method, and acceptance standards. The use of alternate procedures for identification of critical locations, etc., on drawings may be proposed.

e. Basic materials data.

f. Identification and control of variables that affect properties in the material procurement and manufacturing process specifications.

g. Traceability requirements on all tiers of procurement, processing, fabrication, and assembly for durability critical parts. Serialization or time coding requirements for tracking operational exposure of individual parts.

h. Quality control requirements during manufacture. Subcontractor, vendor, and supplier quality control requirements during manufacture. Identification of procedures for certifying and monitoring subcontractor, vendor, and supplier inspection and quality control.

i. Nondestructive inspection requirements for use during depot and base level inspections including supporting manuals (technical orders) and equipment needs.

Most of the tasks contained in the Durability Control Plan have been accomplished by engine manufacturers in past development and production programs. However, the durability requirements established here impose tighter controls and more interface involvement between the functional areas.

REQUIREMENT LESSONS LEARNED (A.4.9)

Increased turbine engine performance requirements have resulted in higher thrust-to-weight ratios. This trend has led to higher stresses in engine components which in turn has forced development of specialized high-strength alloys and new manufacturing processes and techniques. As a result, Air Force engine systems have experienced early structural cracking and often contain components that have to be replaced one or more times during the operational life of the engine. Experience with past engine systems highlights the fact that the Air Force needs a disciplined approach for design, analysis, test, and improvement of engine components so that in-service maintenance and component replacement needs over the operational life of the engine will be minimized.

The J85-21 engine had a compressor blade flutter problem (high cycle fatigue) which was discovered after the engine had successfully passed qualification testing and after engine production started. Structural failures during F100 engine qualification testing threatened the existence of the weapon system program and raised serious questions about military engine procurement techniques. Fatigue failures in the TF41 engines have caused loss of life and aircraft. Although the Navy F-14 aircraft has two engines, TF30 engine problems resulted in loss of life and aircraft. Cracking of expensive turbine blades in the TF30 produced serious maintenance support problems through excessive replacement rates during engine overhaul.

A.5.9 Durability.

The requirements of 4.9 should be evaluated by a strength and life analysis, inspection, demonstration, and part, component, and full-scale engine tests.

EVALUATION RATIONALE (A.5.9)

Attainment of durable parts is achieved through application of detail requirements in the functional areas of design, materials selection, manufacturing control, and inspection. The strength and life analysis report is one of the most important reports submitted by the engine contractor. Special inspections conducted periodically during the durability test programs are essential to preclude part failure and loss of the development engine.

Definitive criteria are needed to judge the success of qualification tests. Problems will likely be discovered during teardown inspection of these engines prior to attaining the required test durations. Therefore, criteria is needed to establish course of action in the event problems occur and to define follow-on actions (i.e., remaining test duration, problem cause, corrective action, operational implications, qualification tests for redesign, etc.).

EVALUATION GUIDANCE (A.5.9)

The following inspection requirements and success criteria should be transferred verbatim into the specification paragraph:

The engine contractor should specify inspection procedures, in addition to those for the endurance test engines. Inspection requirements should include in-service design inspections developed in accordance with the durability and damage tolerance requirements of this specification. Inspection requirements should also duplicate the expected field maintenance concept for the engine. Special inspections to monitor the status of critical parts should be included.

Each structural problem (failure, cracking, yielding, wear, erosion, etc.) discovered during endurance testing inspections should be analyzed to determine cause, corrective actions, and operational implications, including development schedule and cost impacts.

A Strength and Life Analysis report should be prepared containing an analysis which defines: (l) the lives in equivalent LCF cycles for all appropriate parts, (2) the LCF duty cycle for the individual component tests and any full scale engine testing, (3) the cool down time between cycles, and (4) the total number of cycles to demonstrate the equivalent of the LCF life requirements. The LCF lives of all the appropriate parts and the mission hours equivalency for the selected features in a given test mode should also be defined. The predicted burst speeds of critical rotating disc components should be specified.

For parts subject to fatigue (thermal or mechanical) the report should identify the allowable size of cracks which would be cause for failure. The contractor should provide a specific description of the expected failure mode of each part listed.

The Strength and Life Analysis report should define all variables (e.g., material properties, manufacturing and assembly processes and tolerances, and operating temperatures, pressures and stresses, etc.) that significantly affect the durability and life of the engine. The report should define the sensitivity of parts to variations in these variables and other design assumptions. The limits to variation of these variables should be specified. The report should define how design, processing, manufacturing, assembly, quality control, testing, etc., will be used to assure that all engine durability and life affecting variables fall within these limits.

The report should also contain an analysis to establish the accelerated mission oriented engine duty cycle and the resulting equivalencies for selected features for the AMT/endurance test. These engine duty cycles should be constructed such that the AMT/endurance test produces hot parts damage equivalent to at least the hot parts life of A.4.3. The accelerated engine duty cycles should be derived from the mission cycles of A.4.4. A composite accelerated duty cycle (or cycles) may be an acceptable alternative to individual AMT/endurance test duty cycles.

Consistent with the engine duty cycle of TBD, a random sequence schedule for the mission duty cycles should also be established with the approval of the Using Service.

Both a pictorial and tabular definition of the accelerated engine duty cycles should be included in the report and in the model specification. There should also be a detailed description of the methodology used to develop the duty cycles, which lists the test acceleration factors and shows appropriate damage factors.

A fixed level of inlet air temperature and pressure should be established for each AMT/endurance test duty cycle. The inlet air temperature and pressure level determined for each duty cycle should produce the damaging effects on the engine consistent with the actual Mach number and altitude variation defined for each mission and the ambient temperature distribution. The strength and life analysis should also provide the methodology and data utilized to define the engine parts lives (B0.1, B1.0, B10, and B50). Revised or updated reports should include actual data utilized from the development program such as NDI data, etc.

Stress analysis should include such items as engine cases, discs, vanes, blades, mounts, combustion liners, bearing supports, gears, brackets, and tubing.

A strength and life analysis should be performed and a report submitted prior to completion of IFR. The report should be updated by change pages by completion of FFR, ISR, and OCR. A revised report should be issued after completion of OCR.

If desired, this paragraph should include a requirement to evaluate problems or failures that occur during endurance testing (i.e., loss of mission capability or requiring maintenance actions) relative to contract/specification reliability and maintainability goals and to use test results to validate the Life Cycle Cost (LCC) models.

EVALUATION LESSONS LEARNED (A.5.9)

Complete failure of test engines has occurred in past development programs due to undetected damage growth. Many of these failures could have been prevented by use of detail inspection requirements (methods and intervals) developed through the durability and damage tolerance control plans and experience obtained from earlier development testing (e.g., previously observed deterioration and distress).

A.4.9.1 Low cycle fatigue (LCF) life.

Engine parts should have a minimum LCF life which is at least equivalent to the design service life of 4.3.

REQUIREMENT RATIONALE (A.4.9.1)

Low cycle fatigue is one of the most severe and costly problems encountered in service. This requirement is an attempt to reduce or eliminate LCF failures.

REQUIREMENT GUIDANCE (A.4.9.1)

Low cycle fatigue is the damage generated in a material by cyclic load reversals, which cause repeated plastic deformation. Rotating parts are subjected to mechanical and thermal stresses during engine operation. These stresses are represented as cyclic loading on engine parts. A full LCF cycle occurs each time the engine is started, run to Maximum power, then shutdown. Partial LCF cycles occur during throttle changes. The severity depends upon the degree of change in engine speed and temperature that accompanies the change. Miner's rule may be used for the summation of LCF cycles to determine the cumulative damage. Cumulative damage from LCF cycles will, eventually, cause a crack to initiate.

Predicting LCF life is not an exact science and must be determined on a statistical basis. Traditionally, the minimum LCF life of a part is defined as the B 0.1 life to crack initiation. This means that 1 in 1000 parts will develop a LCF initiated crack during the minimum required life of that part.

LCF design procedures must be used to assure that generalized cracking will not occur prior to reaching the required design service life. LCF design and analysis procedures, if properly applied, can generate a component configuration that will experience minimal cracking by proper material selection and control of stress levels, detail design to eliminate or optimize stress concentrations, and control of component surface finish and correlation with LCF material allowables. Special attention should be placed during detail structural design to minimize stress concentrations. Those stress concentrations that are present in the design should be optimized to produce the largest cyclic life possible. Other factors, which effect LCF life, are material properties, subsurface material flaws, surface flaws, operating temperatures, and part finishes.

REQUIREMENT LESSONS LEARNED (A.4.9.1)

Most LCF problems did not surface until a number of years after qualification and acceptance by the Using Service.

A.5.9.1 Low cycle fatigue (LCF) life.

The requirement of 4.9.1 should be evaluated by analyses and tests.

EVALUATION RATIONALE (A.5.9.1)

The LCF lives must be evaluated to preclude the occurrence of part failures.

EVALUATION GUIDANCE (A.5.9.1)

For engines not using the AMT of A.4.9.1.1.1 to evaluate LCF, the following should be conducted:

For ISR and OCR, the length of the LCF engine test should be equivalent to 1/2 of the cold section life, or 1/2 of LCF life, or 4000 cycles, whichever is longer. For IFR and FFR, the LCF test time must be at least twice the proposed/actual flight test time.

The LCF test cycle should be in accordance with table XVII and the following:

a. inlet test conditions corresponding to tables XVIII and XIX condition(s) selected by Using Service.

b. power settings run to initial shaft power levels from tablesXVIII condition(s) selected by Using Service.

c. engine controls operating with maximum acceleration/fuel flow schedules and transient load change commands of 1/2 second or less.

d. output shaft speed operating at maximum operating values from tables XVIII and XIX condition(s) at high power settings decreasing to the minimum self-sustaining speed at idle.

e. with customer bleed and power extraction.

TABLE XVII. LCF engine test cycle turboprop/turboshaft engines.

Time (min)	Event
0.5	Start engine
2.0	Run at idle
0.1	Accel to maximum power
2.5	Run at maximum power
0.1	Decel to idle
3.0	Run to idle
0.1	Accel to max continuous
2.5	Run to max continuous
0.1	Decel to idle
2.0	Run to idle
2.1	Shutdown and cool down
15.0	Total

Notes:
1. Transient power commands are in ½ second or less.
2. Power settings are initial rating values of output thrust or power or specified by Using Service.
3. Engine control and fuel schedules are set for maximum acceleration.
4. Output shaft speeds are rated values at high power settings and minimum self-sustaining speed at idle.
5. With customer bleed and power extractions.

TABLE XVIII. Performance at altitude conditions 4/.

Power setting 1/	Alt. (ft)	Amb. Temp	Mach num.	Minimum net thrust N (lbf)		Maximum SFC (lb/hr/lb)		Maximum engine rotor speed (rpm)		Maximum gas temp. 2/ (°C(°F))		Maximum measured temp 3/ (°C(°F))		Total allow (lb/sec) +/- __%		Cust. bld. air	Cust. pwr. ext.
				New	Det 5/	New	Det 5/	New	Det 5/	New	Det 5/	New	Det 5/	New	Det 5/		

NOTES:
1/. Power settings should be as required by the Using Service to cover the operating envelope and to be compatible with mission requirements.
2/. Defined at the first stage turbine rotor inlet location (contractor should parenthetically insert, in column heading, the station designation).
3/. Contractor should parenthetically insert, in column heading, the measurement plane station designation.
4/. The engine performance values shown should be from the engine computer program of JSSG-2007 para 3.2.1.1
5/. Deteriorated engine performance is specified for _____ TACs (or hours) of use.

TABLE XIX. Turboprop/turboshaft performance at altitude conditions 4/ with ____ nozzle.

Power setting 1/	Alt. (ft)	Amb. Temp	Mach num.	Max gas gen speed (rpm)		Max gas temp 2/ (°C(°F))		Max meas temp 3/ (°C(°F))		Total airflow (lb/sec) +/- __%		Maximum SFC (lb/hr/kw)		Min shaft power kw (shp)		Output torque N-m (lb-ft)		Output shaft speed (rpm)		Resid. Jet thrust N (lbf)		Cust. bld. air	Cust pwr ext
				New	Det 5/	New	Det 5/	New	Det 5/	New	Det 5/	New	Det 5/	New	Det 5/	New		New	Det 5/	New	Det 5/		

NOTES:
1/. Power settings should be as required by the Using Service to cover the operating envelope and to be compatible with mission requirements.
2/. Defined at the first stage rotor inlet location (contractor should parenthetically insert, in column heading, the station designation).
3/. Contractor should parenthetically insert, in column heading, the measurement plane station designation.
4/. The engine performance values shown should be from the engine computer program of JSSG-2007 para 3.2.1.1.
5/. Deteriorated engine performance is specified for _____ TACs (or hours) of use.

Background:

LCF engine testing should be required for engines not tested with AMT duty cycles. These include mainly turboprop and turboshaft engines using the time-at-temperature durability tests from A.4.9.1.1.2. For helicopter engines, the LCF engine test is considered more rigorous and demanding than missionized schedules or schedules simulating partial cycles. LCF engine tests add thermal cycling and fatigue effects and have uncovered problems not found in endurance test runs. The LCF test time should be for 1/4 of the engine LCF design life or 1/4 of cold section design life, whichever is longer.

A Strength and Life Anaysis should be prepared and a report should be submitted to the Using Service for approval.

A minimum of three sets of fracture, safety, mission, and durability critical engine parts, identical to the parts list and configuration of the IFR milestone engine should be subjected to LCF testing as specified below to verify the LCF requirements of A.4.9.1. LCF testing should be conducted in accordance with the requirements of "zero failure verification testing", as referenced in AFWAL-TR-83-2079. This method outlines the number of units to be tested and the amount of time to be accumulated on each unit without failure to verify the life. The underlying failure distribution should be assumed to be Weibull. A confidence level of 90% should be assumed. The test plan should meet all the requirements of "zero failure verification testing" in order to verify the minimum LCF lives.

The LCF testing in the subparagraphs below should constitute the full effect of strain generated by centrifugal, pressure, and aerodynamic forces as well as thermally generated strains. Dwell times at thrust settings should be sufficient to accomplish stabilization of strains equivalent to those encountered in a service mission cycle. The actual number of cycles, duty times, and length of cool down time should be based upon the Strength and Life Analysis Report.

a. One set of fracture, safety, mission, and durability critical engine parts should be subjected to official full scale engine AMT/endurance testing which produces LCF damage equivalent to at least one-half the cold parts lives specified in A.4.3.2. These same parts should then be subjected to further testing, either by individual component tests (spin pit) until the minimum LCF lives required by A.4.9.1 are evaluated, or by continued testing in an engine.

b. Two sets of fracture, safety, mission, and durability critical engine parts should be subjected to LCF testing until the minimum LCF lives required by A.4.9.1 are evaluated. The LCF testing should be achieved in any manner appropriate to the full-scale development program (e.g., full-scale engine tests, individual component tests or combinations thereof). Component testing of these selected parts, except for the combustor, should be performed either with high temperature and loads appropriate for simulating engine maneuver load conditions, or with loads adjusted for material properties at the test temperature. The combustor should be tested only at high temperature conditions.

All repairs and parts replacement should be recorded and reported. Test substantiation (i.e., full-scale engine testing) of critical parts may require other parts to receive damage greater than their LCF life. Part replacement or repair may then be accomplished in order to continue the test. The LCF test should be considered successful and the minimum lives of A.4.9.1 verified, if no units fail within the prescribed test time. Failure is defined as generation of a crack size of A.4.8.2. Test times are derived in accordance with AFWAL-TR-83-2079. The test time for a high-pressure turbine (HPT) disk is determined in the following example:

ASSUMPTIONS:

a. The failure distribution is Weibull.

b. The shape parameter (ß) is 3.0.

c. The confidence level is 90%.

The Weibull distribution can be expressed as:

The reliability goal for the HPT disk is 99.9% at 4000 LCF cycles.

$$R(4000) = 0.999$$

This is equivalent to the goal of having a characteristic life of 39,990 LCF cycles.

Characteristic Life (eta) = 39,990 LCF cycles

From table 5.1 in AFWAL-TR-83-2079, we can determine the characteristic life multiplier. Three sets of hardware will be tested. Therefore, the characteristic life multiplier for a sample size of 3 and ß = 3.0 is 0.916.

$$(0.916)39{,}990 = 36{,}630$$

Hence, we must test three units for 36,630 LCF cycles without a failure to ensure that the reliability goal of 99.9% at 4000 LCF cycles is met. Failure is defined as generation of a crack size per 3.4.1.7.3.

EVALUATION LESSONS LEARNED (A.5.9.1)

Most LCF tests on the complete engine were not conducted for the LCF life of the parts. This would be a very long and expensive program, even when it is accelerated. The lack of statistical significance of one data point (a single engine) justifies running several identical parts in spin pits. An increase in sample size provides an increase in the statistical significance. Disks, which are expensive to replace, have been tested in a spin pit with as many as five samples. Spin pit testing has certain disadvantages. Specifically, it only simulates the centrifugal loading. It does not simulate the vibratory, aero-elastic, thermal or loads from adjacent disks. Of those loads, simulating the thermal stresses imposed on disks is the most difficult.

A.5.9.1.1 Accelerated mission test (AMT).

An accelerated mission test (AMT) should be performed on the initial flight release (IFR) engine configuration. The test run schedule should simulate the design duty cycle of 5.3. The minimum test duration should be two times the initial flight test usage. This test should be completed prior to first flight.

EVALUATION RATIONALE (A.5.9.1.1)

AMT is required prior to first flight to provide assurance that the engine can safely accomplish the flight test program.

EVALUATION GUIDANCE (A.5.9.1.1)

The minimum duration for AMT prior to first flight should be two (2) times the usage planned for the initial flight test program (2 X flight test duration) on a single engine. AMT should be scheduled so that the duration of testing simulated by ground test is accelerated by a minimum factor of two (2) beyond any flight test engine. Additional guidance regarding derivation of the AMT duty cycle is given in section A.5.9.1.2. of this handbook.

EVALUATION LESSONS LEARNED (A.5.9.1.1)

None.

A.5.9.1.2 Full-scale development engine.

An AMT should be performed on the full-scale development engine configuration. The test schedule should simulate the design duty cycle of 5.3. The minimum test durations should be one-half the design service life at full flight release (FFR) and one times the design service life at initial service release (ISR).

EVALUATION RATIONALE (A.5.9.1.2)

Extended duration AMT is required to substantiate the durability/economic life of the engine. Additionally important is that the results of extended tests be available at the time the Air Force is evaluating the suitability of the engine for full production commitment.

EVALUATION GUIDANCE (A.5.9.1.2)

This AMT should be scheduled so that a minimum of one-half X design service life is accomplished at full flight release (FFR) and one X design service life is accomplished at initial service release (ISR) on a single engine. The results of this AMT should be used to determine if the durability requirements of section 4 of the document have been met.

During review of the ENSIP military standard and appendix handbook with the AIA's Project PC 338-2A committee in September 1982, full endorsement of the above guidelines on AMT duration was not received. The main point of difference was AIA concern with the amount (duration) of testing required at each development milestone. Although USAF experience strongly indicates that design service life requirements should be demonstrated prior to volume commitments to avoid production changes and retrofits, the AIA has endorsed test durations significantly less than the above guidelines.

Options for accelerating the AMT should be used when possible. For example, an option is to conduct one-half design service lifetime (one hot parts life) and thereafter change the test cycle to a mission related LCF test. For the LCF test cycle, dwell time at intermediate power is condensed to the minimum time required to simulate thermal gradient. The dwell times for the LCF test cycle should be based on analysis and thermal survey data. The LCF test cycle can allow a greater acceleration of simulated service usage and reduce test costs.

Additional guidance regarding derivation of the AMT duty cycle is provided as follows:

Accelerated mission test (AMT) spectrum derivation. AMT tests should be derived initially based on design mission profiles and mix and continually updated based on real usage from the usage program in Task V (lead the fleet with flight recorder data). When it is necessary, altitude and/or ram testing should be included.

Prior to the start of test, the engine control fuel schedule should be adjusted to obtain starts, restarts, and accelerations and to provide starting and acceleration temperatures all at or above rated or maximum values, as applicable. Deceleration fuel schedules should be preset to provide maximum thermal shock. The customer air bleed should be set with a fixed orifice to provide maximum permissible bleed air flow. The accessory and customer power takeoff pads should be loaded to provide max continuous loads plus transients to maximum allowable loads.

All repairs and parts replacement should be recorded and reported. The actual number of cycles, duty times, and length of cool down time should be based upon a study using thermal survey data and should be that required to obtain at least the same failure and stress rupture damage on the test engine as one operational lifetime predicted in the strength and life analysis. This test substantiation of one life may require certain parts to receive more than one lifetime of damage. If this damage on those parts exceeds the parts' design life, part replacement or repair may be accomplished in order to continue the test.

The accelerated mission related test spectrum (AMT) will be derived from the following:

a. Design duty cycle.

b. Results of thermal survey.

c. Latest usage information.

d. Damage tolerance and durability analysis.

e. Vibration analysis and strain survey.

The test spectrum derivation should consider at least the following:

a. Flight-by-flight mission usage with blocks of ram, alt, and high mach conditions included as appropriate.

b. Low cycle fatigue mechanism.

Number of 0-max/mil-0 throttle excursions.

Number of idle-max/mil-0 throttle excursions.

c. Stress rupture and creep failure mechanism - Time at and above military power.

d. Incremental running to interrogate high cycle fatigue failure modes: 10^6 cycles on a one per rev basis.

Sustained power levels that occur in operation, but not included in normal AMT (idle, cruise, etc.).

Known critical speeds (shaft and blades).

e. Mission mix.

f. Mach Number and altitude, percent time spent at each point in flight envelope.

g. Hold times and sequence of major throttle settings.

h. Number of augmentor lights and time in augmentation.

i. Ground run time and profile, i.e., trim run, test cell, etc.

j. Gearbox Hp extraction and bleed.

k. Field trim procedures and frequency.

l. Oil temperature and fuel temperature.

m. Heated inlet conditions representative of the design duty cycles.

n. Truncation of both small throttle settings and extended time below military power.

The burner pattern factor and radial profile should be established for each "AMT" test engine.

Calibration. The engine including temperature sensing systems and all controls should be checked on the bench and in the engine prior to test to assure that the tolerance limits are met. The engine calibration procedures should be sufficient to establish the performance characteristics through thrust measurements of the complete engine. Calibrations should be made at ambient conditions initially with no customer bleed and no accessory power extraction other than that required for continuous engine operation. Calibrations should also be made with heated inlet conditions simulating operational use. Calibration data should be sufficient to establish compliance data with the specification requirements for performance ratings, thrust transient times, and starting. Recalibration checks at intervals during the test should be made.

Extensive recalibration at the end of the test should be conducted to determine performance retention (thrust and specifc fuel consumption (SFC)) and control temperature shift at intermediate power for use as an indication of anticipated deterioration rate, and to compare with overall pretest calibration values for the engine, temperature sensing systems, and all controls.

Disassembly and inspection. The engine completing and AMTs should be disassembled in accordance with the procedures contained in the pretest plan. These engine parts should be given a "dirty inspection" for evidence of leakage, oil coking, unusual heat patterns, and abnormal conditions. The engine parts should then be cleaned and a "clean inspection" should then be performed. Engine part measurements should be taken as necessary to inspect for excessive wear and distortion. These measurements should be compared with the engine manufacturer's drawing dimensions and tolerances or with similar measurements made prior to the test. During the "clean inspection" an examination and condition assessment should be conducted. The Procuring Service should be provided all results of nondestructive tests and recommendations for modification or redesign of deficient parts. The Procuring Service should be notified of the inspection commencement date prior to each inspection. The following data should be made available to the Procuring Service during both inspections:

a. Inspection forms filled out by the engine manufacturer listing all findings.

b. Tabulation of all parts found deficient.

c. Detailed configuration list of the component or system tested.

d. Test logs and list of test events.

e. Spectrometric oil analysis report.

As a result of the inspection, parts will be categorized as follows:

a. No repair required.

b. Repair required, before further use.

c. Outside repair limits.

Final approval of the pretest plan will be subject to approval of the procuring activity.

EVALUATION LESSONS LEARNED (A.5.9.1.2)

None.

A.5.9.1.3 Production tooled engine.

AMT should be performed on a production tooled engine configuration. The test schedule should simulate the design duty cycle of 5.3. The minimum test duration should be one times the design service life at operational capability release (OCR). AMT of any proposed design changes should be conducted to a duration of one times the design service life at OCR.

EVALUATION RATIONALE (A.5.9.1.3)

Extended duration AMT of the production tooled engine configuration including proposed design changes is required to substantiate the durability/economic life of the engine. Additionally important is that the results of extended tests be available prior to initiation of high production rate.

EVALUATION GUIDANCE (A.5.9.1.3)

The minimum test duration should be (one X design service life) at OCR. AMT of any proposed design changes should be conducted to a duration of (one X design service life) at OCR. Additional guidance regarding derivation of the AMT test schedule is given in section A.5.9.1.2 of this handbook.

EVALUATION LESSONS LEARNED (A.5.9.1.3)

None.

A.5.9.1.4 Production tooled engine configuration.

AMT should be performed on a production tooled engine configuration. The test schedule should simulate a service duty cycle that is derived from operational usage data. The minimum test duration should be one times the design service life.

EVALUATION RATIONALE (A.5.9.1.4)

AMT conducted to duty cycle that is based on operational data is required. The results obtained from this test will be used to update the structural maintenance plan as required. This test is not intended as verification that the durability requirements of section 4 of this document have been met, but rather to define the expected operational life based on measured operational usage of the engine.

EVALUATION GUIDANCE (A.5.9.1.4)

This AMT is not intended to be a contractual requirement to be completed prior to operational capability release (OCR), but to be incorporated as a requirement for subsequent component improvement program (CIP) effort. The minimum test duration should be (one X design service life). The maximum test duration should be (two X design service life). Additional guidance regarding derivation of the AMT test schedule is given in section A.5.9.1.2 of this handbook.

EVALUATION LESSONS LEARNED (A.5.9.1.4)

None.

A.5.9.1.5 Inspections.

Major inspection programs should be conducted as an integral part of the AMT programs.

EVALUATION RATIONALE (A.5.9.1.5)

Special inspections conducted periodically during the test programs are essential to preclude component failure and loss of the development engine. Completion of development milestones rests on maintaining integrity of the development engines.

EVALUATION GUIDANCE (A.5.9.1.5)

The contractor should propose an inspection policy for the AMT engines. Inspection requirements should include in-service design inspections developed in accordance with the durability and damage tolerance requirements of this standard. Inspection requirements should also duplicate the expected field maintenance concept for the engine. Special inspections to monitor the status of critical components should be included. Teardown inspection per A.5.9.1.2 should be identified at the completion of test milestones to support the interpretation and evaluation task of A.5.9.1.5.

EVALUATION LESSONS LEARNED (A.5.9.1.5)

Complete failure of test engines has occurred in past development programs due to undetected damage growth. Many of these failures could have been prevented by use of detail inspection requirements (methods and intervals) developed through the durability and damage tolerance control plans and experience obtained from earlier development testing (e.g., previously observed deterioration and distress).

A.5.9.1.6 Interpretation and evaluation of test results.

Each structural problem, such as failure, cracking, yielding, wear, and erosion, discovered during inspection of the AMT engines should be analyzed to determine cause, corrective action, and operational implications relative to meeting the design requirements contained in this standard. Specific requirements should be identified.

EVALUATION RATIONALE (A.5.9.1.6)

Definitive criteria is needed to judge the success of qualification tests, especially the AMTs of A.5.9.1.1. Problems will likely be discovered during teardown inspection of these engines prior to attaining the required test durations. Therefore, criteria is needed to establish course of action in the event problems occur and to define follow-on actions (i.e., remaining test duration, problem cause, corrective action, operational implications, qualification tests for redesign, etc.).

EVALUATION GUIDANCE (A.5.9.1.6)

The contractor should identify the requirement in A.5.9.1.6 to perform interpretation and evaluation of test results. The requirement should identify the policy for remaining test duration in the event failures or problems occur prior to attaining the required test duration. In general, component failure or other problems that occur prior to attaining the required test duration will not require retest of the full engine to the full duration but will require additional testing to complete the remainder of the duration that existed at the time the failure or problem occurred. However, redesign and/or retest for the full duration will be required for those components that experience failure or problems that in service would endanger the pilot or aircraft and for those components that have to be replaced due to secondary damage (i.e., over-temperature exposure or domestic object damage) although qualification may not be tied to the ISR and OCR milestones. The approach for qualifying these components (i.e., redesign, test vehicle and schedule relative to the development milestones) will be subject to negotiation between the procuring agency and the contractor. It is anticipated that the AMT of A.5.9.1.3 will be utilized to qualify redesigns required as a result of problems uncovered by earlier test, components not qualified for the full test duration by earlier test, and other design changes that occur due to cost, manufacturing considerations, etc.

Additionally, A.5.9.1.6 should identify the requirement to evaluate problems or failures that occur during AMT (i.e., loss of mission capability or requiring maintenance actions) relative to contract/specification reliability and maintainability goals and to use test results to validate the LCC models.

The A.5.9.1.6 requirement should identify the need to establish problem cause, corrective action, operational implications, additional redesign and test requirements together with schedule and costs.

It is recommended that A.5.9.1.6 contain the following specific requirements:

The AMT engine test will be considered to be satisfactorily completed when the engine has (a) completed the test duration per the pretest plan, (b) the test engine and components are operating satisfactorily at the end of the test, (c) recalibrations reveal performance retention to be within limits specified in 4.11 and in the Primary Specification, (d) not experiencing any catastrophic failures, (e) not experiencing in-flight shutdown events, and (f) assessment of failures and impending failures and establishment of corrective actions.

In the event of catastrophic failures of nondiscretionary in-flight shutdowns in the single engine configuration, penalty running requirements will be established by the Procuring Service after a review of the circumstances. Impending failures should be used to set inspection intervals and evidence of impending failure should be included as maintenance and reliability factors for verification of compliance.

EVALUATION LESSONS LEARNED (A.5.9.1.6)

None.

A.4.9.2 High cycle fatigue (HCF) life.

Engine parts should not fail when subjected to the maximum attainable combined steady-state and vibratory stresses.

REQUIREMENT RATIONALE (A.4.9.2)

Experience has shown that engine structural components operating under combined steady and vibratory stress conditions must be designed to ensure resistance to HCF cracking.

REQUIREMENT GUIDANCE (A.4.9.2)

The vibratory or HCF stress should be restricted to forty percent of the material capability. All engine parts should have a minimum HCF life as follows:

MATERIAL	LIFE (cycles)
Ferrous, Nickel-Base Superalloys	10^7 cycles
Titanium	10^9 cycles
Other Materials	3×10^7 cycles

The vibratory or HCF maximum stress, ratioed to the worst location and for the worst condition, should be restricted to a value of 40 percent of that allowed by the minimum value material allowable due to the sensitivity of high cycle stresses to damping variability, part-to-part resonance variation, unknown excitations, ability to analyze, etc. The 40% of maximum stress criteria is based on root mean square (RMS) values. Other percents (using non-RMS stresses), up to 60%, may be used if the maximum stress is based on maximum instantaneous stress. An alternative design approach to achieve margin is to limit the steady stress such that significant levels of vibratory stress (e.g., 210 mPa (30 Ksi) peak-peak) will not exceed the minimum value material allowable. Vibratory stress should also be limited to 70-105 mPa (10-15 Ksi) to ensure robustness. For airfoils having FOD/DOD damage tolerance requirements of K_t=3, the alternating stress should be limited to 40% of the minimum unnotched HCF material allowable or 100% of the K_t=3 minimum notched HCF material allowable, whichever is less.

For materials which do not have a discrete endurance limit knee on the stress versus cycles to failure curve, the engine manufacturer should present in the vibration and stress analysis report the method of achieving adequate high cycle fatigue life. Complications exist with the concept of specifying that all parts be designed to some discrete specified endurance limit. Some of these are:

a. Prior stressing at a higher stress can cause a lowering of the endurance limit.

b. Stress cycling at gradually increased cyclic stress can result in an increased endurance limit (this is known as coaxing).

c. Interactions between LCF and HCF can result in either increased or decreased lives depending upon the magnitude of the loads, the order of the loading, and the material.

d. Installation, handling, and environmental sensitivities can result in significantly higher steady-state and vibratory stresses which will reduce or even have negative margins for HCF capability. Such an example would be external parts which may be sensitive to all of the above. Realistic levels of stress due to these sensitivities should be included when assessing HCF capability.

Parts which are subjected to LCF loads in addition to HCF loads should be designed considering the effect of LCF damage on the material HCF life.

REQUIREMENT LESSONS LEARNED (A.4.9.2)

USAF experience with the F100 and F110 programs has shown that titanium airfoils can be very sensitive to vibratory stresses. Failures of fan and compressor airfoils, resulting from vibratory stresses, have caused domestic object damage and catastrophic failure. Controlling this problem has required significant additional effort by field units. Testing performed as part of these investigations has shown that the fatigue strength continues to decline past 3×10^7 cycles. Based on the results of this testing, the life requirement of titanium materials should be set at 10^9 cycles. USAF experience and materials data has shown that 10-15 Ksi peak-peak to be the maximum vibratory stress desirable to meet the HCF life requirements.

A.5.9.2 High cycle fatigue (HCF) life.

The requirements of 4.9.2 should be evaluated by analysis and test. An up and down stair-step test should be conducted before and after**,** and throughout the specified engine test(s).

EVALUATION RATIONALE (A.5.9.2)

The HCF life must be evaluated to avoid HCF failures.

EVALUATION GUIDANCE (A.5.9.2)

The engine should undergo an increasing and decreasing speed stair-step run consisting of _(a) periods of _(b)_ duration each, at equal increasing rotational speed increments beginning at idle and continuing up to and including the maximum rotor speed.

(a): 25 periods or as determined by analysis. In the event significant peak vibration points exist at any conditions between idle and maximum rotational speed, the number of increments chosen may be altered at the option of the Using Service, to increase the amount of running time obtained at the peak vibration points up to an amount not to exceed 50 percent of the total time of the run.

(b): One hour duration or as determined by analysis.

The engine contractor should provide a HCF analysis. The analysis should be provided at the initiation of EMD to ensure appropriate selection of materials and design configurations. The analysis should identify resonant mode shapes, frequencies, and those stresses produced by a forced response, resonance, and flutter. As a minimum, the analysis should be performed on all support frames, rotating and static airfoils, and engine cases and heatshields. Additional evaluation can be conducted via bench testing of parts to confirm the resonant mode shapes, frequencies, and stresses identified in the analysis. The HCF analysis should be substantiated/correlated with full-scale engine testing.

The source of HCF full-scale engine test data should include all accelerated mission/endurance and altitude tests. The additional tests required in 4.13 should allow further evaluation of the

HCF life of parts. Sufficient instrumentation should be provided on all HCF test engines to obtain resonant mode shapes, frequencies, and stress levels.

EVALUATION LESSONS LEARNED (A.5.9.2)

None.

A.4.9.3 Life design margin.

A life margin should be applied during design of engine components.

REQUIREMENT RATIONALE (A.4.9.3)

Life design margin is needed in early development due to uncertainties in usage, environmental conditions, and quality of the finished part.

REQUIREMENT GUIDANCE (A.4.9.3)

The recommended margin for LCF life design is 100% based on minimum material properties. The weight impact of having a LCF margin can be small and, in many cases, LCF of parts will meet the 100% margin based on design stress levels set by other structural requirements such as high cycle fatigue, creep and stress rupture, burst strength, and stiffness requirements. Optimization of stress concentrations can increase LCF life by an order of magnitude and more than offset any weight increases incurred by imposing an LCF margin. Also, the inverse exponential shape of LCF design curves often enables considerable increase in LCF life by only a modest decrease in nominal stress.

It is not so clear that a significant life margin can be achieved on engine hot parts relative to stress rupture capability. The goal is that a design life margin be achieved on hot parts wherever possible to protect against environmental uncertainties (internal temperatures, deterioration, etc.) or to increase the usable life beyond the minimum specification requirements. The contractor should recommend other design margins to apply to engine hot parts based on consideration of other pertinent failure modes and knowledge of the internal environment.

The LCF design margin may be reduced if measured data on usage of a similar system is available or if other conservative measures are to be utilized in the design. Trade studies should be identified in the durability control plan to identify cost (weight, performance, life cycle cost, etc.) as a function of durability/economic life to establish realistic life design margins.

REQUIREMENT LESSONS LEARNED (A.4.9.3)

None.

A.5.9.3 Life design margin.

Attainment of the life design margin should be evaluated by analysis and test.

EVALUATION RATIONALE (A.5.9.3)

Life design margin must be evaluated to ensure compliance with the requirement.

EVALUATION GUIDANCE (A.5.9.3)

See A.5.9.1

EVALUATION LESSONS LEARNED (A.5.9.3)

See A.5.9.1

A.4.9.4 Corrosion prevention and control.

The engine should operate satisfactorily without detrimental material degradation in the environmental conditions specified in 4.5 - 4.5.3 for the design service life.

REQUIREMENT RATIONALE (A.4.9.4)

Corrosion prevention and control is important to avoid material degradation that will cause an uneconomical maintenance burden and affect operational readiness.

REQUIREMENT GUIDANCE (A.4.9.4)

Repair or replacement of corrosion prevention systems is permitted where engine experience shows that the protective treatments become ineffective prior to attaining the required design service life under realistic environments. However, a minimum period of unrepaired service usage should be specified and this period should be equal to or greater than the depot or base level inspection interval of A.4.8.4.

REQUIREMENT LESSONS LEARNED (A.4.9.4)

None.

A.5.9.4 Corrosion prevention and control.

The corrosion resistance of the engine materials, processes, and protection systems should be evaluated as follows:

EVALUATION RATIONALE (A.5.9.4.)

A plan is needed to identify protective treatments and evaluation methods based on experience obtained with previous engine systems.

EVALUATION GUIDANCE (A.5.9.4)

A corrosion prevention and control plan should be prepared. The contractor should identify the protective treatments to be used in the engine. Prior experience with use of these treatments should be provided as well as identification of tests to qualify proposed new treatments. The contractor should identify problems that have occurred on past engine systems related to corrosion or other environmentally induced material degradation and should provide justification that the proposed engine configuration will not be susceptible to these problems.

EVALUATION LESSONS LEARNED (A.5.9.4)

None.

A.4.10 Strength.

The engine should meet all the requirements of the specification during and after exposure to limit loads, singly and in combination where they occur naturally. The engine should not experience catastrophic failure when subjected to ultimate loads, singly and in combination where they occur naturally. In addition, the engine should meet the following strength criteria.

REQUIREMENT RATIONALE (A.4.10)

Limit and ultimate loading must be addressed since the engine may be exposed to limit and ultimate loading conditions during operation.

REQUIREMENT GUIDANCE (A.4.10)

The limit load conditions of A.4.3 will occur over the life of an engine system. Therefore, it is required that the structure be capable of reacting these loads without incurring detrimental permanent deformation or degraded performance so that operational capability is maintained. Also, stresses greater than design limit load values can occur as a result of inadvertent operation of the engine and/or weapon systems. Stresses greater than material allowables can occur due to variation in material properties (i.e., castings). Therefore, it is required that the engine structure have a margin of strength to withstand without failure externally applied forces that exceed the limit load conditions of A.4.3.

The engine should incorporate fail-safe design objectives to eliminate catastrophic failure including, but not limited to, the following considerations:

a. Compressor and turbine disks should be protected by having blades fail first under overspeed or overtemperature malfunctions.

b. A main rotor shaft bearing or lubrication system failure should not cause parting or decoupling of the shaft(s).

c. In the event of shaft decoupling, the disks should be designed such that the burst speed should be at least five percent greater than the maximum predicted free rotor overspeed or the turbine blading should contact the turbine vanes to minimize a turbine overspeed, or an overspeed trip system should be installed to control turbine overspeed.

d. In the event of a rotor bearing failure, the structures supporting the rotating masses should be designed to minimize the probability of gross misalignment of the engine rotating parts.

e. All areas of the rotor that could puddle oil should have appropriate drains.

Specific guidance for establishing factors of safety and strength requirements is contained in paragraphs A.4.10.1 through A.4.10.10 of this handbook.

REQUIREMENT LESSONS LEARNED (A.4.10)

None.

A.5.10 Strength.

The requirements of 4.10 should be evaluated by structural analysis and part, component, and full-scale engine tests.

EVALUATION RATIONALE (A.5.10)

Structural analyses and tests are required to evaluate that the engine and its components can meet strength requirements.

EVALUATION GUIDANCE (A.5.10)

Specific guidance on structural analysis requirements for A.4.10 and A.4.10.1 through A.4.10.10 are consolidated within this guidance section. The contractor should describe the extent of structural analysis to be performed. Design analysis methods to be used to demonstrate ability to meet operational requirements of A.4.10.2 through A.4.10.10 should be identified. The schedule for the analysis should be identified and should meet the milestone guidance provided in table II.

Structural modeling techniques to be used should be described for each major class of components (e.g., static structures, disks, shafts, airfoils). Detailed modeling for these structures is required. It is recommended that the analysis approach employ direct utilization of the thermal heat transfer model required to establish stress as a function of flight conditions. Final analyses should utilize finite element breakups or comparably precise methods to establish stress concentrations and gradients at structural discontinuities (bolt holes; rim slots and posts; radii; blade shrouds, and dovetails; etc.).

The contractor should describe the extent of component strength tests performed. Specific tests to be used to demonstrate the ability to meet operational requirements should be identified. The schedule for these tests should also be identified.

Strain gauges should be utilized during component strength tests to verify analysis methods relative to nominal stresses and peak surface stresses at concentration details. It is recommended that strain gauges be utilized on each component strength test of static structure. Strain gauge data on rotating structures should be obtained from core and full-scale engine testing.

Stress coat techniques should be used to assist in establishing locations for strain gauges. Photoelastic modeling and test is suggested for better understanding of maximum stresses and gradients at complicated structural details (e.g., blade dovetails, rim slots).

EVALUATION LESSONS LEARNED (A.5.10)

None.

A.4.10.1 Factors of safety.

Factors of safety should be applied to design usage induced loads to establish limit and ultimate conditions.

REQUIREMENT RATIONALE (A.4.10.1)

Sufficient factors of safety (table XX) must be determined to assure adequate safety margins exist in designs.

REQUIREMENT GUIDANCE (A.4.10.1)

REQUIREMENT LESSONS LEARNED (A.4.10.1)

Catastrophic failures of cast parts and pressure vessels have occurred due to porosity and poor manufacturing processes. These parts were designed with a 1.5 factor of safety for ultimate load conditions. A more graceful (i.e., non-catastrophic) failure would have occurred if the hardware had been designed with a 2.0 factor of safety.

TABLE XX. Factors of safety.

LOAD TYPES	LIMIT	ULTIMATE	
		a	b
Externally applied loads	1.0	1.0	1.5
Thermal loads	1.0	1.0	1.5
Thrust loads	1.0	1.2	1.0
Internal pressures	1.5	1.0	2.0
Aircraft flow field loads	1.0	1.0	1.5
Crash loads	N/A	1.0	1.0

NOTES:
(1) For all castings, a factor of safety of 1.33 should be applied to the limit and ultimate load factors specified above, unless the castings have been fully characterized.
(2) Two combinations (a & b) should be used for establishing ultimate loading conditions required in other paragraphs in this section.

A.5.10.1 Factors of safety.

The requirements of 4.10.1 should be evaluated by analyses and tests.

EVALUATION RATIONALE (A.5.10.1)

Factors of safety must be evaluated to assure adequate safety margin.

EVALUATION GUIDANCE (A.5.10.1)

Strain gauges and other instrumentation should be used during tests to evaluate analysis methods. It is recommended that tests be conducted progressively to ultimate load conditions.

EVALUATION LESSONS LEARNED (A.5.10.1)

None.

A.4.10.2 Blade and disk deflection.

The blades and disks should not contact any static parts of the engine other than seals and shrouds, during all phases of engine operation including surge and stall occurrences. Seals and clearances should remain effective under all internal and external operational loads.

REQUIREMENT RATIONALE (A.4.10.2)

Sufficient rigidity must be provided so that the engine can operate to the limit loads and repeated loads that occur within the flight envelope without detrimental damage.

REQUIREMENT GUIDANCE (A.4.10.2)

High thrust bearing loads cause rotors to shift thereby increasing clearances or causing detrimental damage to static or rotating hardware. This happens more in the turbine where high temperature increases creep and thermal stress. The resultant rub opens the blade clearances or can damage hardware where rubs were not intended to occur.

REQUIREMENT LESSONS LEARNED (A.4.10.2)

Rotor shifts have caused blading to contact vanes and led to subsequent blade failure.

A.5.10.2 Blade and disk deflection.

The requirements of 4.10.2 should be evaluated by the analyses and tests.

EVALUATION RATIONALE (A.5.10.2)

Structural analyses and tests are required to evaluate that blade and disk deflection does not result in contact with any static parts of the engine other than seals and shrouds. Blade and disk rigidity must be evaluated to ensure flight safety against blade failures and titanium fires.

EVALUATION GUIDANCE (A.5.10.2)

The test should be conducted in accordance with A.4.10.

EVALUATION LESSONS LEARNED (A.5.10.2)

X-ray photography has been used to determine that seals and clearances are effective under all operational loads.

A.4.10.3 Containment.

Uncontained failures should not cause fire or catastrophic damage to engine external systems or aircraft systems, or injury to personnel.

REQUIREMENT RATIONALE (A.4.10.3)

Uncontained failure of rotating components can cause extensive damage to external engine components, lines, and wiring harnesses. Beyond engine systems, secondary damage can occur to aircraft lines, fuel tanks, and critical systems. In many of these cases damage is severe enough to cause loss of the aircraft either by loss of functionality of critical systems or by uncontained fire.

REQUIREMENT GUIDANCE (A.4.10.3)

Containment is an interface requirement and should be allocated from the weapon system requirements. The engine should have full engine containment unless there is a split of allocation of this requirement between the engine and the airframe. The full allocation requirement for containment should be to ensure failure of a rotating component poses a minimum catastrophic hazard due to secondary damage, or probability of failure for a component is low enough to be considered impossible. For each possible design solution the impact on system weight, performance, cost, and risk must be weighed and evaluated per specific program constraints and requirements.

Failure modes for rotating components must be evaluated to determine if the consequence of failure is uncontained failure and probable loss of the aircraft. In those cases where loss of the aircraft is not remote, component, engine systems, aircraft systems, or some combination must be designed to maximize the probability of safe aircraft recovery. Where containment or aircraft shielding is selected, design procedures should be based on past experience including engine blade failures and test data that supports/establishes material containment capabilities and this must be incorporated in the Interface Control Document (ICD).

Blade manufacturing anomalies and the variability of FOD/DOD levels and design capabilities significantly limit the ability to design for low probability of failure. As a result, design considerations for fan blade failures should focus on containment vs noncontainment of the entire blade (airfoil, platform, and attachment). Considerations include full containment within the engine case, uncontained but low energy penetration (such that no significant damage occurs to the aircraft), uncontained in combination with aircraft shielding to prevent catastrophic airframe damage, and non-uniform tailored containment (example, engine case containment in the upper case only to protect aircraft systems). As part of any solution that allows uncontained failure, external engine and aircraft systems (fuel, hydraulic lines, etc.) must be routed to reduce exposure and limit secondary damage.

The engine should be designed to contain high pressure compressor (HPC) and turbine blades (airfoil, platform, and attachment). These components are subject to more severe environments, material variabilities, complex geometries and tighter tip clearances than fan blades. These factors combine to reduce the credibility of any attempt to calculate probabilities of failure. In addition, the consequence of case penetration by hot parts followed by hot gas has a greater probability of leading to external engine fires.

Containment of larger (increased energy) rotating components such as disks and seals should be evaluated vs alternative methods listed under fan blades. In addition, designs should be considered that reduce the probability of failure so that the hazard is assumed to be non-existent. Low probability of failures for critical parts may be achieved by selection of appropriate structural integrity criteria and guidance (A.4.6 and A.4.10).

REQUIREMENT LESSONS LEARNED (A.4.10.3)

Experience has led to current designs that allow uncontained fan blades. In association with these designs, critical external engine components are kept off of the fan case to the maximum extent possible. Those components that must be placed on or in the fan case are grouped together in as few circumferential locations as possible, limiting the probability that an uncontained failure will impact a critical component.

The decision to contain fan blades should take into consideration total system survivability. While for a multi-engine aircraft full containment may maximize the probability of safe recovery of the aircraft following a failure, it might not be the best approach for single engine aircraft. For example, containment of a fan blade within the engine virtually assures massive damage to the engine and near complete loss of thrust. In a single engine aircraft this scenario assures loss of the aircraft unless a suitable airfield is available very nearby. In contrast, allowing a fan blade to exit the case and be contained by aircraft shielding increases the chance that internal secondary damage will be limited to an extent that allows the engine to continue to operate at a reduced power and permit safe recovery. This has been shown in eight cases of uncontained fan blade failures where single engine aircraft were able to get home.

A.5.10.3 Containment.

The requirements of 4.10.3 should be evaluated by analysis and test.

EVALUATION RATIONALE (A.5.10.3)

Evaluation of engine and component containment capability is necessary to avoid the occurrence of uncontained failures.

EVALUATION GUIDANCE (A.5.10.3)

The engine contractor should perform a blade containment analysis which relates the released blade kinetic energy to the energy required for containment. The containment analysis should be provided at the initiation of EMD to provide confidence that the design will contain certain failures. The analysis should be substantiated/correlated with containment tests. Prior failures on identical structures can be discussed in the analysis and used for substantiation of the containment test. Containment tests are necessary since many uncertainties exist with the various containment analysis procedures (e.g., dynamic considerations of pressure loading versus ballistic loading, effectiveness of containment structure due to varying geometry, material capability forces, etc.).

The tests should be conducted at or above the maximum allowable rotor speeds and maximum operating temperatures. The blades selected for the test (those blades determined to be the most critical) should be modified to fail at a predetermined speed. The test should be considered satisfactorily completed when all damage is contained.

The engine contractor should also provide component containment analyses and/or conduct component testing. The analyses/tests should be conducted to ensure all engine components utilizing rotating parts will contain any rotating part failure at maximum transient speed.

EVALUATION LESSONS LEARNED (A.5.10.3)

Early use of containment criteria and analysis can avoid a redesign. For safety of personnel and equipment it is very desirable to have all blade failures contained within the engine.

A.4.10.4 Blade out.

Subsequent to a single blade failure, with resulting secondary loss of another blade in the same stage at maximum allowable transient speed, the engine should not experience uncontained fire; catastrophic rotor, bearing, support, or mount failures; overspeed conditions; leakage from flammable fluid lines; or loss of ability to shutdown the engine.

REQUIREMENT RATIONALE (A.4.10.4)

The engine must possess adequate structural integrity after blade loss so that a stable time period exists without uncontained catastrophic destruction to allow time for pilot awareness and appropriate action. In addition, to the requirement for containment of the failed blade, the secondary failure modes that would result in catastrophic failure must be avoided.

REQUIREMENT GUIDANCE (A.4.10.4)

The following should be used to tailor the specification paragraph:

a. Blade loss loads for conventional blades should be based on the imbalance equivalent to fracture in two blade attachments at the minimum neck section above the outermost retention feature.

b. Blade loss loads for integrally bladed rotors should be based on the imbalance equivalent to liberation of two airfoils including the fillet material down to the rotor rim diameter.

Blade out conditions should also address the possibility of interactive blade/disk vibration modes resulting from imbalance or acoustics.

Design for blade failures should include the fan, compressor, and turbine rotors individually. A single blade failure results in blade out loads equivalent to two blades out due to subsequent secondary damage. Furthermore, adequate damping must be provided so that a single blade failure does not cause engine operation at a critical speed which would cause further failures of other hardware. Blade out loads are needed for proper design of aircraft engine mounts.

REQUIREMENT LESSONS LEARNED (A.4.10.4)

Blade failures have caused uncontained fire and catastrophic rotor failure in compressors that use titanium for blades and cases. An imbalance condition caused by loss of blades can lead to bearing and rotor support failure. Interactive blade/disk vibration modes have resulted in the failure of a blade retainer and subsequent loss of a fan rotor assembly.

A.5.10.4 Blade out.

The requirements of 4.10.4 should be evaluated by analysis and test.

EVALUATION RATIONALE (A.5.10.4)

Structural analyses and tests are required to evaluate that blade failure does not cause the engine to experience uncontained fire; catastrophic rotor, bearing, support, or mount failures; overspeed conditions; leakage of flammable fluids; or loss of ability to shut down the engine.

EVALUATION GUIDANCE (A.5.10.4)

Evaluation of blade out requirements should include analyses of the fan, compressor, and turbine sections of the engine. Evaluation of the most critical rotors should be accomplished by an engine test. Blade out testing could destroy a complete engine. Hence, it may be permissible to perform part testing instead of full-scale engine testing. This may be done in conjunction with the containment evaluation.

Failure should be assumed to occur at the maximum transient rotor speed (i.e., the maximum normal operating speed plus adjustments to account for deterioration, control and measurement tolerance, engine-to-engine variations, and Idle-to-Intermediate acceleration overshoots).

EVALUATION LESSONS LEARNED (A.5.10.4)

Evaluation by engine test during development is very rare. As part of FAA certification, the GEAE manufactured CF6 was required to demonstrate compliance with blade out requirements via a full-scale engine test.

A.4.10.5 Overspeed/overtemperature.

The engine should meet all the requirements of the specification during and after overspeed and overtemperature conditions.

REQUIREMENT RATIONALE (A.4.10.5)

These requirements are needed to provide an operational margin for rotor structural integrity while allowing continued use after overspeed and overtemperature events.

REQUIREMENT GUIDANCE (A.4.10.5)

a. Engine rotor speeds of __(a)__ percent of the maximum allowable steady-state speed at the maximum allowable turbine temperature or first stage turbine rotor inlet gas temperature limit of 3.2.2.11 for five minutes.

b. __(b)__ temperature of at least __(c)__ °C (__(c)__ °F) in excess of the maximum allowable temperature or above the first stage turbine rotor inlet gas temperature limit of 3.2.2.11, and at maximum allowable steady-state rotor speed for five minutes.

c. Engine component rotor speeds of __(d)__ percent of the maximum allowable steady-state speed for five minutes.

d. Engine component fuel, lube and hydraulic inlet temperatures of __(e)__ °C (__(e)__ °F) above the maximum allowable operating fluid temperature at the maximum allowable steady-state speed for five minutes.

e. For turboprop/turboshaft engines, the power turbine shaft speed should not exceed __(f)__ percent of the transient speed limit, or the predicted speed attained following loss of load with the engine at Intermediate power and the power turbine running at the highest rated speed, whichever is greater. The predicted maximum speed should be specified herein.

Requirement a. provides for an overspeed condition while operating at normal maximum temperature conditions. Requirement b. provides for an overtemperature condition while operating at normal maximum allowable speed conditions.

These requirements (a. and b.) are needed to provide an operational margin for engine rotor structural integrity while allowing continued use (should not yield) as opposed to the requirement of A.4.10.6 which is intended to represent the ultimate strength of the material (should not burst). Requirements c. and d. are specified to provide an operational margin for component rotor structural integrity while allowing continued use.

The following values should be used:

(a): A value of 115 percent, minimum

(b): insert HPT blade metal, HPT inlet, measured, or gas

(c): a value between 42°C (75°F) and 45°C (81°F)

(d): 115 percent

(e): 25°C (45°F)

(f): A value of 115 percent, minimum

The temperature description (e.g., HPT blade metal, HPT inlet, measured, gas, etc.) should be consistent with the performance rating temperature description.

REQUIREMENT LESSONS LEARNED (A.4.10.5)

Past experience indicates that the engine can overspeed or exceed design temperature due to control system malfunctions or other engine operating anomalies.

A.5.10.5 Overspeed/overtemperature.

The requirements of 4.10.5 should be evaluated by analysis and test.

EVALUATION RATIONALE (A.5.10.5)

Overspeed/overtemperature of the engine must be evaluated to ensure structural integrity of rotating parts.

EVALUATION GUIDANCE (A.5.10.5)

An analysis depicting the overspeed and overtemperature capability of the engine should be provided. Overspeed and overtemperature tests should be conducted to substantiate/correlate the analysis.

For the overspeed test, all rotors should be subjected to engine operation for a stabilized period of at least five minutes duration at (value specified in A.4.10.6) percent of maximum allowable steady-state speed at the engine's maximum allowable temperature. Following the test, parts and assemblies should be within allowable dimensional limits and there should be no evidence of imminent failure. If a cold spin pit is used for hot flow components, speed should be added to compensate for temperature effects (with Using Service approval).

Upon successful completion of the overspeed test, the same engine should be operated at a (HPT blade metal, HPT inlet, measured, gas) temperature of at least (value specified in A.4.10.6) in excess of the maximum allowable temperature and at no less than maximum allowable steady-state speed for five minutes. Following the test, parts and assemblies should be within allowable dimensional limits and there should be no evidence of imminent failure.

For engines with more than one rotor system, the test may be performed separately for each rotor system. Rig tests may be performed with Using Service approval.

EVALUATION LESSONS LEARNED (A.5.10.5)

None.

A.4.10.6 Disk burst speed.

The minimum loaded disk burst speed of the complete disk assembly should be greater than or equal to the overspeed requirements of 4.10.5.

REQUIREMENT RATIONALE (A.4.10.6)

This requirement assures adequate margin against the risk of a disk burst in service.

REQUIREMENT GUIDANCE (A.4.10.6)

The minimum loaded disk burst speed of the complete disk assembly should be 115 to 122 percent of the maximum allowable steady-state rotor speed or 5 percent above maximum transient rotor speed, whichever is greater when the disk is subjected to the maximum temperature gradient and maximum material temperature that will occur for that part.

The 122 percent represents a factor of safety of 1.5 (centrifugal stresses vary as the square of speed). The loaded disk burst requirement is necessary since stresses on the disk are obviously greater when it is loaded with blades. The material properties and stress distributions are more severe when subjected to the maximum temperature gradient and maximum temperature conditions for the part.

Proposed values for disk burst speeds may provide a compromise between crack growth capability and tensile strength.

Generally, "damage tolerant" materials provide better crack growth capability, but lack high tensile strength (burst) capability.

REQUIREMENT LESSONS LEARNED (A.4.10.6)

The FAA uses 120 percent of maximum allowable steady-state rotor speed. The USN and USAF have allowed minimum disk burst speeds of 115-117 of maximum allowable steady-state rotor speed. For titanium fan disks, the USAF has required minimum disk burst speeds of 130 percent of maximum allowable steady-state rotor speed.

A.5.10.6 Disk burst speed.

The requirements of 4.10.6 should be evaluated by analysis and test.

EVALUATION RATIONALE (A.5.10.6)

The required disk burst speed must be evaluated to prevent the occurrence of a catastrophic failure.

EVALUATION GUIDANCE (A.5.10.6)

The Strength and Life Analysis of A.4.9.1 should include a detailed evaluation of the operating environment and stress levels seen by each engine disk. The analysis should provide an initial evaluation of the burst capability of each disk. This information should be substantiated/ correlated with disk burst spin pit testing.

Disk burst testing should be conducted to evaluate whether the burst margin requirement of A.4.10.6 can be met with a minimum tensile strength disk (based on the minimum properties specified in A.4.6). Disk burst testing should be conducted on all engine disks. As a minimum, disk burst tests may be conducted on the most limiting rotor (disk with the minimum burst capability) of each module.

Disks should be operated at burst speeds no less than those of A.4.10.6 while exposed to the maximum temperature gradient and maximum material temperature that would occur for that part. Maximum test speed should be sufficient to demonstrate that a minimum tensile strength component (-3 sigma) can meet the burst margin requirement based on the specific ultimate strength capability of the test component. These conditions should be maintained for a minimum of 30 to 60 seconds. The test should be considered successfully completed if there is no evidence of imminent failure.

Since the blades may actually fail before the disk, substitute blades (dummy blades) may be used in lieu of actual disk blades during the evaluation.

EVALUATION LESSONS LEARNED (A.5.10.6)

None.

A.4.10.7 Output shaft torque limits.

For turboprop and turboshaft engines the maximum allowable steady-state delivered shaft torque (mechanical) limit should be at least __(a)__ percent greater than the rating value.

REQUIREMENT RATIONALE (A.4.10.7)

A limit is required to provide a margin of torque to prevent catastrophic component failure.

REQUIREMENT GUIDANCE (A.4.10.7)

The following should be used to tailor the specification paragraph:

(a): 20 percent

REQUIREMENT LESSONS LEARNED (A.4.10.7)

Past experience indicates that the engine output shaft torque can increase because of a malfunction or other anomalies. Some engine contractors have asked for a deviation. They felt they had a good control of output shaft torque and torque limits could be lower. Other systems (helicopters) with torque limits depend upon pilot action for limit observance.

A.5.10.7 Output shaft torque limits.

The requirements of 4.10.7 should be evaluated by analysis and test.

EVALUATION RATIONALE (A.5.10.7)

Evaluations by analysis and tests are needed to assure the engine will not be degraded by shaft torque operation up to the limit.

EVALUATION GUIDANCE (A.5.10.7)

Background:

The test can be conducted on the total engine or only on the effected component. The torque should be conducted for a minimum time of five minutes.

EVALUATION LESSONS LEARNED (A.5.10.7)

None.

A.4.10.8 Output shaft speed limits.

For turboprop and turboshaft engines the maximum allowable steady-state delivered shaft speed (mechanical) limit should be at least __(a)__ percent greater than the rating value. The shaft should be able to operate at this speed for at least __(b)__ and function satisfactorily thereafter. Following loss of load, the output shaft speed should not exceed the maximum shaft speed predicted with the engine at Intermediate power and the output shaft running at the maximum attainable rotor speed.

REQUIREMENT RATIONALE (A.4.10.8)

An output shaft speed limit is required to provide a margin of speed to prevent catastrophic failure.

REQUIREMENT GUIDANCE (A.4.10.8)

The following should be used to tailor the specification paragraph:

(a): A value of 15 percent, minimum.

(b): A value of 5 minutes, minimum.

REQUIREMENT LESSONS LEARNED (A.4.10.8)

Past experience indicates that the engine output shaft speed can increase because of a malfunction or other anomalies. Engine contractors have asked for a deviation on the speed requirement since they believe the newer control systems will prevent any overspeed.

A.5.10.8 Output shaft speed limits.

The requirements of 4.10.8 should be evaluated by analysis and test.

EVALUATION RATIONALE (A.5.10.8)

Evaluations by analyses and tests are needed to prevent catastrophic component failure.

EVALUATION GUIDANCE (A.5.10.8)

Background:

This test can be conducted in conjunction with the rotor overspeed test. The test should prove structure integrity and parts are not stressed to yield.

EVALUATION LESSONS LEARNED (A.5.10.8)

The evaluation was conducted by analysis or similarity on some engines in the past.

A.4.10.9 Pressure vessel/case.

All engine cases and pressure loaded parts and components should withstand the ultimate loading conditions defined in 4.10.1. The cases must remain intact, although permanent deformation and distress, requiring repair or replacement, is permitted. Engine cases should not fail due to combustion process burning or erosion.

REQUIREMENT RATIONALE (A.4.10.9)

Pressurized vessels, cases and components require internal and external load safety margins to preclude failure (e.g., burst and hazardous venting conditions). Also, pressurized vessels, cases, and components must be protected from degradation caused by combustion processes or erosion.

REQUIREMENT GUIDANCE (A.4.10.9)

The pressure vessels should be designed to meet the ultimate load capability of 2.0 times the maximum operating pressure plus 1.5 times the maneuver loads plus 1.5 times the thermal loads. The engine should withstand the combined affects of these loads without catastrophic failure.

REQUIREMENT LESSONS LEARNED (A.4.10.9)

Experience has shown that if a case is designed to a factor of safety of two, problems of rupture, LCF, and burn-through are reduced. The TF39 burner case was initially designed close to yield and exhibited problems in service due to LCF and burn-through. After the engine was redesigned to eliminate these problems, the factor of safety on rupture was checked and found to be approximately two. In the F101 program a factor of safety of two was mandated. During testing of this engine it was found to be capable of tolerating a burn-through without rupture. The F110 program required a factor of safety of two. Subsequently, the F110 has experienced several burn-throughs without rupture.

A.5.10.9 Pressure vessel/case.

The requirements of 4.10.9 should be evaluated by analyses and tests.

EVALUATION RATIONALE (A.5.10.9)

The engine pressure vessels and gas pressure loaded components must be capable of withstanding the combined operating ultimate loads without catastrophic failure to assure that the engine has been designed with appropriate safety margins, and that it can operate satisfactorily for the required design usage and service life.

EVALUATION GUIDANCE (A.5.10.9)

The engine contractor should provide an analysis of all pressure loaded parts and components. The analyses should show that all pressure loaded parts and components can meet the requirements of A.4.10.10 when constructed with minimum strength materials, as defined in A.4.6. The analyses should be substantiated/correlated with pressure vessel/case testing.

All pressure loaded parts and components should be tested to at least two times the maximum operating pressure in combination with the external ultimate loads based on the external loads encountered during engine operation. These tests should be conducted at the maximum allowable temperature or at a test pressure adjusted to account for the differences between operating and test temperatures.

The above tests are qualification tests to demonstrate that the design meets the strength requirements. It is also recommended that the production acceptance/quality control requirements include proof pressure test of each pressure loaded component to 1.33 - 1.50 times maximum operating load pressure. Proof tests of each article are required to screen detrimental porosity, crack/void, below blueprint tolerances or other detrimental anomalies that would reduce the life of the component.

EVALUATION LESSONS LEARNED (A.5.10.9)

None.

A.4.10.10 Pressure balance.

The engine thrust bearings should provide sufficient thrust load to ensure satisfactory bearing operation without skid damage during the design service life.

REQUIREMENT RATIONALE (A.4.10.10)

This loading requirement is necessary to assure against problems due to inadequate engine pressure balance design. Transient engine loads on output shaft components should be "taken-out" by engine structure.

REQUIREMENT GUIDANCE (A.4.10.10)

The contractor should assure that his practices for bearing design include requirements for pressure balance to assure that load and direction are adequate to achieve satisfactory bearing operation. The requirement is not intended to restrict the thrust load to any one direction or even any specific minimum magnitude, but rather to provide a pressure balance system which maintains bearing loads sufficient to assure adequate bearing life. It is necessary that under any steady-state operating condition a minimum thrust be maintained on the thrust bearing in order to prevent skidding. Standard design practices are to design the pressure balance system to provide the minimum required bearing thrust load at the worst (minimum load) steady-state condition and then check the highest thrust load on the bearing by adding the change in engine generated loads to this minimum load. If the thrust load is required to be unidirectional, the maximum bearing load will be greater than if the thrust load is allowed to pass through zero during some transient condition. Restricting the contractor to unidirectional loads could, therefore, result in shorter bearing lives than if bearings were allowed to be null loaded. Trade studies should be performed on sizing bearings to take unidirectional loads vs allowing crossover. Null loaded bearings can lead to rotor vibrational problems within the operating envelope which can lead to bearing failure or reduced life. If crossover is allowed to occur, the loss of loading on the bearing can result in transient rotor dynamic vibration. Transient rotor dynamic vibration in the operating range may result in pilot discomfort and distraction, and cause durability problems.

Engine/airframe system interactions can be excited by these types of vibration and cause similar problems. These interactions are typically difficult to predict and are usually not found until late in the integration effort.

REQUIREMENT LESSONS LEARNED (A.4.10.10)

None.

A.5.10.10 Pressure balance.

The requirement of 4.10.10 should be evaluated by analysis and test.

EVALUATION RATIONALE (A.5.10.10)

The engine pressure balance system must be evaluated to ensure compliance with the requirement of A.4.10.10.

EVALUATION GUIDANCE (A.5.10.10)

The engine contractor should provide an analysis of the engine pressure balance system. The analysis should show that loads imposed on the engine bearing(s) are of sufficient magnitude to assure adequate bearing operation without skid damage. The analysis should be substantiated/correlated with engine testing.

An engine should be suitably instrumented and tested to demonstrate that the loads imposed on the engine bearing(s) are of sufficient magnitude to assure adequate bearing operation without skid damage at all power settings throughout the engine operating envelope. This test should be conducted in an altitude test cell to simulate altitude and ram conditions representative of operational use.

EVALUATION LESSONS LEARNED (A.5.10.10)

None.

A.4.10.11 Gyroscopic moments.

The engine should meet all the requirements of the specification at maximum allowable steady-state engine speeds when subjected to the rotational velocities and accelerations within the flight envelope and the gyroscopic moment conditions.

REQUIREMENT RATIONALE (A.4.10.11)

Engine flight loads are increased due to rotations and accelerations that occur during aircraft rolling, pitching, and yawing maneuvers. The engine must be designed to resist these loads at the limiting conditions.

REQUIREMENT GUIDANCE (A.4.10.11)

The gyroscopic moment conditions should be as specified below:

a. A steady angular velocity of __(a)__ radians per second around any axis in a plane perpendicular to the rotor axis, combined with a ± 1g vertical maneuver load for a total of _(a)_ seconds.

b. A steady angular velocity of __(b)__ radians per second in any axis in a plane perpendicular to the rotor axis for a cyclic life of 10^7 cycles at all load factor conditions within the flight envelope.

The following should be used to tailor the specification paragraph:

(a): this requirement is principally a spin departure criteria requiring a high angular velocity for a short period of time. Angular velocities as high as 3.5 radians per second for fighter aircraft and 1.5 radians per second for bomber and cargo aircraft for 15 seconds are appropriate. For rotary wing aircraft, angular velocities of 2.5 radians per second for 30 seconds is appropriate. The 15-second and 30-second durations are considered to be cumulative exposure time.

(b): this requirement is principally a maximum angular velocity that may be experienced numerous times for long periods such as tight turns or numerous gust induced nacelle oscillations of a pylon mounted engine. For fighter aircraft this angular velocity value is approximately 1 radian per second in pitch or yaw. The angular velocity should be the vector sum of the angular velocities in pitch and yaw. Therefore, it is recommended that a steady angular velocity of 1.4 radians per second in any axis in a plane perpendicular to the rotor axis for a cyclic life of 10^7 cycles at all load factor conditions within the flight envelope. For rotary wing aircraft, a steady angular velocity of 0.9 radians per second in any axis in a plane perpendicular to the rotor axis for a cyclic life of 10^7 should be used.

Alternately, for rotary wing aircraft, use 0.4 radians per second for 24% of duty cycle life, 0.9 radians per second for 20% of duty cycle life, and 1.4 radians per second for 1% of duty cycle life.

REQUIREMENT LESSONS LEARNED (A.4.10.11)

A USAF study showed that a bearing load could be increased by as much as 15 times by a 3.5 rad/sec aircraft turn rate. The force on an individual rotor blade could be three times the magnitude of the corresponding aerodynamic force. Gyroscopic forces are cyclic in nature, thus tending to reduce the cyclic life of rotor blades. The vector sum of pitch and yaw rates is very important from the standpoint of the gyroscopic moments produced on the engine.

The fighter/attack aircraft and the lighter weight engines with tighter clearances will make the gyro requirement even more essential. Simulation data from an F4 aircraft produced yaw rates of less than 0.5 rad/sec and pitch rates less than 1 rad/sec. Intentional departure stall maneuvers have been used as a "last chance" evasive action against SAM's. This action results in high yaw rates and gyro loads. Yaw rates of 2.7 rad/sec were demonstrated years ago, in flight, during accelerated departure stall maneuvers, with the A-7 aircraft. Yaw rates of 3.1 and 3.2 rad/sec were measured on F-4 and F-15 aircraft. A recent mishap involving the F/A-18 aircraft was reported as yawing in excess of 200 degrees per second (3.5 rad/sec). The aircraft had violently departed controlled flight due to asymmetrical positioning of the leading edge flaps. Testing of the F109-GA-100 engine on the gyro rig showed significant mechanical interference occurring at 2 rad/sec. The manufacturer was able to correct the problem without major redesign.

A.5.10.11 Gyroscopic moments.

The requirements of 4.10.11 should be evaluated by analysis and test.

EVALUATION RATIONALE (A.5.10.11)

Aircraft are exposed to gyroscopic moments during normal operation and the ability of their engines to withstand those conditions must be evaluated.

EVALUATION GUIDANCE (A.5.10.11)

The following should be transferred verbatim into the specification paragraph: Prior to installation on the test stand, the engine should be assembled with special emphasis placed on measuring and recording clearances between blades and cases and radial and axial rotor clearances. Rub probes should be installed around compressor and turbine cases at symmetrical locations and at blade tip locations as designated in the pre-test data. Instrumentation should be sufficient to permit measurement of rotor deflection and shift under gyroscopic loads. Strain gage instrumentation should be provided to measure stresses at critical locations. Sufficient instrumentation of the oil system should be provided to evaluate the oil system's ability to scavenge and function properly during the test.

The engine should be operated with an inlet configuration and exhaust nozzle as specified in the pre-test data. Prior to the test, the engine should be subjected to a performance calibration.

The test should be conducted with the gyroscopic rig operated in incremental steps of 0.5 rad/sec from 0.5 rad/sec up to and including 3.5 rad/sec. At each step, the engine should be operated as follows:

a. Idle for one minute.

b. Accelerate from idle to maximum allowable rotor speed in 30 seconds.

c. Dwell at maximum allowable rotor speed 10 seconds or time sufficient to record data.

d. Decelerate from maximum allowable rotor speed to idle in 30 seconds.

e. Stop rig and engine for visual check of rub.

NOTE: At gyro loads above 1.5 rad/sec, snap accelerations and decelerations may be made to reduce time exposure. The total time at 3.5 rad/sec gyro load should not exceed the time specified in A.4.5.3.

The above test should be conducted with the gyroscopic rig rotating in one direction and then the test should be repeated with the rig rotating in the opposite direction. At the completion of the test, the engine should be subjected to a post-test performance calibration and then disassembled for inspection.

The test should be satisfactorily completed when, in the judgment of the Using Service: (1) The post test calibration reveals no significant loss in performance, (2) the engine and its systems operated properly during the test, (3) structural loads were within acceptable limits, and (4) teardown inspection reveals no evidence of excessive blade rubbing or evidence of impending failure.

The engine contractor should provide a gyroscopic moments analysis. As a minimum, the analysis should discuss engine mounts, bearings, and bearing support structure capability while exposed to the gyroscopic moment conditions specified in A.4.10.11. The analysis should be substantiated/correlated with a gyroscopic moment engine test.

EVALUATION LESSONS LEARNED (A.5.10.11)

None.

A.4.10.12 Main mounts.

The engine mounts should have adequate strength to retain the engine, including retained fluids and externals, at all flight, takeoff and landing, and ground conditions.

REQUIREMENT RATIONALE (A.4.10.12)

Engine mounts are necessary to attach the engine to the aircraft. Elastic limit and ultimate tensile strength load limits must be specified in order to ensure that both engine and aircraft designs are sufficiently strong for normal operations and safe for a limited range of crash landings throughout the specified service life. Mounts are required to have sufficient strength to protect the engine against a worst case single attachment point failure in order to ensure safety of flight (i.e., fuel fire and single engine loss of power) and ground safety (i.e., crashed engines or aircraft) (see LESSONS LEARNED). The number, locations, and descriptions of all engine mounts must be specified in order to ensure proper engine installation into the aircraft.

REQUIREMENT GUIDANCE (A.4.10.12)

The mounts should withstand elastic limit loads of (a) without permanent deformation and ultimate tensile strength loads of (b) without complete fracture. A total of (c) mounts should be provided which have sufficient strength to prevent (d) when subject to a single attachment point failure at any location at the end of the engine mount service life. The locations and descriptions of all engine mounts should be specified. The mount system should accommodate all off-axis loads when a thrust vectoring nozzle is used.

The following should be used for tailoring the paragraph except when the airframe's engine mounting requirements have been previously established:

(a), (b): The contractor should specify the maximum system limits in units of force and in reference to the engine. The specified values should include, but not be limited to, the effects of the following requirements and specific design characteristics: externally applied forces (i.e., accelerations) of A.4.5.3, gyroscopic moments of A.4.10.11, all airframe loads which are supported through the engine structure (if such loads exist) and safety factors of A.4.10.1, cyclic fatigue, engine mass, material strength/mechanics and service life. The contractor should specify the bending moment limits in the axial, vertical, and lateral directions. (NOTE: For competitive engine development programs the Using Service should ensure that the engine and aircraft specifications are compatible with the maximum loads of the worst case engine and airframe combination.)

(c): The Contractor should specify the number of mounts.

(d): The Using Service should specify that engine mounts have sufficient strength to prevent "a reduction in engine power and change in engine position" for single engine aircraft or "loss of engine retention" for multi-engine aircraft.

The contractor should specify the locations and description of engine mounts to ensure that both engine and aircraft are designed to a common goal. Redundant mounts should also be indicated on a figure.

NOTE: The Using Service should ensure that limited crash loading accelerations are specified and identified on the figures, so the contractor can specify ultimate load limits.

Background:

For engines which utilize thrust vectoring, the vector forces should be determined by the engine contractor. These forces will be based upon a particular engine/airframe combination. Because of the higher vertical loads imposed during thrust vectoring, it is essential that the engine mount system sustain the worst case load predictions that the aircraft would obtain. The engine mounting system must be suitable for the thrust vectoring nozzle arrangement and the mount system must be durable enough to withstand the various loads that will be imposed when the nozzle is vectored at selected angles.

Part 33 of the FAR requires that engine mounts have both elastic and ultimate strength integrity.

REQUIREMENT LESSONS LEARNED (A.4.10.12)

Engine mounts have failed in flight. The right engine (JT8-PW) on a Boeing 737-200 jetliner fell off shortly after takeoff from O'Hare International Airport on 20 January 1989 (Piedmont flight 1480). According to an eyewitness report, "There was a lot of smoke coming out of one engine, and we saw it leaning, almost falling off, and then it fell off..." (ref.: Washington Post, Jan 21, 1989). Similar incidents involving 737s were a Southwest Airlines flight leaving Dallas on January 3, 1986 and US Air flight leaving Philadelphia on December 5, 1987 (ref.: Washington Post, January 22, 1989).

The single attachment point guidance for multiple engine aircraft will likely result in two forward mounts and one aft mount, with an aft mount failure possibly resulting in partial engine separation (e.g., inelastic mount elongation) and engine shutdown. Guidance for single engine aircraft will likely result in a design with four mounts arranged in a rectangular or diamond shaped pattern, without loss of engine power or change in engine position (33 percent redundancy factor and stresses in the elastic range) after single attachment point failure.

A.5.10.12 Main mounts.

The requirements of 4.10.12 should be evaluated by analysis and test.

EVALUATION RATIONALE (A.5.10.12)

Elastic limit and ultimate tensile strength load limits must be evaluated in order to ensure that the engine is sufficiently strong for normal operations and safe for limited crash landings or single point attachment failures throughout the service life.

EVALUATION GUIDANCE (A.5.10.12)

To minimize cost prior to preflight qualification, engine mount requirements should be evaluated by analysis of the worst case engine mount failures and their consequences. Engine mount testing should be conducted after the completion of endurance test cycling and prior to production qualification. See A.4.10.12 Requirement Guidance for load criteria, which should be included in the evaluation.

Thrust vectoring nozzles impose new structural loads upon the engine and the airframe. These loads must be examined carefully by analysis of test data. Determination as to whether the mount system will withstand these new forces is a factor of mount system strength, durability, and mount system life considerations.

The engine mounting system must be suitable to the thrust vectoring nozzle arrangement and the mount system should be durable enough to withstand the various loads that will be imposed by directing the engine thrust at selected angles.

The load calculations done by the engine contractor during the design phase should be evaluated during sea level demonstrations and tests.

EVALUATION LESSONS LEARNED (A.5.10.12)

The most commonly known failure mode for the engine mounting system was metal fatigue of the mounting bolts.

A.4.10.13 Ground handling mounts.

The ground handling mounts should support the engine, including all engine mounted equipment and externals, components, and operating fluids, under the following maximum inertia load conditions, without deformation to the mounts or damage to the engine: (a) axial, (a) lateral, and (a) vertical acting in combination at the engine center of gravity.

The locations and descriptions for the individual ground handling mounts should be specified. The arrangement should be compatible with ground handling equipment specified herein by the Using Service.

REQUIREMENT RATIONALE (A.4.10.13)

Ground handling mounts are required to provide a means to lift the engine during the installation/removal from the aircraft and for ground transportation and maintenance.

REQUIREMENT GUIDANCE (A.4.10.13)

The following should be used for tailoring the specification paragraph:

(a): The Using Service should specify at least 4g axial, 2g lateral, and 3g vertical.

Background:

For more information on handling mount requirements, see AFGS-87233. The mounts should be designed to be compatible with existing engine transportation and maintenance equipment. Life cycle cost studies, in conjunction with operational requirement studies, should be conducted to determine if particular or existing engine handling equipment should be used.

If adapters are necessary, they should be designed and provided by the engine manufacturer as specified in the contract.

REQUIREMENT LESSONS LEARNED (A.4.10.13)

Ground handling mounts and related support equipment have not always been adequately designed and compatible. Engine damage has occurred due to engine support equipment not containing sufficient shock absorbing capability, thereby transmitting high "g" forces into the engine. Also, engine ground handling mounts have been damaged or have failed because the mounts are not adequately designed for the loads imposed during engine transportation, maintenance, and installation/removal from the air vehicle.

A.5.10.13 Ground handling mounts.

The requirements of 4.10.13 should be evaluated by analysis, demonstration, and test.

EVALUATION RATIONALE (A.5.10.13)

The intent of this paragraph is to evaluate that ground handling mounts provided on the engine are adequate for ground handling, transportation, and maintenance of the engine.

EVALUATION GUIDANCE (A.5.10.13)

The following should be transferred verbatim to the specification paragraph:

The following procedures should be demonstrated:

a. On-base ground transportation
b. Engine installation/removal from the air vehicle
c. Engine maintenance tasks
d. Other ground handling tasks peculiar to the engine.

Background:

Tests should be conducted to load levels sufficient to evaluate limit load and ultimate load operational requirements and to evaluate that minimum strength components can meet the load requirements assuming that the test components have average strength capability.

EVALUATION LESSONS LEARNED (A.5.10.13)

None.

A.4.10.14 Engine stiffness.

The estimated stiffness of the engine in resisting loads and moments applied at the outboard end of the output shaft, relative to the engine mounting points, should be specified herein. The first "free-free" lateral and vertical engine bending modes should be specified herein.

REQUIREMENT RATIONALE (A.4.10.14)

Aircraft maneuvers with turboprop/turboshaft engines cause large moments about the propeller shaft. This may increase propeller shaft and engine/gearbox case deflection thereby requiring better structural rigidity.

REQUIREMENT GUIDANCE (A.4.10.14)

Background:

Engine stiffness is the total deflection of the engine at the output shaft/propeller relative to airframe mounting points.

The loads should include, but not be limited to, the effects of externally applied forces, gyroscopic moments, safety factors, cyclic fatigue, material strength, and service life.

REQUIREMENT LESSONS LEARNED (A.4.10.14)

None.

A.5.10.14 Engine stiffness.

The requirements of 4.10.14 should be evaluated by analysis, demonstration, and test.

EVALUATION RATIONALE (A.5.10.14)

The test of the engine stiffness is required to ensure compatibility with the air vehicle.

EVALUATION GUIDANCE (A.5.10.14)

Background:

Engine stiffness should be evaluated prior to preflight qualification since the design may be impacted. See externally applied forces of A.5.5.3.

EVALUATION LESSONS LEARNED (A.5.10.14)

None.

A.4.11 Deterioration.

The engine should be capable of attaining the hot part design life when operating at temperature conditions representing a typical rate of performance deterioration. The temperature margin above the production acceptance engine maximum steady-state gas temperature under standard day conditions should be consistent with that required for the engine as stated in the engine specification for the design service life of 4.3.

REQUIREMENT RATIONALE (A.4.11)

Ability of engine hot parts to meet design life requirements can be significantly reduced due to engine uptrim or other conditions that result in hot gas stream temperatures higher than that of the production engine. Some margin above the normal maximum steady-state gas temperature should be used during design of engine hot parts to assure that design life goals or requirements will be met.

REQUIREMENT GUIDANCE (A.4.11)

AIA PC Project 338-2A members made a consensus recommendation in 1982, that the procuring activity not establish a specific temperature margin since this number will vary with engine type, application, and desired TBO. They pointed out that the main interest is that the engine achieve some minimum thrust or horsepower for a specified number of hours and that hot section parts be designed to account for the required temperature margin to achieve this objective. Recommended values for allowable thrust or power loss ranged from 0% (i.e., maintain rated thrust or power) to 5.0%. Individual recommendations for temperature allowances of 30°F to 70°F above the production acceptance engine maximum steady-state gas temperature were made. Based on the AIA consensus opinion, the operational requirement for deterioration has been derived as stated in A.4.11. It is recommended that the contractor specify in A.4.11 a usage interval equal to the hot part design life of A.4.3.1. The temperature allowance selected by the contractor based on his engine and experience should be called out in the ENSIP Master Plan.

REQUIREMENT LESSONS LEARNED (A.4.11)

None.

A.5.11 Deterioration.

Capability of engine components to attain hot section part life under deterioration conditions should be evaluated as follows:

A.5.11.a Analysis.

Analysis of LCF, creep, stress rupture, and erosion capability accounting for the required temperature margin above maximum steady-state gas temperature should be performed.

EVALUATION RATIONALE (A.5.11.a)

Early analysis that accounts for a margin above the maximum steady-state gas temperature will assure maximum probability in attaining desired structural performance of the full engine. Early analysis will also identify proposed design configurations that are marginal or unacceptable to this criteria so that design changes can be pursued.

EVALUATION GUIDANCE (A.5.11.a)

The contractor should include results of erosion, stress rupture and creep analysis during design reviews with the procuring activity. These results should also be included in the strength and life reports required by the contract.

EVALUATION LESSONS LEARNED (A.5.11.a)

None.

A.5.11.b Performance.

Component structural performance during conduct of the several engine tests should be verified.

EVALUATION RATIONALE (A.5.11.b)

Final evaluation of the capability of engine hot parts to meet design life requirements must be based on results of full engine tests. Such tests are required by this document.

EVALUATION GUIDANCE (A.5.11.b)

The contractor should identify those engine tests which will be used to evaluate the capability of engine hot parts to meet life requirements under deteriorated conditions. It is recommended that the AMT of A.5.9.1.2 be used for this evaluation. A.4.3.2 of this document will contain the life requirements for hot parts, A.4.11 of this document will state that 100% rated engine thrust be achieved at the end of one (1) hot section life, and it is anticipated that the Primary Specification will require that specific fuel consumption will not be greater than 105 percent of the rating point at the end of one (1) hot section life. In accordance with A.5.9.1.6 of this document, the criteria for successful completion of the AMT is that the engine complete the test duration with the engine and components operating satisfactorily and that post test calibration data reveal that the performance retention requirements have been met. Therefore, the AMT of A.5.9.1.2 is the prime engine test for evaluation that hot section life and deterioration requirements have been met.

It is also recommended that High Energy X-ray (HEX) be performed during full-scale engine testing to better understand component deformations, clearances, and other anomalies that affect performance and deterioration.

EVALUATION LESSONS LEARNED (A.5.11.b)

None.

A.4.12 Creep.

The engine static and rotating parts should not creep to the extent that acceptable field engine operation is impaired for the operating conditions and the lifetime specified in 4.3. Part creep should not affect disassembly and reassembly of the engine or new part replacement at overhaul throughout the specified life of the engine.

REQUIREMENT RATIONALE (A.4.12)

Component dimensional growth must be minimized on static and rotating parts to insure that acceptable engine operation is not impaired during service operation and that part replacement is not required.

REQUIREMENT GUIDANCE (A.4.12)

Design stresses should not exceed minimum value 0.2% creep strength allowables at the operating metal temperatures and time at temperature based on the design service life and design usage of A.4.3. The required useful life of cold parts and hot parts should be as specified in A.4.3.1 and A.4.3.2. Also, it is recommended that design stresses not exceed values associated with utilizing greater than 50% of the minimum stress rupture life during the design service life and design usage. Design extreme flight conditions and deteriorated conditions should be included in creep and stress rupture design analysis. Reasonable shop practices including minor machining or plating repairs is permissible to maintain build tolerances.

In the event that the above recommended guidelines cannot be met, the contractor should provide suggested design guidelines to the procuring activity for review and consideration.

REQUIREMENT LESSONS LEARNED (A.4.12)

None.

A.5.12 Creep.

Creep characteristics of the engine static and rotating parts should be verified per 5.12.a through 5.12.c.

A.5.12.a Analysis.

An analysis should be performed to demonstrate that sustained stress and temperature combinations should not result in detrimental permanent set/growth for the required design service life and design usage.

EVALUATION RATIONALE (A.5.12.a)

Early creep and stress rupture analysis during design is required to establish stress levels that will assure critical components can operate satisfactorily for the required design usage and service life.

EVALUATION GUIDANCE (A.5.12.a)

Analytical prediction of creep and component growth and percent stress rupture life, as a function of design life, should be accomplished on each creep critical component. Design operating stresses should be established based on past experience that indicates a high probability that satisfactory creep and stress rupture life can be achieved (e.g., 0.2% plastic creep life, 0.005 inch diametrical rim growth, 50% stress rupture life, etc.). It is recommended that component capability be established utilizing minimum creep strength and stress rupture material properties (e.g., -3 sigma). Initial creep and stress rupture analysis results should be presented to the procuring activity during the preliminary and critical design reviews.

EVALUATION LESSONS LEARNED (A.5.12.a)

None.

A.5.12.b Test.

A design development test plan and tests for creep evaluation should be developed and performed.

EVALUATION RATIONALE (A.5.12.b)

Early verification of creep and stress rupture capability through early development component tests can identify potential problem areas and avoid the need for redesign/qualification efforts later in full-scale development.

EVALUATION GUIDANCE (A.5.12.b)

It is recommended that component/specimen tests be conducted as early as possible on critical components (e.g., turbine disk rim lugs and turbine airfoils). The scope of development tests to evaluate creep and stress rupture should be identified in an appendix to this document or in the ENSIP Master Plan. Development tests may be waived where the contractor provides adequate, relevant experience.

EVALUATION LESSONS LEARNED (A.5.12.b)

None.

A.5.12.c Inspection.

Inspection and evaluation of components should be performed subsequent to conduct of the several engine tests required by this standard. These inspections should as a minimum be equivalent to the field and depot inspections.

EVALUATION RATIONALE (A.5.12.c)

Final evaluation of creep and stress rupture capability must include extended operation of the full engine. Several test engines will be run during full-scale development (e.g., operability, vibration and thermal surveys, accelerated mission tests, etc.) and inspection of critical components from these engines can verify that creep life is adequate.

EVALUATION GUIDANCE (A.5.12.c)

Inspection requirements for development test engines should include measurement of critical dimensions (e.g., snap and rim diameters, bolt circles, bores) prior to test and at each scheduled inspection interval. Evaluation of dimensional growth as a function of test time should be conducted and included as a part of the interpretation and evaluation of test results (see A.5.9.1.6). The scope of evaluation of critical component growths should be identified in an appendix to this document or in the ENSIP Master Plan.

EVALUATION LESSONS LEARNED (A.5.12.c)

None.

A.4.13 Vibration.

The engine, external controls, accessories, and hardware should be free of destructive vibration at all engine speeds and thrusts (including steady state and transient conditions) within the flight and ground envelope.

REQUIREMENT RATIONALE (A.4.13)

Safety and maintenance costs require that the engine be free of destructive vibration for the design service life and design usage. Vibration levels that may cause problems can occur in various segments of the engine-operating envelope so that the total flight envelope must be examined.

REQUIREMENT GUIDANCE (A.4.13)

Specific guidance for establishing vibrational design criteria is contained in 4.13.1 through 4.13.4 of this handbook.

REQUIREMENT LESSONS LEARNED (A.4.13)

None.

A.5.13 Vibration.

Vibration characteristics of the engine should be evaluated per 5.13.a through 5.13.c.

A.5.13.a Analysis.

Dynamic analysis should be performed to establish component vibrational mode shapes and frequencies. An analytical dynamic model of the engine and accessories should be performed to identify critical system modes, potential forcing functions and resonance conditions.

EVALUATION RATIONALE (A.5.13.a)

Analysis is required to establish system rigidity and to support system design so that large scale problems are not encountered later in the development phase.

EVALUATION GUIDANCE (A.5.13.a)

Analytical dynamic computer models should be developed to accomplish dynamic analysis of engine components and the assembled engine as a dynamical system. The models should be updated and verified throughout the development program as hardware and test information becomes available.

A dynamic model of the total engine system including rotor(s), bearings, frames, cases and engine supports should be developed to analyze maneuver loads and synchronous and nonsynchronous vibration responses. The model should include the effects of shear deformations, rotary inertia, multishaft gyroscopic influences, bearing speed effects on stiffness and damping, anisotropic bearing supports, and speed/frequency influences on supporting structural stiffness. Stiffness values used to represent flanges, spline, couplings, joints and tapered elements of the structure/rotor should be supported/verified by test. The model should be capable of handling unbalanced distributions resulting from bowed rotors or assembly of shaft components including residual unbalance plus angular or offset misalignments of these shaft sections. Vibration amplitudes, clearances, and bearing loads should be determined at each critical speed with the most adverse magnitude and phase relations of the unbalance associated with the critical speed mode shape. Parametric studies of design changes should be conducted to determine a way of altering any detrimental dynamic modes, which exist in the operating range. Results from the models will be used to guide unbalanced engine testing. The models will be updated and verified throughout the development of the engine as hardware and test information becomes available.

Dynamic models should also be developed for major engine components such as blades, vanes, bladed disk assemblies, seals, shafts, spacers, engine mounts, cases, and other components where high vibration can occur. The vibratory stress distribution and the various modes of vibration including complex modes should be obtained. Plots of excitation frequency vs. rotor speed showing the primary orders of excitation and the modes of vibration should be prepared (i.e., Campbell Diagrams). Plots of calculated steady stress and measured vibratory stress throughout the engine operating range should be prepared and compared to component/material capability (i.e., Goodman Diagrams). The analytical studies should be verified/correlated with data obtained from actual engine operation and component test.

EVALUATION LESSONS LEARNED (A.5.13.a)

None.

A.5.13.b Test.

A mechanical impedance static test plan and test should be developed and performed on accessories and plumbing when installed on the engine.

EVALUATION RATIONALE (A.5.13.b)

A resonance search test is required to verify/correlate with dynamic analysis and to uncover any large amplitude vibratory modes that could adversely affect safety and durability.

EVALUATION GUIDANCE (A.5.13.b)

The test engine should be excited by a shaker in mutually perpendicular planes throughout a frequency range sufficient to cover engine operation. Strobe lights and movable accelerometers should be utilized to determine maximum response locations. Resonance frequencies should be determined and compared with potential sources of excitation and with the analysis.

EVALUATION LESSONS LEARNED (A.5.13.b)

None.

A.5.13.c Engine test.

Instrumented engine tests should be performed to measure vibratory stresses and stability margins including flutter at critical points in the flight envelope. Rotor unbalance, off nominal guide vane schedules, aircraft inlet conditions, stalls, and expected distortions should be evaluated.

EVALUATION RATIONALE (A.5.13.c)

Evaluation of the dynamic response characteristics of the engine and critical components requires test evaluation due to the complexity of the variables involved.

EVALUATION GUIDANCE (A.5.13.c)

Instrumented engine tests will be conducted to evaluate the dynamic response of individual components and of the total engine system. Instrumentation should include accelerometers, strain gages, and proximity probes in the vertical and horizontal planes. Tests should be conducted as early as possible on a core engine to determine vibratory stresses and to investigate flutter boundaries. Subsequent tests should be conducted on the full engine. Ram conditions, aircraft inlet conditions, simulated fan distortion, compressor bleed and nonbleed, power extraction, off-nominal guide vane schedules, stalls, and other important variables should be simulated during each test as appropriate. Effects of rotor imbalance up to the maximum allowable should be evaluated.

A sufficient number of blades and vanes in each stage should be instrumented with strain gages to obtain continuous data and to determine worst case value of stress. Disks and other components subject to high vibratory stress should be instrumented. Strain gages should be mounted at locations of maximum stress as indicated by the analysis. Sufficient instrumentation should be installed at appropriate locations on main bearings to permit measurement of bearing loads, cage rotation, and rotor deflections. External components such as fuel controls, fuel pumps, valves, plumbing lines, etc., should be instrumented at appropriate locations with accelerometer vibration equipment. Inlet or exhaust systems and other components that are mounted directly on or supported by the engine in the aircraft installation should be mounted in the same manner for these tests. The tests should check all critical engine speeds where by analysis significant stress or vibratory conditions occur on each component. Vibration and stress measurements should be made during all engine operating modes and should include but not be limited to conditions of maximum inlet distortion, stall, limits of variable geometry travel if applicable, maximum compressor air bleed and power extraction, maximum inlet pressure and temperature capabilities of the engine and combinations thereof. The engine tests should include dwell time (10^7 cycles) at each of the critical speeds above idle where the response in the rotor system dynamic verification testing shows peak values. Overall true RMS velocity measurements and acceleration spectrograms should be obtained for each accelerometer mounted on the engine core and external accessory components.

Effects of rotor imbalance up to the maximum allowable amplitude should be evaluated. The rotor(s) should be unbalanced with the most adverse weight placement for the lowest critical speed and a phase angle predicted by analysis of residual unbalance. Magnitudes of total unbalance should be large enough to overcome typical residual unbalances to reach maximum levels found in similar engines prior to overhaul and to reach field vibration limits. The engine should be run through the operating range to maximum power. The procedures should be repeated for the other critical speeds below maximum speed if these critical speeds lead to maximum response at any point in the engine. Mode above and close to the maximum speed should be checked with the unbalance distribution required to excite these modes. If required, the phase of unbalance distributions will be changed to help determine residual unbalance.

Speeds at which response peaks occur will be correlated with computer model predictions. Measured and predicted amplitudes and clearances should agree when adjusted for residual unbalance. Model flexibilities and damping should be adjusted to obtain agreement between measured and predicted critical speed and response magnitudes.

Component bench tests should be conducted on blades and other components as appropriate to verify/correlate with the analysis and to establish material/component stress capabilities.

EVALUATION LESSONS LEARNED (A.5.13.c)

None.

A.4.13.1 Vibration limits.

Maximum engine mechanical vibration limits should be established as a function of frequency, engine order, and location and direction of measurement. Maximum engine mechanical vibration limits should be based on setting an acceptable margin of safety for the structural capability.

REQUIREMENT RATIONALE (A.4.13.1)

Rationally determined vibration limits can be a quality control tool in production and a maintenance guide for removing engines from operation. Initial vibration limits in design are needed to judge when redesigns or changes are warranted.

REQUIREMENT GUIDANCE (A.4.13.1)

4.13.1 should specify the maximum permissible engine vibration limits (overall velocity or displacement limit, true RMS) at each accelerometer location on the engine compressor and turbine cases, accessory gearbox case and, if applicable, internal structure. The overall velocity limit specified for each accelerometer should be applicable up to a frequency of 10,000 Hertz.

The limits should be specified for the engine in a test stand and for an installed engine. Vibration limits should also be specified for any pad locations for engine mounted accessories. Specified limits have historically been .006 inch double amplitude or less for the production engine installed in a test stand and a limit of 20 g's for pad locations. New or rebuilt engine acceptance limits should be less than the maximum to be used for field limits. Engine limits should be revised based on the total engine test experience to reach the optimum limits that will prevent frequent rejection of production engines or rejection of field engines prior to the desired service interval or life.

REQUIREMENT LESSONS LEARNED (A.4.13.1)

Bearing failure and structural failure problems have been greatly reduced with improved balancing procedures and tighter vibration limits.

A.5.13.1 Vibration limits.

Verification of vibration limits should be in accordance with 5.13.

EVALUATION RATIONALE (A.5.13.1)

See A.5.13

EVALUATION GUIDANCE (A.5.13.1)

See A.5.13

EVALUATION LESSONS LEARNED (A.5.13.1)

None.

A.4.13.2 Critical speeds.

Rotors should be free of detrimental resonance conditions at all speeds in the operating range. Any rotor critical speeds existing above or below the engine operating range should have a factor of safety established on speed to account for the variation in speeds for different operating conditions. Adequate damping and appropriate balancing should be provided so that any critical speed existing below maximum operating speed should be traversed safely with smooth engine operation. The variation in speeds based on operating conditions, etc. should be included. The natural frequencies of the mounting system with the engine installed should have a safety factor established for speeds below idle rotor speed(s) in all detrimental modes of vibration which can be excited by the residual rotor unbalances.

REQUIREMENT RATIONALE (A.4.13.2)

Resonance conditions should be avoided so that amplified response and structural failures do not occur. Margin is required between engine speeds and resonance speeds due to the variation that can occur in engine speeds due to mach number, deterioration or hot day conditions, or combinations thereof.

REQUIREMENT GUIDANCE (A.4.13.2)

It is recommended that a margin of at least 20% be specified for detrimental resonance conditions that exist above maximum operating speed or below idle speed. It is also recommended that a margin of at least 20% be specified between the mounting system resonance and idle speed.

REQUIREMENT LESSONS LEARNED (A.4.13.2)

None.

A.5.13.2 Critical speeds.

Verification of critical speeds should be in accordance with 5.13.

EVALUATION RATIONALE (A.5.13.2)

See A.5.13.

EVALUATION GUIDANCE (A.5.13.2)

See A.5.13.

EVALUATION LESSONS LEARNED (A.5.13.2)

None.

A.4.13.3 Blade, disk, and static structure vibration.

Blade, disk, and static structure natural frequencies should be such that detrimental resonance should not occur in the operating range.

REQUIREMENT RATIONALE (A.4.13.3)

Determining the frequency and relative amplitude of various sources (forcing functions) provides design information on frequencies to be avoided in components as well as information to determine fatigue resistance and vibration associated wear problems.

REQUIREMENT GUIDANCE (A.4.13.3)

Sources of forcing functions which can cause vibration and expected frequency spectra should be identified. Blades, vanes, and disks should be designed so that low order and known excitation orders (e.g., blade passing orders for vanes) are voided in the sustained power operating ranges (i.e., idle, cruise, and intermediate power). It is recommended that a 10% margin with worst tolerance on component resonance frequency be maintained. Proposed design changes should be fully evaluated for their effect and/or response to possible excitation orders.

REQUIREMENT LESSONS LEARNED (A.4.13.3)

Blade failures have been experienced on several occasions due to lack of margin between a resonance or critical condition and a sustained power operating condition.

A.5.13.3 Blade, disk, and static structure vibration.

Verification of blade, disk, and static structure vibration should be in accordance with 5.13, and should be evaluated by analyses and tests.

EVALUATION RATIONALE (A.5.13.3)

See A.5.13.

EVALUATION GUIDANCE (A.5.13.3)

See A.5.13.

EVALUATION LESSONS LEARNED (A.5.13.3)

None.

A.4.13.4 Surge and stall.

The engine should operate satisfactorily without structural degradation in the event of surges and stalls within the flight envelope.

REQUIREMENT RATIONALE (A.4.13.4)

Safety and maintenance considerations dictate that the engine must be tolerant to repeated off-base line occurrences of conditions such as surge and stall.

REQUIREMENT GUIDANCE (A.4.13.4)

The effect of surges and stalls should be considered in design in terms of frequency of occurrence, length of time involved, expected frequency, and magnitude of vibration stresses. The objective is to determine if surges and stalls can result in fatigue over the required life of the engine. Surges and stalls that occur during full-scale development flight testing and results of subsequent teardown inspections should be documented to demonstrate that the requirement is met.

REQUIREMENT LESSONS LEARNED (A.4.13.4)

None.

A.5.13.4 Surge and stall.

Verification of surge and stall should be in accordance with 5.13, and should be evaluated by analyses and tests.

EVALUATION RATIONALE (A.5.13.4)

See A.5.13.

EVALUATION GUIDANCE (A.5.13.4)

See A.5.13.

EVALUATION LESSONS LEARNED (A.5.13.4)

None.

A.4.14 Noise.

The engine should meet the strength and design service life requirements in the presence of the noise environment produced during installed and uninstalled operation at the flight and ground operating conditions consistent with the design usage conditions.

REQUIREMENT RATIONALE (A.4.14)

Maintenance and cost considerations require that the engine structure be resistant to sonic fatigue problems. Airframe/engine configuration and test facility acoustics can produce large effects in the acoustic noise levels and drastically affect the cracking characteristics of exhaust/nozzle components.

REQUIREMENT GUIDANCE (A.4.14)

Acoustic loads should be accounted for during design of exhaust/nozzle components such as stiffeners and fairings. Extra margin in terms of lowered stress levels and increased thickness should be provided where practical.

REQUIREMENT LESSONS LEARNED (A.4.14)

More attention to sources of loading and structural design and evaluation of structures subjected to acoustic fields is required. Exhaust/nozzle component problems have resulted in a significant maintenance burden on some past USAF engine systems.

A.5.14 Noise.

The capability of the engine to meet the strength and durability requirements in the presence of the noise environment generated during engine operation should be verified by test. Specific tests required by this document that will be used to demonstrate compliance with the noise requirement of 4.14 should be as follows: ______________.

EVALUATION RATIONALE (A.5.14)

Determining the magnitude of the various acoustic levels is required to assess adequacy of the design and to determine where design changes may be required. Inspection of engine structure during periodic intervals will allow determination if this operational requirement is met.

EVALUATION GUIDANCE (A.5.14)

Acoustic measurements should be made during operation in the test cell at various conditions. Analysis of the data should be made to estimate if pressure levels are of sufficient magnitude to cause structural cracking. Inspection of AMT engines of A.5.9.1.1 - A.5.9.1.4 should be used to verify resistance to component structural cracking.

EVALUATION LESSONS LEARNED (A.5.14)

None.

A.4.15 Foreign object/domestic object damage (FOD/DOD).

The engine should operate satisfactorily when foreign objects/domestic objects are ingested.

REQUIREMENT RATIONALE (A.4.15)

Engines frequently experience damage to fan blades and other airfoils due to foreign or domestic objects that enter the flow path. Examples are ice, gravel, sand, or nuts and bolts or other retaining mechanisms that come loose. Therefore, structures subject to this type of damage must be capable of operating to the next subsequent depot interval to avoid the requirement for immediate teardown when the damage is detected and determined to be within acceptable limits. Therefore, design criteria is required to establish capability of both fracture critical parts and durability critical parts to operate with damage present.

REQUIREMENT GUIDANCE (A.4.15)

It is recommended that the following requirement be contained in A.4.15.

The engine should be capable of operating for one (1) depot inspection interval after ingestion of foreign or domestic objects which produce damage equivalent to a minimum stress concentration factor (Kt) of 3 and damage equivalent to an initial crack of .030 inch surface length.

REQUIREMENT LESSONS LEARNED (A.4.15)

None.

A.5.15 Foreign object/domestic object damage (FOD/DOD).

Evaluation of the capability of the engine to meet the foreign object/domestic object damage requirements should be by analysis and test.

EVALUATION RATIONALE (A.5.15)

Analysis and tests are required to demonstrate that the fan and compressor airfoils can meet the operational requirement of 4.15 and to establish accept/reject criteria for damage that is detected during flight line inspections.

EVALUATION GUIDANCE (A.5.15)

It is recommended that LCF and residual life analysis be performed. A test engine should be subjected to a foreign object damage test to demonstrate compliance with A.4.15. Simulated foreign object damage should be applied to three (3) airfoils of the most critical stage of both the fan and compressor. The damage should be located at the most critical areas susceptible to foreign object/domestic object damage (i.e., at the most limiting vibratory threshold crack size location on the airfoil considering the combination of steady stresses and vibratory stresses that occur at each sustained power condition). The applied damage should produce a minimum stress concentration factor (Kt) of 3. The engine test should be conducted to an equivalent of two (2) depot inspection intervals simulating the design duty cycle of A.4.3. No calibration or recalibration should be required for this test. The test should be considered to be satisfactorily completed if no blade separations have occurred during the test.

Subject to approval of the procuring activity, the foreign object damage test may be conducted by bench testing or rig testing on full-scale fan or compressor components in lieu of complete engine testing. However, the bench or rig tests must meet the conditions, duration, and severity of testing equivalent to the engine test described above.

EVALUATION LESSONS LEARNED (A.5.15)

None.

A.4.16 Structural maintainability.

The engine should be economically maintainable for the design service life and design usage of 4.3. Engine components should fit and function with new components after being operated to the design service life and design usage of 4.3. The function of structural components, elements, and major bearing surfaces should not be degraded by wear, erosion, or corrosion to the extent that performance or structural capability should be impaired. Authorized repairs should be established for critical components that experience detrimental wear, erosion or corrosion during developmental testing and service operation. The structural life of repaired components specified by the contractor should be equal to or greater than the inspection intervals set forth in 4.8.4. Any repairs must be structurally sound and cost effective.

REQUIREMENT RATIONALE (A.4.16)

It is imperative that the engine and its components be designed to be repaired and maintained in the most cost effective manner possible. Salvage of the engine and its components from the deleterious effects of wear, corrosion, creep deformation, fatigue cracking, oxidation, erosion, and handling during operation must be accounted for in the basic design.

REQUIREMENT GUIDANCE (A.4.16)

Structural design of parts should be such that after one lifetime of use, they should fit and be functional with like new parts. Components should be designed with allowances for repair when possible and repair life should be defined and be at least capable of two planned depot maintenance period, e.g., coating systems.

Repairs should be established for typical modes of deterioration that can be expected to occur during extended operation and for deterioration observed during development testing. Examples of typical repair needs that should be developed are as follows:

Restoring snap diameters.

Blade-blending of FOD/DOD.

Blade-coating strip and recoat.

Removal of hole damage (oversize and bushing).

Restoring compressive surface stresses at areas of galling/fretting by shot peen.

REQUIREMENT LESSONS LEARNED (A.4.16)

None.

A.5.16 Structural maintainability.

Maintainability of the engine should be verified per 5.16.a and 5.16.b.

A.5.16.a Inspection.

Inspection and evaluation of changes in critical dimensions and finish of components after conduct of the several engine tests required by this standard. A maintainability assessment plan should be developed and implemented.

EVALUATION RATIONALE (A.5.16.a)

Maintainability is best assessed by evaluation of component condition after extended operation in the engine.

EVALUATION GUIDANCE (A.5.16.a)

Critical component dimensions should be measured before tests (during assembly) and after test, and the differences compared to analytical growth predictions. These components should be able to fit and function with parts.

EVALUATION LESSONS LEARNED (A.5.16.a)

None.

A.5.16.b Test.

Structural life of component repair procedures should be verified by test, as required.

EVALUATION RATIONALE (A.5.16.b)

Adequacy of repaired components is best assessed by component condition after extended operation in the engine.

EVALUATION GUIDANCE (A.5.16.b)

Repair should be evaluated by AMT tests for the desired, specified period of time.

EVALUATION LESSONS LEARNED (A.5.16.b)

None.

A.4.17 Inspectability.

Critical engine components should be inspectable by use of borescope ports and diagnostic methods so that detrimental damage or other deterioration should be detected to facilitate economical repair and to prevent engine failure. A table of the inspectable components and their methods of inspection should be specified.

REQUIREMENT RATIONALE (A.4.17)

Experience reveals that installed and uninstalled inspection capability for critical components in the assembled engine is tremendously vital to field level maintenance and service operations. The capability to inspect for FOD/DOD and hot section airfoil distress without engine disassembly has been extremely important in past service operations.

REQUIREMENT GUIDANCE (A.4.17)

Emphasis should be placed in design on attaining the maximum possible degree of inspectability. Provisions for inspection of the installed engine by borescope (or equivalent devices) should be made for the fan, compressor, combustor, and turbine sections of the engine. The goal is that each rotor and stator stage be inspectable. Inspection of the combustor and the turbine blades and vanes in the installed engine is required. A positive means of slowly rotating the rotor system(s) should be provided to facilitate borescope inspection. Radiographic inspection capability should be provided for the completely assembled engine. Location of the inspection provisions should assure part access and radiographic access for the installed engine. The contractor should define in an appendix to this standard or in the ENSIP Master Plan the design objectives for inspectability, the inspectable components, and the methods of inspection. Inspection provisions including access envelope should be shown on the engine configuration and envelope figure. The design objectives for inspectability should include special development of inspection methods if event development testing indicates a mode of deterioration or distress that is not inspectable in the installed engine.

Diagnostics in the form of blade metal temperature sensors (e.g., optical pyrometer), oil analysis methods, and bearing mounted accelerometers should be utilized during the development program to reduce risk of engine failure. The diagnostic capability of these sensors should be developed with the engine and should be designed into the engine; i.e., externally removable internal sensors. External vibration sensors location should be selected to maximize vibratory response from the engine.

Table XXI listing of the component and methods should be as follows:

TABLE XXI. Components and methods.

COMPONENT	INSPECTION METHOD	INSPECTION INTERVAL

REQUIREMENT LESSONS LEARNED (A.4.17)

Installed inspection capability for turbine stators (vanes) has historically not been provided since it requires some kind of traveling probe which is extremely difficult to develop. However, past experience has shown that when continued safe operation depends on installed inspection capability for a component (e.g., turbine vane), a strong design and development program often comes up with the inspection method. It is possible that, given more attention during design, inspection methods can be developed during initial design for static structures that are susceptible to deterioration (i.e., turbine nozzles and vanes).

Engine failures during development are very costly in terms of schedule and resources and every effort should be made to detect impending failure prior to loss of the test article. The use of diagnostics has been successful in eliminating development engine failures.

A.5.17 Inspectability.

The ability to accomplish inspection requirements established by 4.17 should be verified during conduct of the engine tests required by this standard.

EVALUATION RATIONALE (A.5.17)

Adequacy of inspection methods requires repeated application to the assembled engine.

EVALUATION GUIDANCE (A.5.17)

Each inspection method developed for the engine should be employed during routine inspections of development engines. Any deficiencies that are discovered should receive design attention as early as possible so that improvement can be made prior to engine flight operation.

EVALUATION LESSONS LEARNED (A.5.17)

None.

A.4.18 Engine/airframe structural compatibility.

The engine should meet the structural requirements of this document when installed in the airframe. The installed engine should operate satisfactorily in the thermal and aerodynamic environment produced by the engine/airframe configuration. The installed engine should possess flutter margin throughout the engine flight envelope.

REQUIREMENT RATIONALE (A.4.18)

The engine and airframe must be dynamically, functionally, structurally, and thermally compatible.

REQUIREMENT GUIDANCE (A.4.18)

An interface control document (ICD) between the engine and airframe contractors should be utilized to ensure functional and structural compatibility. Engine mounting should be such that critical engine clearances are not adversely affected under flight loadings. Aircraft flight and ground loads on the engine static and fatigue spectrum loading should be supplied in the ICD. These loads should include external airloading on the engine, if applicable. The engine contractor should supply to the airframe contractor inlet duct stall loads. The engine should be designed to withstand the distortion induced vibrational loads associated with the air vehicle inlet for all operational conditions. The engine/nacelle cooling should be designed so that installed engine temperature variations do not adversely affect engine critical clearances.

REQUIREMENT LESSONS LEARNED (A.4.18)

None.

A.5.18 Engine/airframe compatibility.

Engine/airframe compatibility should be verified by an instrumented engine test installed in the aircraft. The scope of these tests should be contained in the Interface Control Document.

EVALUATION RATIONALE (A.5.18)

Installed engine ground and flight testing is the only method to verify compatibility.

EVALUATION GUIDANCE (A.5.18)

It is recommended that the scope for these tests include fan stress survey, nacelle temperature survey, vibration survey of the aircraft mounting structure, controls, and accessories during rotor imbalance, and evaluation of clearances and deterioration. These tests should be integrated with the aircraft flight loads survey program to minimize aircraft/flight time test requirements. The flight survey should be conducted at all specified operating conditions, both engine and aircraft, within the aircraft flight operating envelope, including takeoff, transition, climb, descent, landing, altitude restarts, maximum yaw, and mission flight maneuvers. The investigation, where applicable, should explore engine stress conditions during maneuvers consistent with the mission of the aircraft, ordinance firing, thrust reverser operation, augmentation, and during any other unusual maneuver or mode of operation peculiar to a particular aircraft system which could have an effect on engine dynamic vibratory characteristics. Details of the instrumentation such as strain gauge locations, instrumentation ranges, responses, recorders, etc., should be set forth in the approved test plan.

EVALUATION LESSONS LEARNED (A.5.18)

None.

A.4.19 Component life management.

Required maintenance actions (component inspection, repair, or replacement requirements) should be defined to assure adequate structural integrity and operational readiness of each engine for the design service life. Required maintenance actions should be based on duty cycles defined by operational usage of the airframe/engine. Individual component maintenance times should be based on the parameter that causes life degradation.

REQUIREMENT RATIONALE (A.4.19)

Required structural maintenance actions must be defined so that the Air Force can maintain the structural integrity and operational readiness of the engine systems.

REQUIREMENT GUIDANCE (A.4.19)

Identification of the required structural maintenance actions should be based on the results of the analyses and tests required by this standard. Required actions should include component inspection, repair, or replacement needs. Detailed inspection requirements should be included relative to the component to be inspected, location(s) on component, inspection method, and inspection interval. Required actions will be initially defined based on verification tasks that utilize the design service life and design usage. The actions should be updated to reflect the results of verification tasks that utilize operational data as required by this standard. Finally, individual maintenance times should be based on the most significant parameter that influences life degradation (e.g., 0-max-0 throttle cycles, hot time, engine operating time).

It is recognized that only the initial structural maintenance plan per A.5.19.a will be completed as part of the full-scale engineering development (FSED) contract and that the requirement for an updated plan based on operational data and subsequent endurance test will be contracted tasks under follow-on Component Improvement Program (CIP). However, it will be an FSED requirement to develop programs to gather operational usage data and to establish an individual engine tracking program per A.5.19.b and A.5.19.c.

REQUIREMENT LESSONS LEARNED (A.4.19)

None.

A.5.19 Component life management.

Component life management should be defined and implemented by analysis, test, and recording of the operational usage of the engine as follows:

A.5.19.a Plan.

A structural maintenance plan should be prepared.

EVALUATION RATIONALE (A.5.19.a)

Required structural maintenance actions are generated from several analyses and tests conducted during development of the engine. It is necessary that the various actions be consolidated into a single plan for input to the overall engine maintenance plan. The information contained in this plan will also be used to support evaluation of the engine for production.

EVALUATION GUIDANCE (A.5.19.a)

The structural maintenance plan should be initially prepared to reflect the status of analyses and tests completed as part of full-scale development. Later the structural maintenance plan should be updated to reflect results of analysis and accelerated mission testing of the production configuration to a duty cycle utilizing operational data A.5.9.1.4. Additionally, the plan should be kept current to identify required structural maintenance actions for design changes that are incorporated in production.

EVALUATION LESSONS LEARNED (A.5.19.a)

None.

A.5.19.b Data recording.

Engine signals should be provided to the airframe data recording system to record parameters required to establish operational usage duty cycles for the engine. The data recording system should record the following parameters: _____________.

EVALUATION RATIONALE (A.5.19.b)

Usage and engine parameters critical to structural limits must be monitored during aircraft/engine operations so that the design duty cycle required by 5.3 can be updated. The updated duty cycle is then used in analyses and tests to define engine structural characteristics and maintenance actions. The intent is to record continuous time histories of multiple parameters on a percentage of operational engines so that a statistically based definition of mission profiles and usage can be established.

EVALUATION GUIDANCE (A.5.19.b)

The recording system should be capable of monitoring mission profile parameters such as rotor revolutions per minute (RPM), power level angle, engine inlet temperature, and turbine temperature. Small interval sampling of the measured parameters is needed so that frequency distributions can be established (e.g., power lever angle (PLA) level, intermediate and idle dwell time, ground operation time, acceleration/deceleration rates, etc.). The number and selection of airframes and engines requiring recorders should be established so that sufficient data is available within three (3) years after initial operational capability to validate operational usage. Significant factors to be considered in the analysis include planned flying rate, airframe/engine production rate, and number of bases.

EVALUATION LESSONS LEARNED (A.5.19.b)

None.

A.5.19.c Counter.

Each engine should contain a counter which should record parameter events that control the structural limits of engine components. The counter should record the following events: ___________.

EVALUATION RATIONALE (A.5.19.c)

The intent is to place a simple, highly reliable counter on each engine that will record occurrences of parameter events that dominate the rate at which structural life is consumed (e.g., 0-intermediate/max-0 cycles, idle-intermediate/max-idle cycles, hot time, etc.). Experience has shown that these events can vary significantly between individual engines and that accrual of damaging events must be tracked at the component level to establish when maintenance actions are required.

EVALUATION GUIDANCE (A.5.19.c)

As a minimum, the engine counter should record (1) engine operating time, (2) time at or above intermediate power, (3) number of 0-max/intermediate-0 throttle events, and (4) number of idle-max/intermediate-idle throttle events. The capability to record other types of throttle events should be provided in the event the usage sensitivity study shows these events significantly affect life consumption. Consideration should be given to locating the recording device to minimize exposure to thermal and vibration environment.

EVALUATION LESSONS LEARNED (A.5.19.c)

None.

A.5.19.d Tracking program.

A critical component tracking program plan should be established. This system should define the analysis procedures, serialization, data collection, and computer programs necessary to establish maintenance times of individual components based on accrual of parameter events.

EVALUATION RATIONALE (A.5.19.d)

A tracking system is needed to establish individual engine and component maintenance times. The rates at which equivalent 0-max-0 throttle cycles and hot time are accrued will vary significantly depending on such variables as base of operation and mission type. For efficient management of life limited components, accrual of events that dominate the rate of life consumption must be tracked at the component level.

EVALUATION GUIDANCE (A.5.19d)

The tracking system must have the following features: (1) a simple, reliable device that records damaging events, (2) a data retrieval system that provides for transcribing the recorded data from the engine and recorder and transmittal of the data to a central computational facility, (3) computer software programs that provide a summation of the number of damaging events for each component based on damage analysis equations and recorded data, (4) a serialization procedure for entering components into the tracking system, (5) a procedure for recalling engines, modules or components when individual structural limits have been attained, and (6) a procedure for identification of components that have received required maintenance actions.

EVALUATION LESSONS LEARNED (A.5.19d)

None.

A.40. Data requirements.

When this handbook is used in an acquisition which incorporates a DD form 1423, Contract Data Requirements List (CDRL), data requirements substantially like those identified below should be specified by a newly created or an approved Data Item Description (DD Form 1664) and delivered in accordance with the approved CDRL incorporated into the contract. When the provisions of DAR 7104.9(n)(2) are invoked and the DD Form 1423 is not used, data such as that specified below should be delivered by the contractor in accordance with the contract or purchase order requirements. Depending upon those requirements actually specified in the acquisition documents, deliverable data might be required from the following paragraphs:

PARAGRAPH NO.	APPLICABLE DATA REQUIREMENT TITLE	DID NUMBER	OPTION
4.2 and 5.2	ENSIP Master Plan		
5.3	Design Usage (Design Duty Cycle)		
5.3.1	Engine Hot Parts Analysis and Test Plan		
5.6	Material Characterization Plan		
5.8	Damage Tolerance Control Plan		
5.8	Damage Tolerance Analysis		
5.9	Durability		
5.9.1	Low Cycle Fatigue (LCF) Life Test and Analysis		
5.9.1.1**	Accelerated Mission Test (AMT)		
5.9.2	High Cycle Fatigue (HCF) Life		
5.9.4	Corrosion Prevention and Control Plan		
5.10	Strength (Structural analysis and part, component, and engine tests)		
5.10.3	Containment Analysis		
5.12	Creep Analysis and Design Development Test Plan		
5.13.a	Dynamic Analysis of Engine Summary		
5.13.b	Mechanical Impedance Test Plan		
5.15	FOD/DOD Analysis and Test Plan		
5.16	Maintainability Assessment Plan		
5.19.a	Structural Maintenance Plan		
5.19.d	Component Tracking Program Plan		

Custodians:
Army – AV
Navy – AS
Air Force – 11

Preparing Activity:
Air Force – 11

Project No. 15GP-F110

STANDARDIZATION DOCUMENT IMPROVEMENT PROPOSAL

INSTRUCTIONS

2. The preparing activity must complete blocks 1, 2, 3, and 8. In block 1, both the document number and revision letter should be given.
2. The submitter of this form must complete blocks 4, 5, 6, and 7.
2. The preparing activity must provide a reply within 30 days from receipt of the form.

NOTE: This form may not be used to request copies f documents, nor to request waivers, or clarification of requirements on current contracts. Comments submitted on this form do not constitute or imply authorization to waiver any portion of the referenced document(s) or to amend contractual requirements.

I RECOMMEND A CHANGE:	2. DOCUMENT NUMBER MIL-HDBK-1783A	2. DOCUMENT DATE (YYMMDD) 990322

3. DOCUMENT TITLE
Engine Structural Integrity Program (ENSIP)

4. NATURE OF CHANGE (Identify paragraph number and include proposed rewrite, if possible. Attach extra sheets as needed.)

5. REASON FOR RECOMMENDATION

6. SUBMITTER

a. NAME (Last, Middle Initial)	b. ORGANIZATION	
c. ADDRESS (include Zip Code)	d. TELEPHONE (Include Area Code (1) Commercial (2) AUTOVON *(If applicable)*	e. DATE SUBMITTED *(YYMMDD)*

8. PREPARING ACTIVITY

a. NAME ASC/ENSI (AF-11)	b. TELEPHONE (Include Area Code (1) Commercial (937)255-6281	(2) AUTOVON 785-6281
c. ADDRESS *(Include Zip Code)* BLDG 560 2530 LOOP ROAD W WRIGHT-PATTERSON AFB OH 45433-7101	IF YOU DO NOT RECEIVE A REPLY WITHIN 45 DAYS, CONTACT: Defense Quality and Standardization Office 5203 Leesburg Pike, Suite 1403, Falls Church, VA 22041-3466 Telephone (703) 756-2340 AUTOVON 289-2340	