June 22, 2021

Mr. Timothy R. Adams
Acting Executive Director, Office of Rulemaking
Designated Federal Official, Aviation Rulemaking Advisory Committee
Federal Aviation Administration
800 Independence Avenue, SW
Washington, DC 20591

Via email: Timothy.R.Adams@faa.gov and 9-awa-arac@faa.gov

RE: Engine Harmonization Working Group – Revised Final Recommendation Report; 150 Hour Alternate Endurance Test, 14 CFR 33.87

Dear Mr. Adams:

On June 17, 2021, the Aviation Rulemaking Advisory Committee ("ARAC") voted unanimously to accept the revised Recommendation Report ("Report"), submitted by the Engine Harmonization Working Group ("EHWG") on 150 Hour Alternate Endurance Test. The Report was originally accepted by ARAC on December 14, 2017, and subsequently accepted by the FAA by letter dated April 23, 2018. On March 12, 2020, FAA sent ARAC a letter requesting clarification on certain issues. The EHWG was re-established by ARAC specifically to respond to the FAA's letter.

On behalf of ARAC, I would like to thank Mr. Peter Turyk, EHWG Chair and its members for their dedication to the work, its detailed responses and for revising the original report, especially given the challenges of meeting in a virtual environment. We greatly appreciate your commitment and support to ensure the recommendations are clear and the FAA's questions were addressed.

On behalf of the ARAC members, please accept the EHWG's Revised Recommendation Report and submit to the relevant program offices for consideration and implementation. Please do not hesitate to contact me with any questions. Thank you very much.

Sincerely yours,

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Keith Morgan, TAE Chair: keith.morgan@prattwhitney.com
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AVIATION RULE MAKING ADVISORY COMMITTEE (ARAC)

Alternate Test to 14CFR33.87 Endurance Test Revision A

EHWG task from Federal Register Vol.79, #14 Jan 22nd 2014

ARAC working group members – see Appendix A.

3/31/2021

REVISION INDEX

REV LTR.	PAGE	PARAGRAPH	DESCRIPTION	DATE
---			Original Issue	31 January 2017
A	11	2.7	Added Section 2.7 to provide information regarding additional work and rationale for report revision	31 March 2021
	42	6.2 2nd para	Reference to Section 6.3 for clarity	
	43	6.3 last para	Changed reference from “CPA” to “severity comparison” for clarification of the objectives of the CPA and severity comparison	
	43	6.3.2 2nd para	Clarification regarding creep as primary damage mechanism and considerations for other damage mechanisms	
	44	6.3.2	Added paragraph	
	44	6.3.3.1 2nd para	Revisions to clarify roles of CPA and severity assessment. Added reference to Appendix K.	
	45	6.3.3.3 last para	Revised wording for clarity	
	46	6.4.1 1st para	Revised wording for clarity	
	51	7.2.5	Added reference to Appendix K.	
	74	11.4.1	Replaced acronym “TDI” with “teardown inspection”	
	130	12	Added Section 12	
	143	13	Added Section 13 (Appendix K)	

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1 Executive summary

This report provides an alternate approach to the current 150 hour Endurance test, commonly known as the "Block Test", required by 14CFR33.87.

The alternate test is recommended as an optional alternative to the current test. This is because, as written in the 1950s, the current rule's prescriptively defined test profile and sequence cannot be completed on a modern design test vehicle (engine) without significant test enabling and survivability modifications, which take the test vehicle out of type design configuration. These changes must be reconciled by the applicant to the regulatory agencies. Thus the test as prescribed today, does not truly test the type design which will enter revenue service once type certification is approved.

Both industry and regulatory bodies from North America and Europe participated over a 3 year period to define an alternate test which is compatible with modern technology gas turbine engines, such that they may be tested to evaluate their ability to withstand an accelerated severity demonstration in their type design configuration.

This alternate test demonstration is achieved by evaluating, via a Critical Point Analysis (CPA) of the product's design and intended use (operating envelope); and defining a hybrid, prescriptive and performance based severity test for the engine. This tests the engine type design to its limiting speeds and temperatures (redlines) for Type Certificate Limits. Further, the proposed test evaluates the engine's capability to successfully complete running in close proximity to minimum speed and temperature margins (close to redlines) as expected in service whilst still operating at a severity level consistent with the intent of today's 14CFR33.87 prescriptive test.

Key facets of today's prescriptive test requirements, such as bleed level, fuel and oil pressure demonstrations are retained, as is the requirement for pre and post-test performance characterizations per 14CFR33.85 and teardown inspections per 14CFR33.93.

The proposed test will run more hours and contain more cyclic content than today's prescribed test schedule. It will, by analysis and evaluation of field failures, provide a severe test of the engine's capability as intended by the current test and provide results which are more representative of responses to threats characteristic of revenue service extremes seen in today's engines in revenue service.

At the conclusion of this task, there were no dissenting opinions submitted for inclusion in the report.

2 Introduction

2.1 Purpose

The FAA assigned the Aviation Rulemaking Advisory Committee (ARAC) a new task to review the existing engine endurance test requirement per 14CFR33.87, assess its suitability for all turbine engines, and consider an alternate endurance test and associated methods of compliance.

This report details a proposal for an alternate endurance test that will satisfy the constraints of modern High Bypass Ratio (HBPR) engines and provides analysis and explanation to support the need for such a change to the engine certification requirements in accordance with the tasking from the FAA.

2.2 Rationale for the ARAC task

The engine "endurance" test currently prescribed in 14CFR33.87 for turbine engines is defined in AC33.87-1A paragraph 3-1.a as an accelerated severity test intended to demonstrate an acceptable level of engine operability and durability within the approved engine ratings and operating limitations. The AC clarifies that the test is not intended to simulate the expected in-service operation. Significant proportions of the test are run to maximum physical speed and gas path temperature operating conditions that are then declared as the operating limitations to be noted on the Engine Type Certificate Data Sheet (ETCDS). At the time the test conditions were set in the requirements, they were emulating the way reciprocating and gas turbine engines of the era were operated, such as setting take-off power to limits. In those single shaft turbojet engines, achieving combined red line physical speed and temperature was possible with minimal engine adjustment or modifications in a static air breathing test i.e. sea level static conditions.

The endurance test requirement has remained essentially unchanged since 1957 when the current 25 x 6 hour format was implemented, but engine designs have evolved significantly. As engine technology has evolved to yield a more efficient, economical, reliable and environmentally friendly product it has become increasingly difficult to demonstrate the limiting conditions required for modern service operation in the simplified way prescribed by the endurance test requirement. Certification experience shows that substantial modifications are needed taking the test vehicle out of type design configuration and greatly affecting the engine operating cycle in combination with the running the test out of the rule defined sequence.

This evolution of engine technology and required modifications to run the currently prescribed test leads to conflict with the intent to run a test vehicle that "substantially conforms to type design". The degree of modifications required for recent advanced technology designs has raised significant concerns as to whether:

1) the modifications invalidate the intent to demonstrate type design capability
2) the reconciliation of the required modifications can be sufficiently validated, and
3) the test requirements defined by the current rule require modifications to the test vehicle that are not incorporated in the type design for service operation.

As a result, the FAA requested ARAC to review the existing endurance test requirement, assess its suitability for all turbine engines, and consider an alternate endurance test and associated methods of compliance.

2.3 Summary of Proposal

The committee has defined a proposed alternate engine endurance test that is a hybrid of performance and prescriptive based content and meets the original severity intent of the test in 14CFR33.87, and meets the working group's determination of the effect of the rule on operational safety (see Section 2.2), while allowing the test vehicle to be run in its type design configuration. The proposed alternate test content is as follows:

a) Periods of appropriate length, as identified by an applicant's critical point analysis (CPA, see Section 6.2) are to be run at various limiting (redline) maximum takeoff (MTO) and maximum continuous (MCT) physical speeds and temperatures (ETCDS declared values) to prove that the engine as a system can operate to those limits. Some limited modification may be required in order that the engine can attain these conditions. There is no requirement for concurrency of these (limiting) conditions as long as the design can be shown to not run to concurrent redlines anywhere in its declared operating envelope.
b) A number of cycles are to be run to MTO and/or MCT conditions where the measured flow path temperature will be dictated by what is necessary under test day conditions to achieve the maximum component metal temperatures of the life critical turbine component(s) that can be reached in service and the physical speeds that the engine can attain at the test day conditions in the type design configuration. These temperatures may or may not be equivalent to the ETCDS required EGT temperatures and the conditions must be defined by the applicant's CPA and agreed to by the administrator. At typical test day conditions, the engine will be substantially over-boosted (higher OPR and/or thrust than ETCDS thrust rating) to achieve these conditions.
c) The number of cycles and consequent time at MTO and MCT conditions to be completed will demonstrate a severity (life usage) benchmarked to the original intent of the current rule based on creep usage of the life critical turbine component(s) as a function of time on condition, component temperature and physical speed (stress) running concurrently at the proposed ETCDS limits (see Section 4 and Appendices B and D). The minimum number of cycles (rapid acceleration from idle to maximum power and rapid deceleration back to idle) to be run will be, at a minimum, the same as the current test but in reality the alternate test will typically have to complete more cycles and more time on condition to achieve the required severity demonstration.
d) Existing test requirements for ancillary running (bleed, hot oil, starts etc.) are copied over as close as possible to be the same as the existing test.

2.4 Background

An Industry working group under the auspices of the AIA and ASD was established in 2013, to validate the need for a rule change for the Endurance Test. The aim of the group was to define an alternate test to the one prescribed in CS-E 740, 14CFR33.87 & AWM 533.87, that is more relevant to today's high technology gas turbine engines and their mode of operation and could be conducted on a type design bill of material.

The objective was to offer an alternate test that would provide a certificated product that meets the original intent of the current endurance test rule in an equivalent or enhanced manner. Any new or alternate, test may or may not be run in conjunction with the IMI test (ref. 14CFR33.90, for which there is no EASA requirement) and ETOPS test (ref. 14CFR33.201, CS-E1040). This study was limited to multiple-shaft, high bypass (subsonic) airplane turbofan engines and is applicable to all high bypass designs regardless of thrust class. While this study might also be of interest to high technology turboshaft and turboprop engines, there was insufficient industry interest at this time to assess whether the proposal being developed might be directly applicable or modified for application to these engines, therefore the study focus was limited to high bypass turbofan designs.

The proposed alternate developed in the AIA/ASD Study was to conduct a cyclic test based on a profile that has proven effective in replicating field deterioration on an accelerated basis with creep equivalence to the current rule intent. This test was intended to be conducted on a type design bill of material engine. See Appendix C for a detailed description of the AIA/ASD proposal.

In response to the AIA/ASD proposal, the FAA, EASA and TCCA recognized that the current endurance test does not adequately address the technological advances found in modern engines, but did not feel that the proposal sufficiently fulfilled the regulatory intent. Consequently, the FAA assigned the Aviation Rulemaking Advisory Committee (ARAC) a new task to review the existing engine endurance test requirement per 14CFR33.87, assess its suitability for all turbine engines, and consider an alternate endurance test and associated methods of compliance.

2.5 ARAC Tasking

The FAA assigned the Aviation Rulemaking Advisory Committee (ARAC) a task to review and assess the standards and advisory material for 14CFR33.87, engine endurance test requirements, and identify all the issues with running modern architecture engines to the current rule.

ARAC accepted the task and assigned the Engine Harmonization Working Group (EHWG) the task identified in the Federal Register Vol. 79, No. 14, January 22, 2014, to develop an alternate endurance as follows:

1. Develop an alternate endurance test that would allow an engine to be tested in the configuration representative of its type design, and
    a. Maintain compliance with the intent, as well as the basic elements currently in 14CFR33.87, including the ratings, operating limitations, and engine configuration.
    b. The alternate test is to be equivalent to the test currently in 14CFR33.87 with regards to demonstrating engine operability and durability, and is validated with engine data. The engine data must include experience, certification, and additional component and engine tests.
    c. If modifications of the engine from its type design are required, they need to be reconciled.
    d. The alternate test proposal must address all facets of today's endurance test (oil, fuel parameters, bleeds, starts).
2. Develop and document recommended:
    a. Methods of compliance, and
    b. Rule changes, if considered necessary.

   c. *Identify other 14CFR33 tests that may support the objective and definition of the alternate test, e.g. IMI, ETOPS, Vibration, Overspeed, Overtemperature tests. If any are identified, explain how they support the objectives of the endurance test.*
   d. *Determine how validated analysis may be used as an integral part of the alternate test and the limitations related to the use of that analysis.*
3. Review the current foreign requirements for engine endurance test and determine the need for harmonizing any new methodologies.
4. Provide initial qualitative and quantitative estimates of costs and benefits for any new methodologies.
5. Develop a report containing the recommendations for rulemaking or guidance material, or both, and explain the rationale and safety benefits for each proposed change.
6. The working group may be reinstated to assist the ARAC by responding to the FAA's questions or concerns after the recommendation report has been submitted. The final ARAC recommendation report should include a summary of the overall work scope, conclusions, and rationale for all recommendations related to the above tasks. It should document both majority and minority positions on the findings, and the rationale for each position and reasons for any disagreement. Any disagreements should be documented, including the rationale for each position and the reasons for the disagreement. (At the conclusion of this task, there were no dissenting opinions submitted for inclusion in the report.)

Note: sub-bullets in italics were added to clarify industry understanding of the FAA intent when the WG developed the Endurance Test work plan (goals, objectives and expectations) at the first meeting on April 8th 2014

2.6 ARAC Task Schedule

The original Federal Register announcement called for the recommendation report to be submitted to the FAA for review and acceptance no later than December 31, 2015.

The EHWG was organized comprising nominees from industry and regulators (Appendix A). Once the group's membership was set, its initial meeting was held on April 8th & 9th 2014 at the FAA offices in Burlington, MA, USA.

At this initial meeting, the EHWG defined a Work Plan that was designed to meet the Tasking objectives and schedule for delivering a report to ARAC by December 2015.

To support achievement of the milestones, a schedule of quarterly meetings was established, supplemented with teleconferences approximately every 2 weeks.

However, after the team had been meeting for a year and evaluated an initial alternate test proposal, the engine OEMs found they would be unable to perform that initial alternate test as prescribed without engine modifications. In some cases the required deviations from type design would have been similar to those required for today's "triple redline" test. Further, consensus had not been reached regarding how to show that the alternate test was equivalent to the intent of the test currently in 14CFR33.87 with regards to demonstrating engine operability and durability.

To address the shortcomings of the first attempted alternate, the team felt an increase in scope was needed in order to investigate further alternates and determine whether one could be designed that would not require the engine to undergo significant non-type modifications. To accommodate the increased work to define such a test and determine how to quantify equivalence, TAE allowed 18 months' additional time for completion of the report by extending the report deadline to the 2nd quarter of 2017.

2.7 Report Clarification Task

After submission of the original report to the TAE on 31 January 2017 and review by TAE, ARAC and FAA, the FAA responded in March 2020 by requesting clarification for some of the aspects of the report, specifically in reference to the severity assessment and use of the T_{metal} method for defining an alternate test. The Working Group was reconvened to provide the requested clarification. The result was a minor revision to the original report, and details of the Working Group's response to the FAA letter are contained in Sections 12 and Appendix K (Section 13).

3 Intent of the Current Rule

3.1 Rule Summary and Intent

The test as currently prescribed has 25 x 6hr cycles (as shown in Figure 3.1 below). All MTO and MCT running has to be at a minimum of redline (limiting) physical speeds and gas path temperatures. The rule was revised in 1974, to allow running two double redline tests on one set of engine hardware, but this was shown to be impractical because the hardware would have to run the test twice.

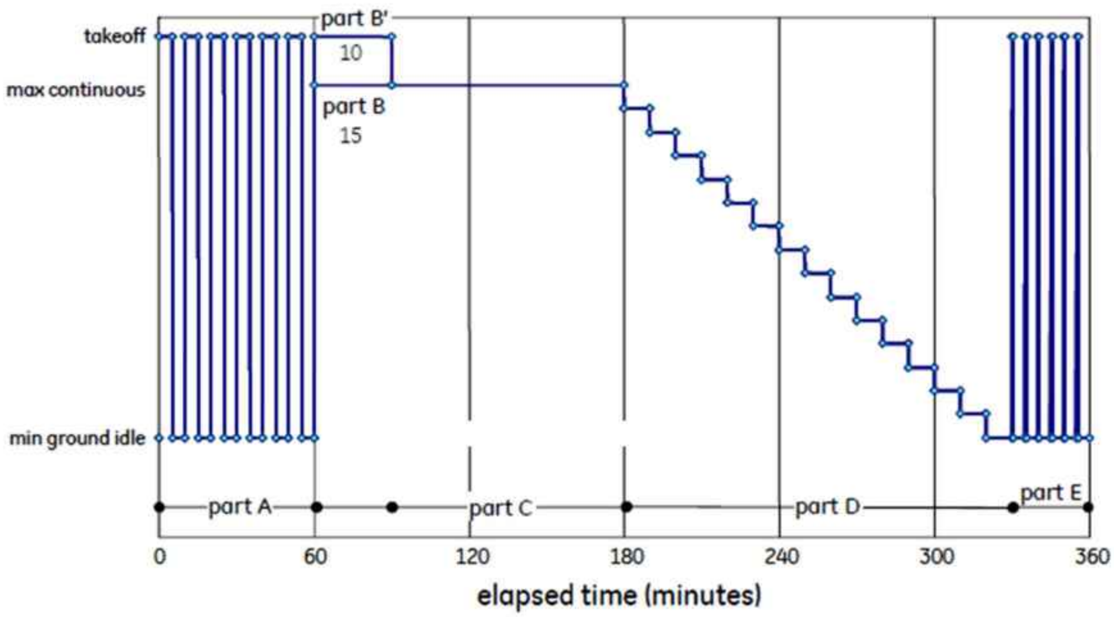


Figure 3.1: the 14CFR33.87 6hr block to be repeated 25 times introduced in 1957

In addition the prescribed test for turbofan & turbojet engines requires demonstration of the following:

- Maximum customer bleed required for 20% of the cycles
- Maximum oil temperature is required for steady state periods in excess of 5 minutes (Exemption can be claimed if the type design does not stabilize within the prescribed stabilization times and applies to both gas path and oil temp. Ref 33.87(a)(7) and AC33.87-1A, 3/9/15, page 14.)
- At least one run must be made with fuel, oil, and hydraulic fluid at the minimum pressure limit and at least one run must be made with fuel, oil, and hydraulic fluid at the maximum pressure limit
- Transient throttle movements are one second or less
- Minimum of 100 starts, with prescribed number (25) of starts preceded by a minimum two (2) hour shutdown time, ten (10) false starts and ten (10) starts within fifteen (15) minutes of a shutdown

Following the completion of the test the engine must be capable of reaching rated thrust at SLS conditions within its declared operating limits per 14CFR33.85. Additionally, following completion of the endurance test, the engine must be disassembled to piece part level and shown to conform to its type design, its parts being capable of reinstallation after inspection and assessment against the Instructions For Continued Airworthiness per 14CFR33.93.

The original endurance test intent has been traced from its genesis in the late 1920s under the Department of Commerce Aeronautics Branch, through its refinements in the 1930s as CAR 13.201, subsequent amendment in 1952 adding CAR 13.254 when turbine engines were first addressed, then updating 13.254 in 1957 by adding the current prescriptive test cycle, through conversion to 14CFR33.87 and as later amended through 14CFR33.87 Amdt. 33-32 in April 2012. A detailed chronological history of the rule as it has developed over time is provided in Appendix B.

The original CAR "intent" for turbines was to demonstrate by test, on a type design bill of materials for the engine, the following:

- Minimum thrust ratings (with no unacceptable thrust loss during test)
- Maximum operating limitations for various key integrity related parameters (including Redlines)
- Minimum level of operability (free from surge/stall and makes thrust/torque/power throughout the test)
- Minimum level of durability (taking into account engine operation levels in the proximity of the operating limitations, to be substantiated by successful test completion, post test calibration demonstration, and detailed post-test teardown inspection)

3.2 Inferred Safety Effect of the Test

The working group was not able to find any pre-existing regulatory or advisory material regarding a safety assessment associated with 14CFR33.87. Following is the working group's agreed understanding of the effect on operational safety:

> *To demonstrate that a new engine design will not exhibit unacceptable effects in service such as significant performance deterioration, operability restrictions, or failures modes, when operated for sustained periods within and up to the limits of the operating envelope.*
>
> *Such effects include minor effects that may present an unacceptable risk of multiple engine power loss or non-availability to an aircraft, in addition to major or hazardous effects (as per the definitions in 33.75).*

It was considered that defining the regulatory intent, and by inference the effects on operational safety, supports the alternate test proposal by identifying the value-added by testing a type design vehicle over a longer period, thus potentially exposing a wider range of failure modes or other effects while still maintaining an accelerated demonstration of durability at extreme conditions.

4 The Rule Relative to Modern Architecture

4.1 Regulators' Acceptance of the Need for an Alternate Test

Although the Regulators did not fully agree with the content of the specific test proposed by AIA/ASD, the work did provided data to the regulators demonstrating that, in order to achieve the original intent of the test for a modern engine in its type design configuration, a new alternate test is needed. The key reasons are given in the following subsections of this part of the report. In summary these are:

a) The design principles of modern engines have changed substantially since the 1950s. The architecture, technology and demands for margin from the airframe manufacturers, have made the current test impossible to achieve as prescribed. Operating characteristics and servicing philosophies have also evolved since the 1950s resulting in significant changes to the primary causes for engine failures and service removals. In particular, increased operating margin requirements added by airframers, inclusion of aircraft thrust management systems with derate operation options, and introduction of advanced cooled turbine technology have all helped shift the servicing philosophy from hard life turbine removals at 100s of hrs. in operation and high numbers of creep failures (the fundamental target of the current test) to soft lives based on condition monitoring. Today, the majority of removals for modern engines are for lack of temperature margin or removal of critical parts that have reached life limits. In addition, the regulatory agencies have added other "endurance" tests (e.g. IMI and ETOPS) that provide a much better indication of real service issues and lives. (section 4.2)
b) The current test forces the test vehicle to be run in a condition (concurrent redlines with substantial over thrust/ boost on a new engine) that it is not designed to achieve (exceeds thrust management program control limits) and will never operate at in service. (section 4.3)
c) In order to complete the test as currently prescribed the test vehicle has to be substantially modified from its type design bill of material with both "enabling" and "survivability" modifications being made to achieve the test conditions and to compensate for the negative impact on the cooling air circuits of both the over-boost of the engine operation and the changes made to achieve redlines (section 4.4).
d) The test as prescribed in the 1950s was run to a maximum EGT (gas path temperature) as the redline or limiting condition for conducting the test. This was a surrogate for limiting turbine component metal temperatures as the turbine metal temperatures are not directly measured in turbine engines as they are on the reciprocating engines (cylinder head and cooling jacket) from which the rule was derived. This was a reasonable and technically logical approach for the uncooled turbine technology of the day, as there was a 1:1 correlation between gas path and component metal temperatures; however, this is no longer the case for modern film cooled and thermal barrier coated turbine hardware. (section 4.5).
e) Service operation shows that very few flights ever cause an engine to reach a single redline (the most likely occurrence is to approach EGT redline with a fully deteriorated engine) and a thorough search of field service data by the WG was

unable to find any reports of multiple redline events on a modern high bypass ratio turbofan engine design. In this respect, if it can be shown that an engine is designed to not incur concurrent redlines, then the requirement to demonstrate redlines concurrently is deemed as overly severe and not a sound technical requirement, therefore it would be technically appropriate instead to demonstrate individual redlines and most likely most extreme combinations that the design might incur within the declared operating envelope (section 4.6)

f) Historical data shows that close to half of all failures occurring in the current test are turbine related, but less than 6% of service failures are turbine related, further highlighting the disparity between service experience and test induced failures where many of the test events are due to issues caused by over-boosting or modifying the engine to achieve or survive the test conditions in a non- type-design bill of material. This demonstrates that the current test is overly severe for the turbines and produces test failures that are not representative of field service experience (section 4.7).

4.2 Engine Technology Evolution

Since the current endurance test was conceived and prescribed, there have been a substantial number of changes in technology, operational characteristics, and failure/wear-out modes that have never been considered with respect to the appropriateness of this test including:

- Engine design evolution from single shaft to two and three shaft engines has resulted in maximum physical speed and temperature limiting conditions occurring at different points in the flight envelope and/or life of an engine. (e.g. max physical fan speed now typically occurs at top of climb whilst max physical core speed occurs at lower altitudes during high power, hot day temperatures takeoff).
- Hydro-mechanical controls have been replaced with full authority electronic controls and aircraft thrust management systems. This ensures that the pilot cannot command the engine to exceed the set thrust for the day conditions and flight regime, i.e. the pilot cannot over-boost the engine.
- Uncooled turbine components have been upgraded to film cooled components (meaning that the turbine component temperatures are no longer in direct proportion to the gas path temperature, instead their temperatures have become significantly more influenced by cooling air temperatures and flows)
- Hard lifed turbines with fixed overhaul intervals at a few 100s of hours have been replaced by on condition engine maintenance, with removals based on observed conditions with respect to the ICAs, leading to typical removals between high 1000s to 10000s of hrs.
- A shift in the limiting failure mode from creep has evolved to other modes due to engine operating characteristics, hardware design and material advancements. In the 1950s, the most limiting failure mode was creep, so it made sense for this to be the philosophical target of the 150 hour test at that time. With technology advancements, creep is no longer the primary life limiting failure mode, thus the test needs to evolve and provide a better balanced scope of appropriate challenges.
- Additional engine tests demonstrating endurance have been added to the 14CFR33 regulations. The IMI test was introduced in 1974 (14CFR33.90) as the current 33.87 endurance test was no longer found to be an indicator of in service life or endurance capability and could not be used to establish in-service overhaul intervals. (The details are given in appendix B, section 11.2.7)

- Advancements in Analytical and modelling tools provide greater understanding of engine operating conditions
- Improvements in measurement capability have been incorporated throughout engine development testing and in engines in service, providing greater understanding of engine operating conditions, as well as providing data for correlation and validation of analytical tools and Critical Point Analyses (CPAs)
- Evolving advancements in materials (capability and consistency) and materials knowledge (data) are applied to new engine programs to improve engine reliability, durability, and safety

Today's engine design cycles include statistically-based margins for setting physical speed and temperature redlines that are established to accommodate the most extreme operating conditions (e.g. hot day, high altitude, takeoff and MCT corner points, etc.), even though they are rarely encountered. This built-in design protection, especially when combined with today's health monitoring practices, minimizes the potential for redline encounters in service. Yet the existing prescribed test schedule, requiring significant demonstration of concurrent redline operation, continues to be used to evaluate failure and wear-out modes, despite the recognition that the prescribed conditions are associated with operating characteristics of legacy engine designs and have not evolved in concert with advances in engine technologies.

4.3 Issues Running the Current Test with Modern Engine Architectures

There are two fundamental ways in which the currently prescribed test forces a disproportionately increased level of severity on engines with higher operating ratios (bypass and compressor pressure) and cooled combustion and turbine components:

1. The various redline (limiting) physical speeds and gas path temperatures on a modern engine cycle do not occur at concurrent operating conditions yet the test prescribes concurrency; (see Fig 4.1)
2. The redline (limiting temperature) gas path temperature prescribed in the test is not directly proportional to the limiting component operating temperatures when secondary cooling is applied via domestic parasitic bleeds.

The current endurance test forces applicants to operate the test vehicle to achieve all redlines simultaneously regardless of actual test day conditions, which is contrary to the design intent and the way engines are power-managed for in service operation. Figure 4.1 identifies where the closest conditions to each redline occurs in service (note: the green line represents low altitude, red mid, and blue high altitude).

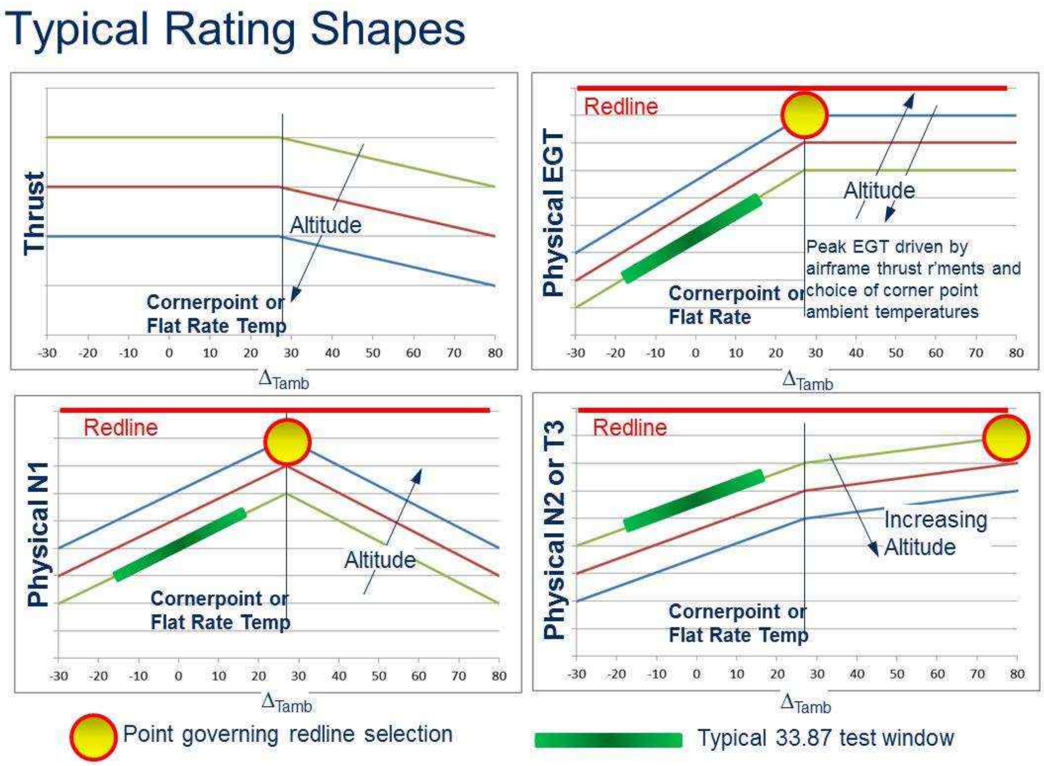


Figure 4.1 – rating shapes and maximum operating conditions

The operating pinch points (locations in the flight envelope where margins to individual redlines are at a minimum) are a function of the engine design (optimized for long/short haul, bypass ratio, growth margin, etc.) and are specific to the engine/airplane installed operating regime. While no two engine designs are expected to have the same pinch point locations, there are general conditions where redlines may typically occur. Figure 4.8 further illustrates the locations where individual pinch points typically occur in the operating envelope. Figures 4.9 - 4.16 in section 4.6 demonstrates where typical modern HBPR engines operate relative to redlines in typical service operation.

In forcing the type design engine to operate outside the power-managed operating envelope, the engine thermodynamic cycle balance is driven beyond type design operating parameters. The magnitude of departure is dependent upon ambient temperature and the special accommodations (“enabling modifications” made to the specific test engine design and operation) necessary to achieve the prescribed test conditions. For example, by forcing the engine to operate at redline mechanical (physical) speeds at sea level static conditions, rotor corrected speeds, and thrust are driven beyond type design levels, and associated internal flows will no longer be at type design levels, with potentially severe impact on cooled components. Operation with the enabling modifications at minimum physical idle speeds may drop corrected speeds and associated flows below design levels. To counter these test-induced problems, additional modifications of various hardware and systems are often necessary to accommodate the off-design thermodynamic effects. These “survivability modifications” that are added to counter undesired effects from the “enabling modifications” must then be reconciled using analytical techniques to show that the net sum does not adversely affect the conclusions about the type design engine that are intended to be drawn from the test.

To achieve redline conditions, the engine under test in the standard nacelle configuration at the prevailing (typical) SLS (ISA) conditions has to be over-boosted significantly (up to approximately 20%) at the start of the test.

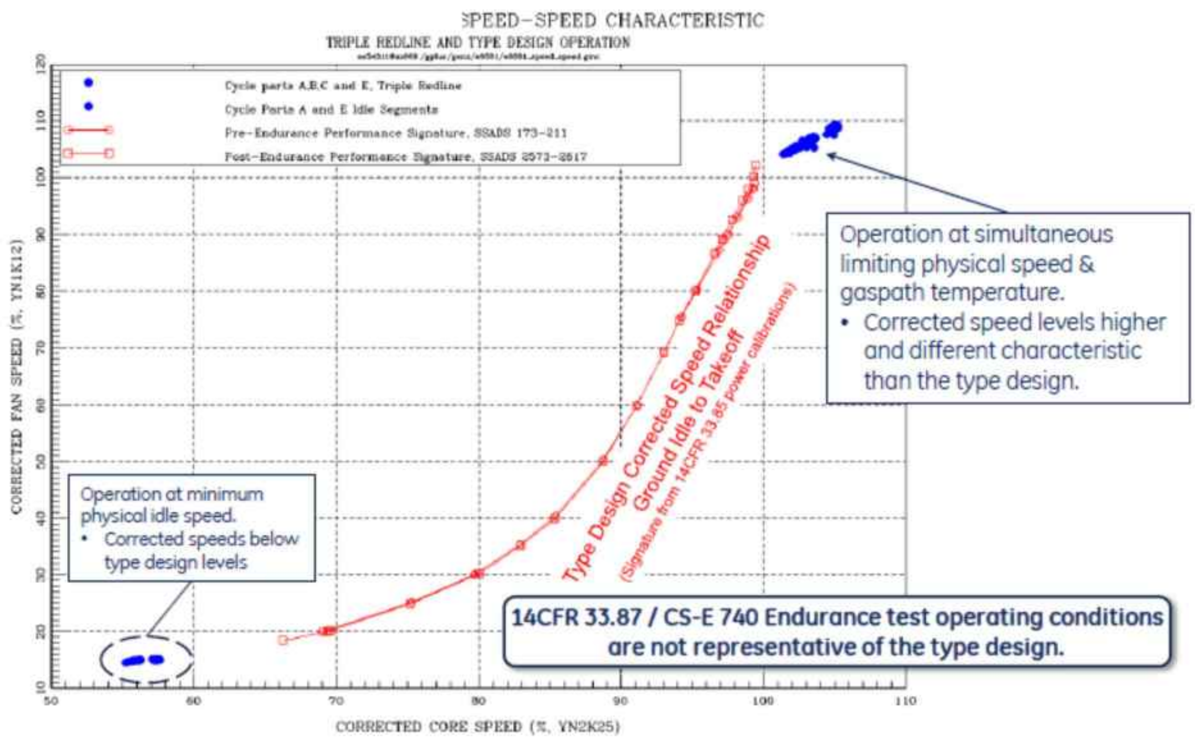


Figure 4.2 – non dimensional operation is in excess of in service envelope

Figure 4.2 shows an example of corrected fan speed vs corrected core speed for normal operation from idle to takeoff power. The blue data shown on the plot illustrates that operation to the physical redline speed limits as required for the prescribed triple redline condition, takes the engine to corrected speeds beyond takeoff power and to minimum conditions with physical speed below normal SLS operation (extent depends on the engine control laws, ambient test day conditions, and enabling modifications).

As the test engine deteriorates, further re-matching actions need to be taken to maintain the limiting conditions. Depending upon test facility configuration (fan IGV or open primary nozzle as an example), at a fixed turbine temperature, thrust and physical fan speed drop and physical core speed falls as the engine deteriorates, these natural effects of deterioration must be countered during the test to maintain the prescribed conditions. At the end of the test the engine still typically over-boosts/thrusts by more than 10-15% in standard nacelle configuration at the limiting turbine temperature.

Figure 4.3 shows an example plot of compressor efficiency vs core corrected speed. The compressor is sized for peak efficiency and near peak efficiency at key operating conditions. Operation at Double or Triple redline forces the compressor beyond the normal (type design intent) operating regime for sea level operation resulting in poor efficiency, lower cooling circuit source pressures and elevated compressor inter-stage and discharge (cooling flow) temperatures. The impact of this drives turbine cooling effectiveness well below type design intent.

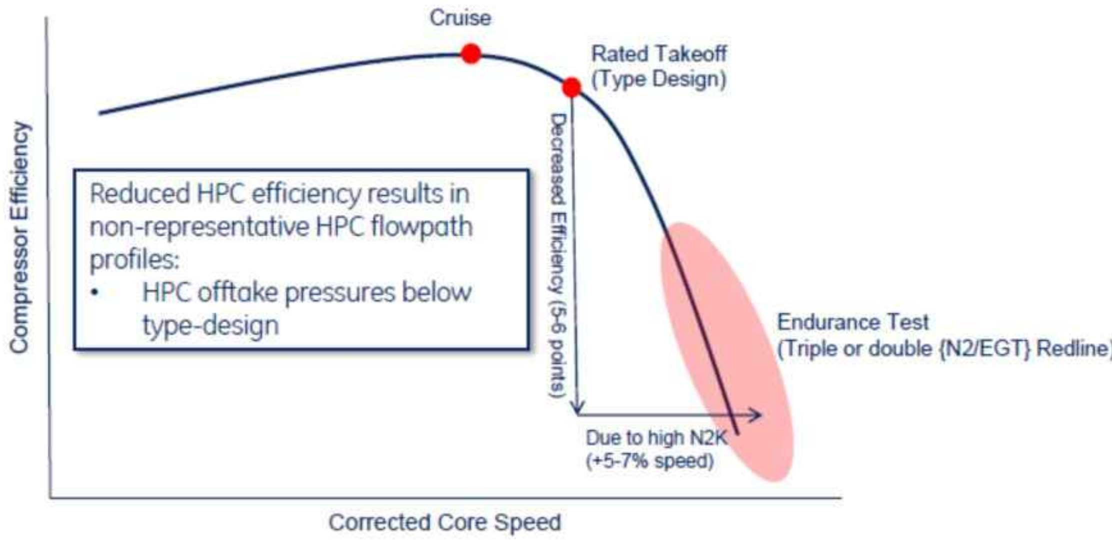


Figure 4.3 – Compressor forced to operate inefficiently well off in-service design point

Figure 4.4 illustrates this detrimental impact on turbine cooling flows and the consequent effect of turbine metal temperatures. Note in figure 4.4 that "point 1" illustrates the most extreme deteriorated service condition and combined with most extreme environment, and that the blue lines to the left of point 1 represent service operation within the declared operating envelope and range of acceptable deterioration conditions.

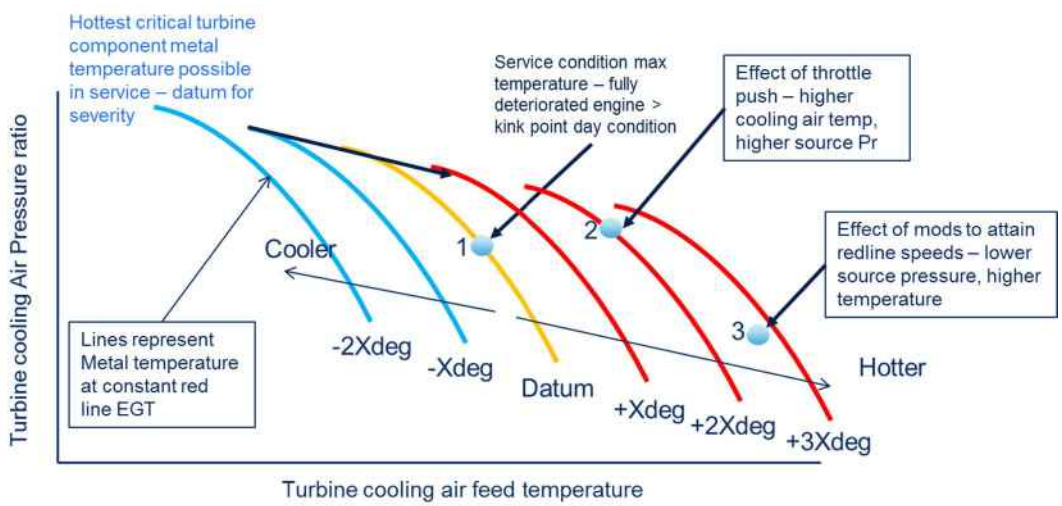


Figure 4.4 – Test condition suppresses cooling air effectiveness and increases turbine component temperatures at an EGT

This thermal cycle imbalance as created by the current test, typically leads to unrepresentatively high turbine metal temperatures resulting in a creep usage rate (and potentially other modes of damage) far beyond that which would occur in type design configuration operation within the declared operating envelope. (The mechanism for this is explained in report section 4.5.) This unrealistic creep exposure threatens the engine's ability to pass the test and forces in many cases, the need for survivability modifications (also explained in section 4.5). In addition, the disc rim cooling air flows are compromised and taken outside the service design intent. During the test, turbine deterioration drives flows further down, so parts of the prescribed cycle order are changed (called blocking by EASA) to maintain representative flows for each part of the test as much as possible.

4.4 Deviations from Type Design Are Required To Run the Current Prescriptive Test

For a modern HBPR engine to complete the currently prescribed 150 hour endurance test, engine components have to be specifically designed to meet test operating conditions in a combination that by design intent will not occur in service.

While it may be argued that the concurrency requirements for modern engines may be related to how limits are independently displayed in the cockpit (flight crew has no indication that they should not occur simultaneously), this does not constitute a sound technical reason to force the engine to be run to concurrent redlines. The engine manufacturers participating in this study have shown that current and foreseeable high technology engine designs do not approach concurrent redlines (see section 4.5) anywhere in the operating envelope, particularly not at sea level static (where the endurance test is typically run), unless there is a fault in the engine. Therefore taking the test vehicle out of type design configuration and operating it off schedule, so that it can be forced to demonstrate operation at concurrent limits at sea level static conditions, does not constitute a sound engineering approach to demonstrate accelerated severity capability for a new engine design.

Testing a modern HBPR engine to the current endurance test requires:

- Substantially over boosting/ thrusting, which forces the test vehicle to operate to a thermodynamic cycle unrepresentative of type design, and hence what is possible in service
- Specific modification of components to achieve test conditions (enabling modifications) and/or cope with the consequences of running off service design conditions (survival modifications) take the test vehicle out of type design
- Modifications to the control system operation to allow limit condition combinations that cannot happen in service or cannot be met without exceeding test vehicle thrust limits take the test vehicle out of type design
- Use of abnormal variable vane scheduling and taking bleed to adjust inter-stage work splits in order to increase physical speeds and/or gas path temperatures take the test vehicle out of type design
- Cumbersome requirements for unique test facility hardware, such as a fan inlet guide vane, contribute to operation outside the type design cycle and may also introduce potential for facility equipment anomalies and/or failures that are not associated with the type design
- Modifications to 14CFR25 hardware (use of slave and/or facility hardware that is not aerodynamically representative of type design) to be compatible with unique test facility and test vehicle hardware take the test vehicle out of type design
- Allowing a different test sequence than the one specified in the regulation deviates from test intent in order to accommodate deterioration effects that will not allow certain conditions to be achieved at the end of the test

- Significant applicant and regulator resources are required to develop the accommodating modifications necessary to conduct the test as prescribed and to resolve or mitigate the resulting uncertainties introduced.
- It is difficult to develop a reconciliation that is acceptable to the regulator for all test specific changes to type design hardware and controls.

This test is intended to show engines are sufficiently durable and thereby implied as safe for entry into service. With the increasing complexity in modern engines and with correlation data from only one 33.87 endurance test in this test-specific configuration, it is becoming increasingly difficult to validate the assessments and assumptions used to justify all modifications from a type design configured engine.

4.5 Relationship Between EGT and Turbine Component Metal Temperatures

When the 33.87 test was created from the original reciprocating engine rule and throughout its evolution into its current form for turbine engines, EGT was set as the key limiting temperature parameter for the test. At that time, airfoils were typically manufactured from simple wrought or forged materials of more variable manufacturing process capability and tolerances than exist today. They were also uncooled or in a few cases had limited internal ventilation flow. At that time, the metal temperature of gas path components had a proportional relationship to the local gas path temperature. Therefore gas path temperature (i.e., EGT) for turbine component temperatures.

As materials and cooling technologies evolved, the direct proportionality between EGT and turbine components (especially hottest stage airfoils) changed significantly. The ability to convective cool internal features and film cool external features, enabled by highly sophisticated and controlled casting capability, and thermal barrier coatings have allowed engines to run to higher EGTs without increasing blade metal temperature. This makes the engine substantially more efficient without imposing a proportional increase to the temperatures of the airfoils in the gas path and provides for acceptable hot section component life between overhauls. Turbine operating temperatures have also been allowed to increase because of new materials technology. The result is that turbine components can operate in gas path temperatures several hundred degrees above the melting point of the materials they are made from. The component's bulk and surface temperatures, not the gas path temperature, causes the damage potentially leading to a component's failure. Figure 4.5 below shows the rough order of magnitude effect of the gas path temperature and the cooling air temperature on the bulk metal temperature of turbine components.

Air temperature effect on turbine airfoil metal temperatures

Aerofoil cooling design regime	Typical gas path metal temp proportional effect	Typical cooling air metal temp proportional effect
uncooled	100%	0%
ventilated	>95%	<5%
Internal cooling	75-85%	15-25%
Film cooling	50-60%	40-50%
Film cooling + thermal barrier coating	35-45%	55-65%

Figure 4.5 – proportionality of turbine component temperatures to cooling and gas path air temperatures

In service, the Max EGT (redline) on a production engine (the EGT critical pinch point condition) occurs at the following typical conditions as shown by the green star in figs 4.6a and b below:

1. The engine is operated in a deteriorated state, with no de-rate, and close to end of service life (operates at end of life minimum EGT margin).
2. Day temperature at or above thrust rating corner point (kink point) e.g. >ISA +15°C.

Additionally:

3. Engine max rated thrust for day conditions above kink point is reduced from the standard day max rated thrust declared in the TCDS for operation above kink point.
4. The power that can be extracted from the core above corner point will be less than that extracted at constant thrust below kink point. (Kink, or Corner point temperature is where the EGT is highest when operating at maximum thrust conditions.) Operating at a higher OAT beyond the corner point temperature is possible, however the thrust must be reduced (de-rated) to avoid an EGT redline exceedance (see figure 4.6a).
5. The cooling air feed to the cooled turbine components is not at the matched engine operating design conditions because the compressor operating point is off design with resultant cooling circuit pressure (low) and temperature (high) impacts as described in figures 4.2, 4.3 and 4.4 in section 4.3.

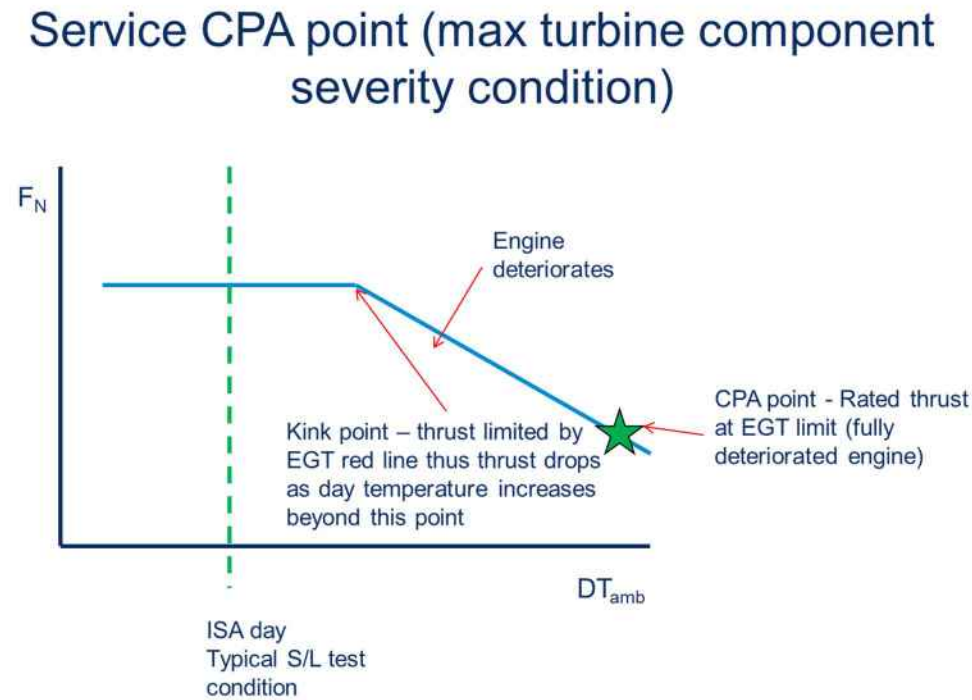


Figure 4.6a – Service operation max turbine component severity condition

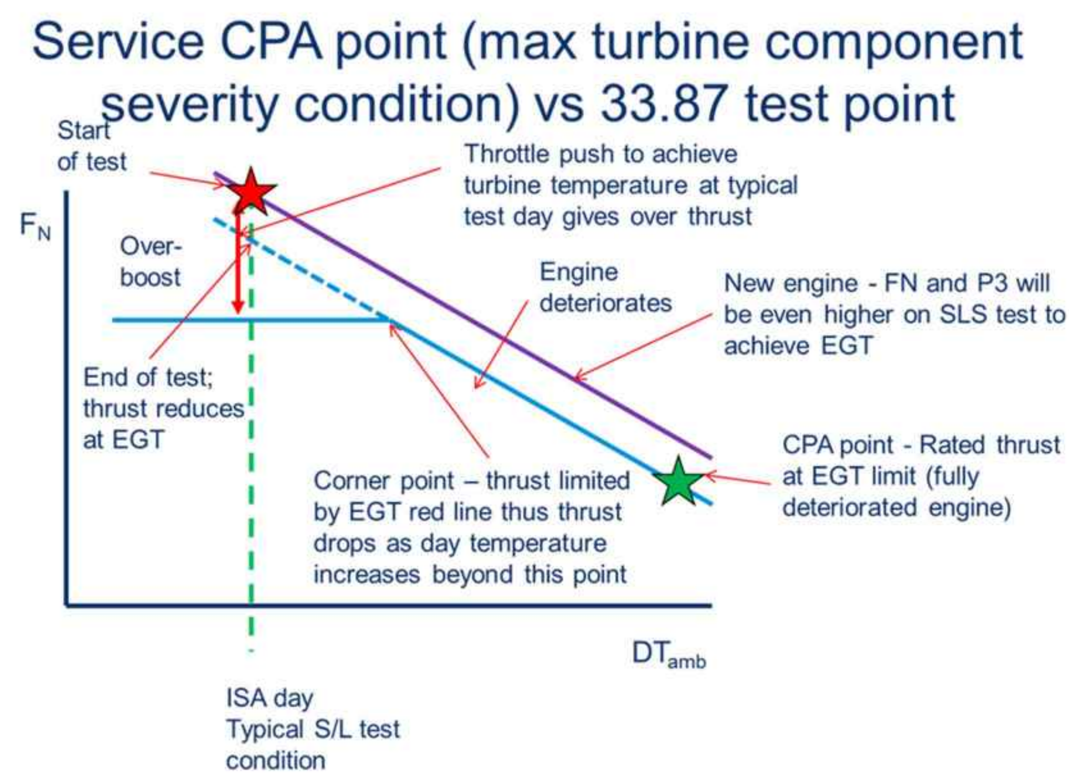


Figure 4.6b – SLS test max EGT condition vs service operation max EGT condition

[Notes for Figures 4.6a &4.6 b. The blue line represents the type certified rating. The 33.87 test forces running well above that rating, particularly at ambient temperatures below the corner (kink) point conditions. Engines are typically controlled to corrected fan speed (N1K) or an Engine Pressure Ratio as a surrogate for thrust. Thrust management is always set with margin to ensure rated thrust is always delivered regardless of deteriorated condition.]

However, modern HBPR new production engines do not behave the same thermodynamically as do the “fully deteriorated” engines that would achieve redline EGT as described above. Thus, in order to force a new production engine to reach maximum EGT (redline) at S/L ISA (typical type test) day conditions in an endurance test environment (as shown by the red star in Figure4.6b), the following considerations come into play:

1. The test vehicle will have little or no deterioration at the start of the test and a proportion of in service EGT deterioration at the end of the test which is not necessarily caused by the same mechanisms
2. The test vehicle has to be over-boosted and/or bled to achieve redline EGT
3. To get the over-boost, the test vehicle core must generate more power than can ever be demanded of it in service on type design power management schedules. This can be up to 20% at the start of the test for a large high OPR engine
4. Because of the extra power, the gas generator compressors are operating above the normal non-dimensional (corrected conditions) and are thus operating inefficiently i.e. compressor stage temperatures are above type design levels for that condition (as previously shown in figures 4.2 and 4.3 in section 4.3).
5. To get that extra power, the OPR of the engine and resultant compressor discharge conditions are in excess of CPA conditions that can be achieved in service even with a lower day temperature.
6. As a result, at limiting EGT the cooled gas path components are being fed with hotter cooling air at a lower driving pressure ratio than can be achieved in service, even at the CPA pinch point in service.
7. Consequently any cooled component in the gas path will be at a higher T_{metal} in the test than at the CPA point in service
8. Thus, life usage rate (damage accumulation) is higher at EGT redline in the current 33.87 test than would ever be expected in service operating at the CPA EGT pinch point

On an engine modified to achieve redline EGT concurrent with rated thrust and redline rotor physical speeds for the current 33.87 test, the following additional effects occur:

1. The engine is re-matched to achieve redline physical core speeds
    a. This has the additional effect of reducing mid stage pressures for cooling air feeds, which in turn;
    b. Drives metal temperatures even higher to the point that
    c. Cooling effectiveness needs to be restored by increasing mass flow and/or increasing protection from heat transfer (e.g. coatings), but even so
    d. Typically all the cooling effect cannot be restored to type design intent
2. The bill of material (BoM) of the test engine is no longer in type design configuration and must be reconciled by the applicant via the analyses that justify the test configuration, which drives a higher degree of uncertainty than for the production intent BoM. Some non-type design changes, such as VSV

closures, FADEC over-speed limits removals etc., cannot be reconciled per se, since they are required to physically run the test.

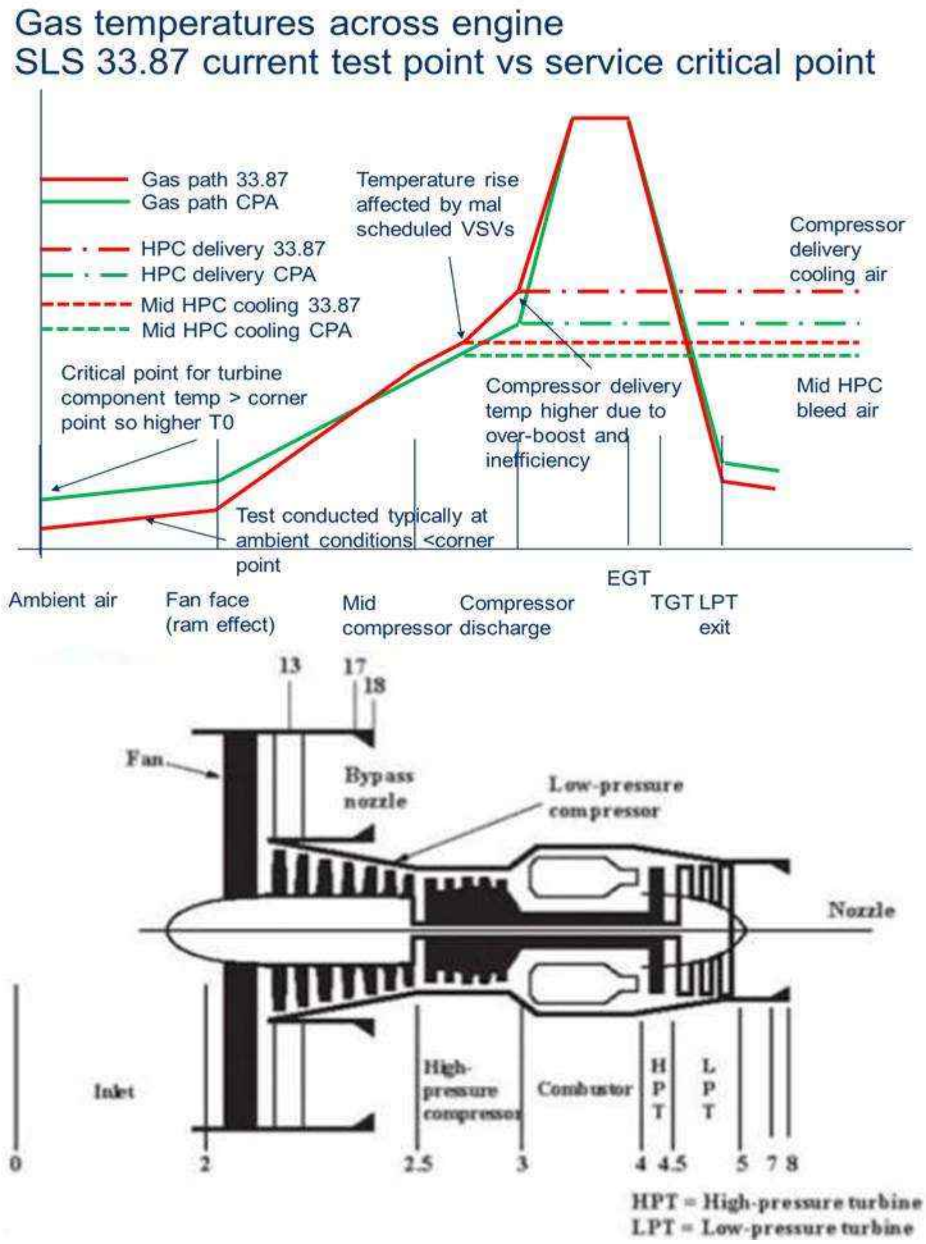


Figure 4.7 – temperature profile through engine for critical point and during 33.87 test

4.6 Engine Service Data

With the evolution of turbine engine technology over the past 30 years, the limiting engine conditions have shifted from operating at concurrent declared maximum limits occurring during SLS takeoff (turbojets and early Low Bypass Ratio (LBPR) turbofans) to limiting conditions that do not occur concurrently at the same operating condition (modern HBPR turbofans). Figure 4.8

shows service data for several turbofan engines that demonstrate where in the operating envelope the maximum declared limits are achieved.

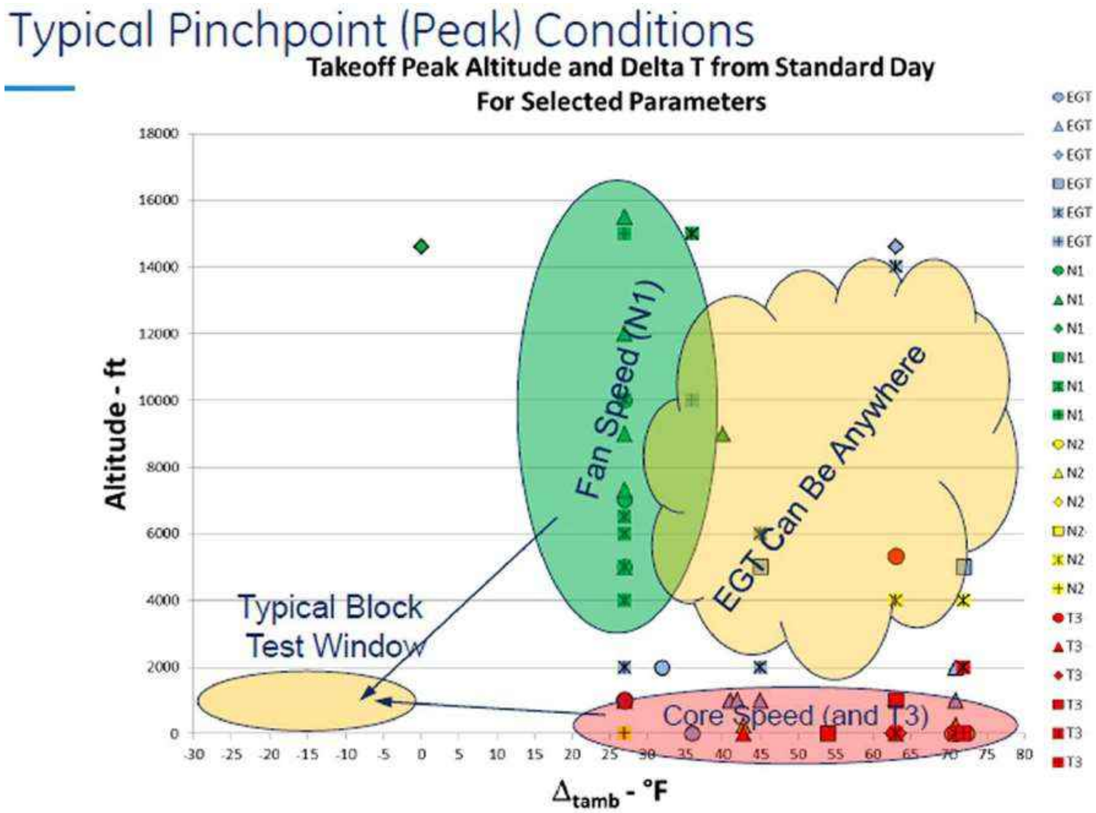


Figure 4.8 Typical Predicted Pinch Point Conditions In The Flight Envelope

The purpose of Figure 4.8 is to show generally where in the operating envelope limiting parameters tend to occur. These data come from a number of HPBR engines certified from the 1970s through current programs. While the generic clouds for each parameter in the figure may appear to imply there is a potential for concurrent overlap in operating limits among HPBR engines, if one looks at the individual symbols (each symbol represents a different engine) it can be seen that each engine design encounters its own limiting conditions at different locations in the associated operating envelope.

Corrected Fan speed is directly related to thrust, so it is held constant as the engine deteriorates. When viewed as a function of environmental conditions: higher fan physical rotor speeds typically occur at altitude with the highest occurring on corner point days. Physical core speeds vary with environmental conditions and deterioration. The highest physical core speeds typically occur with a new engine operating on a hot day at low altitude when thrust is limited to well below max rated thrust (well above the corner point ambient temperature as previously shown in Figure 4.6a) due to turbine temperature limits and the engine's power management and rating structure. With deterioration, physical core speed reduces at a given operating thrust condition for the vast majority of engine designs, and the general trend is still for core physical speeds to be higher at low altitude and high ambient temperature than at altitude.

Analysis of current (and extrapolation to near term foreseeable) engine technology indicates that it is almost impossible to achieve maximum declared limits simultaneously for all limiting parameters when testing a new engine at sea level with the intended type design hardware. As Figure 4.8 shows, achieving two declared limits simultaneously, as allowed in Advisory Circular 33.87-1A, is also difficult without altering from the type design configuration (same alterations as required for triple redlines) to achieve the engine conditions required by the test.

Since current and near term foreseeable technology engines are not likely to achieve simultaneous redline conditions during normal operation, the prescriptive requirement in the current test to run to concurrent redline conditions (for prolonged periods) should be replaced with a requirement for the engine manufacturer to assess the engine design to determine if the design can or cannot achieve simultaneous redlines. If it cannot, then the test should allow testing to individual redlines. However, if the assessment shows that some or all redlines might be achieved simultaneously by the type design engine when operating within the declared operating envelope, then the test should include appropriate concurrent demonstrations and be shown in the applicant's CPA.

Fleet data was provided by three engine manufacturers to substantiate the assertion that current high bypass ratio turbofan engines do not achieve multiple maximum permissible operating (limiting) conditions in service. The following discussion and plots review individual examples that are grounded in these data.

Figures 4.9 and 4.10 show fleet data (more than 200,000 flights) for a high thrust, high bypass ratio engine type over a 4 year period illustrating operating proximity to redlines.

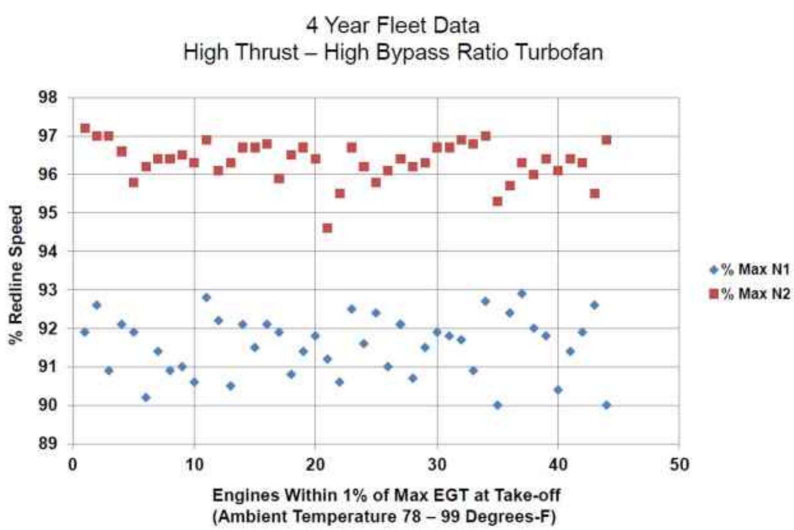


Figure 4.9 - Rotor physical speed proximity to redline, takeoff EGT within 1% of the Redline

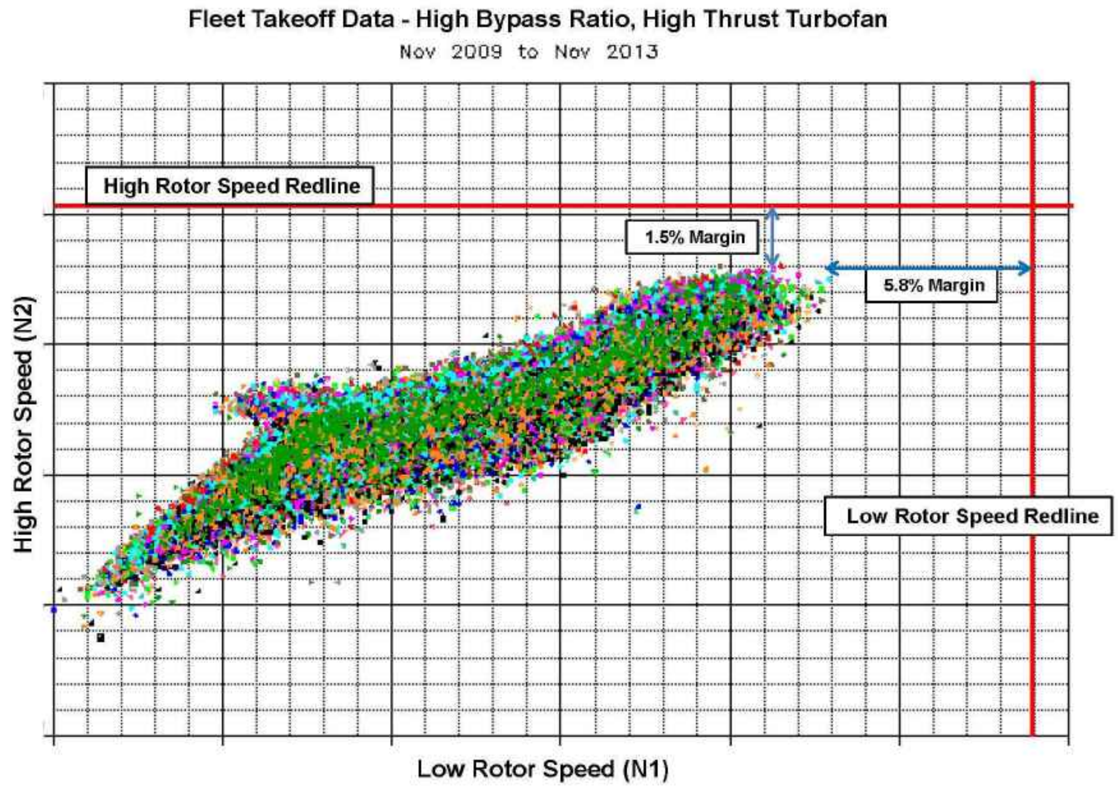


Figure 4.10 - N1, N2 Physical Speed Proximity to Redline

Over this four year period, there were 44 cases where EGT at takeoff was within 1% of the maximum permissible EGT (Figure 4.9). In all of these cases, N1 and N2 rotor physical speeds were below the declared maximum permissible. The average N1 rotor physical speed was 91.5% of maximum permissible and the average N2 physical rotor speed was at 96.5% of maximum permissible. Figure 4.10 shows all of the N1 vs N2 takeoff points for the 4-year period (each color point is a separate engine serial number, where multiple points fall over one another the last point plotted sets the color). The data shows that there were no occurrences where both N1 and N2 maximum permissible physical speeds were encountered concurrently, nor were there any cases where a single maximum physical speed was encountered.

Figure 4.11 shows operational data for a lower thrust turbofan engine (thrust setting via fan corrected speed, FADEC-controlled, variable geometry compressor vanes, advanced technology high pressure turbine cooling). The data includes 84 engines covering over 63,000 missions from 1996 to 2014. At takeoff, the data shows substantial low and high rotor physical speed margin at the engine approached maximum declared gat-path temperature. Figure 4.12 shows similar trends for out of takeoff conditions.

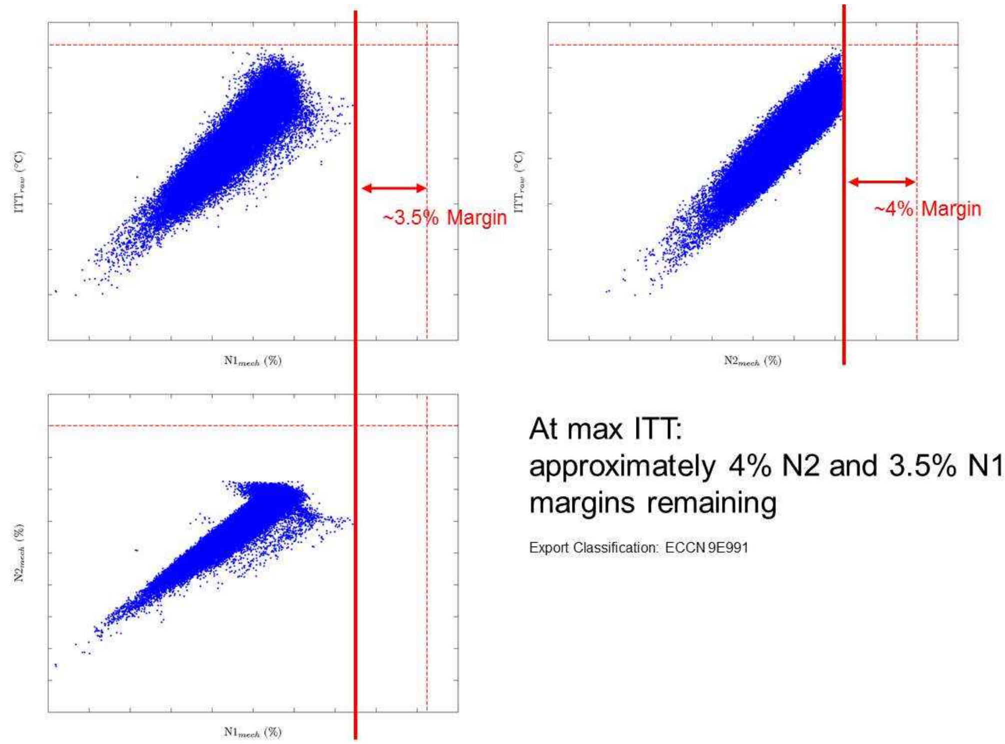


Figure 4.11 - Lower Thrust Turbofan – Takeoff Data

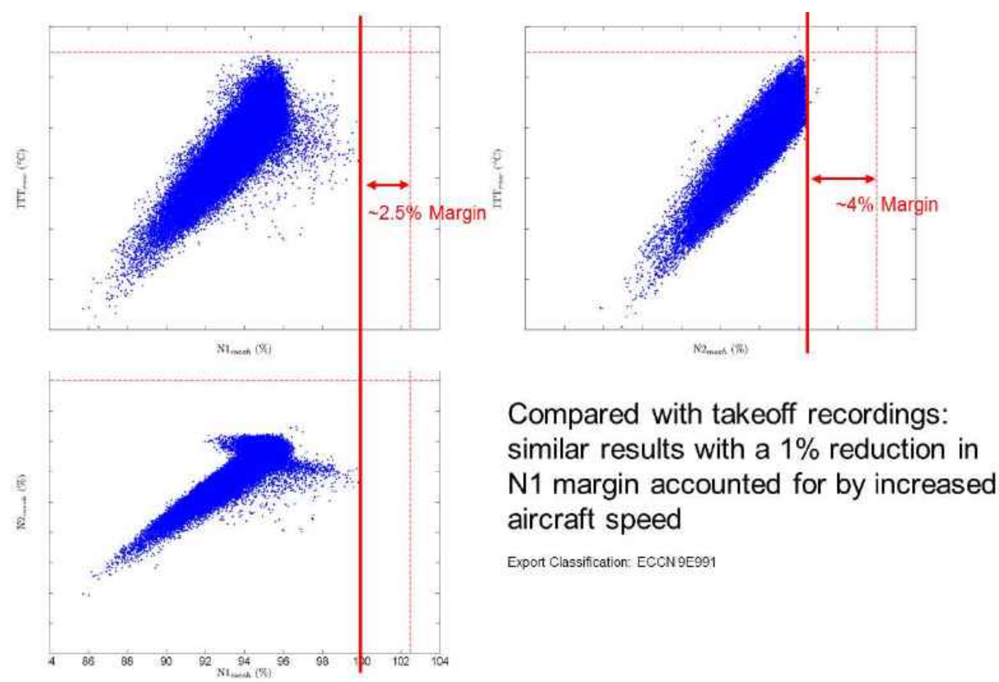


Figure 4.12 Lower Thrust Turbofan – Out of Takeoff Data

Figure 4.13 shows data from a turbofan engine type used on short haul missions on a narrow body aircraft. It groups instances where the engine approaches the maximum permissible physical speeds and EGT. The figure shows there are no data points on the far right (0% margin for low and high rotor physical speeds and EGT). The closest approach to a triple redline condition has an 8°C EGT margin, a 1.5% low rotor physical speed margin, and 1.3% high rotor physical speed margin. Stated another way, at the lowest EGT margin, the engines had more than 1% physical speed margin to redlines.

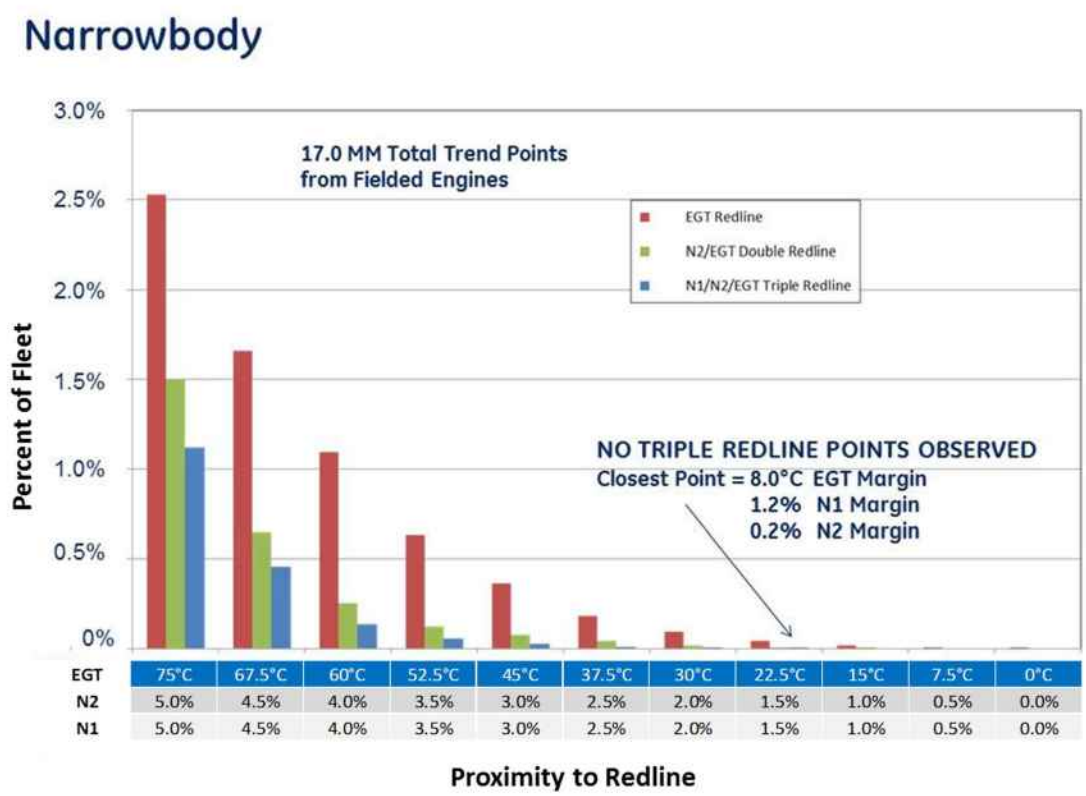


Figure 4.13 Narrow body frequency of occurrences of simultaneous proximity to Redline physical speeds and EGT

Figures 4.14 and 4.15 provide in-service trending distributions for two different engines in long haul fleets covering a full year of service operation.

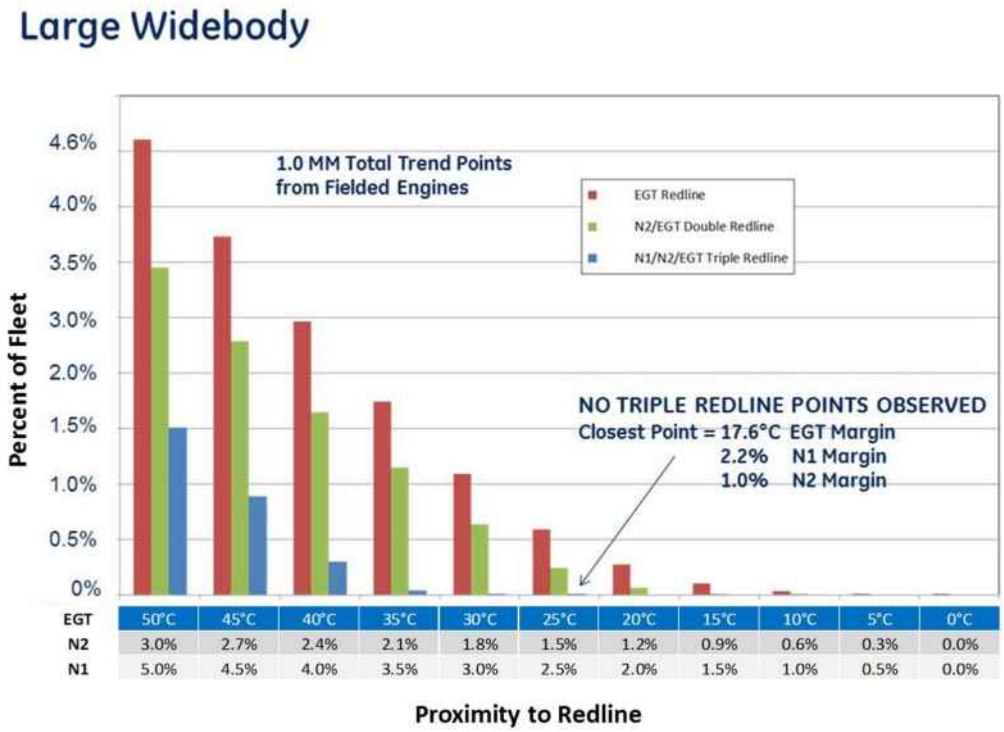


Figure 4.14 – Large Widebody (OEM 1) Frequency of occurrences of simultaneous proximity to Redline physical speeds and EGT

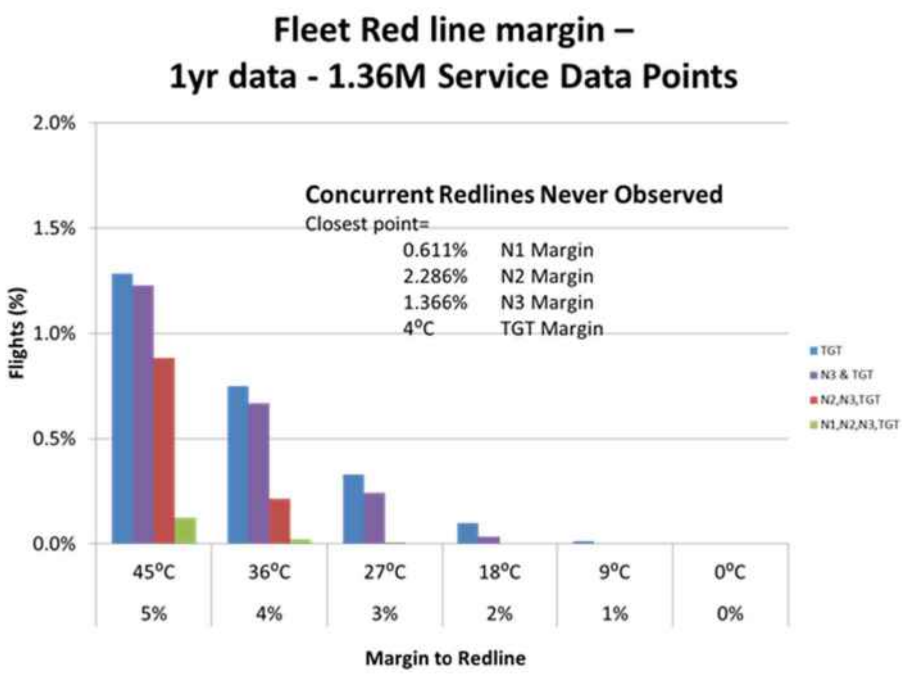


Figure 4.15 – Large Widebody (OEM 2) Frequency of occurrences of simultaneous proximity to Redline physical speeds and EGT

The data was captured as individual flight snapshots by aircraft systems at peak EGT in each takeoff and climb segment. The fleets were selected to compare long haul (twin isle) utilization of different architecture engines. Data is grouped to illustrate the fleet proximity to the following:

- EGT redline
- EGT and core physical speed (N2 or N2/N3) simultaneous redline
- EGT and physical fan speed (N1) and physical core speed(s) (N2 or N2/N3) "Multiple" redline

The data demonstrate that it is extremely rare for modern engine designs to come anywhere close to a multiple limiting (concurrent redline) condition, and that at no time did an engine in this sample database, which covers over 2.5 million flight hours over a four year period, encounter multiple redline conditions.

Figure 4.16 shows service data for an engine that is used in two different fleets

Shaft Physical Speed distributions for Entire Flight					
Engine Type & Shaft Speed	Engines within 5% of redline	Engines within 4% of redline	Engines within 3% of redline	Engines within 2% of redline	Engines within 1% of redline
A Fleet					
N1	0.8%	0.1%	0.01%	0.005%	No Flights
N2	1.9%	0.3%	0.0%	1 Flight	1 Flight
N3	1.6%	0.3%	0.01%	No Flights	No Flights
B Fleet					
N1	18.4%	6.2%	0.2%	No Flights	No Flights
N2	1.8%	0.3%	0.002%	1 Flight	1 Flight
N3	3 Flights	No Flights	No Flights	No Flights	No Flights

Figure 4.16 – Table of proximity to redlines for sample specific fleets

The data in Figure 4.16 shows that operator mission utilization characteristics do not affect the probability of approaching redline rotor physical speeds. Statistically, this data shows that there is minimal probability that the engine will reach an operating condition within 2% of the core speed physical redlines. This further demonstrates the independent nature of engine operating limits (redlines) in modern engine designs, as well as the protections provided by robust engine power management systems.

In conclusion, working group review of millions of samples of service data taken from complete fleets show that concurrent redlines do not happen in service on modern engine designs.

4.7 Historical Engine Issues Data & Comparison to Proposed Test

Figure 4.17 compares the number of failures by engine section experienced during the endurance and other regulatory cyclic tests against the occurrence of failures in service.

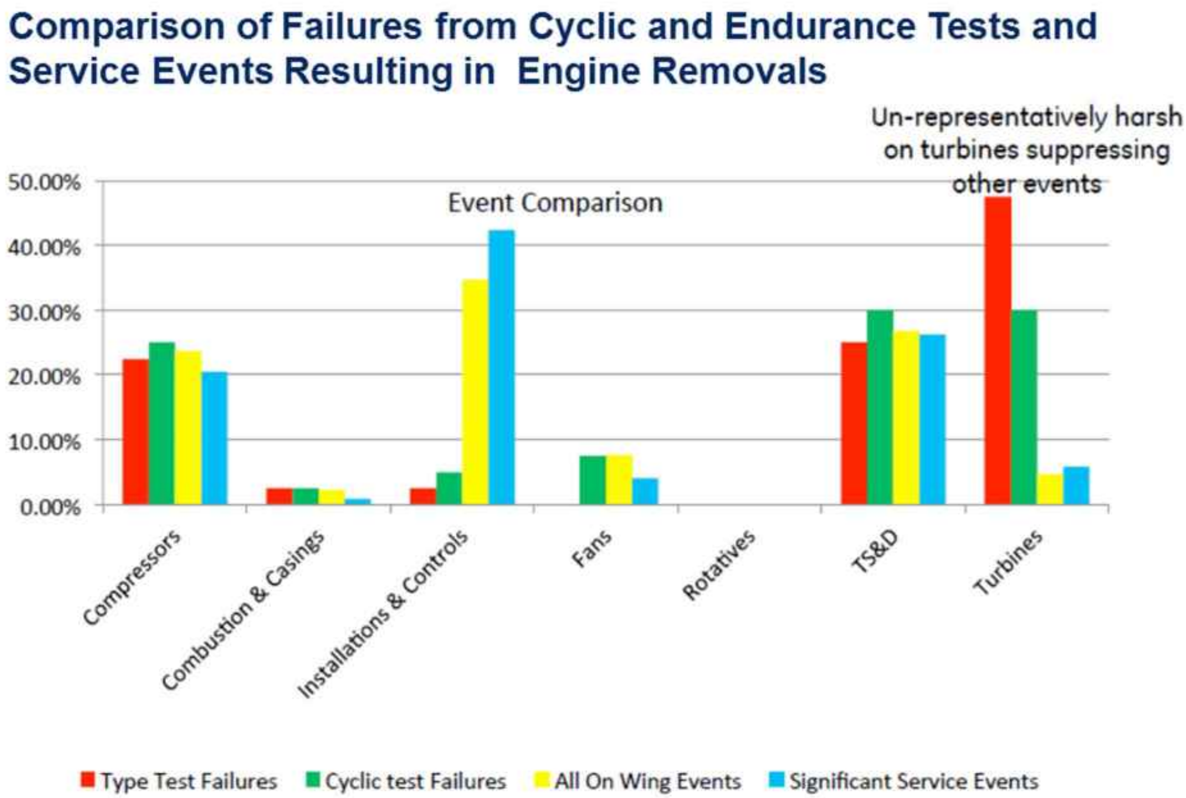


Figure 4.17 – Cyclic and Endurance (Type) Test Failures vs Field Events for Constituent Parts of the Engine

Note: TS&D: Transmissions, Structures & Drives

The data in figure 4.17 shows that while the other regulatory cyclic tests (e.g. IMI, ETOPS) generate approximately 6 times more turbine failures than service, the 150 hour endurance test increases this difference by half again to 9 times more failures. Furthermore, the endurance test fails to expose issues in installations and controls and in recent history has missed turbine failure modes that were found during entry into service. Based on the distress and failures experienced in the certification tests and in service, it is clear that the 14CFR33.87 type test is primarily a hot section creep test and fails to uncover some other failure modes that the type design engine is more likely to encounter in service.

Creep failures in service are now extremely rare with engines most often removed on condition due to life limited parts reaching their service life limit or lack of temperature margin. Other component failure modes can occur in the current test but most test failures are likely to be (test "as-run" related) creep or local extreme temperature (high rate oxidation) related which do not often result in shut down related failures. Also of note, none of the seven 150 hour removals from test caused by Turbine failures over the last 15 years (on the engine types examined in detail by the working group) have provided conclusive evidence in support of leading indicator for service reliability; however, more service representative failures would be exposed by hot cyclic tests (conducted in type design configuration) (e.g. IMI or ETOPS tests).

150 Hour and IMI Findings - Engines E1 Through E8

PART FAMILY	150 HR. END. TEST FINDINGS	IMI TEST FINDINGS
FAN BLADES	E1 E1	
FAN EXIT GUIDE VANES	E3	
LPC & HPC VANES		
LPC & HPC BLADES	E1 E3 E3	E4
COMPRESSOR NON-ROTATING AIRSEALS & SHROUDS	E4	
COMPRESSORSTATIC STRUCTURE PARTS		
COMPRESSOR BEARING COMPARTMENT (SEALS, ETC)	E2 E3	E1
COMPRESSOR MAJOR CASES		
COMPRESSOR ROTATING LIFE LIMITED PARTS	E3	
COMPRESSOR ROTATING NON-LIFE LIMITED PARTS		
COMBUSTOR PARTS	E3 E4 E8	E4 E4
HPT BLADES AND VANES	E1 E1 E3 E5 E7 E7 E7 E8	E1 E3 E3 E7
LPT BLADES AND VANES	E3	E3 E3 E3 E3
TURBINE NON-ROTATING AIRSEALS & SHROUDS	E2 E2 E3	E3 E3
TURBINE STATIC STRUCTURE PARTS	E2	E2
TURBINE MAJOR CASES	E3 E3	
TURBINE ROTATING LIFE LIMITED PARTS	E1 E1 E2	
TURBINE ROTATING NON-LIFE LIMITED PARTS		
TURBINE BEARING COMPARTMENT (SEALS, ETC)	E3 E5	E3 E3 E7
GEARBOX (SHAFTS, GEARS, HOUSINGS)	E5 E5	
EXTERNALS (TUBES, MANIFOLDS, DUCTS, BRACKETS)	E1 E3 E3 E5 E8	E3 E3 E7
CONTROLS & ACCESSORIES COMPONENTS	E1 E2 E2 E3	E1 E2 E3 E3 E4
EEC HARDWARE		
EEC SOFTWARE		

Notes: Engine E6 with no 150 hour or IMI findings
Engine E3 is the same engine as E3 in AD listing

Four "E1" findings were due to engine mis-match to achieve concurrent redlines (temperatures outside of perating envelope). Would not be found with new alternate test.

One "E2" finding were due to engine mis-match to achieve concurrent redlines (temperatures outside of perating envelope). Would not be found with new alternate test.

Figure 4.18 – Hardware Modifications Due to IMI and Endurance Test Findings

Past 150 hour endurance test results of several turbofan engines were reviewed. Figure 4.18 below summarizes the types of hardware modifications that were required due to test findings. E1 through E6 are engine models and the type of hardware modifications are listed by part family. Note that engine type E6 has no findings that required a change in design. The Initial Maintenance Inspection Test (33.90) is also included.

Most of the test findings for both the IMI and endurance tests are related to hot section distress. The IMI findings uncovered basic design limitations or deficiencies. The endurance test also has the potential to find these same deficiencies, but due to the test vehicle being run in a non-type-design configuration, other, non-type-design related issues are also induced (see Section 4.4).

Airworthiness Directives (ADs) issued during the first three years of service were compiled from 11 turbofan engine models which were FAA certified from the 1980s to current day. The majority of the ADs address safety issues related to external components and assorted tubes and brackets (examples: fuel tube cracking, fuel metering unit). Other ADs required electronic engine control software updates to preclude engine operational issues (examples: ice crystal icing, un-commanded acceleration), or a reduction in LCF life of critical components. A summary of the ADs categorized relative to engine part family is shown in Figure 4.19 below. The ADs do not correlate with any detailed 150 hour test findings from Figure 4.18 above. Even though both the Endurance and IMI tests uncover many external component (e.g. tubing, brackets, etc.) shortfalls, additional shortfalls in the same part family have caused an unsafe condition which warranted an AD. Several ADs were for life limited parts. These life reductions (shortfalls) were uncovered by analyzing service data and re-analyzing low cycle fatigue missions and clearly would not have been found in either the 150 hour or IMI tests since those tests do not exercise LCF either.

ADs - First Three Years of Service - Engines E1 Through E11

PART FAMILY	AD Published
FAN BLADES	
FAN EXIT GUIDE VANES	
LPC & HPC VANES	
LPC & HPC BLADES	
COMPRESSOR NON-ROTATING AIRSEALS & SHROUDS	
COMPRESSORSTATIC STRUCTURE PARTS	
COMPRESSOR BEARING COMPARTMENT (SEALS, ETC)	
COMPRESSOR MAJOR CASES	
COMPRESSOR ROTATING LIFE LIMITED PARTS	E2 E9 E9 E6 E10 E11
COMPRESSOR ROTATING NON-LIFE LIMITED PARTS	E4
COMBUSTOR PARTS	E4
HPT BLADES AND VANES	
LPT BLADES AND VANES	E2
TURBINE NON-ROTATING AIRSEALS & SHROUDS	
TURBINE STATIC STRUCTURE PARTS	E2
TURBINE MAJOR CASES	E6
TURBINE ROTATING LIFE LIMITED PARTS	E9
TURBINE ROTATING NON-LIFE LIMITED PARTS	
TURBINE BEARING COMPARTMENT (SEALS, ETC)	E1 E1
GEARBOX (SHAFTS, GEARS, HOUSINGS)	E1 E9 E5 E6
EXTERNALS (TUBES, MANIFOLDS, DUCTS, BRACKETS)	E1 E1 E9 E8 E11
CONTROLS & ACCESSORIES COMPONENTS	E1 E9 E4 E5 E7
EEC HARDWARE	
EEC SOFTWARE	E1 E1 E9 E9 E5 E7 E10 E11

Notes: Engine E3 with no ADs in first three years of service
Engine E3 is the same engine as E3 in test listing

E1: RR
E2: GE90-115
E3: GP7200 none
E4: CF34-10
E5: CFM56-7B
E6: CFM56-5B
E7: PW4000-94
E8: PW2000
E9: GE90-04
E10: GEnx-1B
E11: GEnx-2B

Figure 4.19 –Airworthiness Directives During the First Three Years of Service

The full data set compiled to develop these findings is contained in Appendix E – section 11.5

4.8 Effects of Future Technology

Trying to assess either the current 14CFR33.87 test or a proposed alternative test against how engine technology may evolve in the future is difficult because there is no way to know what innovative and disruptive technologies may be introduced and whether these technologies may have significant impact on how gas turbine engines operate. A test that focuses on one era's technology may not provide sufficient or appropriate challenges to demonstrate capabilities of another. For example, the introduction of ceramics in static parts has reduced threats like creep and oxidation, but ceramics also introduce new potential failure mechanisms related to thermal cycling.

Regular re-assessment of the ability of the endurance test to evaluate new engine technologies will be required to understand the extent to which the test needs to adapt to properly evaluate new engine designs. The use of critical point analysis (CPA) to assess where and how operating pinch points occur across the operating envelope and over the range of deterioration conditions is explained in Sections 4 and 6, and will be critical to understanding how a new performance based test run significantly to operating pinch points should be structured.

Additionally, new technologies will need to be assessed for performance, failure mode, and wear-out sensitivities across the full range of operating conditions and deteriorated states. For example, does the new technology show greater sensitivity to thermal cycling, and does deterioration or operating condition influence this sensitivity? If so, does the currently proposed endurance test, and the way various engine cycles are sequenced, sufficiently challenge the range of extremes that might be encountered across the declared operating envelope? Alternatively, given the mix and the relative differences in operating conditions among time at takeoff, maximum continuous, and cruise change, does the test provide sufficient challenge for expected operating conditions?

5 Aircraft Manufacturer and Airplane Certification Considerations

5.1 Aircraft Manufacturer Input

Original Equipment Manufacturers of airplanes were requested to provide input on what specific data is used from the current 14CFR33.87 test for the purposes of meeting airplane specifications or attaining airplane certification.

The data required for airplane certification are primarily and directly the engine limitations placed in the TCDS and consist of EGT and Rotor physical Speed redlines, along with airplane maximum bleed for cabin or anti-ice extraction. The 5 minute duration (or 10 minute when requested for additional one engine inoperative capability) is also used to substantiate that the engine can operate in the takeoff and MCT flight envelope without exceeding the declared limits. If new rated conditions are recorded in the engine instruction such as APR, its associated limits also need to be proven. Other 14CFR25 requirements are to incorporate results from the test that directly or indirectly affect the Engine Operating Limitations, Installation Manual, or Instructions for Continued Airworthiness (e.g. in certain instances results of the testing completed to satisfy 33.87 have led the Engine OEM to place limitations in the ICA that in turn must be reflected in the Airplane OEM ICA documents). Prior to gaining FAA Airplane Type Inspection Authorization, it must be shown that there is sufficient accumulation of engine testing but there are no specified hours, cycles, or number of engines.

There are also airplane specification requirements that are satisfied by this test. The test is used to establish that there are adequate margins for each of the redlines to assure that the airplane can be certified and delivered. The test is also used to establish minimum durability (ostensibly for time on wing, but there is no direct correlation between the test and time on wing) and transient throttle conditions within the operating, installation, and maintenance limitations/instructions, including atypical conditions such as rejected take-offs or go-arounds.

5.1.1 Airplane Manufacturer Certification and Specification Inferences of the Engine Endurance Test:

For 14CFR25 certification: For 14CFR25 certification, the following list gives the functional requirements from the 33.87 test.

1. Performance: The Airplane Manufacturer does not use 33.87 directly to show compliance, but 33.87 establishes the values that they do need to show compliance to for sections listed below.
    a. 25.1521 Cleared EGT and rotor physical speed (N1, N2, N3) redlines for takeoff Thrust and Max Continuous Thrust.
    b. 25.1521 Max bleed limitations for EAI and cabin bleed extraction. Additional bleed usage for Wing Anti Ice and Nitrogen Generating System and all other airplane pneumatic systems.
    c. 25.1521 substantiation showing that the engine can operate in the takeoff & MCT flight envelope without exceeding the declared limits at rated thrust.
    d. 25.1583 substantiation. Redlines are included in the Airplane Flight Manuals. Engines have also recently cleared transient takeoff EGT redlines.
    e. 25.1521 Takeoff redlines (EGT, N1, N2, N3) are cleared for 5 min duration (or 10 min when one engine inoperative). Time duration at Takeoff Thrust and MCT are stated in the 14CFR1 rating definition. 10 minute takeoff duration when an engine fails is an Airplane Manufacturer B requirement that the engine

companies accommodate in their 14CFR33 cert. OEMs include a statement in TCDS that engine can be operated for 10 min at takeoff.

f. 25.1581 and 25.1583(b) Operating limitations.

2. Operability:
   - No requirements from 33.87 for 14CFR25 Airplane Operability. Airplane Operability does use other 14CFR33 sections (33.65, 33.68, 33.77, 33.78, and 33.89).
3. Flight Test:
   - No requirements from 33.87 are needed for flight test, except for any results that affect Operating limitations, Installation Manual, Maintenance instructions.
4. Safety of Flight:
   - FAA Type Inspection Authorization demonstration of sufficient accumulation of engine testing (hours/cycles) is required (Ref: FAA Order 8110.4C Type Certification).
5. Installations:
   - No requirements from 33.87. Installations comply with 25.901(b)(1i,2), 25.903(d)(2), 25.1521, 25.1583(b) include results from 33.87 that can affect Operating limitations, Installation Manual, Maintenance instructions, Continued Airworthiness.

For Specification Compliance:

1. Performance:
   a. Redline limitations are declared by the engine companies but assessed to ensure adequate margins to specification requirements are achieved (spec margins are not FAA requirements).
   b. MCT limits have no time restriction.
      - Extended ETOPS for example require 240 minutes of MCT operation without exceeding Redlines.
   c. Maximum Climb (MCL) thrust is used for periods of up to approximately 30 minutes on each flight cycle (MCL is typically 90% to 100% of MCT).
2. Flight Test Readiness:
   a. More sustained MCT as in flight test MCT of two hours or more are tested.
   b. Many aircraft OEMs want to see completion of the 33.87 endurance test prior to TIA. Endurance test viewed as one of the few whole engine system tests that demonstrate integrity for the FT campaign
   c. First flight readiness requires demonstration of sufficient accumulation of engine testing (hours/cycles) is required. This includes representative transient conditions (Burst/chops), domestic and customer loading, and durability within operating, installation, and maintenance limitations and instructions.

A key additional finding of this Airplane Manufacturer survey is that the current test is also used holistically along with other 14CFR33 tests to establish a demonstrated satisfactory level of durability and that it is one of few tests that require a type design configuration. Note: The regulators have accepted non-type design configuration to enable the test to be performed, provided the non-type design can be reconciled against the test intent.

5.2 Aircraft Regulatory Input

Airplane certification offices were requested to provide input on what specific data is used from the current 14CFR33.87 test for the purposes of meeting airplane specifications or attaining airplane certification.

Government Agency response:

Below are the 14CFR25 regulations that could be affected by any changes to the 14CFR33.87 Endurance Test rule. It does not necessarily mean that changes to the endurance test will result in a change to a 14CFR25 regulation.

Title 14 CFR:

25.901(b)(2) – Installation

25.903(d)(2) – Engines

25.934 – Turbojet engine thrust reverser system tests

25.1167(a) – Accessory gearbox

25.1521 – Powerplant limitations

25.1583(b) – Operating limitations

14CFR33 endurance testing directly supports the above compliance showings. Any change to the endurance testing that could affect (1) the assurances given for the operating limits (such as redline N1, N2, N3, and EGT), (2) the integrity of the engine hardware for both reliability and margins (Note: Margins are not required by 14CFR25, but are implied in order to provide for economical and practical considerations in delivering a useful airplane) to the operating limits, and (3) the acceptability of timeframes established for operating limits.

5.2.1 Other Aircraft Considerations

Depending on the responsible Type Certification holder, Airplane certification can also include demonstration of Thrust Reverser endurance. While this report is intended to respond to the FAA Tasking with respect to developing an Alternate Test to 14 CFR33.87, the team consensus was there is also an opportunity to address the use of a Slave Thrust Reverser during 33.87. This can and is routinely performed via an Issue Paper. A separate section is provided (See Appendix F) to discuss the rationale for formal adoption of the use of a Slave Thrust Reverser.

6 Basis for the alternative test

The ARAC tasking for this project was very specific in its expectation that the Alternate Test allow the engine, or test vehicle, to be tested in type design configuration while maintaining the intent, central elements, and equivalence with the current rule. The working group captured these expectations in the table shown in Figure 6.1.

33.87 Rule Intent Using An Engine That Substantially Conforms To Type Design

	Existing	Future
Engine intended to run in Type Design Configuration with minimal modifications		
Demonstrate ratings and applicable TC data sheet parameters	X	X
Demonstrate max operating limitations (i.e. RL's)	X	X
Demonstrate operability Free from surge/stall & makes thrust/torque/power throughout test	X	X
Demonstrate minimum level of durability by operating, including effects of starting, over the length of the test, including operating at/near max operating conditions (including atypical) that can be reached in service with the engine in TC configuration (duration of new demonstration TBD)	X Fixed Cycle Prescribed Times	X

Figure 6.1 – table of original intent against existing and alternate test proposal

6.1 Prescriptive, Performance, and Hybrid Based Concepts

A prescriptive based regulation tells an applicant exactly what test must be conducted and provides a measure of acceptability against which to assess the test results. The current 14CFR 33.87 test defines a prescribed test cycle (Parts A-E), the number of times the cycle is to be conducted, the required variations on the basic cycle that must be run (e.g. fuel/oil temperature extremes, bleed extraction), the performance expectations during and following the test, and how the hardware is to be assessed post-test. The prescribed cycle was defined in the 1950s and despite advances in engine technology resulting in changes in engine operating characteristics, this prescriptive approach is used to qualify all modern engines regardless of the engine design or intended operating characteristics.

A performance-based regulation tells an applicant what the desired outcome is rather than the details of how to achieve that outcome. The regulated party is responsible for deciding how to achieve that outcome. With performance-based standards, regulated entities are responsible for meeting the regulatory intent, but they are free to choose, or invent, methods to comply. This all comes with the caveat that a performance based requirement must be stated in terms of a practical goal that can be understood by the applicant and regulator, the approach to achieve the goal must be enforceable, and must preserve the current level of integrity of the final product. Additionally, the approach cannot create mismatch with other regulations, and must affect all regulated entities equally. Since the situation that gave rise to desiring a performance based approach may not be common for all applicant designs, an approach to maintaining a level playing field is to make a performance based approach an alternate to the requirement in the regulation.

A hybrid-based approach identifies a combination of prescriptive requirements and performance based targets that are specifically selected to preserve the intent of the current rule, challenge the intent of the engine design being certified, and maintain the current level of operational safety (ref. section 2.2). As applied to the proposed alternate test, this approach still requires an engine demonstration at the declared redline physical speeds and temperatures, rated thrust and the associated engine conditions, but the dwell times at these conditions and whether limiting conditions should be run individually or concurrently are test variables. Analytical methods like CPA can be used to identify the most severe operating conditions that should be run for dwells and transients as well as the times for which these conditions should be run. The dwell times for each condition may be less than those in the current 14CFR33.87 test if the conditions cannot be achieved within the declared operating envelope and non-type design engine operation is required to achieve these conditions. However, the alternate test conditions, as determined by CPA and the conditions necessary to achieve rated thrust in a sea level test facility, will expose the engine to durations at physical and corrected speeds, temperatures and pressures that are more challenging than the actual operating environment in service. The alternate test also preserves other demonstration requirements related to accessory loads, bleed air, oil temperature and transients, and therefore achieves the same goals intended by the current 14CFR 33.87 test. The hybrid approach accommodates a wider range of engine designs than the current prescriptive 14CFR 33.87 test, it is adaptable to new engine technologies while maintaining a test vehicle that accurately represents proposed type design, and the test can be designed to show equivalency to the intent of the current regulation.

6.2 Critical Point Analysis (CPA)

Using a thermodynamic engine model (accounting for new and fully deteriorated engine conditions) in conjunction with the airplane flight envelope, the applicant will identify (i.e. perform a CPA) the critical points (Rotor physical speeds, temperatures, altitude, etc.) representing the most severe operation. This would normally reflect the redline targets which the applicant will have previously identified and should provide the extent of exposure to these conditions. The CPA analysis must also establish maximum levels of rotor speed for a red line temperature case, or temperature for a red line speed case, which must then be met or exceeded in the demonstration. If it is found that red line conditions could at any point be coincident then this would need to be reflected in the demonstration. These results will be used in establishing the redline demonstration engine conditions (section 7.2.3).

The applicant will then conduct analyses to identify the areas in the declared flight envelope where critical components are exposed to the most damaging component conditions (section 6.3 et seq.). This would normally also be a red line engine condition on a fully deteriorated engine. This component condition is then to be used in the extended operating periods of the test (section 7.2.5).

6.3 Severity Comparison for Alternate Test

The ARAC charter states that "The alternate test is to be equivalent to the test currently in 14CFR33.87 with regards to demonstrating engine operability and durability, and is validated with engine data." The ARAC WG has therefore been tasked to establish a method by which equivalency of the alternate test and the test currently in 14CFR33.87 can be assessed.

The current test in 14CFR33.87 provides a number of challenges to the engine design. The committee has concluded, however, that the rule and related test as originally written was primarily intended as an accelerated severity test of creep capability, i.e. durability at sustained high turbine temperature and physical speed, and effects of deterioration on operability driven by the prescribed operating conditions (not inclusive of all flight environment deterioration effects).

While it would be desirable to design a test that vetted all significant damage challenges an engine is designed to accommodate, that is beyond the scope of this working group's charter.

The ARAC WG recommendation is therefore that equivalency of the alternate test will be assessed on the basis of accelerated creep life usage as related to the intent of the current test and will add a requirement that the alternate test should demonstrate equal or more damage accumulation in the other damage mechanisms evaluated in the engine severity comparison and assessment.

6.3.1 Severity Comparison to Current Test Intent

The original test intent was a prescriptive test for accelerated severity, run to the limits declared for the engine at what the WG believes to be the most severe operating conditions early turbine engines were expected to encounter (TRL), run with minimal enabling modifications, and the damage mechanisms to be demonstrated were not specifically identified. The WG identified that the key input parameters to characterize the severity of the test were time on condition and cycles run to critical component temperatures, and physical speeds while operating to rated thrust.

In order to assess the proposed alternate test, the WG arrived at a methodology based on comparative severity whereby it would identify the damage mechanisms associated with operation at each of the critical points, and compare damage severity relative to the original intent based on the effects of the input parameters. The proposal would thus meet the terms of the ARAC charter.

6.3.2 Elements to be Used in a Severity Comparison

To demonstrate that the proposed test is adequately severe, i.e., commensurate with the original test intent - a method of severity comparison to the original intent is required.

In addition to creep as the primary damage mechanism, other damage mechanisms should be assessed at the operating conditions determined by the CPA. The following elements should be considered in a severity comparison:

1. Declared operating limits
2. Temperature- and physical Speed-related damage mechanisms (Creep, SPLCF, TMF, etc.)
3. Cyclic content
4. Transients
5. Oil system demonstrations
6. Fuel system demonstrations
7. Start/Stop

This list is not comprehensive, and the applicant must evaluate their proposed type design for all significant elements and damage mechanisms.

6.3.3 Application of a Severity Comparison:

The comparative methodology and damage mechanism(s) proposed for a hybrid performance/prescriptive based alternate test is dependent on the applicant's CPA, details in the engine application, and negotiations with the Administrator.

6.3.3.1 Comparative Severity Analysis

One approach discussed and analyzed at length by this working group was to use creep damage to critical gas-path components as a comparative arbiter to the original intent of the current test. Stress-rupture and creep damage were the prevalent failure mechanisms when the current test was originally adapted for turbine engines (appendix B, section 11.2.3), and since the prescriptive elements of the test were most challenging to this mechanism the team felt it was an appropriate basis of comparison.

It is important to understand that an approach based on creep damage as a comparative means to assess severity for an alternate test does not mean the alternate test must be defined only to identify creep issues, or that it will not adequately assess other potential failure mechanisms. Rather, it is just a means of comparing any alternate test's severity to that of the original intent of the current test for the creep mechanism. It is expected that within the applicant's severity assessment and comparison, any other relevant damage mechanisms will be identified and an engine specific comparison of the existing to the alternate test will be provided to demonstrate that the hybrid based test proposed will adequately expose the engine to the relevant failure and/or deterioration mechanisms to meet the test intent. See also Appendix K (Section 13) for additional considerations for severity assessment.

6.3.3.2 Reference Severity

The reference severity is determined based on the critical component(s) identified using the CPA and on the time at elevated temperature and physical speed to which the component(s) is subjected. Therefore, the severity representing the intent of the test per the current rule (if the engine could be run to the prescribed conditions in type design configuration at SLS) is the total time spent at the limiting conditions prescribed in the current rule. The damage that would be accrued at these conditions for those durations represents the reference severity for this approach, and can be normalized to 1 for comparison to an alternate test.

6.3.3.3 Comparative Severity

With a reference severity representing the original intent of the current rule (with a type design engine) and a method for conducting an alternate test both in place, the next aspect required is a methodology for determining the severity of the alternate proposal. The proposed methodology is dependent on the limiting component, the failure mechanism for that component, the operating duration at the CPA condition, and the engine systems that affect and are affected by the failure mechanism.

To create a comparison metric, the damage on the critical components can be characterized per hour of operation for all potential power-setting conditions and then used to calculate the actual damage accrued for the proposed cyclic conditions and time durations in the alternate test. This will provide the ability to accumulate damage consumed for cycles of varying number, duration, and power setting. Examples of damage include (SPLCF, TMF, creep, HCF, etc.).

Methods such as spreadsheet tools may be developed to facilitate implementation of the severity comparison during the applicant's test planning phase. This will aid in defining the hybrid based aspects of the alternate test that best suits the particular design and intended operation of the engine, while ensuring the test is adequately severe. The proposed test consists of a mix of cycles run at various power-settings for varying durations as derived from the CPA to accumulate the expected damage for each test segment. Section 7.3 illustrates the concept of using a spreadsheet tool to show comparative severity within the framework of the alternate test proposed in Section 7.2.

With a type design test vehicle, it is important to note there are at least 2 potential sources of additional conservatism inherent in the conduct of an alternate ground-based static test relative to the most extreme operation at pinch point in service operation.

The first source of conservatism results from running a new type design engine to certain CPA conditions that are only representative of a fully deteriorated type design engine. An engine will not deteriorate in the same manner during the endurance test (current or alternate) as it would in field service. This difference in deterioration is due to many factors including: maneuver loads, aero loads, altitude and temperature effects, length of time (on wing vs. on test stand), exposure (time) to sulfidation, oxidation, environmental pollutants, and abrasive contaminants, etc. As outlined in Section 4, in order to achieve the component surface temperatures representative of an engine approaching end of service life (due to lack of EGT margin), a new production engine must be significantly over-boosted, resulting in: higher thrust, rotor physical and corrected speeds, and compressor exit conditions than could occur at the declared operating limits. Any excessive compressor exit temperature resulting from the over-boost condition yields increased cooling air temperatures relative to those achieved in service. Consequently for cooled components (e.g. rotor bores and turbines), their relative temperatures will be in excess of type design intent.

The second source of conservatism results from running an engine at SLS to CPA conditions that are only likely to occur at higher altitude (e.g. max N1 physical speed typically occurs at top of climb, ~25,000-35,000 ft.). Running these conditions at SLS also requires overboost, thus forcing the maximum cooled component surface temperatures to exceed the design intent for the cycle point identified by the CPA as occurring in service. Absolute gas-path pressures and bearing loads may also significantly affected, and under these test conditions will typically be well away from expected service experience during the conduct of this test.

6.4 Substantiation of TCDS Physical Speed and Temperature(s)

At the conclusion of the test (either current or alternate), the TCDS redline limits will be based on demonstrated capability.

Since the alternate test is to be conducted in or very close to type design configuration, the amount of time that can be spent at physical speed and EGT redlines will be limited by the test vehicle architecture and environmental conditions at the test site. It may not be possible to clear all limiting conditions for 18.75 hours at MTO and 45 hours at MCT, so the proposed alternate test proposes to use a combination of what can realistically be run under test location environmental conditions and additional significant time at CPA identified operating conditions to show the test vehicle can accumulate equivalent damage and still meet the pass fail criteria of the current rule. To accomplish this, the substantiation of redlines will be based on the combination of sufficient time at redlines that covers what might be expected in service and sufficient time at CPA conditions to provide equivalent damage accumulation to the intent of the current rule.

6.4.1 Core Rotor Physical Speed Redline

The core speed redline demonstration shows that a type design test vehicle is capable of operating at its design limit for a limited time related to the operational environment it is expected to experience (see Section 7.2.3.1). The demonstration time is dependent on the findings of the CPA but is proposed to be a minimum of 10 minutes. For the remainder of the test the core speed will fall out based on environmental conditions of the test day. Any speed shortfall during the remainder of the test is accounted for in the comparative severity assessment and will result in requiring a longer test to achieve the same severity as originally intended.

The minimum time is justified based on the operational data documented in Sections 4.6 and 5, which shows that the high pressure rotor system speed redlines (NH) are very infrequently, if ever, encountered. The 10 minute minimum requirement at MTO redline is further justified by the TCDS limitation of 10 minutes maximum usage for an OEI takeoff.

6.4.2 Fan Rotor Physical Speed Redline

The fan speed redline demonstration shows that a type design test vehicle is capable of operating at its design limit for a limited time related to the operational environment it is expected to experience (see Section 7.2.3.2). The MTO LP (fan) limiting (redline) physical speed shall be demonstrated for a minimum of 30 minutes. The MCT LP redline physical speed shall be demonstrated for a minimum of 90 minutes. For the remainder of the test the fan speed will be maintained on average within +/- 3% of the limiting speed. Any speed shortfall during the remainder of the test, if the limiting component is an LP system rotating component must be accounted for in the comparative severity assessment.

The 30 minute MTO demonstration is justified based on the typical time required for a takeoff and climb to cruise conditions. The 90 minute MCT demonstration is related to a typical non-ETOPS diversion scenario.

6.4.3 EGT Redline

The MTO and MCT turbine temperature (EGT) redline demonstrations show a type design test vehicle is capable of running at its designed EGT limits for a minimum amount of time related to the engine's declared limiting operational capabilities (see Section 7.2.3.3). The majority of the testing will be accomplished at the maximum metal temperature associated with EGT redline for an engine modeled in its fully deteriorated condition. The applicant's CPA will define the pinch point operating condition for maximum Tm, and then assess the fully deteriorated engine at this limiting condition to determine the maximum Tm that would occur for EGT redline if the engine were operated to this extreme. It is important to note that this limiting condition is most likely to be at or beyond the conditions expected in-service, regardless of the value of measured gas-path turbine temperature, especially considering the additional conservatism discussed in Section 6.3.3.3. This running will accumulate a level of damage equivalent to the original intent of the current rule, and thereby establish the declared EGT redline for the TCDS.

7 Alternate Test Recommendations

7.1 Alternate Test Description

The proposed alternate test recommended by the ARAC Working Group combines elements of the currently defined test with new prescriptive requirements and performance based aspects (see section 6.1), making it a hybrid performance/prescriptive based test.
It is important to note that the test described in the subsequent sections is proposed as an alternate, not a superseding replacement, for the test currently defined in 14CFR33.87 for turbofan engines.

7.2 Alternate Test Definition

The definition of the test can be segregated into 6 separate elements; the first 4 of which are prescriptively defined, while the final 2 are performance based elements supported by analysis:

1. Test Vehicle Definition
2. Engine Redline Limit Demonstration (TCDS physical speeds & temperatures)
3. Ancillary TCDS Limits Demonstration
4. Incremental Cruise Power and Thrust
5. Engine Severity Demonstration over extended operating periods
6. Engine Rated Performance Demonstration
7. Additional Testing

7.2.1 Test Vehicle Definition

The test should be conducted using a test vehicle that substantially conforms to type design. Exceptions could include external test equipment, controls systems settings, and other modifications required to achieve the test conditions described below. Engine hardware modifications should be minimized, to preserve the type design hardware configuration and engine cycle match. Hardware modifications may be temporarily applied to achieve specific test conditions (e.g., for the limiting redline physical core speed test segment). Also included in the definition of the test vehicle is the current requirement of 14CFR33.87(a)(4) for the test vehicle to use fuel, lubricants, and hydraulic fluid that conform to the specifications for complying with 14CFR33.7(c).

7.2.2 Ancillary TCDS Limits Definition

The alternate test must meet the requirements of 14CFR33.87(a)(5),(6),(7) & (8) and (b)(6). This includes testing at bleed, horsepower extraction, oil temperature, fuel minimum and maximum pressure, transient, and start limits. Minor facilitating modifications may need to be made to run the conditions as required. The fact that the alternate test will not specifically define a test sequence or the number of times to complete this sequence, the applicant will define a proposed test sequence acceptable to the administrator. The requirements are shown below.

14CFR33.87(a)(5) Excerpt from the current rule - *Maximum air bleed for engine and aircraft services must be used during at least one-fifth of the runs, provided the validity of the test is not compromised. However, for these runs, the power or thrust or the rotor shaft rotational speed may be less than 100 percent of the value associated with the particular operation being tested if the FAA finds that the validity of the endurance test is not compromised.*

14CFR33.87(a)(6) Excerpt from the current rule - *Each accessory drive and mounting attachment must be loaded in accordance with the following 2 paragraphs.*

- *The load imposed by each accessory used only for aircraft service must be the limit load specified by the applicant for the engine drive and attachment point during rated maximum continuous power or thrust and higher output.*
- *The endurance test of any accessory drive and mounting attachment under load may be accomplished on a separate rig if the validity of the test is confirmed by an approved analysis.*

This is the same as current requirement.

14CFR33.87(a)(7) Excerpt from the current rule - *During the runs at any rated power or thrust the gas temperature and the oil inlet temperature must be maintained at the limiting temperature except where the test periods are not longer than 5 minutes and do not allow stabilization. At least one run must be made with fuel, oil, and hydraulic fluid at the minimum pressure limit and at least one run must be made with fuel, oil, and hydraulic fluid at the maximum pressure limit with fluid temperature reduced as necessary to allow maximum pressure to be attained.*

In the alternate test, fuel, oil, and hydraulic fluid pressure must be at their minimum and maximum pressure limits for 6 hours. The 6 hour requirement preserves equivalence to the current test and will include an appropriate amount of time at MTO and MCT segments.

14CFR33.87(a)(8) Excerpt from the current rule - *If the number of occurrences of either transient rotor shaft overspeed, transient gas overtemperature or transient engine overtorque is limited, that number of the accelerations required by paragraphs (b) through (g) of this section must be made at the limiting overspeed, overtemperature or overtorque. If the number of occurrences is not limited, half the required accelerations must be made at the limiting overspeed, overtemperature or overtorque.*

To be consistent with the current requirement, transient overshoots must be demonstrated on at least 155 of the accels to MTO (155 is equivalent to the number of accels/decels in the current rule).

14CFR33.87(b)(6) Excerpt from the current rule - *One hundred starts must be made, of which 25 starts must be preceded by at least a two-hour engine shutdown. There must be at least 10 false engine starts, pausing for the applicant's specified minimum fuel drainage time, before attempting a normal start. There must be at least 10 normal restarts with not longer than 15 minutes since engine shutdown. The remaining starts may be made after completing the 150 hours of endurance testing.*

This is the same as current rule requirement.

The recommendation is for a cyclic accumulation of approximately 500-750 cycles (in order to expose any potential incipient LCF, SPLCF, TMF type damage to airfoil components), although one minority opinion recommends that the current 355 cycles is sufficient. A cycle is defined as a rapid acceleration (throttle move in one second or less) from ground idle to at least maximum rated thrust and a rapid deceleration back to ground idle.

7.2.3 Engine Redline Demonstration (TCDS speeds & temperatures)

TCDS physical speed and temperature limiting conditions (redlines) must be demonstrated. Declared shaft redline values will be no greater than the average shaft physical speeds demonstrated in the engine redline demonstration sections of the test. Concurrent redline demonstration is required unless the CPA indicates it is not possible to occur in service within the declared operating envelope. The corresponding speed or temperature identified in the CPA must be met or exceeded on average during the demonstrations below. Rated thrust must be met (or exceeded) during all redline demonstration testing.

7.2.3.1 Core Speed Redline Demonstration

The greater of Maximum Takeoff (MTO) and Maximum Continuous (MCT) redline physical core speed must be demonstrated for a minimum of 10 minutes. However, if the CPA for a new design engine shows that more than 10 minutes could be used in service, or that NH physical speed redlines could be encountered regularly in service, then the NH speed redline test time will be extended accordingly.

For situations where MCT and MTO declared redlines are the same, additional analysis would be required to show that the MCT NH physical redline speed is never achievable at MCT power settings, if not then the demonstration time must be extended accordingly.

In conjunction with meeting minimum severity requirements, this will set the TCDS MTO and MCT declared core speed.

Additional testing to demonstrate equivalent severity (to the original intent of the test) to justify unlimited operation to the physical core speed pinch point will be explained in Section 7.2.5.

7.2.3.2 Fan Speed Redline Demonstration

The MTO LP (fan) limiting (redline) physical speed shall be demonstrated for a minimum of 30 minutes. The MCT LP redline physical speed shall be demonstrated for a minimum of 90 minutes. If MTO and MCT have the same declared LP redline speeds, then 120 minutes must be demonstrated.

Additional time may be necessary if the applicant's CPA indicates additional time at MTO or MCT redline physical fan speed could occur in service within the declared operating envelope; however, this demonstration is for basic engine certification and is not intended to include the additional test conditions required in the ETOPS qualification test (14CFR 33.201). In conjunction with meeting minimum severity requirements, this will set the TCDS MTO and MCT declarable fan speed.

Additional testing to demonstrate equivalent severity (to the original intent of the test) to justify unlimited operation to the fan physical speed pinch point will be performed in Section 7.2.5.

7.2.3.3 Gas Turbine Temperature Redline Demonstration

MTO redline EGT temperature must be continuously demonstrated for 10 minutes. Three snap/burst accelerations (1 second or less) from idle to the MTO redline temperature (hold redline for a duration of 90 seconds each) must also be demonstrated. MCT redline turbine temperature must be continuously demonstrated for 90 minutes.

Additional time at any or all of these conditions may be necessary if the applicant's CPA indicates additional time at the redline temperatures may occur in service within the declared operating envelope.

The 10 minute requirement at MTO redline coincides with the 10 minute TCDS limitation for an OEI takeoff at the maximum rating. The requirement for three accelerations from idle to max with 90 second hold times serves to represent the potential operational go-around scenario. The 90 minute MCT demonstration relates to an operational diversion scenario in a non-ETOPS flight.

The showing of equivalence for EGT red line demonstration to the intent of the rule is achieved by running significant time and cycles to cooled component metal temperatures in excess of design intent and will be performed in Section 7.2.5.

Additional testing to demonstrate equivalent severity (to the original intent of the test) to justify unlimited operation to the limiting turbine temperature pinch point will be performed in Section 7.2.7. The TCDS MTO and MCT declared redline gas temperatures will be determined by analysis upon completion of the test and is established as the lower of the following values:

1. Values no greater than the average temperatures demonstrated in the gas turbine temperature redline demonstration.
2. Values for MTO and MCT for which the severity demonstration for the entire test can be shown to have damage greater than or equal to the reference severity (section 6.3.3.2).

7.2.4 Incremental Cruise Power and Thrust

This section defines the twenty-five 15 step incremental cycles from idle to maximum continuous (figure 2.1 part D). The Definition of this part of the alternate test demonstration is identical to requirements of 14CFR33.87(b)(4) of the current rule, and is presented here.

Two hours and 30 minutes at the successive power lever positions corresponding to at least 15 approximately equal physical speed and time increments between maximum continuous engine rotational speed and ground or minimum idle rotational speed. For engines operating at constant speed, the thrust and power may be varied in place of speed. If there is significant peak vibration anywhere between ground idle and maximum continuous conditions, the number of increments chosen may be changed to increase the amount of running made while subject to the peak vibrations up to not more than 50 percent of the total time spent in incremental running.

The Definition of this part of the alternate test demonstration is identical to requirements of 14CFR33.87(b)(4) of the current rule.

7.2.5 Engine Severity Demonstration over extended operating periods

Limiting temperatures must be demonstrated for extended periods to accumulate the same damage to the critical components originally intended by the 18.75 hours at MTO and 45 hours at MCT conditions prescribed in the current rule. The limiting temperature(s) are either the redline gas path turbine temperature or the gas path temperature that corresponds to the maximum critical component temperature as defined by the applicant's CPA and agreed by the Administrator (ref. section 6.2; also refer to Appendix K (Section 13) for further considerations of severity assessment). The duration and exposure to MTO vs. MCT operation is to be determined and justified by the applicant.

This portion of the test is performance based, and the applicant determines the mix of cycles and cycle durations that best suit the engine design and operation. As discussed in Section 6.3, a methodology showing how damage to critical components accumulates is necessary for a comparative severity assessment to the original intent of the current test. The testing completed in this phase accounts for the majority of the damage accumulated during the entire test, and along with the prescriptive limit phases of testing defined in Sections 7.2.1 through 7.2.4 and the post-test comparative severity assessment form all the elements of the proposed test.

During this testing phase, rotor physical speeds should be maintained at the highest levels feasible with a test vehicle that meets type design per the guidance in Section 7.2.1, and on average should be held within +/-3% of the limiting speeds. Rated thrust (corrected for test stand/cell/inlet/nozzle as appropriate) must be met or exceeded during all of the extended limiting temperature testing.

7.2.6 Engine Rated Performance Demonstration

Completion of the test is determined by the applicant's methodologies for assessing damage and showing the damage accumulated represents a severity equivalent to the original intent of the current rule. Qualitatively, however, all of the testing outlined in Sections 7.2.3, 7.2.5, and 7.2.6 occurs at or above the rated performance allowed during normal operation (excluding any slave nacelle effect), using a test vehicle that substantially conforms to type design.

The engine's rated performance demonstration will be performed per 14CFR33.85.

7.2.7 Additional testing

Additional test demonstration may be required to complete the demonstration of equivalent severity. Any additional testing required must be at or above rated thrust. Additional cyclic content may also be included during this test phase. An example of a potential cycle is shown in Figure 11.2. The applicant may develop alternate cycles based on their CPA.

7.3 Alternate Test Example

The test proposal defined in Section 7.2 provides a framework for testing that is intended to meet the requirements for equivalency to the original intent of the current rule. The following illustrates an approach, but not the only approach, to create an alternate test that uses the comparative severity methodology presented in Section 6.

Section 7.2.1, *Test Vehicle Definition,* requires using a test vehicle that substantially conforms to type design. Further, the requirements in Section 7.2.2, *Ancillary Limits Definition,* are essentially identical to those identified in 14CFR33.87(a)(5)(6)(7)(8) and (b)(6) with the addition of a minimum engine cyclic requirement of 400 cycles from idle to rated thrust and back to idle. These requirements are satisfied during the testing defined in subsequent sections.

In this example, comparative severity to the original intent of the current test is based on the Creep failure mode as explained in Section 6.3.4. Damage factors relating to this failure mode are calculated for 1 hour of operation at each of the intended limiting power-settings and input into the spreadsheet accounting tool (see below).

Severity / Hr. for Critical Components			
Test Segment	Component #1	Component #2	Component #3
MTO NL Redline	0.00324		
MTO NH Redline	0.01354		
MTO EGT Redline	0.00726		
MCT NL Redline	0.00284		
MCT NH Redline	0.00933		
MCT EGT Redline	0.00448		
MTO EGT Limiting	0.00551		
MCT EGT Limiting	0.00273		
MTO Rated Thrust	0.00156		
MCT Rated Thrust	0.00142		

Damage Factors for Each Condition Normalized to 1 Hour at That Condition.

Figure 7.1 – Severity Factors (Life Usage Rate) for Critical Components

The requirements of Section 7.2.3, *Engine Redline Demonstration,* are illustrated below, along with the damage factors associated with engine operation at each power-setting condition for each prescribed duration. These test requirements represent minimum durations in a prescribed portion of the test. Additional testing at these conditions may be required based on the results of the applicant's CPA.

Engine Redline Demonstrations -- Rated thrust must be met or exceeded.:

		Accumulated Damage
30	minute minimum demonstration for N1	0.00112
10	minute minimum demonstration for N2	0.00225
10	minute minimum demonstration for N3	N/A
10	minute minimum continuous demonstration for MTO Temp.	0.00103
4.5	minute minimum demonstration for MTO Temp. Completed as three 90 second cycles.	0.00047
90	minute minimum continuous demonstration for MCT Temp.	0.00135

Damage Accumulated for Each Condition and Duration at That Condition.

Figure 7.2 – Severity Usage for Engine Redline Demonstrations

Meeting the requirements of Section 7.2.4 consists of testing at 15 equally-spaced power-settings between MCT and Idle. A duration of 10 minutes is prescribed at each power-setting. Twenty-five total cycles are also prescribed. The accumulated damage at the MCT power-setting is accounted for. The damage accumulated at the lower power-settings is minor, and not accounted for in the overall comparison.

Powerset	Cycles	MCT Duration (min.)	Total MCT Time (hr.)	Accumulated Damage
MCT	25	10	4.2	0.00592

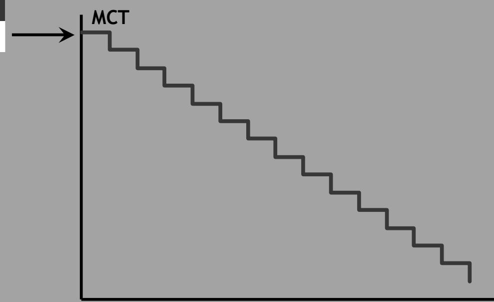
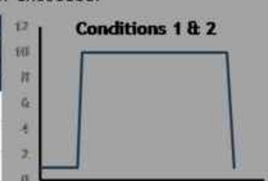


Figure 7.3 – Severity Usage for Part D Stair Step Cycles

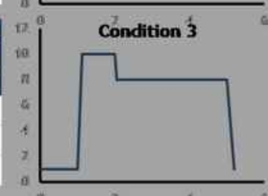
Engine limiting temperature (EGT) demonstration testing is a performance based aspect of the proposed alternate test. It requires analysis from the applicant to support the limiting temperature, and methodologies for how to conduct the test to represent the limiting temperature, and for demonstrating its severity. A mix of cycles is illustrated here that defines durations related to operation (e.g. 5 or 10 minutes at MTO, 30 or 90 minutes at MCT), and includes some cyclic content that contributes to the minimum cycle count defined in Section 7.2.2, *Ancillary Limits Definition.*

Engine Limiting Temperature Demonstration -- Rotor speeds must be held at or above the speeds predicted for the CPA condition. Rated thrust must be met or exceeded:

Condition No.	Powerset	Cycles	MTO Duration (min.)	Idle Duration (min.)	Total MTO Time (hr.)	Accumulated Damage
1a	MTO	20	10	5	3.3	0.01837
1b	MTO	60	5	5	5.0	0.02755
1c	MTO				0.0	0.00000



Condition No.	Powerset	Cycles	MCT Duration (min.)	Idle Duration (min.)	Total MCT Time (hr.)	Accumulated Damage
2a	MCT	10	90	5	15.0	0.04095
2b	MCT	20	30	5	10.0	0.02730
2c	MCT				0.0	0.00000



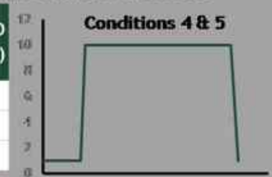
Condition No.	Powerset	Cycles	MTO Duration (min.)	MCT Duration (min.)	Idle Duration (min.)	Total MTO Time (hr.)	Total MCT Time (hr.)	Accumulated Damage
3a	MTO/MCT	20	5	30.0	5	1.7	10.0	0.03648
3b	MTO/MCT					0.0	0.0	0.00000
3c	MTO/MCT					0.0	0.0	0.00000

Figure 7.4 – Severity Usage for Extended Operating Periods

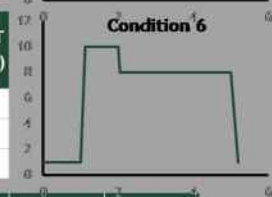
Engine rated performance demonstration is also a performance based element of the proposed alternate test, and is also supported by analysis that accumulates damage for critical components as part of the overall test severity assessed. A similar mix of various cycles and durations has also been used in this illustration, along with the respective accumulated damage. In this example, much of the cyclic content is conducted during this test segment.

Engine Rated Performance demonstration -- Rated thrust must be met or exceeded:

Condition No.	Powerset	Cycles	MTO Duration (min.)	Idle Duration (min.)	Total MTO Time (hr.)	Accumulated Damage
4a	MTO	50	0.5	5	0.4	0.00065
4b	MTO	200	5	5	16.7	0.02600
4c	MTO				0.0	0.00000



Condition No.	Powerset	Cycles	MCT Duration (min.)	Idle Duration (min.)	Total MCT Time (hr.)	Accumulated Damage
5a	MCT	20	90	5	30.0	0.04260
5b	MCT	20	30	5	10.0	0.01420
5c	MCT				0.0	0.00000



Condition No.	Powerset	Cycles	MTO Duration (min.)	MCT Duration (min.)	Idle Duration (min.)	Total MTO Time (hr.)	Total MCT Time (hr.)	Accumulated Damage
6a	MTO/MCT	30	5	20.0	5	2.5	10.0	0.01810
6b	MTO/MCT					0.0	0.0	0.00000
6c	MTO/MCT					0.0	0.0	0.00000

Figure 7.5 – Severity Usage for Additional Extended Conditions

Finally, in this example a summary of the test times and accumulated damage is compiled. This accumulated damage can be normalized by the reference severity, which, for this example was the Creep damage caused by 18.75 hours of operation at MTO limits and 45 hours of operation at MCT limits; the total accumulated times at these conditions in the current test.

Endurance Test Dashboard

Power-Setting	Test Time (hrs.)
MTO	30.7
MCT	70.7
Idle	50.0
Part Power Thrust	54.2
Total Time	205.5

Cycles	No.
MTO	380
MCT	70
Total Cycles	450

Power-Setting	Accumulated Damage	Reference Damage	Normalized Damage
MTO	0.09128	0.16000	0.57051
MCT	0.17327	0.06000	2.88783
Total Damage	0.26455	0.22000	1.20251

Accumulated damage normalized by the reference severity

Figure 7.6 – Cumulative Severity Usage for Whole Test –first example

In this example, the total test time is more than 35% longer than the current test, with the portions conducted at or above the MTO and MCT ratings approximately 50% longer. This example alternate test also includes 30% more cyclic content than the current test. The comparative severity of this alternate test example indicates it is 20% more severe with regards to Creep damage than the original intent of the current test.

A different mix of cycles more weighted to MCT operation illustrates that more time at lower temperatures can yield the same comparative severity. This example reflects a ratio between MTO and MCT power-setting more indicative of modern large air transport operation. In this example, the total test time is nearly 60% more than the current test, but the comparative severity to the original intent of the current test is the same as the previous example.

Endurance Test Dashboard

Power-Setting	Test Time (hrs.)
MTO	17.9
MCT	130.7
Idle	31.7
Part Power Thrust	54.2
Total Time	234.4

Cycles	No.
MTO	240
MCT	240
Total Cycles	480

Power-Setting	Accumulated Damage	Reference Damage	Normalized Damage
MTO	0.04111	0.16000	0.25692
MCT	0.22462	0.06000	3.74367
Total Damage	**0.26573**	**0.22000**	**1.20785**

Figure 7.7 – Cumulative Severity Usage for Whole Test –second example

7.4 Alternate Test Summary

In summary, the largest benefit gained by the use of the alternate test in this example is having completed the test with a type design test vehicle (ref. Section 7.2.1) while subjecting the test vehicle to conditions that result in equal or greater damage with respect to the original test intent. The alternate test content defined in Sections 7.2.2 and 7.2.4 retains prescriptive content defined in the current rule. The alternate test allows separate redline demonstrations of the rotor physical speeds and turbine temperatures (ref. Section 7.2.3), for engines for which it is shown by the CPA that concurrent redlines are not expected to occur. The durations at redline conditions are driven by the requirement for a type design test vehicle that does not contain enabling or survival modifications. Modern engine designs cannot successfully achieve all maximum operating conditions near Sea Level (ref. sections 4.3 & 4.6). In the declared operational envelope in type design configuration, these engines independently reach their maximum physical speeds and temperatures at disparate conditions (see Figure 4.8), in contrast to early designs that were designed to operate at maximum conditions at Takeoff.

Sections 7.2.5 presents a performance based element of testing conducted at or above the most extreme conditions the engine could see in service as defined by the CPA, but not necessarily at redline conditions. The nature of the performance based aspects of the test also allows the test to be somewhat customized for a particular engine design and operation. This gives the alternate test the potential to cover failure modes not addressed by the current test, and to evolve with the pace of technology. Finally, this example also includes a method for determining a severity comparison to the original intent of the current rule to ensure the test is adequate in its severity.

7.5 Follow-On Recommendations

The report indicates that the 33.87 test content and time duration originated in the 50's and was intended to demonstrate the "durability" of early gas turbine engines. In this context, durability is the ability of the engine to still generate the required thrust, retain adequate surge margin and retain sufficient efficiency and thus fuel consumption so as not to affect range. It is not a demonstration of future in-service reliability. In the early days of gas turbine service operation, the test completed a number of hours and cycles that were within a reasonable percentage of what was achieved in service before removals were required (for actual or impending failure or one of the aforementioned durability reasons most often inability to generate thrust within the temperature limits due to efficiency drop as a result of deterioration). The test was therefore a reasonable indicator of the "endurance" capability of the engine – i.e. how long it would take to experience a durability restriction (deterioration beyond ICA limits).

Today's engines can operate in service for orders of magnitude more hours and/or cycles than the contemporary engines when the rule was formulated. Durability can thus be interpreted as having been significantly increased. However, what has really happened is that the endurance capability of engines has substantially increased and therefor the test cycle and time duration from the 50s is no longer representative of today's engine's endurance capability.

What the current or future 33.87 test really does is demonstrate that the engine can accommodate a fixed amount of prescribed severity that is independent of what may be expected to be encountered by the engine in service. The endurance capability – how long the engine will take to consume the severity equivalent to the test in service is totally dependent on how the engine is operated and the margins that are set for a new engine to the operating limits.

Recommendations:

1. This test should be renamed as a "Severity Test" rather than the current "Endurance Test".
2. If a performance based goal for demonstrating the engine's endurance capability is necessary, with regard to both the cycle content and the total cumulated test time a separate piece of work needs to be commissioned. This should explore all tests that could be interpreted as having severity, durability and endurance content (e.g. IMI, ETOPS, and the military derived ASMET "Accelerated Simulated Mission Endurance Tests" approach taken by the military and referred to in appendix C section 10.3)
3. Follow-on work needs to be performed to develop an alternate test for turboshaft and turboprop engines, including the case where an OEI rating may be desired.

8 Harmonization of 14CFR33.87 and CS-E 740

In the early 2000s an FAA/JAA Engine Study Group working on establishing regulatory Standard Differences assessed the harmonization of the Endurance Test and concluded that the task was too difficult to undertake. Instead, the group found that the service record of engines certificated against 14CFR33 provided a similar aircraft level of safety as engines certificated against the CS-E standards and therefore equivalence could be assumed without direct harmonization of the texts.

Discussions during the ARAC meetings have come to a different general conclusion. Despite text differences and differing arrangement of the elements of the requirement, it was agreed that effectively 14CFR33 and CS-E Endurance tests are largely similar and for the purposes of HBPR engines and the alternate test, that harmonization is possible. This is not therefore concluding that all aspects of the regulations can be harmonized, but that the new changes introduced for the alternate test can be.

Appendix G (section 11.7) contains a detailed breakdown of the rule comparison for reference purposes. While capturing where harmonization was considered a part of the ARAC tasking, performing rule harmonization is outside the scope and is left to the agencies to undertake.

The fundamental differences that were discussed by the ARAC group are summarized in the following sections.

8.1 Derivation of the limitations, averaging vs minimums

The method for deriving the limitations from the test results differs. 33.87(a)(7) specifies that operating limits must be maintained at at-least 100% during the endurance test. 740(f), however, specifies operating limits are based on the mean values demonstrated in the appropriate periods of the endurance test with adjustment by analysis for the turbine entry temperatures to reduce the value obtained from the average test result to ensure that in service engines will not exceed the temperature demonstrated in the test (necessary due to the accuracy issues associated with gas temperature measurements, note that the adjustment does not apply to physical shaft speeds). Typically certification experience shows that this gives a similar result because each applies some conservatism to the test average, however the method of establishing the degree of conservatism is clearly different.

The alternative test proposal requires calculation of reference severity and severity equivalence which by necessity will be based on average test result values, the use of averaging is therefore appropriate for the alternative test proposal under both regulations.

8.2 Transients

740 Endurance Test transitory exhaust gas temperature (EGT) exceedance at take-off CS-E 740 (f)(4)(iii) vs 14CFR 33.87(a)(8) and AC ch3-2(h). The 14CFR 33 requirement for 30 sec transient over-temperature is to run the 30 second over-temperature on 50% of the Take-Off power accelerations giving in total 1 hr. 18 minutes at over-temperature levels. CS-E 740(f)(4)(iii) requirement for 2 minutes transient over-temperature is to run a 2 minute over-temperature at all accelerations to Take-Off power (6 hrs. 35 minutes at over-temperature). Each Authority has found the others approach acceptable and adopted

the others policy in the past through AC material and CRI/Issue Papers, therefore this difference may be harmonized.

8.3 Incorporation of the Alternative Test into the current rule

The Working Group has carried out a study of the impact of the alternative test proposal on the text of the existing endurance test requirements.

In the case of both 14CFR 33 and CS-E it is concluded that the task can be achieved without major disruption to the existing structure of the text. Both rules currently cover a number of generic issues associated with the test and then provide specific schedules which are selected according to the desired ratings or engine usage regime. It is foreseen that the majority of new material for the proposed test would be into a new schedule option inserted in each rule (33.87 and CS-E 740). The generic material will require minor revision in several areas only. A detailed breakdown is included in Appendix H.

9 Aftermarket Perspective

9.1 Current Test and AC Material

AC 33.87-2 "Comparative Endurance Test Method to Show Durability for Parts Manufacturer Approval of Turbine Engine and Auxiliary Power Unit Parts." was released in June 02 2009. The purpose of this AC is to describe "a comparative endurance test method to support showing compliance of certain turbine engine or auxiliary power unit (APU) parts when produced under Parts Manufacturer Approval (PMA). This method may be used when PMA applicants introduce changes that could affect the durability of their proposed designs. It may also be used when an applicant has insufficient comparative data to show that the durability of their proposed PMA part is at least equal to the type design."

Paragraph 6.d. of AC 33.87-2 supports the idea that a modified (alternate) test with an equal severity can be proposed by the applicant (and accepted by the authority.) The AC proposes using the Larson-Miller method to develop alternate time at temperature requirements for equivalent exposure.

The AC 33.87-2 methodology for modified/alternate tests with equivalent severity is consistent with the section 6.3.1 Severity Comparison to Current Test Intent.

9.2 Effect of Alternate Test Proposal

As discussed in Section 7.1 Alternate Test Description, the alternate test would be an alternate, not a superseding replacement, for the current test. Since the Alternate Test proposal would have an equivalent severity as the original intent of the current test, the modified (alternate) test methodology described in Paragraph 6.d. of AC 33.87-2 would still be appropriate and acceptable.

9.3 AC 33.87-2 Recommendations

With the proposed Alternate Test, AC 33.87-2 will not need a substantive re-write as it already contains provisions for a comparative severity methodology. The AC would need minor updates based on any final rule change and/or any updates to AC 33.87-1.

9.4 Cautionary Note:

The proposed alternate test would be an alternate, not a superseding replacement, for the current test. However, if the proposal were to change to a superseding replacement, there would need to be provisions to clearly identify which type of testing was performed. In the event of the test becoming a superseding replacement, significantly more work/thought would need to be applied to the exclusionary nature of using a DAH specific CPA as the basis for determining acceptable time at temperature requirements. One possible scenario would be to retain the 'equivalent severity' performance based requirement in the proposed Alternate Test and identifying the CPA as an aid, not a requirement, however the PMA applicant shall be expected to provide sufficient analysis to the agency to demonstrate appropriate severity. Since the team's focus was devoted to an alternate (not replacement) test these other ideas were not necessary and therefore not flushed out.

10 References

FAA Airworthiness Regulations

14CFR Part 33 Sec. 33.85 Calibration Tests (Amdt. 33-18, Eff. 8/19/1996)

14CFR Part 33 Sec. 33.87 Endurance Test (Amdt. 33-32, Eff. 4/13/2012, and prior historical amendments)

14CFR Part 33 Sec. 33.90 Initial Maintenance Inspection Test (Amdt. 33-21, Eff. 2/15/2007)

14CFR Part 33 Sec. 33.93 Teardown Inspections (Amdt. 33-25 Eff. 10/17/2008)

14CFR Part 33 Sec. 33.201 Design and Test Requirements for Early ETOPS Eligibility (Amdt. 33-21, Eff. 2/15/2007)

FAA Advisory Material

AC 33.87-1A Engine Overtorque Test, Calibration Test, Endurance Test, and Teardown Inspection for Turbine Engine Certification (March 9, 2015)

AC 33.87-2 Comparative Endurance Test Method to Show Durability for Parts Manufacturer Approval of Turbine Engine and Auxiliary Power Unit Parts (6/25/2009)

FAA Orders

FAA Order 8110.4C Type Certification (Change 5 effective 12/20/2011)

EASA Airworthiness Regulations

CS-E 730 Calibration Tests (Amdt. 4, Eff. 3/12/2015)

CS-E 740 Endurance Tests (Amdt. 4, Eff. 3/12/2015)

11 Appendices

11.1 Appendix A - List of Working Group Members

Last Name	First Name	Organization	Date On	Date Off
Mihail	Dorina	FAA	04/01/2014	--
Queitzsch	Chip	FAA	04/01/2014	--
Bouyer	Mark	FAA	06/01/2016	
Boud	Tony	EASA	04/01/2014	--
Cousineau	Yves	TCCA	04/01/2014	--
Drew	Walter	Airbus[2]	04/01/2014	09/15/2015
Lacomme	Olivier	Airbus[2]	09/15/2015	--
Oncina	Carlos	Boeing	04/01/2014	--
Thompson[1]	Peter	GE Aviation	04/01/2014	--
Markham	Pat	HEICO	04/01/2014	--
Rogozinski	Tom	Honeywell Aerospace	04/01/2014	09/25/2014
Niessink	Jim	Honeywell Aerospace	09/25/2014	--
Mias	Greg	Pratt & Whitney	04/01/2014	--
Beauregard	Mark	Pratt & Whitney Canada	04/01/2014	07/15/2015
Turyk	Peter	Pratt & Whitney Canada	07/15/2015	--
O'Connell	Pat	Rolls-Royce Corp.	04/01/2014	--
Forrest[1]	Neill	Rolls-Royce plc	04/01/2014	--
Bouvier	Dominique	Safran Aircraft Engines	04/01/2014	--
Senk	Jeff	Williams Int'l.	01/01/2015	01/06/2016
Hogge	Doug	Williams Int'l.	01/06/2016	--

Note 1: Co-Chair

Note 2: Airbus participation reduced with Walter Drew's departure. Airbus commented as they felt appropriate.

11.2 Appendix B - Detailed Chronological History of the Endurance Test Rule

11.2.1 Introduction

The “Endurance Test” prescribed currently in 14CFR33.87 sub part C for turbine engines has remained essentially unchanged since 1957 when the current 25 x 6 hour format was implemented. The origins of the test have been traced back to an endurance test defined for reciprocating engines that first appeared in the 1928 Department of Commerce Aeronautics Branch Aeronautics Bulletin No. 14. In the 1930s and 40s, the test was updated and refined to address lessons learned and technology advances. The prescribed test did not differentiate between reciprocating and turbine engines until 1952 when sub part C (turbines) was added. Understanding the evolution of that test is important in establishing why the test came to be prescribed as it is when considered in the context of engine technology, design intent, field operation, and service life expected at that time. The turbine endurance test has obvious roots in reciprocating engine operation with firewalled throttle operation and power chops, many of which were similar for early low technology turbine engines. Military operation may also have influenced the test rule. Aircraft of the day were drag critical, power challenged (rotor physical speed and temperature), and every ounce of power was needed to provide thrust so de-rate operation was not considered in designing this test.

11.2.2 Reciprocating engine origins

The original 1928 reciprocating engine endurance test was 50 hours total time, run 5 hours “throttle wide open” at rated speed and 10% over rated power, followed by 45 hours at rated speed and horsepower. Following the test, the engine was subjected to a full teardown inspection and then had to perform a 10 hour flight test. Updates implemented in the 1930s split the endurance demonstration into a manufacturer’s 100 hour test (13.201) that had to be passed to qualify an applicant for certification and a 50 hour certification “endurance” test (13.23). The manufacturer’s 100 hour test was to be run: 50 hours at full throttle at an average speed within +/- 3% of the proposed rated speed; and 50 hours at 75% proposed rated power at propeller load speed. After successful completion of the manufacturer’s test and correction of any problems identified during the test, the 50 hour endurance test was conducted. The 50 hour test was run “at full throttle”, “at a speed approximately equal to the proposed rated speed”. Also at this time, additional requirements were added for monitoring and declaring limiting cylinder head temperature (13.232), testing to certify a takeoff only rating above the rating declared for the type test (13.24), and testing of super-turbocharged Commercial Altitude Engines (13.3).Super-turbocharging (generic term includes super charging, turbo charging, or a combination of the two) was implemented so that power levels could be sustained at altitude condition by increasing the volume of air that the engine could consume. At sea level, the boost pressure ratio could not be fully exercised without causing unrepresentative over-boost and damage to the engine. This meant that Altitude Engines had to be tested with enabling modifications in order to assess their ratings as a function of altitude and boost over the declared operating envelope

The rule dictated that the endurance test had to be run in periods of at least 5 hours’ duration on consecutive days with as few stops and starts as possible. Stops for normal required maintenance were allowed, but no more than three forced stops (unintended shut downs) were allowed. For each forced stop, a 5 hour penalty run at maximum power was added. Any work associated with a normal maintenance stop or repairs to correct an unintended stop, had to be accomplished in time to allow testing to re-start the following day thus limiting the extent of allowable repairs. A failure of a component that would have been judged to force an immediate landing or major component replacement was grounds to terminate the test. The engine could be run with a propeller or against a water brake. If run with a propeller, the propeller could be changed during the test to maintain consistent loading with changes in ambient conditions.

To certify a takeoff power rating of no more than 10% above the endurance rating required running an additional 10 hours at the declared takeoff power., This demonstration could be run either as the last 10 hours of the endurance test or as an additional 10 hours added to the test. The 10 hours of takeoff power could be run either as two 5 hour consecutive blocks (total 10 hours) or as 20 hours total time conducted in blocks of 5mins at idle followed by 5mins at max power. This second option was similar to the current 33.87 part A cycles. If the applicant desired a takeoff rating greater than 10% above the declared rating or takeoff shaft speed in excess of the endurance test demonstration, then additional testing would be required in addition to a special ruling by the Secretary. The 10 hour flight test requirement from the 1928 regulation was retained in section 13.205 but was changed to not require flight demonstration using the endurance test engine

At this time, engine and aircraft operation would have been basic. The throttle will have been “firewalled” for takeoff and the maximum physical speeds and cylinder temperatures will have been co-incident with maximum power. Power will then have been reduced for climb and cruise. There would be limited controls intervention in the operation of the engines. The likely overhaul life of an engine would have typically been less than 200hrs and in flight shut downs were frequent. The test was therefore likely to reproduce the distress, wear out and failure mechanisms that could be seen through service operation. Note that the maximum temperature measured was the 2 hottest cylinder head (and barrels for air cooled engines) temperatures. That temperature would have a direct proportional relationship to the peak temperature of the burning gas inside the cylinder cavity and was likely to vary cylinder to cylinder due to engine design, installation, and tolerances etc.

The CAR issue in 1941 made a number of significant changes to the engine regulations. It eliminated the manufacturer’s 100 hour test, eliminated the Commercial Altitude Engine section (boosted engines), rolled most endurance test relevant requirements into a new section, 13.215 (including the takeoff only rating), eliminated the 10% above endurance test limit on takeoff ratings, increased the endurance block test time to 150 hours, and dropped the +/-3% speed variation allowance. The new block test was conducted at 4 different power settings; 1) 50 hours at “maximum except takeoff” power, 2) 50 hours at the most critical cruise condition (“critical” was not defined but could have been dictated by the peak vibration response characteristic of that particular reciprocating engine, or may have been dictated by boost limitations, the criteria were not found in this review), 3) 40 hours at 91% takeoff power (roughly equivalent to maximum continuous rating) but not less than “maximum except takeoff”, and 4) 10 hours at the declared takeoff power. The test had to be conducted in the above specified order and in periods of not less than 30mins running time. Section 13.250 was added to clarify what engine adjustments and parts replacements were allowed without declaring termination of the test.

For a normally aspirated engine without special takeoff rating, the revised test reduces to 100 hours at the declared rating and 50 hours cruise. The intent of the four segments of the 13.215 endurance test become apparent for engines with special takeoff rating and/or boost capability. One detail the revision left out was the explanatory material allowing enabling modifications for testing boosted engines at sea level static. It is not documented why the regulation was mute on this, but it has to be assumed that either altitude cell testing was becoming available or enabling modifications must have been allowed. It was also not documented why the option to perform the takeoff demonstration at 5mins at takeoff followed by 5mins at idle was withdrawn. However operating conditions and limitations (13.212), calibration tests (13.213) and operation tests (13.214) were added at this time.

11.2.3 Introduction of turbine engine rule

The CAR issue of 1952 was where the reciprocating engine and turbine engine endurance tests were first definitively separated. The reciprocating engine "Endurance" test became 13.154 and the turbine engine "Endurance" test 13.254. The test retained the 150hrs total test time but the running of the test was changed. The 5 min chops/accels from idle to max that had been dropped in the 1942 issue became compulsory at this point as it was probably realized that thermal and stress cycles as well as time on fixed condition had a detrimental effect on engine life and the wear out and failure mechanisms. Per 13.254, the engine would be run, without bleed extraction, to the thrust or power rating required for each condition, while holding a single predetermined variable (a speed or temperature) constant (except for the cycling portions (a and f), and the applicant was to record the corresponding thrust/power setting used for each condition. To try to ensure maximum physical speeds and temperatures were achieved during the test, the calibration requirement (13.252) stipulated that prior to the endurance test the controls would be adjusted to produce the maximum speeds and temperatures when the engine was operated at takeoff. It is not documented why, but the 1952 issue retained the speed control allowance of +/-3% for reciprocating engines (13.154) but did not include the allowance for turbine engines (13.254). Note that the gas temperature on a gas turbine design of the day would be directly proportional to the turbine gas path components "metal" temperature as the blades were uncooled.

The 1952 Endurance test was split into 30x 5 hour blocks to be completed in the following prescribed order:

a. 60mins of alternating 5mins at max takeoff power/thrust and 5mins at idling power/thrust (6 cycles). (as part A of current 14CFR 33.87 test)
b. 30mins at 91% of max takeoff power/ thrust (Similar to part B of current test – power between max Continuous and max Takeoff)
c. 90mins at max continuous power/thrust (As part C of current 14CFR 33.87 test)
d. 60mins at 90% of maximum continuous power/thrust
e. 30mins at 75% of maximum continuous power/thrust
f. 30mins of alternating accels to Maximum takeoff power for 30secs followed by approximately 5mins at idling power/thrust (5 cycles) (Similar to Part E of the current 14CFR 33.87 test)

In addition, the engine had to complete 75 starts of which 30 had to be after a 2 hour shutdown.

Note that the target engine settings for all test conditions were to rated (maximum or continuous) power or thrust. Gas temp and physical speed conditions were derived from the test at the power run for the rating. The test was not run to the maximum declared physical speeds or temperatures (similar to traditional reciprocating engine endurance testing), rather these values fell out from the test. Implicitly, the engine would get faster and hotter as the engine deteriorated so the "constant" speed or temperature held for a given test condition, would have been the speed or temperature as achieved based on the day environmental condition and engine deterioration state. Mention of the need to run on consecutive days was also eliminated in this issue.

On completion of the test, an "operation" test (13.255) was required on the engine to demonstrate starting, idling, accelerations, transient overspeed, propeller function (if required), ignition and any other characteristic as found necessary by the administrator. The engine also had to undergo a detailed teardown inspection (13.256) to check for "wear and fatigue". Servicing, adjustment and minor repairs were allowed during the test by 13.257. Any major repairs or parts replacement found necessary during the test or as a result of the teardown inspection would be subject to additional testing as found necessary by the Administrator.

It is worthy of note that paragraph 13.204 of this issue of the CARs defines a requirement for the "Durability" of the design and construction of the engine. It states that, "All parts of the engine shall be designed and constructed to minimize the development of an unsafe condition of the engine between overhaul periods".

11.2.4 The test in the format used today

The 1957 issue of CAR 13, changes were made to harmonize with the military specifications. The changes included the first instance of what is still today's 14CFR 33.87 endurance test cycle using the 25x6 hours cycle structure. This was also the revision where the test was changed to require running to maximum temperatures and physical rotor speeds rather than rated power/thrust, but the revision did reintroduce the allowance to control rotor speeds to +/-3% of declared values. It also specified that the engine had to demonstrate at the end of the test that it could still achieve rated thrust/ power with full deterioration and within the declared physical speed and temperature redlines. At this time gas path temperature and turbine component "metal" temperature were still close to being directly proportional as the most sophisticated engines of the time had only progressed to internally cooled airfoils. Maximum continuous thrust came in at a specified altitude condition (correcting thrust for gross and net was allowed in setting the test condition) and was thus application dependent rather than specified as a percentage of maximum power (as was done for reciprocating engines). In addition, a component test requirement was introduced to provision for instances where the whole engine test didn't adequately exercise a component, feature, or sub-system. That has evolved through the years and is occasionally used to justify not doing things on the engine test for convenience. (e.g. accessory loading on external gearbox).

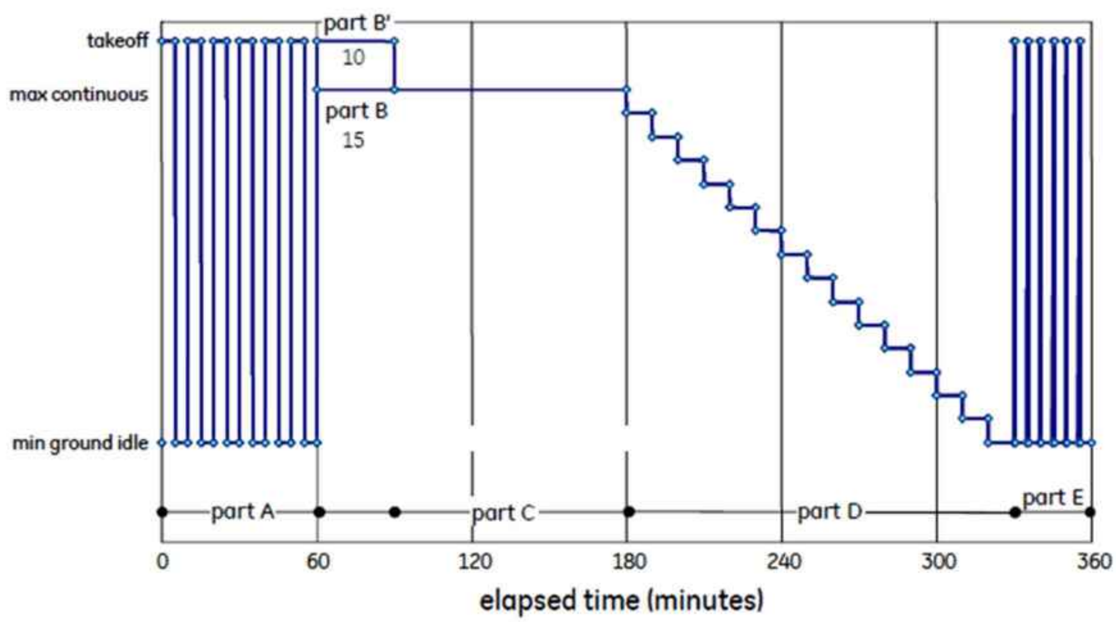


Figure 11.1: the 33.87 6hr block to be repeated 25 times introduced in 1957

The 1958 issue of CAR 13 amendment 13-2 effective May 17, 1958 revised the specification of power and/or thrust and of engine rotational speed of a tolerance in the endurance test from “+/-3 percent of the specified values” to “at not less than 100 percent of the specified values.”

There quickly followed a series of changes from 1958-1964 for helicopters and OEI (One Engine Inoperative) conditions to address the demands of those applications and control problems (no “set and forget”). In summary, helicopters in low speed and hover operation require continual power setting input change from the pilot. Following an engine out event the pilot needed the ability to demand a short burst of “excess” power in order to execute a safe landing. In this case the engine would have to be subject to a thorough inspection and a level of damage was allowed should such an event be instigated.

11.2.5 Endurance Test Requirements - Evolution of 14CFR 33.87 Since 1965

The new 14CFR33 became effective on February 1, 1965 when the FAA recodification program was issued to replace the airworthiness requirements contained in part 13 of the CAR. Section 33.85 Calibration tests, is the same as its equivalent paragraph in the CAR part 13, except for an additional requirement that the engine power control be adjusted to produce the maximum allowable gas temperatures and physical rotor speeds at takeoff operating conditions before the endurance test, and may not be changed during calibration tests and the endurance test. The contents of 14CFR33.87 Endurance test and 33.93 Teardown inspection, are the same as their equivalent paragraphs in the CAR part 13, except for minor editorial differences. Section 33.99 General conduct of block tests was completely revised from its equivalent paragraph in the CAR part 13.

A new amendment 6 was introduced in October 1974. It adopted a new section 14CFR33.82, General, requiring the applicant to establish and record certain adjustment settings and functioning characteristics of engine components before starting the endurance test. This paragraph is the same in the current regulations. Section 33.85(a) of the calibration test was revised to include only the compressor air bleed essential for engine functioning during the test. Section 33.85(b) was revised to the current regulation. This amendment added 14CFR33.87(a)(3) to address the allowance for multiple engine tests when all engine parameters could not be held simultaneously at the 100 percent level that was to be certified. The revision based on certification experience with high-bypass large turbofan engine certifications and was in response to the increasing complexity of airframes, engines, and their interfaces. Other revisions were to expand 14CFR33.87(a) to the current requirements, except that the test may be run at reduced power or thrust or rotor speeds below the 100 percent physical value specified in 14CFR33.87(a)(3) during maximum air bleed runs, and the testing of accessory drives and mounting attachments may be accomplished on a rig in 14CFR33.87(a)(6). The amendment also added the endurance test schedule for supersonic aircraft engine.

A new amendment 10 was introduced in March 1984. This amendment updated 14CFR33.87(a)(3), (a)(5), and (a)(6) to the current requirements. Sections 33.87(a)(3) and (a)(5) were revised to allow the applicant to reduce power or thrust or physical rotor speeds below the 100 percent value specified in 14CFR33.87(a)(3) during maximum compressor air bleed runs, as it is not always possible to reach redline physical speeds at takeoff and maximum continuous thrust/power without exceeding gas temperature limits. Section 33.87(a)(6) was revised to allow separate rig testing of accessory drives and mounting attachments. A new requirement was added to address the rotorcraft engines OEI rating.

The later amendments 12, 18, and 25 added rotorcraft OEI requirements. Amendment 30 added transient engine overtorque to 14CFR33.87(a)(8).

There is no rationale provided in the available record that explains why each part of the 6hr cycle is specified in the way that it is. In conducting this ARAC exercise the authorities and industry believe the following hypothesis explains the rationale:

1. Overall duration – 25x6hrs stages, total 150hrs. This is believed to show accelerated durability demonstration at roughly a 2:1 rate. The typical time between overhauls with hard lifed turbines was approx. 300hrs in the early 1960s In the late 1960s this jumped to around 1000hrs when turbine blade manufacturing moved from forged to cast and then to directionally solidified cast technology.
2. Part As/1s – 6x5mins at MTO and idle with burst accels and chop decels in between. 5mins was the MTO rating time. The slams were likely to maximize the damage in the shortest possible time by combining maximum thermal gradients with the time at max temperature. All engines at that time ran labyrinth seals and these cycles would cut seals and tip clearances quickly. The engine designs however had bigger clearances and non-rubbing compressors so this maneuver was less critical to clearance deterioration than for today's engines.
3. Part Bs/2s – 30mins at MCT (part B) and MTO (part B'). 30 minutes was typical time to climb to get to cruise and aircraft of the day were generally very underpowered requiring use of the rating.
4. Parts Cs/3s – 90mins at MCT. This was perceived to be related to nominal cruise duration with one engine out. Max power would be selected on the other engines and altitude would decrease until the aircraft could sustain level flight.
5. Part Ds/4s – The incremental stair step at even speed intervals from max continuous to high idle were designed to cover potential cruise settings and expose vibration issues that may occur at intermediate speed conditions. On reciprocating engine there are pronounced characteristic higher vibration zones in the upper power range and the reciprocating test asked for prolonged running in these zones. Running at those specific speeds exposed vibration related failures. With smooth running gas turbines, the characteristics are not as pronounced so the test needed to cover whole running range.
6. Part Es/5s – 6x30secs at MTO interspersed with 6x5mins at idle with bursts in between. These are likely to represent aborted takeoff maneuvers. Repeated accelerations to max takeoff and roll aborted for a myriad of reasons were not uncommon on engines of the 1950s-1970s.

7. The test schedule was also intended to maximize component deformation and growth and facilitate discovery of any subsequent undesired effects (such as hot air ingestion from the gas path) with extended dwell times (e.g. 30 minutes MTO cycles).

In addition to the requirements of 25 cycles, its defined profile and redline demonstrations, the prescribed test for turbofan & turbojet engines requires demonstration of the following:

- Maximum customer bleed required for 20% of the cycles. The current test requirement for 1/5th of the cycles to be operated with bleed appears to be arbitrary. Includes engine bleed used for engine nacelle anti-ice and aircraft environmental conditioning/control system (ECS). It may have been based on early engine bleed use for anti-ice or other intermittent aircraft bleed air use but no documentation exists to explain the rationale.
  Note, the original 1952 turbine engine test requirement stated no bleed would be taken during the test unless required for normal engine operation. This was updated to the current test bleed usage requirement in 1957.
- Maximum oil temperature is required for steady state periods in excess of 5 minutes. Maintaining maximum gas path temperature (EGT) and oil system inlet temperature during

maximum thrust/power operations demonstrates the engine's ability to acceptably operate (including in a deteriorated condition), and with appropriate durability, under maximum, steady state, system temperature conditions. The engine system is 'soaked' at elevated temperature level. It also demonstrates the engine's oil lubricating and cooling system capacity capabilities under maximum steady state thermal conditions for extended time periods. The, "Not longer than 5 minutes" exception reinforces that intent is more for steady state, 'soaked', thermal conditions rather than transients.

- At least one run must be made with fuel, oil, and hydraulic fluid at the minimum pressure limit and at least one run must be made with fuel, oil, and hydraulic fluid at the maximum pressure limit. Runs conducted with engine fuel, oil and hydraulic fluid systems operating at these pressure levels demonstrate the engine's (and its fuel, oil and hydraulic systems') ability to acceptably operate (steady state and transiently) at these conditions throughout its rotor physical speed ranges and at maximum gas path temperature level. It also demonstrates fuel, oil and hydraulic system hardware durability when operated under these conditions. The quantity (one of each) may be arbitrary, but practical in that there are only 6 "A" cycles available in order to run the minimum and maximum pressure conditions.
- Transient throttle movements are within one (1) second.
- Minimum of 100 starts, with prescribed number (25) of starts preceded by a minimum two (2) hour shutdown time, ten (10) false starts and ten (10) starts within fifteen (15) minutes of a shutdown.

Following the completion of the test the engine must be capable of reaching rated thrust at SLS conditions within its declared operating limits per 14CFR33.85. Additionally, following completion of the endurance test, the engine must be disassembled to piece parts and shown to conform to its type design, its parts being capable of reinstallation after inspection and assessment against the Instructions For Continued Airworthiness per 14 CR 33.93.

11.2.6 "Deviations" to the existing rule to allow test to be conducted

The current test cannot be conducted on modern HBPR engines as prescribed in the regulations without modifying the engine and running the test out of sequence. As stated in the AIA/ASD section of this report, this has become more and more difficult as the engine cycle becomes more demanding (high OPR and BPR) and the turbine cooling design more sophisticated (film cooling and thermal barrier coatings).

Order of the test: The rule specifies that the test should be conducted in the prescribed order, i.e. 25 sequential repeats of parts 1-5. The test today is never run in the prescribed sequence on HBPR engines. The test order is varied (blocked) to allow more efficient test utilization and the recognition that early deterioration does not allow the engine to complete the MCT portions of the test without exceeding the declared MCT redline with suitable justification provided by the applicant, the agencies have allowed the test sequence to be substantially altered within predetermined limitations. A common limitation has been that each portion of an "A" cycle (i.e. 6 back-to-back G/I –to-T/O rapid accel/decel) had to be maintained.

11.2.7 Introduction of the IMI test 14CFR 33.90

At some point in the early 1970s, it became clear that with advancing engine technology the practice of relying on extrapolation of the results of the 150-hour endurance test to imply demonstration of the initial service period to first overhaul life was no longer valid. At that time, service overhaul life varied from approximately 500 to 2000 hours depending on the engine type. Consequently the regulatory tests, including 14CFR 33.87 were recognized as not providing a direct demonstration of entry into service durability. This was supported by observation that the 14CFR33.87 test was not giving an accurate representation of service experience and it was believed that the initial overhaul times needed to be set based upon test conditions that more fairly represented actual service conditions and cyclic operation.

As engine and airframe capabilities advanced, engine requirements and operation in service evolved and airframers required more sophisticated rating structures as they offered aircraft for a broader market. Engine OPR and BPR were increasing and de-rated takeoff operations were being introduced; primarily to increase engine on wing life and thus reduce operating cost by ensuring engines were not operated to max power where it was not required.

Additionally, more advanced turbine designs were evolving that incorporated cooling schemes and thermal barrier coatings which lowered turbine flow path hardware (blades, nozzles, shrouds, etc.) metal temperatures below gas path temperature and broke the historical proportionality between gas path temperature (EGT/TGT) and component metal temperature. While producing great benefit for hot component life in service, it broke any connection that may have existed earlier between service expectation and the turbine thermo-mechanical damage accumulated during the 33.87 test. This was because cooled turbine components were being less directly influenced by the turbine gas path temperature and more by the cooling air temperature that was in turn influenced by day temperature and compressor operation. In addition, the inclusion of cooling shifted the HP turbine blade failure mode from creep to longer time (>>150 hours) mechanisms such as oxidation and sulfidation. Therefore, completing the 33.87 block test could no longer be used to establish in service overhaul intervals. This gave rise to creating the “Initial Maintenance Inspection” or IMI test which was added to the FAA regulations in 1974.

The IMI test requirement, 14CFR 33.90, is an addition to the endurance test in 33.87. It was included in proposal #32 of NPRM 71-12 Federal Register: May 5, 1971 and was adopted as Amendment 33-6 effective October 31, 1974. As adopted, rule 33.90 applied only to engines being originally type certificated from that point forward. It did not apply to engines being certificated through amendments to existing type certificates or through supplemental type certification procedures (e.g. an existing engine design could be cleared for a new airframe application without the additional need to complete this test). The test was required to be accomplished on an engine which substantially conforms to the final type design. It is unclear why that specific statement was made but it could be implied, that by that time, modifications were required to meet the 33.87 “endurance” test and it was probably becoming clear that these modifications created questions about the test’s relationship with service expectations.

Opinion was expressed at the time that it was unreasonable to require the completion of an overhaul test in addition to the endurance test as a condition of type certification and believed that past practices were adequate to establish an initial overhaul period. One commentator stated that the 150 hour endurance test, because of its accelerated nature, should be equivalent to a 1000 hour overhaul period. The FAA did not agree since experience on certain engines had shown that the endurance test has not been equivalent to longer service operations, especially for periods as long as 1000 hours. Note that even to this day there is and has never been a European BCAR/ JAR/ EASA equivalent regulation to the IMI test although validation by the US FAA requires the test be conducted by non-US applicants.

11.3 Appendix C – AIA/ASD Study Results

The proposed alternate developed in the AIA/ASD Study was to conduct a 1000 cycle test based on a profile that has proven effective in replicating field deterioration on an accelerated basis. The cycle the AIA/ASD recommended is very similar to that used for IMI and ETOPS tests but is run to more severe temperatures and speeds. A key presumption was to follow the military lead where they now solely use cyclic ASMET "Accelerated Simulated Mission Endurance Tests" to demonstrate durability at harsh operating speeds and temperatures. The cycle as proposed was based upon an accelerated representative flight cycle and includes:

- Run to Redline/Limiting EGT (TET) for all declared rating conditions consistent with the 14CFR 33.87 and CS-E 740 requirements
- Rotor physical speeds fall out based upon the tested conditions – no artificial changes to the fan and/or core speeds or speed relationships
- Equivalent creep life consumption to the current 14CFR33.87 / CS-E 740 requirement intent replicates worst (lowest) creep life turbine stage for average worst (harshest) operator
- Creep life consumption for other turbine stages through test to be shown by analysis to be at least that of service consumption for same worst average operator over same operational duration for worst stage

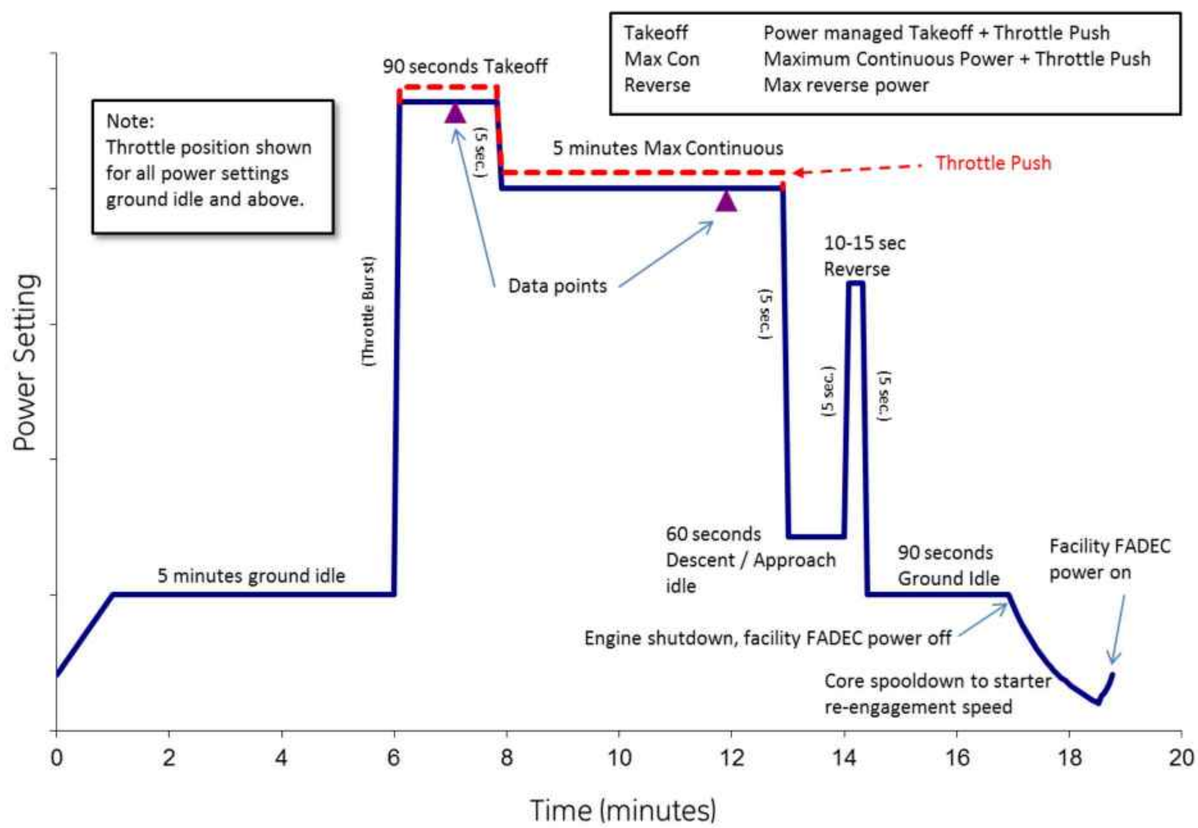


Figure 11.2 - Cyclic Test to Exercise Low Cycle Fatigue with throttle push (red colored line) to exercise limiting EGT (TET)

Note that cycle times can be amended to best represent accelerated service cycle but 90secs. at MTO and 5 mins. at MCT should be averages over the 1000 cycles

The test would accumulate a total of 18.75 hours at takeoff limiting EGT (TET) and 45 hours Max Continuous limiting EGT (TET) exposure during the test as per the current regulation. To reach that target and show creep equivalence, the test would have to include a minimum of at least c. 450 cycles. Additional cycles at or above rated thrust for the day conditions would be conducted to up the LCF content to c.3x that of the current test (325 accelerations). Engine operation at or above rated takeoff thrust / Max Continuous thrust for 25 hrs. / 83 hrs. respectively, in excess of the current 18.75/45 hrs. requirement and a total engine run time of >280 hrs. would be completed vs. current requirement of 150 hrs.

The corrected speeds achieved in the test would correspond to the engine power setting and would result in mechanical speeds corresponding to the tested ambient conditions. For standard practice sea level static testing, that would mean a redline (mechanical speed) shortfall on average throughout the test of the order of 3%. This would vary from engine to engine as a function of design and build.

To retain aspects of the current test, some cycles were proposed to be prescribed with extended and reduced times and run for a limited number of cycles:

- 5 cycles at 30 mins. MTO
- 10 cycles at 30 mins. MCT
- 150 cycles at 5 mins. MTO
- 150 cycles at 30 secs. MTO

155 of the cycle accelerations run will have to show the transient max EGT/TET if an applicant wants to declare overshoot capability (as current test).

The pass/fail criteria would be the same as for the existing test.

The key secondary requirements from the existing test would also be fulfilled during this test as follows:

- Bleed. Max services bleed must be applied for 75 cycles (as current test) with roughly even distribution across the cycles and durations at max conditions. All other cycles demonstrate nominal range of bleed conditions.
- Oil temperature. Max oil temp would be sustained for 250 cycles in blocks spread between the beginning and end of test and distributed across any differing cycle times (replicated time at MTO and MCT from current test). All other cycles at normal (unadjusted) oil temperature.
- Oil pressure. 15 cycles would be conducted at min oil pressure between cycles 800 and 900 incorporating any difference in cycle times. 15 cycles would be conducted at max oil pressure with normal (unadjusted) oil temp. Note that this can be demonstrated on a separate test as currently allowed by 14CFR 33.87 and CS-E 740.
- Transient max EGT/TET. If required, this limit would run for 155 cycles, spread across duration of test in blocks and across any differing cycle times but will not exceed 2 minutes at any time as per the current test.

To ensure that the gap between average demonstrated physical speeds and the declared redlines is covered, this test relies on demonstrations made under several other regulations that show there are no unsafe conditions, namely:

- Aeromechanics (14CFR33.83 / CS-E 650)
- Over temperature (14CFR 33.88 / CS-E 870)
- Over-speed test and analysis (14CFR 33.88 /CS-E 830)
- Analysis to show that rotor growth is acceptable at limiting (redline) physical speed
- Demonstrate HCF capability via conduct of vibration endurance engine test under 14CFR 33.63

In addition, the test would be used to demonstrate starting and fluid drainage consistent with 14CFR33.87 / CS-E 750. Any engine maintenance would be conducted per draft ICA requirement.

If negotiated with the regulators, the test could also be conducted to additionally meet the requirements of IMI test ref 14CFR33.90, thus covering both requirements with one test.

The proposed test achieves the goal of accelerated durability demonstration via a cyclic test with LCF exposure in excess of that contained in the currently prescribed “Endurance” test. No flowpath or cooling modifications to the type design are necessary and engine operation will be within type design characteristic. The cycles are more representative of in-service operation while maintaining demonstration of EGT limits. The fundamental difference in durability demonstration means is LCF versus time at temperature and speed. HCF capability would be demonstrated via conduct of the 14CFR33.63 vibration test.

Industry has previously requested collaboration with the agencies on developing an alternate to 14CFR33.87 and CS-E 740 using the industry’s AIA/ASD proposal as a basic straw man and this cycle has been part of the cyclic content considered by the ARAC WG in developing their alternate proposal.

11.4 Appendix D – Intent of the Rule – Supporting Information

The following narrative describes in detail an interpretation of the intent of 14CFR33, Section 33.87(a) and (b) (Amendment 32, 4/13/2012), as it relates to modern large turbofan engines.

Purpose: The purpose is to provide insight into an understanding of the intent of the subject regulation, so as to assist in defining a proposed Alternate to today's test.

Where appropriate this discussion will include references to legacy, FAA-accepted, test methods of compliance (MoC) to 14CFR33.87.

Scope: This paper's scope is limited to contemporary large, turbofan engine experience, and is also limited to the following paragraphs and sub-paragraphs of 14CFR33.87: 14CFR33.87(a)(1) through (8) and 14CFR33.87(b). However, regulation wording content within these paragraphs and sub-paragraphs that is not applicable to a large turbofan engine will be excluded.

Additionally, where appropriate, reference(s) to FAA guidance provided by AC 33.87-1A will also be included.

Discussion: The following discussion will be presented, to the greatest extent possible, in order of the regulations content.

11.4.1 General

"(a) General. Each engine must be subjected to an endurance test that includes a total of at least 150 hours of operation and, depending upon the type and contemplated use of the engine, consists of one of the series of runs specified in paragraphs (b) through (g) of this section, as applicable. For engines tested under paragraphs (b), (c), (d), (e) or (g) of this section, the prescribed 6-hour test sequence must be conducted 25 times to complete the required 150 hours of operation. …"

Understanding of intent:

- This is a prescriptive endurance test definition intended to maintain regulatory compliance consistency with what the FAA has determined, at some point in the past, was acceptable initial, entry-into-service , operational airworthiness-related durability.
- The 150 hour total test duration, individual cycle portion durations and/or 6 hour "A" cycle duration and 25 repetitions is seen as arbitrary.
    - It's not clear whether this total duration was set and the individual test cycle portion contents/durations and 25 occurrences defined to fit into 150 hours, or the individual cycle portion contents/durations were defined first, then 25 repetitions decided upon and the 150 hour total test duration fell out. However, it appears to have its 150 total duration roots in the reciprocating regulations dating to the early 1930s, while the cycle content evolved quickly over the first two CAR amendments for turbine engines in the 1950s.0s

- The 6-hours test cycle was intended to combine damaging redline conditions that could occur in service (and could be run at SLS for engines of the era in which the cycle was developed) and cover emergency and corner of the envelope type operations. While for the early engines, TRL occurrences or extended running time durations at single or double redlines were likely to occur, today's modern engines potential for concurrent redlines is considered to be far less likely and in some cases possibly remote. The 25 repetitions were intended to expose an engine as it becomes increasingly deteriorated to the same 6 hours test cycle conditions with the goal to verify engine durability as the engine deteriorates.

- The Post-test engine calibration test and teardown inspection show (respectively) that the engine continues to be able to produce rated thrust without exceeding declared redlines and its hardware are serviceable per the engine manual.

Relevant notes regarding historical applications:

- Conduct the endurance test for a total duration of at least 150 hours. Typically FAA-credited, total certification test time has been no more than minutes over 150 hours. (Note: under 14CFR33.87, credited time runs from when the engine stabilizes on condition, until the condition is concluded.)
- Test runs contained in paragraph (b) are used for compliance.
- The engine is required to run each part of the 6 hour sequence 25 times in order to satisfy this requirement.

11.4.2 Test order

"… The following test requirements apply: (1) The runs must be made in the order found appropriate by the FAA for the particular engine being tested."

Understanding of intent:

- Sequence prescribed by the rule in the "A" cycle appears arbitrary, but could be intended to produce a constant rate of deterioration of the engine throughout test. This would provide a demonstration of the engine's ability to acceptably perform (i.e. produce thrust, not surge or stall, etc.) throughout its LP and HP speed ranges, as well as up to its declared redline levels, as it progressively deteriorates.

Relevant notes regarding historical applications:

- With suitable justification provided by the applicant, the FAA has allowed the test sequence to be altered within predetermined limitations. A common limitation has been that each portion of an “A” cycle (i.e. 6 back-to-back G/I –to-T/O rapid accel/decel) had to be maintained.
- All test portion/part re-sequence allowances have been documented in recent FAA-approved test plan.

Control system: the rule requires that *“Any automatic engine control that is part of the engine must control the engine during the endurance test except for operations where automatic control is normally overridden by manual control or where manual control is otherwise specified for a particular test run.”* In plain language, it says we must operate the test engine using the type design control system (hardware and FADEC software logic including schedules, limits, etc.). Applicants typically incorporate a pre-production version of the engine’s FADEC software and logic. Multiple logic ‘scripts’ are included in order to bring the system’s function up to latest intended production schedules, limits, etc. Scripts are also typically used to alter the type design logic in order to allow endurance test operational requirement to be met. Examples are acceleration rates, bleed and VSV schedule changes, electronic over-speed (EOS) limit(s) ‘moved out of the way’ and using non-type deign engine control modes (N2 vs N1 control).

Instances of control system hardware modification have included installing ‘hot rod’ fuel control hardware to allow engine fuel flow at (or slightly above) engine redline rotor speed because the fuel flow required to achieve the required over-boost cannot be provided by the standard equipment.

Accessory loading: *“(6) Each accessory drive and mounting attachment must be loaded in accordance with paragraphs (a)(6)(i) and (ii) of this section, except as permitted by paragraph (a)(6)(iii) of this section for the test required under paragraph (f) of this section.*

1. *The load imposed by each accessory used only for aircraft service must be the limit load specified by the applicant for the engine drive and attachment point during rated maximum continuous power or thrust and higher output.*
2. *The endurance test of any accessory drive and mounting attachment under load may be accomplished on a separate rig if the validity of the test is confirmed by an approved analysis.*
3. *The applicant is not required to load the accessory drives and mounting attachments when running the tests under paragraphs (f)(1) through (f)(8) of this section if the applicant can substantiate that there is no significant effect on the durability of any accessory drive or engine component. However, the applicant must add the equivalent engine output power extraction from the power turbine rotor assembly to the engine shaft output.”*

Demonstration is intended to show engine’s capabilities (such as operability, including in a deteriorated condition) and durability when operated (steady state and transiently) with engine-required, gearbox-mounted accessory loading (torque/horsepower extraction), simultaneously with redline rotor speeds and gas path temperature and up to maximum declared thrust/power level. Additionally, show that the gearbox and the engine-applicant-designed accessories mounted to gearbox demonstrate suitable durability (functional, structural and part-to-part interfaces) when operated at its maximum drive (engine low- or high-pressure rotor system off-take) speed and with maximum lubricating oil temperature and maximum/minimum lubricating oil supply pressures. Use of a gearbox rig endurance test, accompanied by an FAA-accepted justification, can be used in addition to, or in place of an engine test in order to satisfy this portion of the requirement. Some applicants have historically conducted an accessory gearbox (AGB) rig endurance test rather than loading the gearbox on the endurance test. The rig test includes (as applicable) the AGB and relevant drive train components and all AGB-mounted components or simulated loading systems allowing the AGB internal drive hardware to be subjected to maximum horsepower/torque during the test. Component weights (mass and CG) are also simulated. The rig test replicates the engine test cycle with respect to AGB input drive speeds, oil temperature, pressures, durations, etc. This test does not however cover the impact on the operability of the engine thus to allow this approach to be taken that effect has to be justified as being negligible.

11.4.3 Automatic engine control

"(2) Any automatic engine control that is part of the engine must control the engine during the endurance test except for operations where automatic control is normally overridden by manual control or where manual control is otherwise specified for a particular test run."

Understanding of intent:

- Operate the test engine using the type design control system (hardware and FADEC software logic including schedules, limits, etc.).
- Deviation from the type design system where test definition is contrary to the engine control system operation, e.g. altering or removing engine's schedules or limits related to physical speed redlines.

Relevant notes regarding historical applications:

- Applicants typically incorporate a pre-production version of the engine's FADEC software and logic. Multiple logic 'scripts' are included in order to bring the system's function up to latest intended production schedules, limits, etc. Scripts are also typically used to alter the type design logic in order to allow endurance test operational requirement to be met. Examples are VBV and VSV schedule changes, electronic over-speed (EOS) limit(s) 'moved out of the way', using non-type deign engine control modes (N2 vs N1 control).

- Instances of control system hardware modification have included installing 'hot rod' fuel control hardware in order to allow engine fuel flow compatible with low duration operation at (or slightly above) engine redline physical rotor speed.

- The control system modifications are outlined and justified within the FAA approved certification test plan document.

11.4.4 Simultaneous redlines

"(3) Except as provided in paragraph (a)(5) of this section, power or thrust, gas temperature, rotor shaft rotational speed, and, if limited, temperature of external surfaces of the engine must be at least 100 percent of the value associated with the particular engine operation being tested. More than one test may be run if all parameters cannot be held at the 100 percent level simultaneously."

Understanding of intent:

- Stipulation of the requirement to conduct a single triple-redline (TRL) or multiple double-redline engine testing is intended to demonstrate that the engine is capable of operating acceptably at its declared redline (rotor speed and gas path temperature) and produce maximum rated thrust/power levels both in non-deteriorated and deteriorated conditions. In addition, it is intended to cover for the most severe engine operating conditions that could occur in the declared envelope, including running to the redline(s) and rated thrust conditions for the permissible durations of time.
- Demonstrate an acceptable level of engine system and hardware durability for the intended type design while maintaining its ability to produce rated thrust without exceeding its redlines.
- The significant amount time operating at combined redline and maximum thrust levels provides for deterioration of the engine over the relatively short test duration.

Relevant notes regarding historical applications:

- Applicants (large engine) typically conduct a single TRL engine test with a significantly modified (relative to type design) test engine in order to enable the engine to conduct the test.

- Applicants have provided the FAA with information showing that running a pair of double-redline test (N1-EGT and N2-EGT) also require significant, test enabling, engine modifications and expose the test engine's hardware (particularly in the hot section) to 2 EGT redline operational durations. Applicants with 3 shaft engines experience similar issues.

- Typically, during the testing the engine will exceed rotor redline speed to assure that all test time is credited to meeting the requirements. Engines with HP compressor variable geometry typically maintain the HP speed redline exceedance to no more than 0.4%. However, engines without HP compressor variable geometry, except for certain 3 shaft turbofan engines run under CS-E 740 requirements, significantly more HP (N2 or N3) speed exceedance is required.

11.4.5 Fluids to be used

"(4) The runs must be made using fuel, lubricants and hydraulic fluid which conform to the specifications specified in complying with 14CFR33.7(c)."

Understanding of intent:

- Demonstration is intended to show engine's capabilities and durability (wear) when operated using with fluids having correct lubricity, specific gravity, energy content, coking characteristics, etc. with respect to those with which it will operate in the field.

Relevant notes regarding historical applications:

- Applicants conduct testing with type design specified fluids and conduct verification sampling before, during and after the test.

11.4.6 Air bleed

"(5) Maximum air bleed for engine and aircraft services must be used during at least one-fifth of the runs, except for the test required under paragraph (f) of this section, provided the validity of the test is not compromised. However, for these runs, the power or thrust or the rotor shaft rotational speed may be less than 100 percent of the value associated with the particular operation being tested if the FAA finds that the validity of the endurance test is not compromised."

Understanding of intent:

- Demonstration is intended to show the engine's capabilities (including in a deteriorated condition) and durability when operated at the maximum bleed air levels to be provided to, and as required by, the aircraft simultaneously with redline rotor speeds and gas path temperature.
- Requirement for $1/5^{th}$ of the cycles to be operated with bleed appears to be arbitrary. May have been based on early engine bleed use for anti-ice or other intermittent aircraft bleed air use.
- Allowance for coincident thrust/power level to be less than maximum declared reflects practicality that operating the engine at maximum bleed levels at the same time as demanding maximum takeoff thrust does not occur in service.

Relevant notes regarding historical applications:

- Includes engine bleed used for engine nacelle anti-ice and aircraft environmental conditioning/control system (ECS).

11.4.7 Accessory loading

"(6) Each accessory drive and mounting attachment must be loaded in accordance with paragraphs (a)(6)(i) and (ii) of this section, except as permitted by paragraph (a)(6)(iii) of this section for the test required under paragraph (f) of this section.

4. *The load imposed by each accessory used only for aircraft service must be the limit load specified by the applicant for the engine drive and attachment point during rated maximum continuous power or thrust and higher output.*
5. *The endurance test of any accessory drive and mounting attachment under load may be accomplished on a separate rig if the validity of the test is confirmed by an approved analysis.*

6. *The applicant is not required to load the accessory drives and mounting attachments when running the tests under paragraphs (f)(1) through (f)(8) of this section if the applicant can substantiate that there is no significant effect on the durability of any accessory drive or engine component. However, the applicant must add the equivalent engine output power extraction from the power turbine rotor assembly to the engine shaft output."*

Understanding of intent:

- Demonstration is intended to show the engine's capabilities (such as operability, including in a deteriorated condition) and durability when operated (steady state and transiently) with engine-required, gearbox-mounted accessory loading (torque/horsepower extraction), simultaneously with redline rotor speeds and gas path temperature and up to maximum declared thrust/power level.

- Additionally, show that the gearbox and the engine-applicant-designed accessories mounted to gearbox demonstrate suitable durability (functional, structural and part-to-part interfaces) when operated at its maximum drive (engine low- or high-pressure rotor system off-take) speed and with maximum lubricating oil temperature and maximum/minimum lubricating oil supply pressures.

- Use of a gearbox rig endurance test, accompanied by an FAA-accepted justification, can be used in addition to, or in place of an engine test in order to satisfy this portion of the requirement.

Relevant notes regarding historical applications:

- Some applicants have historically conducted an accessory gearbox (AGB) rig endurance test rather than loading the gearbox on the endurance test.
- The rig test includes (as applicable) the AGB and relevant drive train components. It also includes all AGB-mounted components or simulated loading systems allowing the AGB internal drive hardware to be subjected to maximum horsepower/torque during the test. Component weights (mass and CG) are also simulated.
- The rig test replicates the engine test cycle with respect to AGB input drive speeds, oil temperature, pressures, durations, etc.
- The engine endurance test includes all AGB-mounted accessory components to be part 33 certified and all necessary to operate the engine. Any other AGB-mounted components (e.g. aircraft hydraulic pump, etc.) are simulated by non-functional 'dummy' weights. In some instances, where significant horsepower extraction is required (such as on an all-electric airplane with gearbox-mounted generators, airframe supplied components are also included in order to simulate their drive train loading.

11.4.8 Maintaining limiting temperatures

"(7) During the runs at any rated power or thrust the gas temperature and the oil inlet temperature must be maintained at the limiting temperature except where the test periods are not longer than 5 minutes and do not allow stabilization. At least one run must be made with fuel, oil, and hydraulic fluid at the

minimum pressure limit and at least one run must be made with fuel, oil, and hydraulic fluid at the maximum pressure limit with fluid temperature reduced as necessary to allow maximum pressure to be attained."

Understanding of intent:

- Maintaining maximum gas path temperature (EGT) and oil system inlet temperature during maximum thrust/power operations demonstrates the engine's ability to acceptably operate (including in a deteriorated condition), and with appropriate durability, under maximum, steady state, system temperature conditions. The engine system is 'soaked' at elevated temperature level.
- Demonstrates the engine's oil lubricating and cooling system capacity capabilities under maximum steady state thermal conditions for extended time periods.
- "Not longer than 5 minutes" exception reinforces that intent is more for steady state, 'soaked', thermal conditions rather than transients.
- Runs conducted with engine fuel, oil and hydraulic fluid systems operating at minimum pressure and maximum pressure levels demonstrate the engine's (and its fuel, oil and hydraulic systems') ability to acceptably operate (steady state and transiently) at these conditions throughout its rotor physical speed ranges and at maximum gas path temperature level. Also demonstrates fuel, oil and hydraulic system hardware durability when operated under these conditions.
- Quantity (one of each) may be arbitrary, but practical in that there are only 6 "A" cycles available in order to run the minimum and maximum pressure conditions.

Relevant notes regarding historical applications:

- The engine's oil system is required to be slightly modified (removal of one or two oil supply tubes) in order to allow engine oil to bypass the oil cooler(s) in order to allow for maximum oil inlet temperatures to be maintained.
- In some cases, the engine endurance test facility's fuel supply system is not able to provide or operate at fuel pressure levels low enough to demonstrate minimum declared fuel inlet pressure during the engine test. In this case, the engine test is conducted with the lowest possible facility-supplied inlet pressure and post-test the test engine's main fuel pump is removed and shipped to a component test facility capable of operating at minimum fuel pressure conditions. The pump is exposed to a test cycle (pump input drive shaft speed) replicating an entire endurance "A" cycle at minimum declared fuel inlet pressure and demonstrates that the pump outlet flow and pressure is suitable for engine operations under this condition throughout the cycle run.
- During recent tests, due to engine oil system temperature stabilization characteristics, accels from ground idle to takeoff thrust during all cycles conducted with maximum oil temperature are conducted as stair-step accels with stabilizations at intermediate speed(s) as required to achieve oil temperature stabilization.

11.4.9 Transient overshoots

“(8) If the number of occurrences of either transient rotor shaft overspeed, transient gas overtemperature or transient engine overtorque is limited, that number of the accelerations required by paragraphs (b) through (g) of this section must be made at the limiting overspeed, overtemperature or overtorque. If the number of occurrences is not limited, half the required accelerations must be made at the limiting overspeed, overtemperature or overtorque.”

Understanding of intent:

- Intent is to demonstrate that, if the applicant desires overage allowance(s), the engine is capable of acceptably operating at the declared overage condition(s).
- For unlimited overage allowance the requirement to conduct half of the total accels at or above the desired overage level appears arbitrary, but reasonable.

Relevant notes regarding historical applications:

- N/A

11.4.10 Allowance For 10 Minute Take-Off Operation

“(b) Engines other than certain rotorcraft engines. For each engine except a rotorcraft engine for which a rating is desired under paragraph (c), (d), or (e) of this section, the applicant must conduct the following runs:”

Understanding of intent:

- Define a prescriptive test that all applicants must meet. Provides commonality across applicants and connection to successful legacy certified products and entry-into-service (EIS) experiences.

Relevant notes regarding historical applications:

- Applicants have historically conducted all required parts, quantities and durations of the endurance test. However, with FAA concurrence, the order/sequence of the testing has been altered so as to allow test operating space to be maximized for ambient test conditions (T_{amb}). Other FAA-accepted deviations from the described test cycle definitions are as described elsewhere.
- During the endurance test applicants typically overachieve with respect to declared rated thrust and redline levels in order to assure meeting the test demonstration requirements.

11.4.11 Conducting part As– alternating 6x5mins at max take off and idle

“(1) Takeoff and idling. One hour of alternate five-minute periods at rated takeoff power or thrust and at idling power or thrust. The developed powers and thrusts at takeoff and idling conditions and their corresponding rotor speed and gas temperature conditions must be as established by the power control in accordance with the schedule established by the applicant. The applicant may, during any one period, manually control the rotor speed and power or thrust while taking data to check performance. For engines with augmented takeoff power ratings...” [remainder is not applicable]

Understanding of intent:

- Provides for demonstration of the engine's acceptable operability (absence of surge or stall) during maximum (between ground idle and takeoff redline) rotor speed transients (accel & decels).
- 5 minute dwell times at idle and takeoff attempts to create an accelerated level of deterioration and expose possible failure modes and aspects of durability under severe conditions, such as the combination of takeoff speeds and temperatures for the rated 5 minute periods.

Relevant notes regarding historical applications:

- Applicants typically conduct these throttle maneuvers as defined by the requirement.

11.4.12 Conducting part Bs – 30mins at max take off or max continuous

"(2) Rated maximum continuous and takeoff power or thrust. Thirty minutes at—

(i) Rated maximum continuous power or thrust during fifteen of the twenty-five 6-hour endurance test cycles; and

(ii) Rated takeoff power or thrust during ten of the twenty-five 6-hour endurance test cycles."

Understanding of intent:

- Provides for extreme duration at the engine's takeoff (10 instances) and a more moderate duration at maximum continuous (15 instances) thrust/power with simultaneous redline conditions (rotor speeds and gas path temperature).
- Demonstrates engines capability to continue to produce rated thrust when operated repeatedly, for specified extreme/moderate periods of time, at extreme operating conditions (simultaneous speed-temperature redlines), including when the engine is in a deteriorated condition.
- 30 minute duration appears arbitrary and very extreme, particularly for takeoff, which an in-service engine will rarely, if ever, experience for more than 5 minutes at each occurrence. The 30 minute takeoff time duration has its origin in the CAR 13 rules when a pilot could have required addressing an emergency situation with takeoff thrust for more than the normal 5 minutes. This situation is no longer believed to be relevant due to modern power management and thrust availability.
    - In the '90s, these 5 and 30 minutes takeoff test cycles were found adequate to support the industry request for extending the takeoff time allowance from 5 minutes to 10 minutes in case of an OEI; refer to EPD/TAD policy PS-ANE100-1994-00008 dated 8/19/94.

Relevant notes regarding historical applications:

- Applicants typically conduct these throttle maneuvers as defined by the requirement.

11.4.13 Conducting part Cs – 1hr 30mins at max continuous

"(3) Rated maximum continuous power or thrust. One hour and 30 minutes at rated maximum continuous power or thrust."

Understanding of intent:

- Similar to (b)(2), this demonstrates the engine's capability to continue to produce rated maximum continuous thrust when operated repeatedly, for extended periods of time (1 ½ hours, and when coupled with 30 minute MaxCon runs above, 2 hours), at extreme operating conditions (simultaneous speed-temperature redlines), including when the engine is in a deteriorated condition.
- 90 minute duration appears arbitrary and extreme.

Relevant notes regarding historical applications:

- Applicants typically conduct these throttle maneuvers as defined by the requirement.

11.4.14 Conducting part 4s – 15 step increments between max continuous and idle over 2hrs 30mins

"(4) Incremental cruise power or thrust. Two hours and 30 minutes at the successive power lever positions corresponding to at least 15 approximately equal speed and time increments between maximum continuous engine rotational speed and ground or minimum idle rotational speed. For engines operating at constant speed, the thrust and power may be varied in place of speed. If there is significant peak vibration anywhere between ground idle and maximum continuous conditions, the number of increments chosen may be changed to increase the amount of running made while subject to the peak vibrations up to not more than 50 percent of the total time spent in incremental running."

Understanding of intent:

- These stair-step portions of each "A" cycle exercise either the engine's flow path rotor and stator airfoil dynamic responses or the engine's structural dynamic response to rotor unbalance, or both.
- Number of steps (15) appears to be arbitrary.

Relevant notes regarding historical applications:

- Applicants typically conduct the 15 equal spaced, decreasing (or increasing for EASA applicants) fan speed (N1) steps between MaxCon and ground idle N1 values.

11.4.15 Conducting part 5s – 6x cycles over 30mins with 30secs at max take off and <4mins 30secs at idle

"(5) Acceleration and deceleration runs. 30 minutes of accelerations and decelerations, consisting of six cycles from idling power or thrust to rated takeoff power or thrust and maintained at the takeoff power lever position for 30 seconds and at the idling power lever position for approximately four and one-half minutes. In complying with this paragraph, the power-control lever must be moved from one extreme position to the other in not more than one second, except that, if different regimes of control operations

are incorporated necessitating scheduling of the power-control lever motion in going from one extreme position to the other, a longer period of time is acceptable, but not more than two seconds."

Understanding of intent:

- These throttle accelerations and decelerations, conducted in rapid succession, are intended to aggressively accelerate the deterioration of the engine during the course of the test by creating significant rotating-to-stationary seal interference, as well as blade tip –to- shroud rubs.
- May also be intended to demonstrate the engine's ability to sustain rapid accel-decel and/or decal/accel throttle maneuvers (such as during a rejected takeoff) without surge and stall, including when the engine is in a deteriorated condition.

Relevant notes regarding historical applications:

- Applicants typically conduct these throttle maneuvers as defined by the requirement. However, due to the non-representative nature of test and the engine hardware/system modifications involved, the applicant will typically evaluate and exercise a high level of caution regarding when, and under what ambient conditions, portions of the test cycle are conducted.
- The MaxCon portions of the test are the most limiting from a cycle balance / HPT cooling perspective and typically have the smallest (ambient condition) operating space. Deterioration incurred during the transient portions of the test can drive the MaxCon portions exacerbating off-design operation.

11.4.16 Conducting starts

"(6) Starts. One hundred starts must be made, of which 25 starts must be preceded by at least a two-hour engine shutdown. There must be at least 10 false engine starts, pausing for the applicant's specified minimum fuel drainage time, before attempting a normal start. There must be at least 10 normal restarts with not longer than 15 minutes since engine shutdown. The remaining starts may be made after completing the 150 hours of endurance testing."

Understanding of intent:

- Demonstrate the engine's starting capability, including when the engine (and starting system) is in a deteriorated condition. Demonstration includes starting conditions (cold, hot and false/aborted) that could reasonably be expected to be experienced in service.
- Quantity of required of required starts appears arbitrary, but reasonable.

Relevant notes regarding historical applications:

- Applicants typically conduct these starts as defined by the requirement.

11.5 Appendix E – Consideration of Past Engine Endurance Test

11.5.1 Airworthiness Directive Study

A list of Airworthiness Directives (ADs) issued during the first three years of service was compiled from 11 turbofan engine models which were FAA certified from the 1980s to current day. The results from this study were used to create the summary provided in section 4.7.

ADs - First Three Years of Service - Engines E1 Through E11

PART FAMILY	AD Published
FAN BLADES	
FAN EXIT GUIDE VANES	
LPC & HPC VANES	
LPC & HPC BLADES	
COMPRESSOR NON-ROTATING AIRSEALS & SHROUDS	
COMPRESSORSTATIC STRUCTURE PARTS	
COMPRESSOR BEARING COMPARTMENT (SEALS, ETC)	
COMPRESSOR MAJOR CASES	
COMPRESSOR ROTATING LIFE LIMITED PARTS	E2 E9 E9 E6 E10 E11
COMPRESSOR ROTATING NON-LIFE LIMITED PARTS	E4
COMBUSTOR PARTS	E4
HPT BLADES AND VANES	
LPT BLADES AND VANES	E2
TURBINE NON-ROTATING AIRSEALS & SHROUDS	
TURBINE STATIC STRUCTURE PARTS	E2
TURBINE MAJOR CASES	E6
TURBINE ROTATING LIFE LIMITED PARTS	E9
TURBINE ROTATING NON-LIFE LIMITED PARTS	
TURBINE BEARING COMPARTMENT (SEALS, ETC)	E1 E1
GEARBOX (SHAFTS, GEARS, HOUSINGS)	E1 E9 E5 E6
EXTERNALS (TUBES, MANIFOLDS, DUCTS, BRACKETS)	E1 E1 E9 E8 E11
CONTROLS & ACCESSORIES COMPONENTS	E1 E9 E4 E5 E7
EEC HARDWARE	
EEC SOFTWARE	E1 E1 E9 E9 E5 E7 E10 E11

Notes: Engine E3 with no ADs in first three years of service
Engine E3 is the same engine as E3 in test listing

E1: RR
E2: GE90-115
E3: GP7200 none
E4: CF34-10
E5: CFM56-7B
E6: CFM56-5B
E7: PW4000-94
E8: PW2000
E9: GE90-04
E10: GEnx-1B
E11: GEnx-2B

AD Summary - First Three Years of Service
Rolls-Royce Corporation

Engine E1

AD Effective Date	Safety Issue	Action Required for compliance	Could the root cause have been discovered in 33.87 Test?
9-Sep-1997	Prevent failure of the mid-span roller bearing, damage to the accessory gearbox, and an engine shutdown.	Inspection of accessory gearbox and the mid-span bearing	Unlikely; failure was related to a production assembly procedure that could allow the rollers to fall out of the bearing undetected; this issue did not affect the test article
25-Sep-1997	Prevent failure of the fuel manifold, fuel leakage, and engine shutdown.	Inspection of fuel manifold and installation of additional clamps	No; test duration at idle speeds of approximately 60% N2 insufficient to reveal the clamping shortcomings that precipitated this AD
16-Mar-1998	Prevent failure of the variable vane torque tube system that can result in an engine shutdown.	Testing the variable-vane torque tube system to determine the force required for operation and the potential life limit of the torque tube.	Unlikely; factors contributing to a wide variation in CVG actuation force were not recognized in early design & production; root cause investigation into field failures revealed weld/braze strength production variation, and a reassessment of theCVG actuation force revealed the potential strength shortfall
10-Feb-1998	Prevent pressurization of the oil tank that can lead to an engine shutdown.	Inspect the oil tank and installation of new oil vent system.	Unlikely; a post-certification change to increase the allowable maximum oil pressure resulted in inadequate functioning of the existing vent system
22-Apr-1998	The actions specified by this AD are intended to prevent a No. 4 bearing failure due to lubrication system contamination, which can result in an inflight engine shutdown.	Requires removal of bearing part number 20362504 as terminating action.	Unlikely; test duration insufficient to initiate the bearing wear-out mode that precipitated this AD; the issue was exacerbated by a bearing production quality issue that did not affect the test article
16-Jan-1998	The actions specified by this AD are intended to prevent a No. 4 bearing failure due to lubrication system contamination, which can result in an inflight engine shutdown.	Requires frequent inspection of engine magnetic chip detectors	Unlikely; test duration insufficient to initiate the bearing wear-out mode that precipitated this AD; the issue was exacerbated by a bearing production quality issue that did not affect the test article
18-Jun-1998	The actions specified by this AD are intended to prevent a No. 4 bearing failure due to lubrication system contamination, which can result in an inflight engine shutdown.	Requires removal of bearing part number 20362504 as terminating action.	Unlikely; test duration insufficient to initiate the bearing wear-out mode that precipitated this AD; the issue was exacerbated by a bearing production quality issue that did not affect the test article

AD Summary - First Three Years of Service
Rolls-Royce Corporation

Engine E1

AD Effective Date	Safety Issue	Action Required for compliance	Could the root cause have been discovered in 33.87 Test?
24-Jun-1998	The actions specified in this AD are intended to prevent inflight engine shutdowns due to inadequate fault accommodation logic.	Reprogram the FADEC software.	Unlikely; test duration and conditions insufficient to reveal the fault accommodation logic shortcoming that precipitated this AD
8-Jan-1999	Prior to further flight, all ground engine starts at engine oil temperatures below 32 deg. F (0 deg. C) are prohibited except as provided in ... this AD.	Perform a high-power leak check on each engine and monitor the engine oil level. An alternate method of compliance is to cap the starter pad overboard drain.	No; root cause was cold ambient temperature coupled with a violation of the IDM interface requirement for the length of the aircraft-provided starter drive shaft
16-Feb-1999	The actions specified by this AD are intended to prevent an unintentional or uncommanded in-flight engine shutdown.	Remove listed FADEC assemblies containing specified software from service.	No; test duration and conditions insufficient to reveal the software fault that precipitated this AD

AD Summary - First Three Years of Service?
GE90-115

Engine E2

AD Effective Date	Safety Issue	Action Required for compliance	Could the root cause have been discovered in 33.87 Test?
6/14/2007	Turbine Center Frames (TCFs)	Remove TCF from service before specified interval due to non-inclusion in ALS of some P/N	No
1/19/2010	Blade	Inspect LPT blade interlock for wear, terminate action by replacement with redesigned part	No
2/3/2012	HPC stages 1-2 seal teeth	Inspect 2-5 spool for seal cracks, reinstall with pre-grooved honeycomb	Yes

Engine E3

AD Summary - First Three Years of Service
Engine Allaince (High-Thrust)
Certified 2001

AD Effective Date	Safety Issue	Action Required for compliance	Could the root cause have been discovered in 33.87 Test?
		NONE IN FIRST THREE YEARS	

Engine E4

AD Summary - First Three Years of Service?
CF34-10

AD Effective Date	Safety Issue	Action Required for compliance	Could the root cause have been discovered in 33.87 Test?
7/10/2007	Combustor case	LLP reduction	No
7/19/2007	Main fuel pump (MFP)	Change fuel strainer and replace parts as necessary	No
4/3/2008	Fuel metering units (FMU)	One time inspection due to Quality Escape	No
9/26/2011	Fan rotor spinner	Remove certain P/N spinners from service	No

Engine E5

AD Summary - First Three Years of Service
CFM56-7B

AD Effective Date	Safety Issue	Action Required for compliance	Could the root cause have been discovered in 33.87 Test?
10/16/1998	Uncommended engine acceleration events, with potential inflight engine shutdown.	Requires installation of improved EEC software, within 75 cycles in service (CIS) after the effective date of this AD, or by November 9, 1998, whichever occurs first.	Unlikely, resulted from EEC software change.
09/22/1998	Prevent a dual inflight engine flameout due to failed Hydromechanical Unit (HMU) overspeed governor (OSG) spool valve shaft.	Requires initial and repetitive inspections of Hydromechanical Unit (HMU) overspeed governor (OSG) spool valves for out-of-specification conditions or the presence of heavy contact or galling on the spoll valve, and optional installation of an improved HMU as a terminating action to the inspections.	No, resulted from failed Hydromechanical Unit (HMU) overspeed governor (OSG) spool valve out-of-specification conditions.
09/16/1998	Prevent a dual inflight engine shutdown due to uncontained failures of the Accessory Geabox (AGB) starter gearshafts, which could result in a forced landing and loss of the aircraft.	Requires checks of the Accessory Geabox (AGB)/Transfer Gearbox (TGB) Magnetic Chip Detector (MCD) for abnormal magnetic particules that indicate a pending starter gearshaft failure, and removal from service of suspect starter gearshafts and replacement with serviseable parts.	No, the gearshafts failed due to inadequate fatigue capability caused by high residual tensile stresses introduced during the manufacturing process, coupled with the elimination of shotpeening in the gearshaft hub.

AD Summary - First Three Years of Service
CFM56-5B

Engine E6

AD Effective Date	Safety Issue	Action Required for compliance	Could the root cause have been discovered in 33.87 Test?
5/19/1998	Prevent inflight engine shutdowns due to an AGB starter gearshaft, TGB input bevel gear, TGB output bevel gear, AGB gearshafts cluster spur assembly or AGB intermediate assembly failure.	Requires the removal of one engine on twin engine aircraft and replacement with a serviceable engine or replacement of parts if both engines are affected. It requires also the removal of all necessary engines on four engine aircraft and replacement with a serviceable engine or replacement parts. In addition, this AD requires daily cheks of the AGB/TGB magnetic chip detector (...).	No, resulted from improper cleaning procedure prior to the black oxide process during manufacture that causes residual stresses around the welding areas that could lead to a crack.
4/4/1997	Prevent a failure of the stage 1 disk of the High Pressure Compressor Rotor (HPCR) Stage 1-2 Spool, which could result in an uncontained engine failure and damage to the aircraft.	Requires initial and repetitive borescope inspections of the stage 1 disk bore of certain high pressure compressor rotor (HPCR) stage 1-2 spools for rubs and scratches, and replacement, if found rubber or scratched, with a serviceable part. Also requires removal and replacement of certain stationary number 3 bearing aft air/oil seals as terminating action to the inspection program.	Unlikely, resulted from a geometrical condition affecting a limited number of parts.
9/18/1998	Prevent a low cycle fatigue (LCF) failure of the low Pressure Turbine (LPT) case, which could result in damage to the aircraft.	Requires removing from service one LPT case part number (P/N) and replace it with a serviseable part, prior to accumulating limiting (10,500 or 15,500 depending of the models) cycles. Establishes the new LCF retirement lives for this P/N, which are published in Chapter 5 of the Engine Shop Manual.	Unlikely, resulted from low-cycle-fatigue endurance, more relevant to the 33.90 than 33.87.

AD Summary - First Three Years of Service
Pratt Whitney (Mid-Thrust)
Certifed 1986

Engine E7

AD Effective Date	Safety Issue	Action Required for compliance	Could the root cause have been discovered in 33.87 Test?
9/1/1988 (88-03-53)	To prevent the inability to reduce engine thrust that can lead to asymmetrical power.	FMU replacement within 150 hours of service.	Possibly. There were no issues during the edurance or overhaul test.
7/12/1993 (93-08-16)	Severe HPC blade rub causing engine shutdown.	Modified software modification.	
10/18/1990 (90-22-02)	To prevent LPT shaft failure.	One time inspection of population of LPT shaft.	No. Manufacturing issue.

AD Summary - First Three Years of Service
Pratt Whitney (Mid-Thrust)
Certified 1983

Engine E8

AD Effective Date	Safety Issue	Action Required for compliance	Could the root cause have been discovered in 33.87 Test?
7/13/1988 (88-03-52)	To prevent tube cracking, fuel leak, and possible engine fire.	Install new clamping design for TCC air valve and 2.5 bleed valve tubes.	Possibly. Test does not include engine imbalance which may have uncovered the issue.

AD Summary
GE90-04

Engine E9

AD Effective Date	Safety Issue	Action Required for compliance	Could the root cause have been discovered in 33.87 Test?
6/27/1997	Liberated CDP Manifold Material	Repetitive inspections & replacement at SV	No
6/27/1997	(VSCF) Gearshaft Flange ball Bearing	Debris monitoring system checks, replace VSCF bearing shaft bearings with new design at SV	No
7/6/1998	Rotating Components	LLP reduction in Ch5	No
4/7/2000	LLP	LLP reduction in Ch5	No

AD Summary
GEnx-1B

Engine E10

AD Effective Date	Safety Issue	Action Required for compliance	Could the root cause have been discovered in 33.87 Test?
9/21/2012	Fan mid shafts (FMS)	Inspection program	No
8/24/2015	Power loss in ice crystal icing (ICI) conditions	Use updated FADEC software within 30 days of AD issuance	No
12/17/2015	Non-conforming ball valve in the oil filler cap	Inspect at periodic times and replace with conforming parts	No

AD Summary
GEnx-2B

Engine E11

AD Effective Date	Safety Issue	Action Required for compliance	Could the root cause have been discovered in 33.87 Test?
9/21/2012	Fan mid shafts (FMS)	Inspection program	No
9/23/2013	Booster anti-ice (BAI) air duct	Inspection program and replacement with new design	No
1/7/2014	Critical rotating life-limited parts (LLPs)	LLP adjustment for Flight Test Engines	No
8/24/2015	Power loss in ice crystal icing (ICI) conditions	Use updated FADEC software within 30 days of AD issuance	No

11.5.2 Endurance Test Failure Findings Study

The findings from past 150 hour endurance and IMI tests were investigated for several turbofan engines in order to identify the types of hardware modifications that were required due to test findings. The results of this study were used to create the summary provided in section 4.7. (see first table in section 11.5.2 for explanation of engine E1-E8 labels)

150 Hour and IMI Findings - Engines E1 Through E8

PART FAMILY	150 HR. END. TEST FINDINGS	IMI TEST FINDINGS
FAN BLADES	E1 E1	
FAN EXIT GUIDE VANES	E3	
LPC & HPC VANES		
LPC & HPC BLADES	E1 E3 E3	E4
COMPRESSOR NON-ROTATING AIRSEALS & SHROUDS	E4	
COMPRESSORSTATIC STRUCTURE PARTS		
COMPRESSOR BEARING COMPARTMENT (SEALS, ETC)	E2 E3	E1
COMPRESSOR MAJOR CASES		
COMPRESSOR ROTATING LIFE LIMITED PARTS	E3	
COMPRESSOR ROTATING NON-LIFE LIMITED PARTS		
COMBUSTOR PARTS	E3 E4 E8	E4 E4
HPT BLADES AND VANES	E1 E1 E3 E5 E7 E7 E7 E8	E1 E3 E3 E7
LPT BLADES AND VANES	E3	E3 E3 E3 E3
TURBINE NON-ROTATING AIRSEALS & SHROUDS	E2 E2 E3	E3 E3
TURBINE STATIC STRUCTURE PARTS	E2	E2
TURBINE MAJOR CASES	E3 E3	
TURBINE ROTATING LIFE LIMITED PARTS	E1 E1 E2	
TURBINE ROTATING NON-LIFE LIMITED PARTS		
TURBINE BEARING COMPARTMENT (SEALS, ETC)	E3 E5	E3 E3 E7
GEARBOX (SHAFTS, GEARS, HOUSINGS)	E5 E5	
EXTERNALS (TUBES, MANIFOLDS, DUCTS, BRACKETS)	E1 E3 E3 E5 E8	E3 E3 E7
CONTROLS & ACCESSORIES COMPONENTS	E1 E2 E2 E3	E1 E2 E3 E3 E4
EEC HARDWARE		
EEC SOFTWARE		

Notes: Engine E6 with no 150 hour or IMI findings
Engine E3 is the same engine as E3 in AD listing

Mid Thrust Commercial Engine E1

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
FAN BLADES	**Blade Platform Seal** - Excessive wear - EC to improve durability **Minor Delamination** - EC to add coating				FMD: Fan Blade
FAN EXIT GUIDE VANES					
LPC & HPC VANES					
LPC & HPC BLADES	**HPC 3rd Vane Crack** - Mfg issue causing high residual steady stress - Process modified				
COMPRESSOR NON-ROTATING AIRSEALS & SHROUDS					
COMPRESSOR STATIC STRUCTURE PARTS					
COMPRESSOR BEARING COMPARTMENT (SEALS, ETC)		**No. 3 Bearing** - Oil wetting in flowpath - EC to fix issue			
COMPRESSOR MAJOR CASES					
COMPRESSOR ROTATING LIFE LIMITED PARTS					
COMPRESSOR ROTATING NON-LIFE LIMITED PARTS					
COMBUSTOR PARTS					

Mid Thrust Commercial Engine E1

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
HPT BLADES AND VANES	**HPT 1st Blades** - Oxidation and burnback - Platform cracking - EC **HPT 2nd Vanes** - Alloy burning/material depletion - Negative airflow - EC to adjust cooling scheme	**HPT 2nd Vanes** - Alloy burning/material depletion - Negative airflow - EC to adjust cooling scheme			
LPT BLADES AND VANES					
TURBINE NON-ROTATING AIRSEALS & SHROUDS					
TURBINE STATIC STRUCTURE PARTS					
TURBINE MAJOR CASES					
TURBINE ROTATING LIFE LIMITED PARTS	**HPT 1st Stage Mini Disk** - Fracture - High temperature/creep/HCF failure - New cooling scheme and disk redesign **Mini Disk Heatshield** - Fracture - Redsigned				
TURBINE ROTATING NON-LIFE LIMITED PARTS					

Mid Thrust Commercial Engine E1

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
TURBINE BEARING COMPARTMENT (SEALS, ETC)					
GEARBOX ASSEMBLY (SHAFTS, GEARS, HOUSINGS)					
EXTERNALS (TUBES, MANIFOLDS, DUCTS, BRACKETS)	**Internal Oil Tubes (Supply and Return)** - heat shield damage - Excessive temp due to triple point - EC to change tube material		**Oil Tube Crack** **Fule Tube Crack**		
CONTROLS & ACCESSORIES COMPONENTS	**BAV Solenoid** - Fail to open - Pull-in current exceeding limit - EC to fix issue	**Tcore Sensor** - Out of range - Durability fix planned			**FMD: Fuel Oil Cooler (3 events)** - material compatability
EEC HARDWARE					
EEC SOFTWARE					

Mid Thrust Commercial Engine E2

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
FAN BLADES		**Fan Blade Platform Seal** - Acceptable delamination - Changing ICA			
FAN EXIT GUIDE VANES					
LPC & HPC VANES					
LPC & HPC BLADES					
COMPRESSOR NON-ROTATING AIRSEALS & SHROUDS					
COMPRESSOR STATIC STRUCTURE PARTS	**Inner Case Aft Support Ring** - Slight fretting - Updated ICA				
COMPRESSOR BEARING COMPARTMENT (SEALS, ETC)	**Carbon Seal** - Acceptable wear - EC for durability				
COMPRESSOR MAJOR CASES					
COMPRESSOR ROTATING LIFE LIMITED PARTS					
COMPRESSOR ROTATING NON-LIFE LIMITED PARTS					

Mid Thrust Commercial Engine E2

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
COMBUSTOR PARTS	**Panels** - Oxidation/Erosion - ICA modified	**Panels** - Oxidation/Erosion - ICA modified - bulkhead panels were downchanged parts			
HPT BLADES AND VANES	**HPT 1st Stage Vane** - TE oxidation **HPT 1st Stage Blade** - Platform oxidation				
LPT BLADES AND VANES					
TURBINE NON-ROTATING AIRSEALS & SHROUDS	**HPT 1st Stage Blade Outer Air Seal** -Thermal distress - New seal, increased cooling **LPT Insulation Segments** - Acceptable cracks - EC for durability				
TURBINE STATIC STRUCTURE PARTS	**Mid Turbine Frame** - Braze cracks - AWL inspection incorporated	**Mid Turbine Frame** - Braze cracks - Not as severe as 150 hour test			
TURBINE MAJOR CASES					
TURBINE ROTATING LIFE LIMITED PARTS	**1st and 2nd Stage Sideplates** - Knife edge creep - Supressed cooling flow for triple point				
TURBINE ROTATING NON-LIFE LIMITED PARTS					

Mid Thrust Commercial Engine E2

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
TURBINE BEARING COMPARTMENT (SEALS, ETC)					
GEARBOX ASSEMBLY (SHAFTS, GEARS, HOUSINGS)					
EXTERNALS (TUBES, MANIFOLDS, DUCTS, BRACKETS)					
CONTROLS & ACCESSORIES COMPONENTS	**Oil Pump Shaft Keyway** - Acceptable spalling - EC for durability **ABAV Solenoid** - Over pull-in current but acceptable	**EGT Probe** - Channel A and B failure - Investigating			
EEC HARDWARE					
EEC SOFTWARE					

Large Commercial Engine E3

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
FAN BLADES				**Fan Root** - N1 Vibration	
FAN EXIT GUIDE VANES	**OGV Leaf Seals Springs**				
LPC & HPC VANES					
LPC & HPC BLADES	**HPC Blade** - HCF **HPC Blade Lock** - Material				
COMPRESSOR NON-ROTATING AIRSEALS & SHROUDS					
COMPRESSOR STATIC STRUCTURE PARTS					
COMPRESSOR BEARING COMPARTMENT (SEALS, ETC)	**#1 & #2 Bearing** - Inner ring galling		**Compartment Seal** - Abnormal wear		
COMPRESSOR MAJOR CASES					
COMPRESSOR ROTATING LIFE LIMITED PARTS	**HPC Stage 2-5 Spool** - Material / Coating		**HPC Spools**	**HPC Disk**	**HPC Disk (AD)**
COMPRESSOR ROTATING NON-LIFE LIMITED PARTS					
COMBUSTOR PARTS	**Combustor Case Inserts**			**Combustor Dimple**- Cracking	

Large Commercial Engine E3

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
HPT BLADES AND VANES	**Nozzles** - Thermal	**Nozzles** - Thermal **Blade** - Thermal		**Nozzles** - Dust & corrosive elements, thermal **Blades**- Dust & corrosive elements, thermal	**HPT Stage 2 Nozzle (AD)**
LPT BLADES AND VANES	**Blade/Vane** - Clashing / Rotor axial movement	**Blade/Vane** - Clashing / Rotor axial movement **LPT 4, 5, 6 Blades** - Cracks (welding process)	**Blade/Vane - Clashing. Rotor axial movement**		
TURBINE NON-ROTATING AIRSEALS & SHROUDS	**LPT Stage 3 Outer Seal** - Clashing with rotor	**LPT Stage 3 Outer Seal** - Clashing with rotor **LPT Stg 2 Inner Air Seal** - Cracking	**Outer Air Seal - Thermal**		
TURBINE STATIC STRUCTURE PARTS				**TCF Fwd Seal Anti-Rotation Tabs** - Wear **TCF Flowpath Panel to Fairing Overlaps and Dorito Clamps** - Wear	
TURBINE MAJOR CASES	**Turbine Exhaust Case** - Stress/thermal cracks **LPT Case** - High temp crack				**LPT Case**
TURBINE ROTATING LIFE LIMITED PARTS					
TURBINE ROTATING NON-LIFE LIMITED PARTS					

Large Commercial Engine E3

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
TURBINE BEARING COMPARTMENT (SEALS, ETC)	**#3 & #4 Seal** - Excessive wear	**#3 & #4 Seal** - Excessive wear		**Bearing Compartment Seal** - Wear	
GEARBOX ASSEMBLY (SHAFTS, GEARS, HOUSINGS)				**PMA Driveshaft**	
EXTERNALS (TUBES, MANIFOLDS, DUCTS, BRACKETS)	**Air Duct** - Cracking (cyclic) **Fuel Manifold Ferrules**	**Air Duct** - cracking (150 hour also) **Air Duct** - cracking	**Temp Sensor - Duct Start Seal** **Bracket** - HCF **Drain Hose** - HCF **Tube Hose** - HCF **Hydraulic Hose** - HCF	**Oil Tubes, Nozzles** - System Issues **B Sump Scavenge Tube** - HCF **Fuel Manifold** - HCF	
CONTROLS & ACCESSORIES COMPONENTS	**Main Fuel Pump**	**PT25 Sensor** - vibration **ODM** - Wire Chafing		**Oil Pump** - Wear	**Fuel Pump** **Servo Valve Manifold** **Fuel Manifold**
EEC HARDWARE					
EEC SOFTWARE					

Mid Thrust Commercial Engine E4

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
FAN BLADES					
FAN EXIT GUIDE VANES					
LPC & HPC VANES		**HPC 7th Vane** - ID fillet crack - New design to lower stress			
LPC & HPC BLADES					
COMPRESSOR NON-ROTATING AIRSEALS & SHROUDS	**Abradable Rubstrip** - Excessive disbondng - EC to improve durability				
COMPRESSOR STATIC STRUCTURE PARTS					
COMPRESSOR BEARING COMPARTMENT (SEALS, ETC)					
COMPRESSOR MAJOR CASES					
COMPRESSOR ROTATING LIFE LIMITED PARTS					

Mid Thrust Commercial Engine E4

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
COMPRESSOR ROTATING NON-LIFE LIMITED PARTS					
COMBUSTOR PARTS	**Panel** - Panel burn through - inspection interval required	**Inner and Outer Liner** - burn through - EC for improved cooling			
HPT BLADES AND VANES					
LPT BLADES AND VANES					
TURBINE NON-ROTATING AIRSEALS & SHROUDS					
TURBINE STATIC STRUCTURE PARTS					
TURBINE MAJOR CASES					
TURBINE ROTATING LIFE LIMITED PARTS					
TURBINE ROTATING NON-LIFE LIMITED PARTS					

Mid Thrust Commercial Engine E4

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
TURBINE BEARING COMPARTMENT (SEALS, ETC)					
GEARBOX ASSEMBLY (SHAFTS, GEARS, HOUSINGS)					
EXTERNALS (TUBES, MANIFOLDS, DUCTS, BRACKETS)					
CONTROLS & ACCESSORIES COMPONENTS		**Igniter Cable** - failure of signalriction - EC for improved durability			**FMD: Main Oil Pressure Sensor**
EEC HARDWARE					**FMD: Pb sense line**
EEC SOFTWARE					

Commercial Engine E5

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
FAN BLADES					
FAN EXIT GUIDE VANES					
LPC & HPC VANES		NO TEST FINDINGS			
LPC & HPC BLADES					
COMPRESSOR NON-ROTATING AIRSEALS & SHROUDS					
COMPRESSOR STATIC STRUCTURE PARTS					
COMPRESSOR BEARING COMPARTMENT (SEALS, ETC)					
COMPRESSOR MAJOR CASES					
COMPRESSOR ROTATING LIFE LIMITED PARTS					
COMPRESSOR ROTATING NON-LIFE LIMITED PARTS					
COMBUSTOR PARTS					
HPT BLADES AND VANES	**HPT 1 Blade** - Tip rub - HCF due to resonance				
LPT BLADES AND VANES					
TURBINE NON-ROTATING AIRSEALS & SHROUDS					

Commercial Engine E5

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
TURBINE STATIC STRUCTURE PARTS					
TURBINE MAJOR CASES					
TURBINE ROTATING LIFE LIMITED PARTS		NO TEST FINDINGS			
TURBINE ROTATING NON-LIFE LIMITED PARTS					
TURBINE BEARING COMPARTMENT (SEALS, ETC)	**#7 Seal** - High oil consumption				
GEARBOX ASSEMBLY (SHAFTS, GEARS, HOUSINGS)	**Accessory Gearbox** - bevel and spur gear				
EXTERNALS (TUBES, MANIFOLDS, DUCTS, BRACKETS)	**Rear Inner Bypass Duct** - HCF due to areo loading				
CONTROLS & ACCESSORIES COMPONENTS					
EEC HARDWARE					
EEC SOFTWARE					

Commercial Engine E6

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
FAN BLADES					
FAN EXIT GUIDE VANES					
LPC & HPC VANES	NO TEST FINDINGS	NO TEST FINDINGS			
LPC & HPC BLADES					
COMPRESSOR NON-ROTATING AIRSEALS & SHROUDS					
COMPRESSOR STATIC STRUCTURE PARTS					
COMPRESSOR BEARING COMPARTMENT (SEALS, ETC)					
COMPRESSOR MAJOR CASES					
COMPRESSOR ROTATING LIFE LIMITED PARTS					
COMPRESSOR ROTATING NON-LIFE LIMITED PARTS					
COMBUSTOR PARTS					
HPT BLADES AND VANES					
LPT BLADES AND VANES					
TURBINE NON-ROTATING AIRSEALS & SHROUDS					
TURBINE STATIC STRUCTURE PARTS					

Commercial Engine E6

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
TURBINE MAJOR CASES	NO TEST FINDINGS	NO TEST FINDINGS			
TURBINE ROTATING LIFE LIMITED PARTS					
TURBINE ROTATING NON-LIFE LIMITED PARTS					
TURBINE BEARING COMPARTMENT (SEALS, ETC)					
GEARBOX ASSEMBLY (SHAFTS, GEARS, HOUSINGS)					
EXTERNALS (TUBES, MANIFOLDS, DUCTS, BRACKETS)					
CONTROLS & ACCESSORIES COMPONENTS					
EEC HARDWARE					
EEC SOFTWARE					

LargeThrust Commercial Engine E7

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
FAN BLADES		**Fan Blade -** **Fan Blade Retainer -** Mechanical			
FAN EXIT GUIDE VANES					
LPC & HPC VANES					
LPC & HPC BLADES					
COMPRESSOR NON-ROTATING AIRSEALS & SHROUDS					
COMPRESSOR STATIC STRUCTURE PARTS					
COMPRESSOR BEARING COMPARTMENT (SEALS, ETC)					
COMPRESSOR MAJOR CASES					
COMPRESSOR ROTATING LIFE LIMITED PARTS					
COMPRESSOR ROTATING NON-LIFE LIMITED PARTS					
COMBUSTOR PARTS			**Combustor Aft Support Leg** - LCF		
HPT BLADES AND VANES	**HPT Shroud Hanger-** **HPT Shroud -** **HPT Blade -** Creep	**HPT Nozzles -** Cooling Flow	**HPT Blade -** **HPT Shroud -** **HPT Shroud Hanger -** **HPT Nozzles -** Creep		
LPT BLADES AND VANES					

LargeThrust Commercial Engine E7

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
TURBINE NON-ROTATING AIRSEALS & SHROUDS					
TURBINE STATIC STRUCTURE PARTS					
TURBINE MAJOR CASES					
TURBINE ROTATING LIFE LIMITED PARTS					
TURBINE ROTATING NON-LIFE LIMITED PARTS					
TURBINE BEARING COMPARTMENT (SEALS, ETC)		**#4 Bearing Aft Rotating Seal** - Mechanical	**LPT Brush Seal Damper Support**		
GEARBOX ASSEMBLY (SHAFTS, GEARS, HOUSINGS)					
EXTERNALS (TUBES, MANIFOLDS, DUCTS, BRACKETS)		**Fire Block -** Mechanical			
CONTROLS & ACCESSORIES COMPONENTS					
EEC HARDWARE					
EEC SOFTWARE					

Commercial Engine E8

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
FAN BLADES					
FAN EXIT GUIDE VANES			**Booster IGV Inner Shroud** - HCF		
LPC & HPC VANES					
LPC & HPC BLADES					
COMPRESSOR NON-ROTATING AIRSEALS & SHROUDS					
COMPRESSOR STATIC STRUCTURE PARTS					
COMPRESSOR BEARING COMPARTMENT (SEALS, ETC)					
COMPRESSOR MAJOR CASES					
COMPRESSOR ROTATING LIFE LIMITED PARTS					
COMPRESSOR ROTATING NON-LIFE LIMITED PARTS					
COMBUSTOR PARTS	**W-Seal** - Thermal				
HPT BLADES AND VANES	**HPT Blade** - Thermal		**HPT Blade** - Thermal		
LPT BLADES AND VANES					
TURBINE NON-ROTATING AIRSEALS & SHROUDS					
TURBINE STATIC STRUCTURE PARTS					

Commercial Engine E8

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
TURBINE MAJOR CASES					
TURBINE ROTATING LIFE LIMITED PARTS				**Fan Mid Shaft -** Material	
TURBINE ROTATING NON-LIFE LIMITED PARTS					
TURBINE BEARING COMPARTMENT (SEALS, ETC)				**#4 Bearing Seal -** Mechanical	
GEARBOX ASSEMBLY (SHAFTS, GEARS, HOUSINGS)					
EXTERNALS (TUBES, MANIFOLDS, DUCTS, BRACKETS)	**Clamp** - Mechanical		**B-Sump Vent Tube & Clip** - HCF **TBV Exhaust Screen** - HCF **B-Sump Drain P-Clamp** - HCF **TR Cross Tie Brackets** - HCF **Fuel Tube** - HCF **Fuel Hydraulics Bracket** - HCF **Heat Shield** - HCF	**Main Fuel Hose Support Bracket** - HCF **Boster Anti-Ice Duct** - HCF	
CONTROLS & ACCESSORIES COMPONENTS			**Harness** - HCF **Ignition Lead** - HCF **FMU** - Mechanical	**BAI Valve** - Mechanical **Fuel Filter Bowl Pawl** - HCF	
EEC HARDWARE					

Commercial Engine E8

PART FAMILY	150 HR. ENDURANCE TEST FINDINGS	IMI TEST FINDINGS	ETOPS TYPE TEST FINDINGS	FIELD ISSUES	FMDs/ADs
EEC SOFTWARE					

11.6 Appendix F - Use of Substitute Thrust Reverser

The following is a proposal, background, and basis to incorporate a provision into 14CFR33.87 and 14CFR33.97(a) to allow the use of a Slave Thrust Reverser. While the specific Tasking of this ARAG WG did not include the need to address the use of a Slave Thrust Reverser, the WG did consider what other potential improvements or refinements could be made to the existing 14CFR33.87 rule. The WG recommends addition of this provision primarily to reduce the additional burden on the agencies and the applicants of meeting the regulations via Issue Paper.

Section 14CFR25.934 requires that thrust reverses installed on turbo-jet engines meet the requirements of 14CFR33.97(a), which includes a requirement for engines incorporating thrust reversers to accomplish the engine endurance test, prescribed in 14CFR33.87, with the thrust reverser installed, and 14CFR33.97(b). A current practice has been to use a slave for the forward thrust part of engine endurance test and a production equivalent thrust reverser for the reverse thrust part of the test as required by 14CFR33.97(b). This practice results in the need for a finding of equivalent safety to accomplish the forward thrust part of the engine endurance test with a slave duct installed in lieu of direct compliance with 14CFR25.934 in accordance with an FAA Issue Paper.

The Issue Paper generally acknowledges that with respect to the reverser, the intent of the endurance test referenced in 14CFR33.97(a) and prescribed in 14CFR33.87 is not primarily to evaluate the structural integrity of the thrust reverser but to show compatibility of the thrust reverser with the engine. The Issue Paper addresses the use a slave duct for the engine tests required by 14CFR33.97(a) and a production equivalent thrust reverser for the test required by 14CFR33.97(b).

Tests specified by 14CFR33.97(a) are typically conducted with substitute thrust reversers (STR) developed to provide equivalent internal lines and nozzle exit area. STR's are designed and built to match the aerodynamic lines of the production thrust reversers but do not have the translating cowl, blocker doors, drag links, actuation system or acoustic treatment of a production unit. There may be small differences in the aerodynamic lines, leakages and operating effective nozzle area due to the different construction of the two units, resulting in a slightly lower duct pressure loss for the STR's than for the production T/R's. This difference can be accounted for in determination of the engine rated thrust.

Tests to be conducted include the following:

14CFR33.83 Vibration Test

> These tests can be conducted with a STR or with variable fan nozzle (VFN) to allow the engine to reach redline physical speeds. With the exception of the fan outlet/exit guide vanes, the reverser and fan nozzle configuration has no impact on the measured vibratory responses. The VFN will be used to simulate operation with an active reverser to show that the guide vanes have sufficient flutter margin and that they therefore meet the requirements of 14CFR33.83 when operating with a reverser.

14CFR33.85 Calibration Test, 14CFR33.87 Endurance Test, and 14CFR33.89 Operations Test

These tests can be conducted with a STR, which does not affect the test conduct or test results other than the small impact on rated thrust.

Correction factors will be developed to adjust the engine rated thrust as required.

Operation and vibratory data collected during this testing can be compared to data collected during the reverser cycling testing in accordance with 14CFR33.97(b) to demonstrate that the operation and vibratory characteristics of the engine are not changed.

For the reverser cycling testing prescribed in 14CFR33.97(b), a production thrust reverser will be installed. A 225-cycle test will be conducted to fulfill both 14CFR 33.97(b) and EASA CS-E890(c) requirements by completing 175 normal reverse cycles, 25 maximum power RTO cycles, 15 part power RTO cycles and 10 "Refused Landing" cycles. Engine parameters will be monitored throughout the testing to ensure engine compatibility for both forward and reverse thrust operations. A "compatibility statement" is typically provided by the engine manufacturers indicating satisfactory engine operation with the thrust reverser installed.

11.7 Appendix G - Endurance test rule comparison 14CFR33 and CS-E

The following tables provide a comparison of the Endurance Test requirements between 14CFR33 and CS-E. The comparison covers the main related requirements however other minor links and references to the test may exist in other sections. “?” indicates that no comparable requirement was not found.

14CFR33 basis with CS-E equivalents.

33.82 General				***Equivalent CS-E***	***comments***
			engine settings	140(c) and (e)	equivalent
33.85 Calibration tests				***Equivalent CS-E***	***comments***
(a)			pre test	730	equivalent
(b)			post test	730	equivalent
(c)			stabilisation	730	not equivalent
(d)			OEI provision	730	not equivalent, 30 sec and 2 min OEI are exempted
33.87 Endurance test				***Equivalent CS-E***	***comments***
(a)			**General**	various	equivalent
	(1)		ordering	740(b)(1)	equivalent
	(2)		auto controls	140(b)	equivalent
	(3)		power at 100%	40, 740(f), 740(f)(4)	not equivalent Power is covered in 40 and 730 where it need be “adequately justified”. Gas temp is cover in 740 (f)(4) based on average minus scatter (see Note 1). Speeds are covered in 740 (f) based on

					average. "More than one test" is covered by 740(f)(1).
	(4)		fluids spec		not equivalent 560(a)(1), 570(g)(1) are related but do not refer to the Endurance Test.
	(5)		max bleed 1/5	690(a)(3)	equivalent
	(6)		access'y load	140(d)(1)	
		(i)	at limit	140(d)(1)	equivalent "suitably loaded"
		(ii)	separate rig	170 and AMC	equivalent
		(iii)	OEI exempt'n	140(d)(2)	equivalent
	(7)		temps and pressures	740 (e), (f)	not equivalent average temps are used oil temps similar but not equivalent see Note 1 for gas temps
	(8)		transients	740(f)(4)(iii)	not equivalent see Note 2
	(9)		supersonic specific	none	not equivalent
		(i)	throttle	none	not equivalent
		(ii)	hyd fluid temp	none	not equivalent
		(iii)	inlet temp	none	not equivalent
		(iv)	config	none	not equivalent
		(v)	inlet distor'n	none	not equivalent
(b)			**Schedule (norm)**	740(c)(1)	equivalent

	(1)		stage 1	740(c)(1)	not equivalent schedule itself is equivalent but additional comments for control and augmented thrust are not covered.
	(2)		stage 2	740(c)(1)	equivalent
		(i)	max cont	740(c)(1)	equivalent
		(ii)	max T/O	740(c)(1)	equivalent
	(3)		stage 3	740(c)(1)	equivalent
	(4)		stage 4	740(c)(1)	equivalent
	(5)		stage 5	740(c)(1)	equivalent
	(6)		starts	750	equivalent
(c)			**Schedule (rotorcraft 30 min OEI)**		
	(1)		stage 1	740(c)(2)	not equivalent schedule itself is equivalent but additional comments for control and augmented thrust are not covered.
	(2)		stage 2	740(c)(2)	equivalent
		(i)	max cont	740(c)(2)	equivalent
		(ii)	max T/O	740(c)(2)	equivalent
	(3)		stage 3	740(c)(2)	equivalent
	(4)		30 min OEI power	740(c)(2)	equivalent
	(5)		stage 4	740(c)(2)	equivalent
	(6)		stage 5	740(c)(2)	equivalent
	(7)		starts	750	equivalent

(d)			**Schedule (rotcr cont OEI)**		
	(1)		stage 1	740(c)(2)	not equivalent schedule itself is equivalent but additional comments for control and augmented thrust are not covered.
	(2)		stage 2	740(c)(2)	equivalent
		(i)	max cont	740(c)(2)	equivalent
		(ii)	max T/O	740(c)(2)	equivalent
	(3)		stage 3 OEI power	740(c)(2)	equivalent
	(4)		1 hr max cont	740(c)(2)	not equivalent CS-E is only 30 mins
	(5)		stage 4	740(c)(2)	equivalent (CS-E is 30 mins longer however)
	(6)		stage 5	740(c)(2)	equivalent
	(7)		starts	750	equivalent
(e)			**Schedule (rot.cr $2^1/_2$ min OEI)**		
	(1)		add’l test	740(c)(2)	not equivalent minor difference, CS-E 740 (c)(2) is 5 mins shorter on OEI power.
	(2)		add’l test	740(c)(2)	equivalent
(f)			**Schedule (rot.cr 2 min+30sec OEI)**	(c)(3)(iii)	equivalent
	(1)		add’l test	(c)(3)(iii)	equivalent

	(2)		add’l test	(c)(3)(iii)	equivalent
	(3)		add’l test	(c)(3)(iii)	equivalent
	(4)		add’l test	(c)(3)(iii)	equivalent
	(5)		add’l test	(c)(3)(iii)	equivalent
	(6)		add’l test	(c)(3)(iii)	equivalent
	(7)		add’l test	(c)(3)(iii)	equivalent
	(8)		add’l test	(c)(3)(iii)	equivalent
(g)			**Supersonic engines**		
	(1)		subsonic conds	none	not equivalent
		(i)	add’l test	none	not equivalent
		(ii)	add’l test	none	not equivalent
		(iii)	add’l test	none	not equivalent
		(iv)	add’l test	none	not equivalent
	(2)		supersonic conds	none	not equivalent
		(i)	add’l test	none	not equivalent
		(ii)	add’l test	none	not equivalent
		(iii)	add’l test	none	not equivalent
		(iv)	add’l test	none	not equivalent
		(v)	add’l test	none	not equivalent
	(3)		Starts	750	equivalent
33.93 Teardown inspection				***Equivalent CS-E***	***comments***
(a)			Normal	740(h)(1)	equivalent
	(1)		engine settings	140(c) and (e)	equivalent

	(2)		condition	740(h)(1)	not equivalent, 14CFR33 require overhaul acceptance standard, CS-E requires maintenance acceptance standard.
(b)			OEI		equivalent
	(1)		engine settings	140(c) and (e)	equivalent
	(2)		condition	740(h)(1)	equivalent
(c)			insp option		equivalent
33.99 General conduct of block tests				***Equivalent CS-E***	***comments***
(a)			engines	730	equivalent
(b)			interruptions	740(b)(1), 150(b)	equivalent
(c)			ownership	Part 21 Subpart J	equivalent

CS-E basis with 14CFR33 equivalents

CS-E 140 Tests – Engine Configuration				***Equivalent 14CFR33***	***comments***
(a)			representative config	none	Covered in AC ch 3-1 c.
(b)			automatic controls	33.87(a)(2)	equivalent
(c)			setting of variable devices	33.82	equivalent
(d)	**(1)**		loading of drives	33.87(a)(6)(i)	equivalent
	(2)		loading of drives OEI	33.87(a)(6)(iii)	equivalent

(e)			representation of a/c feat.	none	not equivalent
(f)			prop, combined tests	none	not equivalent
CS-E 150 Tests – General Conduct of tests				***Equivalent 14CFR33***	***comments***
(a)			Fuel and oil choice	none	not equivalent
(b)			Servicing and repair during test	33.99	equivalent
(c)			Humidity adjustment	none	not equivalent
(d)			Recording of paramenters	none	not equivalent
(e)			Record of drift of variable setttings	none	not equivalent
(f)			Calibration of equipment	none	not equivalent
CS-E 600 Tests - General				***Equivalent 14CFR33***	***comments***
(a)			intake standard	none	not equivalent
(d)			cleaning	none	not equivalent
(e)			engine attitude	none	not equivalent
Engine bleed air CS-E 690(a)				***Equivalent 14CFR33***	***comments***
(a)	**(1)**		**General**		
		(i)	once per stage	none	not equivalent
		(ii)	other tests	none	-
		(iii)	allowance	33.87(a)(5)	equivalent

	(2)		**calibration test**	none	not equivalent
	(3)		**Endurance test**	-	-
		(i)	stage 3, 7, 13, 17, 23	33.87 (a)(5)	equivalent
		(ii)	OEI exemption	none	not equivalent
CS-E 720 Continuous Ignition				***Equivalent 14CFR33***	***comments***
(c)			use during endurance test	none	not equivalent
(d)			10 hrs min endurance	none	not equivalent
CS-E730 Engine Calibration Tests				***Equivalent 14CFR33***	***comments***
			tests	33.85	equivalent
CS-E 740 Endurance Test				***Equivalent 14CFR33***	***comments***
(a)			ref to E 890	33.97	equivalent
(b)	**(1)**		ordering	33.87(a)(1), 33.99(b)	equivalent
	(2)		power set time	33.87(a)(7)	equivalent
	(3)		speed tolerance	33.87(a)(3)	not equivalent, but similar, sets a minimum
	(4)		prop type	none	
	(5)		pre test records	none	
(c)			**Schedules**		
	(1)		normal	33.87(b)	Optional Part 2 is not covered
	(2)	**(i)**	21/2 , cont, or 30 min OEI, parts 1-5		30 min OEI is equiv, cont OEI is not equiv for Part 4s (30 mins shorter under Part 33)

					$2^1/_2$ is equiv (different ordering).
		(ii)	if only 1 rating		equivalent
		(iii)	14CFR33.87 option		equivalent
	(3)	**(i)**	30 sec, 2 min OEI, parts 1-5		equivalent
		(ii)	above +30 min OEI		equivalent
		(iii)	add'l test	(f)	equivalent
(d)			**accels and decels**		
	(1)				
		(i)		33.87(b)(5)	equivalent
		(ii)		33.87(c)(6)	equivalent
	(2)				
		(i)	data reading	none	
		(ii)	data reading	none	
(e)			**oil pressure**		
	(1)			33.87(a)(7)	equivalent
	(2)			33.87(a)(7)	equivalent
(f)			**operating limitations**	33.87(a)(3)	not equivalent, limits are based on minimums, see Note 1
	(1)		multiple tests	(a)(3)	equivalent
	(2)		speeds allowance with bleed	33.87(a)(5)	equivalent
	(3)		torque shortfall	AC33.87-1A 3-2(c)(4)(a)	equivalent
	(4)		temperatures	-	-
		(i)	general	33.87(a)(3)	equivalent

		(ii)	averaging	33.87(a)(3)	not equivalent, limits are based on minimums, see Note 1
		(iii)	2 min transients	33.87(a)(8)	not equivalent, see Note 2
		(iv)	OEI transients	33.87(a)(8)	not equivalent, see Note 2
		(v)	oil temp allowance, 10 min rating	none	not equivalent
		(vi)	oil temp exceedance	none	not equivalent
(g)			**incremental periods**	-	-
	(1)		peak vibs	33.87((b)(4)	equivalent
	(2)		constant speed case	33.87((b)(4)	equivalent
	(3)		power turbine case	none	not equivalent
	(4)		rotorcraft case	none	not equivalent
(h)			**Inspection checks**	-	-
	(1)		acceptance	33.93(a)	equivalent, note: 14CFR33 require overhaul acceptance standard, CS-E requires maintenance acceptance standard.
	(2)			-	-
		(i)		33.93(c)	equivalent
		(ii)		33.87(f)	equivalent
		(iii)		33.93(b)(2)	equivalent
Starting Tests CS-E 750				***Equivalent 14CFR33***	***comments***
(a)			cold starts	33.87(b)(6)	equivalent “evenly distributed” is not mentioned

(b)			false starts	33.87(b)(6)	equivalent “evenly distributed” is not mentioned
(c)			total 100 starts	33.87(b)(6)	equivalent
(d)			free power turbine	none	not equivalent
(e)			recording	none	not equivalent

Note 1

CS-E 740 Endurance Test Operating Limits

CS-E 740 (f) vs CFR14 Part 33.87(a)(3), (a)(7)

Gas Temperature Limit margin

Temperature margin is necessary to account for variations for in-service engines relative to the temperature levels in the certification test, the rules differ in the method by which it is achieved:

CS-E requires an adjustment to be derived and then subtracted from the average temperature from the test:

CS-E 740(f) specifies operating limits are based on the mean values demonstrated in the appropriate periods of the endurance test with a debit to reduce the value obtained from the average test result to ensure that turbine entry temperatures in service cannot exceed the temperature established in the test. This is interpreted to mean that a fleet engine-to-engine scatter value (T41(TET) – EGT(TGT) relationship scatter plus EGT measurement error scatter) and instrumentation accuracy tolerance value should be debited from the average obtained during the test with consideration also for ambient conditions and engine deterioration effects (which may reduce the declared EGT further) to give the declared Red Line EGT limit.

14CFR33 uses test minimum instead of average.

14CFR33.7 states operating limits are established by the Administrator and 14CFR 33.87(a)(7) specifies that operating limits must be maintained at at-least 100% during the endurance test. Implying that the minimum EGT(TGT) temperature demonstrated during the test will be the declared Red Line EGT limit. Temperature setting scatter from the test provides the conservatism that the CS-E debit provides.

T41(TET) – EGT(TGT) relationship

The T41(TET) – EGT(TGT) ratio is an complex factor in the calculation of the Red Line EGT limit because only a single ratio value is selected to establish the Red Line EGT limit at certification however in reality the relationship varies over the service life of an engine and across the engine operating envelope. As a turbine deteriorates it becomes less effective at converting gas temperature to shaft energy and therefore a higher EGT level would correspond to limiting T41 than would have been the case for a new engine. Setting a limit by EGT derived from a new engine therefore gives excess margin when the engine becomes deteriorated and conversely, setting a limit by EGT derived from a deteriorated engine is inadequate while the engine is new. It is therefore important to understand exactly how the EGT limit has been set in order to ensure a fully effective EGT limit.

The CS-E approach takes average EGT from the endurance test then subtracts scatter factors to account for the worst case engine. The scatter factors must account a conservative assumption for T41(TET) – EGT(TGT) relationship (i.e. for a worst case engine in the un-deteriorated state) thus the concerns raised here of an ineffective EGT limit while the engine is relatively new are addressed. (It is possible that the correction factors could be revised post certification however, in order to gain increased time on-wing.)

The FAR approach takes the minimum EGT from the endurance test and declares this as the Red Line EGT limit with no account of the relevant variables for the in-service situation or for deterioration effects. There is no guarantee that a worst case engine will be safely covered by an EGT limit that is derived in this way.

In defence of the FAR approach it has been argued however that the risk of a T41 exceedance only applies to deteriorated engines, other limitations (such as thrust control or shaft speed limits) preventing an exceedance for newer engines.

Note 2

CS-E 740 Endurance Test transitory exhaust gas temperature (EGT) exceedance at take-off

CS-E 740 (f)(4)(iii) vs 14CFR33.87(a)(8) and AC33.87-1A ch3-2(h)

The 14CFR33 requirement for 30 sec transient over-temperature is to run the 30 second over-temperature on 50% of the Take-Off power accelerations giving in total 1 hr 18 minutes at over-temperature levels.

CS-E 740(f)(4)(iii) requirement for 2 minutes transient over-temperature is to run a 2 minute over-temperature at all accelerations to Take-Off power (6 hrs 35 minutes at over-temperature).

(This transitory EGT exceedance does not correspond to the definition of the Maximum Exhaust Gas Over-temperature limit in CS-D because its use may not be inadvertent. The test of CS-E 870 "Exhaust Gas Over-Temperature Test" is therefore not applicable).

The same applies to continuous and 30 min OEI power however for shorter OEI ratings 14CFR33 allows a 10 sec transient but the CS-E requires this be included in the speed/temperature/torque limit for that rating.

11.8 Appendix H - Incorporation of the Alternative Test into the current rule

The following tables identify where changes may be needed to incorporate the alternate test into the current 14CFR33 and CS-E rules.

Requirement				New text required	Pertinent to Alt Test	comments
33.82 Block tests, General						
			engine settings	No	Yes	
33.85 Calibration tests						
(a)			pre test	No	Yes	
(b)			post test	No	Yes	
(c)			stabilisation	Yes	No	Not relevant to averaging method, exception required for 33.87 (h).
(d)			OEI provision	No	Yes	
33.87 Endurance test						
(a)			**General**	Yes	No	Not applicable to the Alt Test (h), alternate text required to outline the structure and planning requirements of the alternate test.
	(1)		ordering	No	Yes	
	(2)		auto controls	No	Yes	
	(3)		power at 100%	Yes	No	Not applicable to the Alt Test (h), alternate text required subject to harmonisation agreement on the use of averages, details required of method of establishing redlines, some text from CS-E 740 (f) and (f)(4) could be adopted.
	(4)		fluids spec	No	Yes	
	(5)		max bleed 1/5	Yes	Yes	Additional comment to accommodate averaging method of section (h) for limitation parameters.
	(6)		access'y load	No	Yes	
		(i)	at limit	No	Yes	
		(ii)	separate rig	No	Yes	

		(iii)	OEI exempt'n	No	No	
	(7)		temps and pressures	No	Yes	
	(8)		transients	No	Yes	
	(9)		supersonic specific	No	No	
		(i)	throttle	No	No	
		(ii)	hyd fluid temp	No	No	
		(iii)	inlet temp	No	No	
		(iv)	config	No	No	
		(v)	inlet distor'n	No	No	
(b)			**Schedule (norm)**	Yes	No	Alternate option (h) should be introduced into the existing text.
	(1)		stage 1	No	No	
	(2)		stage 2	No	No	
		(i)	max cont	No	No	
		(ii)	max T/O	No	No	
	(3)		stage 3	No	No	
	(4)		stage 4	No	No	
	(5)		stage 5	No	No	
	(6)		starts	No	No	Will be copied into new section (h).
(c)			**Schedule (rotorcraft 30 min OEI)**	No	No	
	(1)		stage 1	No	No	
	(2)		stage 2	No	No	
		(i)	max cont	No	No	
		(ii)	max T/O	No	No	

	(3)		stage 3	No	No	
	(4)		30 min OEI power	No	No	
	(5)		stage 4	No	No	
	(6)		stage 5	No	No	
	(7)		starts	No	No	
(d)			**Schedule (rotcr cont OEI)**	No	No	
	(1)		stage 1	No	No	
	(2)		stage 2	No	No	
		(i)	max cont	No	No	
		(ii)	max T/O	No	No	
	(3)		stage 3 OEI power	No	No	
	(4)		1 hr max cont	No	No	
	(5)		stage 4	No	No	
	(6)		stage 5	No	No	
	(7)		starts	No	No	
(e)			**Schedule (rotcr $2^1/_2$ min OEI)**	No	No	
	(1)		add'l test	No	No	
	(2)		add'l test	No	No	
(f)			**Schedule (rotcr 2 min+30sec OEI)**	No	No	
	(1)		add'l test	No	No	
	(2)		add'l test	No	No	
	(3)		add'l test	No	No	

	(4)		add'l test	No	No	
	(5)		add'l test	No	No	
	(6)		add'l test	No	No	
	(7)		add'l test	No	No	
	(8)		add'l test	No	No	
(g)			**Supersonic engines**	No	No	
	(1)		subsonic conds	No	No	
		(i)	add'l test	No	No	
		(ii)	add'l test	No	No	
		(iii)	add'l test	No	No	
		(iv)	add'l test	No	No	
	(2)		supersonic conds	No	No	
		(i)	add'l test	No	No	
		(ii)	add'l test	No	No	
		(iii)	add'l test	No	No	
		(iv)	add'l test	No	No	
		(v)	add'l test	No	No	
	(3)		Starts	No	No	
(h)			**Alternate to (b)**	Yes	Yes	New section required to detail the alternate test.

33.93 Teardown inspection						
(a)			Normal	No	Yes	
	(1)		engine settings	No	Yes	
	(2)		condition	No	Yes	
(b)			OEI	No	No	
	(1)		engine settings	No	No	
	(2)		condition	No	No	
(c)			insp option	No	No	
33.99 General conduct of block tests						
(a)			engines	No	Yes	
(b)			interruptions	No	Yes	
(c)			ownership	No	Yes	

Requirement				**New text required**	**Pertinent to Alt Test**	**comments**
CS-E 140 Tests – Engine Configuration						
(a)			representative config	No	Yes	
(b)			automatic controls	No	Yes	
(c)			setting of variable devices	No	Yes	
(d)	(1)		loading of drives	No	Yes	
	(2)		loading of drives OEI	No	Yes	
(e)			representation of a/c feat.	No	Yes	
(f)			prop, combined tests	No	Yes	
CS-E 150 Tests – General Conduct of tests						
(a)			Fuel and oil choice	No	Yes	
(b)			Servicing and repair during test	No	Yes	
(c)			Humidity adjustment	No	Yes	
(d)			Recording of parameters	No	Yes	
(e)			Record of drift of variable settings	No	Yes	
(f)			Calibration of equipment	No	Yes	
CS-E 600 Tests - General						
(a)			intake standard	No	Yes	

(d)			cleaning	No	Yes	
(e)			engine attitude	No	Yes	
Engine bleed air CS-E 690(a)						
(a)	(1)		**General**	Yes	Yes	Adjustment of reference to endurance test / alternate test required.
		(i)	once per stage	Yes	Yes	Adjustment of reference to endurance test / alternate test required.
		(ii)	other tests	No	No	
		(iii)	allowance	No	Yes	
	(2)		**calibration test**	No	Yes	
	(3)		**Endurance test**			
		(i)	stage 3, 7, 13, 17, 23	Yes	Yes	Adjustment of reference to endurance test / alternate test required.
		(ii)	OEI exemption	No	No	
CS-E 720 Continuous Ignition						
(c)			use during endurance test	No	No	
(d)			10 hrs min endurance	No	No	
CS-E730 Engine Calibration Tests						
			tests	No	Yes	
CS-E 740 Endurance Test						
(a)			ref to E 890	No	Yes	
(b)	(1)		ordering	No	Yes	
	(2)		power set time	No	Yes	
	(3)		speed tolerance	No	Yes	
	(4)		prop type	No	Yes	
	(5)		pre test records	No	Yes	
(c)			**Schedules**			

	(1)		normal	Yes	No	Alternate option (c)(4) should be introduced into the existing text.
	(2)	(i)	21/2 , cont, or 30 min OEI, parts 1-5	No	No	
		(ii)	if only 1 rating	No	No	
		(iii)	FAR 33.87 option	No	No	
	(3)	(i)	30 sec, 2 min OEI, parts 1-5	No	No	
		(ii)	above +30 min OEI	No	No	
		(iii)	add'l test			
	(4)		**Alternate to (1)**	Yes	Yes	New section required to detail the alternate test cycles and severity guidelines.
(d)			**accels and decels**			
	(1)					
		(i)	control lever – a/c	No	Yes	
		(ii)	control lever – r/c	No	No	
	(2)					
		(i)	data reading	No	Yes	
		(ii)	data reading	No	No	The alternate test was not intended for rotorcraft engines.
(e)			**oil pressure**	Yes	No	
	(1)			No	Yes	To be reworded to suit the alternate test option, in addition to current wording
	(2)			No	Yes	

(f)			**operating limitations**	Yes	Yes	Requires revision to recognise that TET limitations may be derived from an analysis for 740 (c)(4) alternate tests.
	(1)		multiple tests	No	No	
	(2)		speeds allowance with bleed	Yes	Yes	To be reworded to suit the alternate test option, in addition to current wording.
	(3)		torque shortfall	No	No	
	(4)		temperatures			
		(i)	general	Yes	No	
		(ii)	averaging	Yes	Yes	New text required to define limit definition for EGT (similar to modification to 33.87(a)(3)).
		(iii)	2 min transients	Yes	Yes	To be rewording to clarify how transient delta will be applied to the varying MTO conditions of the alternate test.
		(iv)	OEI transients	No	No	The alternate test was not intended for rotorcraft engines.
		(v)	oil temp allowance, 10 min rating	Yes	Yes	To be rewording to clarify how this is accommodated in the schedule of the alternate test.
		(vi)	oil temp exceedance	Yes	No	
(g)			**incremental periods**			
	(1)		peak vibs	No	Yes	
	(2)		constant speed case	No	No	
	(3)		power turbine case	No	No	
	(4)		rotorcraft case	No	No	
(h)			**Inspection checks**			
	(1)		acceptance	No	Yes	

	(2)			No	No	
		(i)		No	No	
		(ii)		No	No	
		(iii)		No	No	
Starting Tests CS-E 750						
(a)			cold starts	No	Yes	
(b)			false starts	No	Yes	
(c)			total 100 starts	No	Yes	
(d)			free power turbine	No	No	
(e)			recording	No	Yes	

11.9 Appendix I - Acronyms Used in this Report

ACRONYMS	**Definition**
AC	Advisory Circular
AD	Airworthiness Directives
AIA	Aerospace Industries Association
APR	Automatic Power Reserve
APU	Auxiliary Power Unit
ARAC	Aviation Rulemaking Advisory Committee
ASD	AeroSpace and Defence Industries Association of Europe
ASMET	Accelerated Simulated Mission Endurance Test
AWM	Transport Canada Airworthiness Manual
BoM	Bill of Materials
BPR	By-Pass Ratio
CAR	Civil Aviation Regulations
CPA	Critical Point Analysis
CFR	Code of Federal Regulations
CRI	Certification Review Item
CS-E	Certification Specifications - Engines
DAH	Design Approval Holder
DT_{AMB}	Delta Temperature From Standard Day Conditions (delta from 59 deg F or 15 deg C)
EAI	Engine Anti-Ice
EASA	European Aviation Safety Agency
EGT	Exhaust Gas Temperature
EHWG	Engine Harmonization Working Group
ETCDS	Engine Type Certificate Data Sheet
ETOPS	Extended Operations
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Engine Control
FN	Thrust
HBPR	High By-Pass Ratio
HCF	High Cycle Fatigue
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ICAs	Instructions For Continued Airworthiness
IGV	Inlet Guide Vane
IMI	Initial Maintenance Inspection
IPC	Intermediate Pressure Compressor
IPT	Intermediate Pressure Turbine
ISA	International Standard Atmosphere
ITT	Interstage Turbine Temperature
JAA	Joint Airworthiness Authorities
LBPR	Low Bypass Ratio

LCF	Low Cycle Fatigue
LP	Low Pressure
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
MCL	Maximum Climb (Thrust)
MCT	Maximum Continuous Thrust
MEPS	Most Extreme Parameter Stack
MTO	Maximum Take-Off
N1	Low Pressure Spool Physical Speed
N1K	N1 speed corrected to standard day conditions
N2	High Pressure Spool Physical Speed on a Two Shaft Engine, Intermediate Pressure Spool Physical Speed on a Three Shaft Engine
N3	High Pressure Spool Physical Speed on a Three Shaft Engine
NGV	Nozzle Guide Vane (Turbine)
NH	High Pressure Spool Physical Speed
NL	Low Pressure Spool Physical Speed
OAT	Outside Air Temperature
OEI	One Engine Inoperative
OEM	Original Equipment Manufacturer
OPR	Overall Pressure Ratio
P3	High Pressure Compressor Discharge Pressure
PMA	Parts Manufacturer Approval
RTS	Return To Shop (Assembly)
S/L	Sea Level
SLS	Sea Level Static
SPLCF	Sustained Peak Low Cycle Fatigue
Stg	Stage
T_{41}	Turbine Inlet Temperature
TAE	Transport Airplane and Engine Sub-Committee
TCCA	Transport Canada Civil Aviation
TCDS	Type Certificate Data Sheet
TET	Turbine Entry Temperature
TGT	Turbine Gas Temperature
TIA	Type Inspection Authorization
TIT	Turbine Inlet Temperature
T_m, T_{metal}	Metal Temperature
TMF	Thermo Mechanical Fatigue
TRL	Triple Red Line
VG	Variable Geometry
VGV	Variable Guide Vanes
VSV	Variable Stator Vane
WG	Working Group

11.10 Appendix J - Definitions of Terms Used

Term	**Definition**
Corner Point	Corner point temperature is where the EGT is highest when operating at maximum thrust conditions. Operating at a higher OAT beyond the corner point temperature is possible, however the thrust must be reduced (de-rated) to avoid an EGT redline exceedance
Corrected Speed (nondimensional speed)	Speed a component would rotate at if the inlet temperature corresponded to ambient conditions at Sea Level, on a Standard Day (i.e. 288.15K or approx 15C or 59F).
Critical Component	Component within the engine which is most limiting in terms of useful (serviceable) life
Critical Point Analysis	An analysis of an engine's limiting operating characteristics throughout the flight envelope
Domestic Cooling	See Secondary Cooling
Kink Point (pinch point)	See Corner Point
Limiting Design Feature/Parameter	Feature or failure mode of a component or system which is expected to limit its useful (serviceable) life
Limiting Temperature	Maximum temperature which an engine or component is designed to be able to operate at with adequate safety margin (see Red Line)
Margin	Proximity to a red line (limiting) speed or temperature
Most Extreme Parameter Stack	An analysis of an engine's most extreme operating conditions throughout its declared flight envelope, analogous to CPA
Nondimensional Speed	same as corrected speed
Overboost	Operation of an engine beyond its type design rated thrust or power
Overthrust	Synonymous with Overboost
Pinch Point (kink point)	Point(s) in the flight envelope where the margin to a red line (limiting) rotor speed or temperature is at a minimum
Red Line	Maximum (limiting) temperature or rotor speed as declared on the engine's Type Certificate Data Sheet
Secondary Cooling	An engine's internal, or domestic, cooling supply for turbine and rotor components, usually fed from the high pressure compressor
Type Inspection Authorization (TIA)	Showing that the airplane manufacturer makes to the regulator to show that the airplane is representative of type design

12 Response to FAA Letter Requesting Clarification of Report

The Working Group (WG) was reconvened to review and provide responses to questions raised by the FAA in respect of the report “Alternate Test to 14CFR33.87 Endurance Test, EHWG task from Federal Register Vol.79, #14 Jan 22nd 2014” dated January 31, 2017 (herein referred to as the “Final Report”). Questions were documented in the letter from Brandon Roberts, Acting Executive Director, Office of Rulemaking, Federal Aviation Administration to Ms. Yvette A. Rose, Chair, Aviation Rulemaking Advisory Committee dated March 12, 2020. For ease of reference, this letter will be herein referred to as the “Issues Letter”.

Members:

The Working Group (WG) Team membership comprised the following individuals from the regulatory agencies and industry, authorized by the FAA, and approved by the ARAC Executive Committee. It should be noted that while the intent was to incorporate members from the original Team, membership was changed to account for personnel retirements and withdrawals from the Working Group.

Neill Forrest**	(Rolls-Royce plc)	WG Chair
Peter Turyk**	(Pratt & Whitney Canada)	WG Chair
Alan Strom***	(FAA-ANE Standards)	FAA Representative
Philip Haberlen***	(FAA-ANE Standards)	FAA Representative
Keith Morgan	(Pratt & Whitney)	ARAC Representative
Yves Cousineau*	(Transport Canada)	
Antony Boud*	(EASA)	
Ed Barry	(GE Aviation)	
Pat Markham*	(HEICO)	
Colin French	(Rolls-Royce plc)	
Bruce Cook	(Rolls-Royce Deutschland)	
Joelle Rambour	(SAFRAN)	
Doug Hogge*	(Williams International)	
Dave Manion	(Boeing)	
Pierre-Emmanuel Arnaud	(Airbus)	

* Continuing from previous ARAC working group
** Neill Forrest assumed duties as WG Chair from Pete Thompson (GE). Mr. Forrest retired during the course of the reconvened WG, after which Peter Turyk was appointed Chair of the WG.
*** Alan Strom assumed the duties as the FAA Representative for the reconvened WG. At the beginning of 2021, Mr. Strom was reassigned on a detail within FAA, after which Mr. Haberlen assumed the role of the FAA Representative.

Other Participants/Subject Matter Experts:
Brent Hart – Office of Rulemaking, FAA

Goals/Objectives/Expectations:

1. Provide responses to the following questions (with adequate rationale) raised in the Issues Letter based upon the previously submitted Endurance working group Final Report.

Specific clarification was requested for the following:

1. Severity equivalence process and its intended purpose.
2. Severity equivalence process for other than creep failure modes, including failure modes not currently addressed by § 33.87 regulation.
3. Constraints for implementing the recommended hybrid performance-based and prescriptive solutions.
4. Role of the engine CPA.
5. Simplify the possible approaches by removing the T_{metal} option.
6. Various acceptable outcomes for an alternate endurance test.

These will herein be referred to as the "Questions".

2. Develop and submit to the ARAC an appropriate document as in boundaries and expectations above.

This revised report and new Sections 12 and 13 (Appendix K) serve as the vehicle for providing the response to the Issues Letter to the FAA and ARAC, as it encompasses both responses to the requested specific clarifications as well as modifications to the Final Report intended to provide better clarity to the Alternate 150 Hour Endurance Test proposal.

Target Completion Date:

The target completion date set by the WG to submit responses to the FAA letter to the Transport Airplane and Engine (TAE) Subcommittee is 31 March 2021.

Responses to Issues Letter – Major Paragraphs on page 2

1. "The ARAC recommendation report reflects an intent that the alternate test must meet a benchmarked severity level. Sections 6 and 7 regard creep as a comparative arbiter for test severity and adds an unspecified amount of damage to account for other failure modes that are typical of modern engine designs. Specifically, in sections 2.3(c), 6.3, and 7.2.5 through 7.2.57, the severity benchmark is based on creep levels, while sections 6.3.2, 6.3.3, and 6.3.3.1 suggest the possibility of other damage criteria being used instead, leading to the confusion over the options that are being suggested. Furthermore, there are references (section 6.3.2) that indicate these other damage mechanisms should be identified in the Critical Point Analysis (CPA) process in section 6.2. However, the description of the CPA process (section 6.2) does not cover this."

While sections 6 and 7 do indeed regard creep as the comparative arbiter, other damage mechanisms mentioned in Sections 6.3.2, 6.3.3, and 6.3.3.1 are to be assessed *in addition to* creep (not "instead of"), and are not intended to replace creep. If creep is assessed as a relevant damage mechanism, its severity in the alternate test must at least match the severity of the current test. If other damage mechanism(s) are shown to be more relevant for a particular component, then that/those mechanism(s) must *also* be demonstrated.

Sections 6.2 and 6.3.3.1 have been revised accordingly to clarify that the CPA is intended to establish the conditions for assessing severity, and that it is the severity assessment which defines creep damage to be demonstrated and identifies other relevant damage mechanisms.

2. "The ARAC recommendation report presents the concept that the alternate test embodies a hybrid of performance-based and prescriptive elements (sections 2.3, 6.3.3, and 7.1). This concept has been interpreted that the applicant may compose a hybrid approach with a relatively high degree of freedom to determine severity targets, among outcomes affecting the overall cycle content and test duration."

While the applicant may compose a hybrid approach for their proposed type design, the applicant does not have a high degree of freedom to determine severity targets. The severity target for any alternate test proposal must be equal to or greater than that accumulated for the current test, as described in Section 6.1 ("preserve the intent of the current rule" and "show equivalency of the current regulation"), and Section 6.3.3.2. Section 7.2.6 further reinforces the objective of demonstrating "severity equivalent to the original intent of the current rule".

3. "The ARAC recommendation report, section 6.4.3, describes a T_{metal} method to determine the power levels for test points (also introduced in 2.3(b)). It is understood that once successfully substantiated, this approach would allow a less conservative test to be completed. However, the FAA notes that substantiation of this method is likely to be complex. The report does not address how this substantiation might be controlled. Therefore, retaining this option will present challenges within the confines of a certification exercise to the FAA in establishing the adequacy of the methods."

It is not the intention of the T_{metal} method to be a less conservative test. If carried out in accordance with the severity assessment principles of Section 6.3.3. et seq., the requirements still remain to demonstrate equivalent severity to the current rule. It is acknowledged that this process may be more complex, but the validation and substantiation will depend on the sophistication and rigour of the applicant's design system. It will be the responsibility of the applicant to justify their methods are validated. While it was considered out of scope by the WG to specify in detail how an applicant could validate their own methodology, Appendix K (Section 13) outlines some considerations for how a framework for developing an alternate test could be devised and for evaluating the rigor of the validation.

Responses to Issues Letter – Specific Clarification Requests

Specific clarification regarding the following Questions:

1. **Severity equivalence process and its intended purpose.**
2. **Severity equivalence process for other than creep failure modes, including failure modes not currently addressed by the § 33.87 regulation.**
6. **Various acceptable outcomes for an alternate endurance test.**

Response:

The current test is a severity test conducted for prescribed operating time at limiting conditions as described in section 6.3.1 of the report. The ARAC working group was chartered to develop an alternate test that was equivalent to the intent of the current test in demonstrating engine operability and durability. As described in Section 6.3 of the report, the working group concluded that the current test was intended as "an accelerated severity test …"; with that determination, the group rationalized that an alternate test that demonstrated equal or more damage accumulation would be considered equivalent. In addition, section 6.3 of the report states that creep will be used as the damage mechanism for comparison. With regards to questions 2 and 6, the intent of the working group was that the applicant would identify other relevant damage mechanisms and those mechanisms would be used, in addition to creep, to evaluate severity. Substantiation of the applicant's proposed limitations is dependent upon achieving an actual test severity greater than or equal to the reference severity based upon demonstrated damage accumulation in each case, for creep and for the other identified relevant mechanisms. The hybrid of prescriptive and performance requirement, that is described in the report, should be understood to be enabling the maximizing of damage mechanisms, other than creep, whilst also respecting the severity target for creep.

The current test requires that test-enabling modifications be implemented on tested hardware to recover the off-design effects induced by the prescribed test conditions. However, to benchmark the severity comparison to the current test, the ARAC team introduced the concept of an "idealized test" for the purposes of individual component severity assessment. The idealized test conditions are established, starting with the type design engine CPA assessment of maximum metal temperature. Holding that metal temperature constant, operation at applicable limiting conditions are assumed on a component-by-component basis. While these idealized conditions are not realistic operating conditions without test enabling modifications, they do provide a basis for component by component comparisons that are consistent with test intent. The evaluation of these idealized test conditions for each portion of the current test schedule (example provided in paragraph 7.3 of the report) is used to establish the accumulated theoretical damage, or severity, for each component. These values are then input to the reference severity assessment.

To identify the reference severity for the purposes of the alternate test, the individual severities, described above, are assessed for each relevant damage mechanism of each relevant component.

By a similar process, but this time using modelled conditions anticipated for the engine test, the applicant would propose a mix of cycles (portions) for the alternate test that would accumulate actual test severity greater than or equal to the reference severity.

Note: When actually performing the test, the applicant may modify the mix of 'actual' cycles achieved to ensure that the actual test severity greater than or equal to the reference severity. The applicant will be required to monitor damage accumulation throughout the test to make these adjustments.

Specific clarification regarding the following Question:

3. **Constraints for implementing the recommended hybrid performance-based and prescriptive solutions.**

Response:

The proposed alternate test will provide a severe test of the engine's capability by evaluating the engine's operation at a severity level consistent with the intent of today's 14 CFR 33.87 prescriptive test. As such, the proposed alternate test and the current test are considered equivalent approaches to demonstrate the limiting speeds and temperatures (redlines) for the engine's Type Certificate limits. Both test approaches would evaluate the engine's capabilities to the same level of severity, therefore there would be no constraints on which test, the proposed alternate test or the current prescriptive test, the applicant must conduct. The alternate test is provided as an optional alternative to the current prescriptive test schedule.

Sections 4.3, 4.4, and 4.5 of the ARAC 150 Hour Alternate Endurance Test Final Report ("Final Report") provides reasons and/or factors that would influence an applicant's choice whether to conduct the alternate test. In particular, the enabling modifications and the survival modifications described in section 4.4 take the test vehicle out of type design configuration and operating the engine off schedule. In current practice, these modifications must be reconciled for the type design configuration through validated assessments and assumptions.

As technology has advanced in modern high bypass ratio engines, the enabling modifications have increased in quantity and complexity. This has resulted in the applicant and regulator both expending significant resources to develop, substantiate and resolve or mitigate the resulting uncertainties introduced. For engine architectures or models that are able to test the type design to the current prescriptive test schedule without significant test enabling modifications, either test could be performed as they both demonstrate the engine's capabilities to the same level of severity. However, the total endurance test duration when following an alternate schedule will typically be longer as summarized in section 2.3(c).

The following summarizes and consolidates from the Final Report aspects of the test definition and conduct which show that the alternate endurance test, i.e. a hybrid of certain aspects of the current prescriptive test and performance based elements, is constrained to the overall severity equivalent of the current test. It is incumbent upon the applicant to show this to the Administrator prior to the test during the planning stages.

The current test is prescriptive, and by definition constrains the test to be carried out in a certain manner and under certain conditions. These are outlined in Final Report Section 6.1:

- Number of cycles to be run to include the following elements
  - temperatures and speeds to be declared on the TCDS
  - staircase running
  - number of rapid accels / decels
- Fuel and oil temperatures and pressures
- Bleed
- Performance expectations prior to and after the test

All these prescribe/constrain how compliance to 14 CFR 33.87 is demonstrated.

The Final Report states that the:

Alternate Test = [Elements of Current Test (prescriptive)]
+ [New Prescriptive Requirements +Performance-Based Aspect]

The second bracketed portion represents the innovative part of the proposal.

The Final Report Section 7.2 provides the "must haves" of any alternate test proposed to the authority for compliance with 14 CFR 33.87. As such, they represent the "constraints" on the test:

1. Test vehicle must substantially conform with the type design
2. Ancillary TCDS Limits determination must meet the current requirements of 33.87(a)(5),(6),(7),(8), & (b)(6)
   - bleed
   - accessory power extraction
   - oil temperatures
   - fuel min/max pressures
   - transients for a minimum number of accels
   - number of starts
   Also, the Administrator must accept the test sequencing proposed.
   All these are prescriptive per the current test and as such are constraints.
3. Redline demonstrations:
   - running at concurrent redlines is required, unless the CPA shows that it is not possible
   - all CPA-defined temperatures and speeds must be demonstrated
   - Declared TCDS redline speeds cannot exceed values which have been demonstrated
   All these represent constraints on how redlines are demonstrated and declared.
4. Stairstep demonstrations must meet the current requirements of 14 CFR 33.87(b)(4) - current cycle "Part D".
   All these are prescriptive per the current test and as such are constraints.
5. The severity demonstration (the performance-based portion of the test):
   The compliance demonstration must show that any alternate endurance running will subject the components most vulnerable to creep[1] (i.e. the reference damage mode) the equivalent severity of 18.75 hours at takeoff and 45 hours at maximum continuous thrust in the current test, as assessed in the severity comparison[2].
   These are considered constraints on any proposed alternate test; while this is the performance based portion of the alternate test proposal, it is constrained/tied to the current rule and must be justified by the applicant and agreed by the Administrator in their oversight function.
   Further, the test itself must be executed to the highest levels determined by the severity comparison (+/- 3% of the limiting speeds, Ref. Section 6.4.2 and 7.2.5); and rated thrust must be met or exceeded.

[1] per the Final Report section 6.3.3.1: Creep is only one of the measures/metrics that could be used and one that is logically proposed by the report as it is a failure/damage mode common to most if not all type designs. However, this does not preclude other damage modes from being identified as the most relevant modes for any particular design - this would need to be identified / justified in the severity analysis, in conjunction with the CPA, and subject to the Administrator's agreement.

[2] per the Final Report Section 6.3.2: Several elements to be used in the severity comparison of the performance based portion of the alternate test are outlined. The comparison must be made to the original intent of the current rule, i.e. the severity target is the same as the current test and no freedom to determine a (different) severity target was intended nor implied. Only the means to achieve the target has been given broader freedom compared with the prescribed method in the current rule. The severity targets are still tied to the current test, i.e. temperatures, speeds, pressure vessel loading, cyclic content, etc., as delineated in section 6.3.2.

Finally, monitoring of test parameters, i.e. ensuring they are being held to the test instruction levels, would be carried out as is done for the current test.

6. The performance demonstration pre- and post-test would be carried out in the manner prescribed in section 14 CFR 33.85 as is currently done (constraint).

Specific clarification regarding the following Question:

4. Role of the engine CPA.

Response:

The Critical Point Analysis is the technique by which the actual running conditions of a production engine (new and aged) in service are assessed. These cases are then considered further in the Severity Assessment for creep and other relevant damage mechanisms.

The applicant should assess the flight envelope using models for new and deteriorated engines to identify conditions at the most critical point(s), including any coincident maxima. These will likely be associated with limit temperature cases. (For a secondary air system operating at design conditions, it is reasonable to assume the highest EGTs would be coincident with the highest metal temperatures, even if T_{metal} is not directly scalable with EGT.)

The main body of the report has been accordingly revised in Sections 6.2, 6.3, and 6.4 to distinguish more clearly the roles of the CPA (establishment of conditions) and the Severity Comparison/Assessment (analysis of severity under the conditions identified in the CPA).

Specific clarification regarding the following Question:

5. Simplify the possible approaches by removing the T_{metal} option.

Response:

The target test conditions used for setting the reference severity of the alternate test are based on the metal temperature of the critical components at a fully deteriorated condition as this is where an engine may operate at its EGT redline. The alternate test is expected to be undertaken with a new engine. A simplified approach that removes the T_{metal} option would require that the new engine is run at its EGT redline. To determine if it is reasonable to simplify the possible approaches by removing the T_{metal} option, the consequence of testing a new engine at its EGT redline condition via overboost (ref. report section 4.5) rather than the metal temperature seen on a fully deteriorated engine operating at its EGT redline must be understood.

The conclusion is that a new engine operating at redline EGT could experience significantly higher metal temperatures than a deteriorated engine operating at EGT redline. On the engine examined this temperature difference equates to more than a 100% increase in the creep damage per hour on the first stage / high pressure turbine blades for a new engine when compared to a fully deteriorated engine. It is important, therefore, to maintain the option to consider T_{metal} in the definition of reference severity and for conducting an alternate test.

A thermodynamic performance model was interrogated to determine key engine parameters for a new engine operating at redline EGT via overboost and a fully deteriorated engine operating at redline EGT. The change in behavior of the engine which causes the above conclusion is summarized below:

- An engine running at a constant EGT as its components deteriorate would produce progressively less thrust as the level of deterioration increases.
- A new engine produces significantly more than the maximum rated thrust when the throttle is pushed to achieve redline EGT. This is often described as "over-boost" through the report.
- As the turbine deteriorates it extracts less energy at constant EGT. Therefore, with less energy, the compressor does less work.
- The result of the compressor doing less work is that the compressor exit temperature and pressure reduces.
- Concurrent with the turbine deterioration, the compressor is also deteriorating as the engine is used. As the compressor deteriorates it generates a higher temperature rise for a fixed amount of work. On the engine examined this temperature rise was smaller than the reduction in temperature caused by the deteriorated turbine.
- Broadly, T_{metal} of the high pressure turbine blades has two components: surrounding gas temperature (T41 or turbine entry temperature, TET) and cooling air temperature. Figure 12.2 below shows that the relationship between EGT and T41 is not significantly affected by the deterioration of the engine. With EGT, and hence T41, held constant, the only component changing as the engine deteriorates would be the cooling air temperature (compressor exit temperature).

Therefore, a deteriorated engine has a lower T_{metal} at the same EGT than a new engine.

The output from the performance model is shown in Figure 12.2.

In Figure 12.1 key performance parameters and temperatures for the over-boosted new engine relative to the deteriorated engine, both at constant redline EGT, are compared.

Parameter	New engine, SLS Corner Point Temp Throttle push to EGT redline (Overboost)	Comment
Corrected core speed	+	Corrected speed increase due to throttle push
T3	++	High T3 due to high powerset / high core power
T41	+	Increased T41 due to increased fuel flow at high core power, closed HPT clearances
Delta T41 – T3	-	Overboost case yields a lower temperature rise due to HPC/HPT efficiencies and constant EGT
First stage / HPT blades (HPT S1B) T_{metal}	++	HPT S1B Metal Temperature higher than CPA point with new engine "overboosted" to EGT R/L

Legend: ++ Significant increase + Increase - Decrease -- Significant decrease

Figure 12.1: Table of Qualitative comparison of over-boosted new engine to corner point deteriorated engine

Creep was examined between a new engine pushed to redline EGT and a fully deteriorated engine running at redline EGT: on the engine type examined the creep damage accumulation rate per hour on the first stage of turbine blades more than doubles.

The cause of the higher compressor exit temperature on a new engine is that pushing it to the redline EGT is a significant over-boost; the engine is producing significantly more than its rated maximum take-off thrust. Component efficiency is optimized around cruise, and so this over-boost takes the compression system away from its optimal design point. Therefore, two factors are driving an increase in the compressor exit temperature: the over-boost which is asking more work of the compressor and the reduction in efficiency as power is increased.

Future airplane design may benefit from lower drag at cruise conditions, requiring less cruise thrust but still require significant take-off and climb thrust, which would further offset the optimal design point from the overboost condition. In other words, widening the thrust difference between cruise and take-off exacerbates how far off optimal design the compression system is operating at the over-boost condition required to achieve red line EGT on a new engine.

Further, it is reasonable to assume that future technology improvements will seek to improve turbine cooling effectiveness, and this may further exacerbate the effects described: The difference between T_{metal} for a new engine and a deteriorated engine, at a fixed EGT, is caused by the deteriorated engine having a lower compressor exit temperature. The more effective the turbine cooling the larger this difference will be.

In conclusion, the recommendation is that the T_{metal} option be retained as it is consistent with the original intent of the test (ref. report section 6.4.3); it provides a means to equivalently demonstrate red line gas temperature on engines that incorporate advanced technologies while minimizing any off-design effects induced by the test. Appendix K (Section 13) outlines considerations for developing a framework of an endurance test using either the T_{metal} or EGT methods.

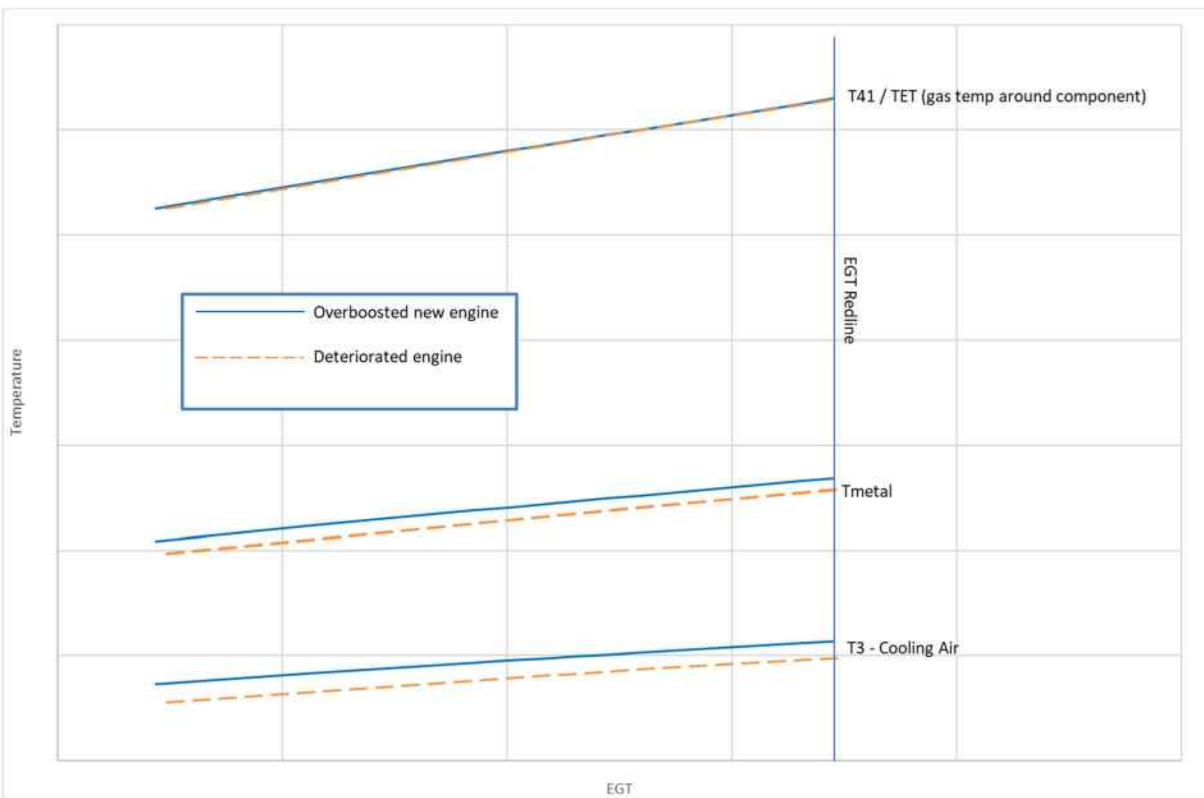


Figure 12.2 Over-boosted new engine vs deteriorated engine – comparison of key temperatures for a film cooled and coated turbine blade

13 Appendix K: Severity Equivalence Process Error Assessment for T_{metal} and EGT methods

Contents

13.1 Introduction

The work presented in this section provides a breakdown of the steps involved in establishing the alternate endurance test severity equivalence, and hence EGT RL (red line), for the alternate test. The purpose of this exercise was to allay concerns about inaccuracies in the method leading to undertesting, and to illustrate that there is an element of error cancelation in the process whereby the effect of engine model inaccuracies on the results, is minimized.

The process visualization provided by the flow charts was also intended to provide a better understanding of two optional alternate endurance test approaches, the T_{metal} method, and the simpler red line EGT method.

13.2 Discussion

The establishment of the test severity equivalence, required to substantiate the cleared EGT RL, demonstrated during the alternate endurance test is a new and complex aspect of this compliance method. This is illustrated by comparing the process for each type of endurance test against the classic test:

1. For the currently-defined test: the EGT recorded for the test is simply accepted as the red line, no test severity equivalence is required.

2. For the alternate test (by T_{metal} method): the red line EGT is derived from the metal temperatures demonstrated during the test. This derivation requires that the applicant is able to establish the metal temperatures using performance/thermal modelling of the test engine, and to establish the EGT values corresponding to this metal temperature, which will be claimed as red line EGT, for the case of a deteriorated version of the engine, by similar modelling, but of a deteriorated engine. The metal temperatures are also used to assess the accumulated severity of the alternate test and to ensure equivalence to the target severity which comes from a simulation of the classic test (which assumes the metal temperature for the case of a deteriorated version of the engine). Validated analytical methods would be necessary for these steps. (See Figure 13.1.)

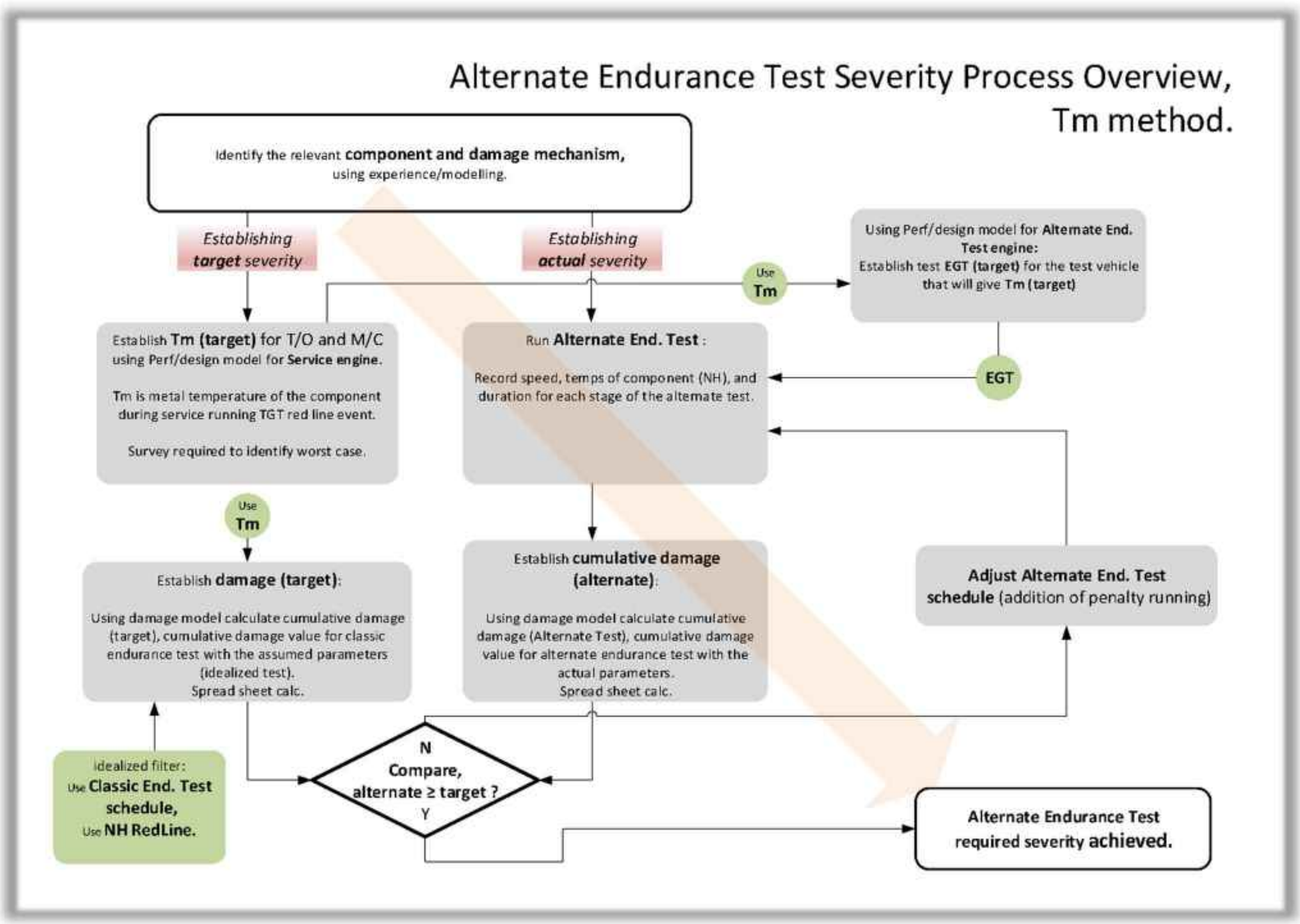


Figure 13.1 T_{metal} Method 2 Overview[3]

[3] Note that in Figures 13.1 and subsequent, the abbreviation "End." is intended to denote "Endurance".

3. For the alternate test (by red line EGT method), a compromise alternate test, avoiding the complications of the metal temperature methods above, the EGT recorded for the test is accepted as the red line contingent upon substantiation of severity equivalence to the target severity. (See Figure 13.2.)

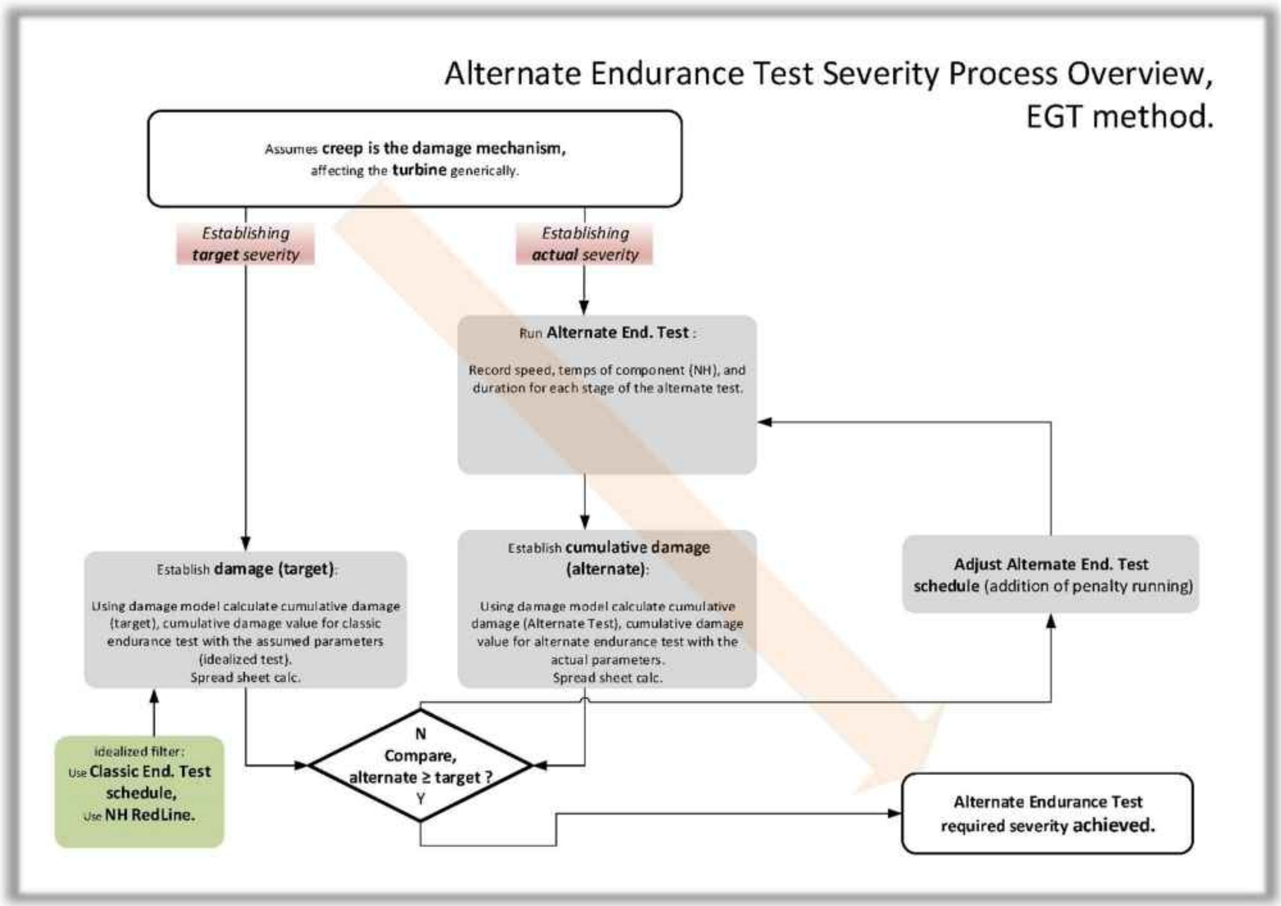


Figure 13.2 EGT Method 3 Overview

Due to the complexity that is apparent in the alternate test of Method 2, concerns were raised following the original ARAC report that the scope for error was too high, particularly with the reliance on thermal modelling. It was proposed that Method 2 be removed from the new test proposal on the assumption that Method 3 has significantly less error risk and that it may still deliver much of the benefit in terms of reducing the excessive severity of the classic test.

The ARAC group has considered this concern. Initially the concern was countered by a mathematical argument that modelling errors in Method 2 were cancelled, due to the double conversion. In order to clearly present this argument, the idea of analyzing the EGT derivation process by means of a flow chart was agreed upon. This work, the mathematical summary and the flow charts is presented in the following section.

The flow charts also have a secondary benefit of illustrating the general concept of the alternate test in a way which may work for some readers, in the case where the text has left some confusion. This also applies to the difference between metal-temperature-based Method 2 and an EGT-based Method 3.

13.3 Explanation of the Mathematical argument

The mathematical argument was compiled to demonstrate that errors accumulated from a modelling sequence used to derive the severity (on a part) of a certain test, for the purpose of comparison to another test which has been assessed by the same method, will not affect the accuracy of the comparison.

The mathematical argument is the central part of this piece of work, the flow charts have been provided to illustrate the mathematical argument. A referral system is provided between the mathematical text and the flowcharts, indicated by the encircled letters (in green), to provide orientation to the reader.

13.4 Explanation of the flow charts

The flowcharts represent the process used to calculate a severity level for a particular cumulative damage mechanism affecting a particular engine part/component, during an endurance test.

The severity calculation process will be performed for the alternate test during a certification program, using the recorded test data, to give the "**Actual** Severity" level achieved (Figure 13.5). The severity calculation process will also be performed for a theoretical test of the same component but completed to the classic test requirements, using a combination of data taken from a service engine simulation and assumed redline speeds, to give the **target** levels required, the "Idealized Severity" (Figure 13.3). While the processes appears similar, the inputs are actually different, therefore separate flow charts are provided for each. Also included is a Plan Severity flow chart which would be used prior to commencement of an engine test to establish an accurate test plan (Figure 13.4). Thus, three separate calculation processes are envisaged each represented by a separate flowchart, the calculation of the target/Idealized Severity level, the Plan and the Actual engine test level.

The main flow charts (Figures 13.3, 13.4, 13.5, 13.9, 13.12, 13.13, 13.14) divide into two parts:

> The left column is the main loop that will be repeated for each fixed condition of the test, for each of which a particular damage per hour value will be derived to calculate increments of accumulated damage, to give the overall sum for the process.
>
> On the right side is the sequence required to calculate the damage per hour that utilizes three separate models. The modelling sequence starts with a performance model that simulates the particular engine fixed (power) conditions (Z_m) and derives the local conditions (Y_m) for the particular part being assessed. A design model of the part would then be used to simulate the part under those local conditions to give the local input parameters (X_m) for the damage mechanism. A damage model would then simulate those material conditions to provide the damage per hour (DPH).

Some secondary charts are also included to provide further insight into the concept for each model.

13.5 Mathematical Background / Basis

Ⓐ Severity is the sum of accumulated damage.

$$Severity = \sum_{k=1}^{k_n} Damage_k$$

Ⓑ Damage is the accumulated Damage per cycle (k)

$$Damage = \int Dph\,dt \cong Dph * t$$

For the ease of calculation (and introducing only a small error) we neglected the small amount of damage accumulated in the ramp up to and down from the stabilized points.

$$Dph = Dph(x_1, x_2, x_3, x_4, .., x_n)$$

Ⓒ Dph (Damage Per Hour) is calculated based on the damage mode specific inputs (x_m). Typical local inputs include, local stress (σ_{metal}), local temperature (T_{metal}) etc.

$$x_m = x_m(y_1, y_2, y_3, y_4, .., y_n, z_1, z_2, z_3, z_4, .., z_n)$$

Ⓓ Each of these local inputs into the damage model, are in turn calculated from other parameters (y_m and z_m). Typical other parameters include both instrumented engine conditions (z_m) and derived engine conditions (y_m). Typical instrumented engine conditions (z_m) include N1, N2, EGT, EPR, etc.. Typical derived engine conditions (y_m) include $\dot{m}_{bleed}, T_{bleed}, P_{bleed}, P_{upstream}, P_{downstream}, T_{upstream}, T_{bulk},$ etc.

Ⓔ The derived engine conditions are calculated by performance analyses, CFD, FEA etc. Ultimately each of the derived engine conditions are functions of the instrumented engine conditions.

$$y_m = y_m(z_1, z_2, z_3, z_4, .., z_n)$$

Therefore, while very complicated and including potential multiple modeling calculations, each of the local inputs, can ultimately be written as a function of the instrumented engine conditions.

$$x_m = x_m(\, z_1, z_2, z_3, z_4, .., z_n)$$

13.6 Main T_{metal} method flow charts

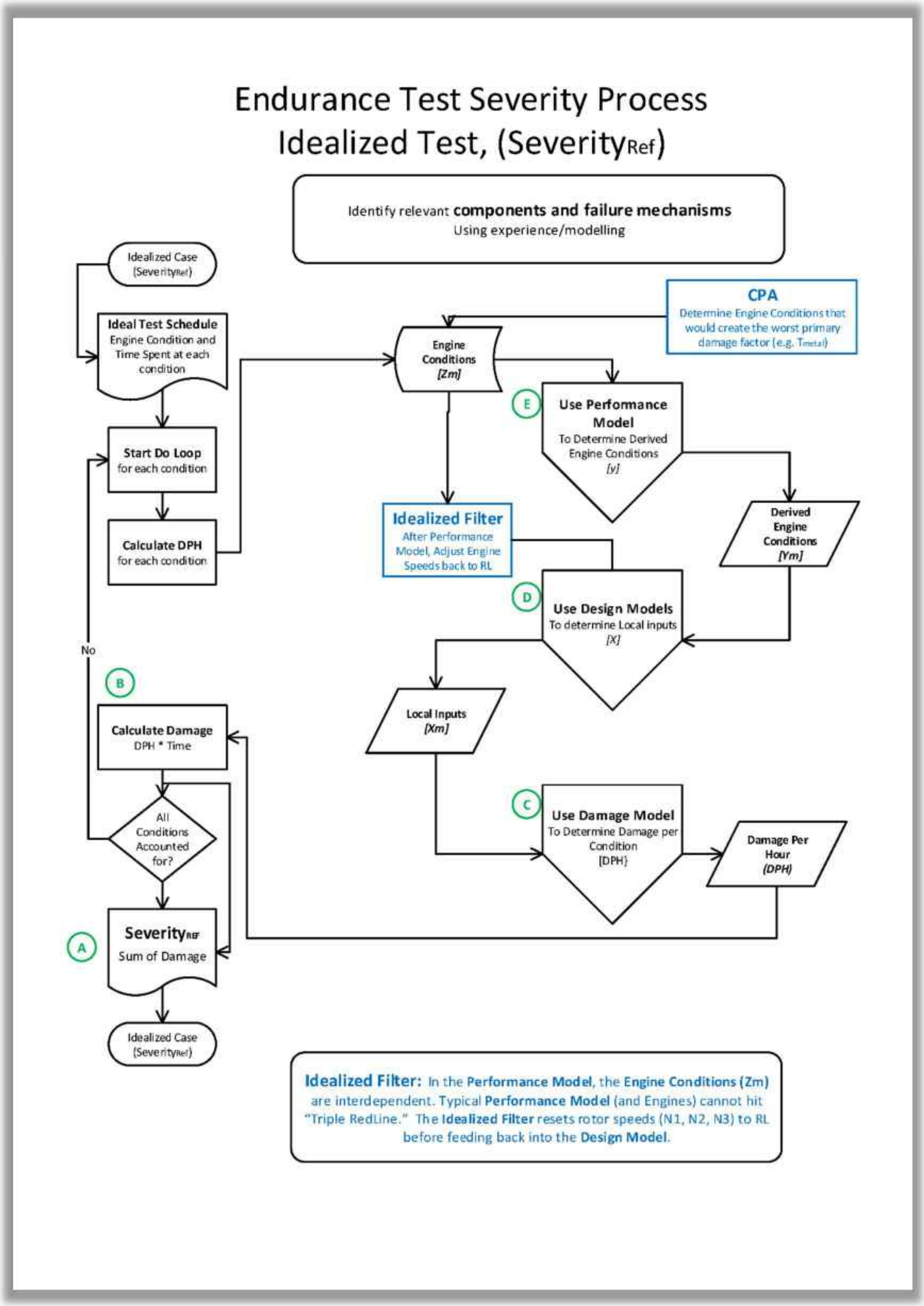


Figure 13.3 Endurance Test Severity Process – Idealized Test, ($Severity_{Ref}$)

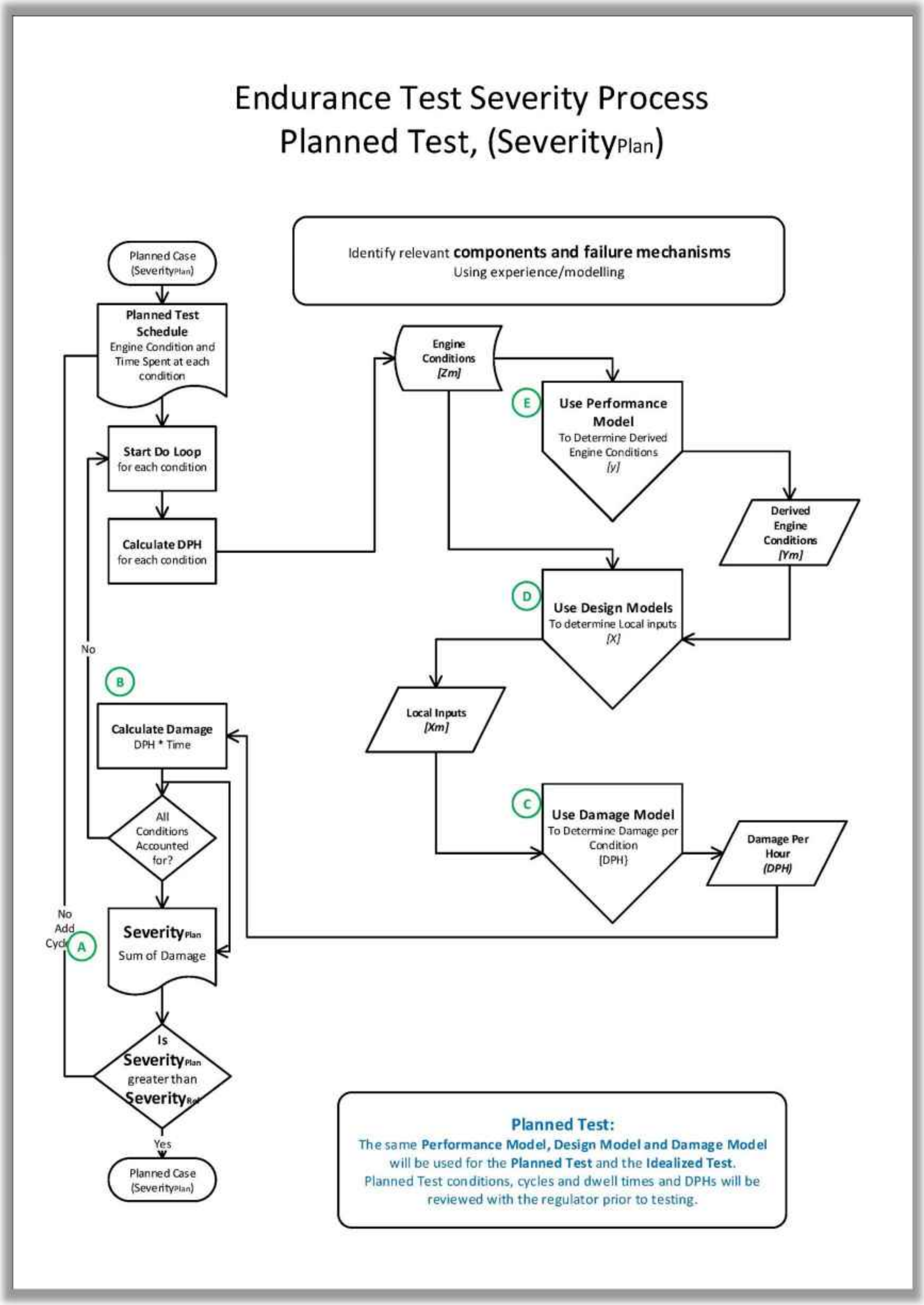
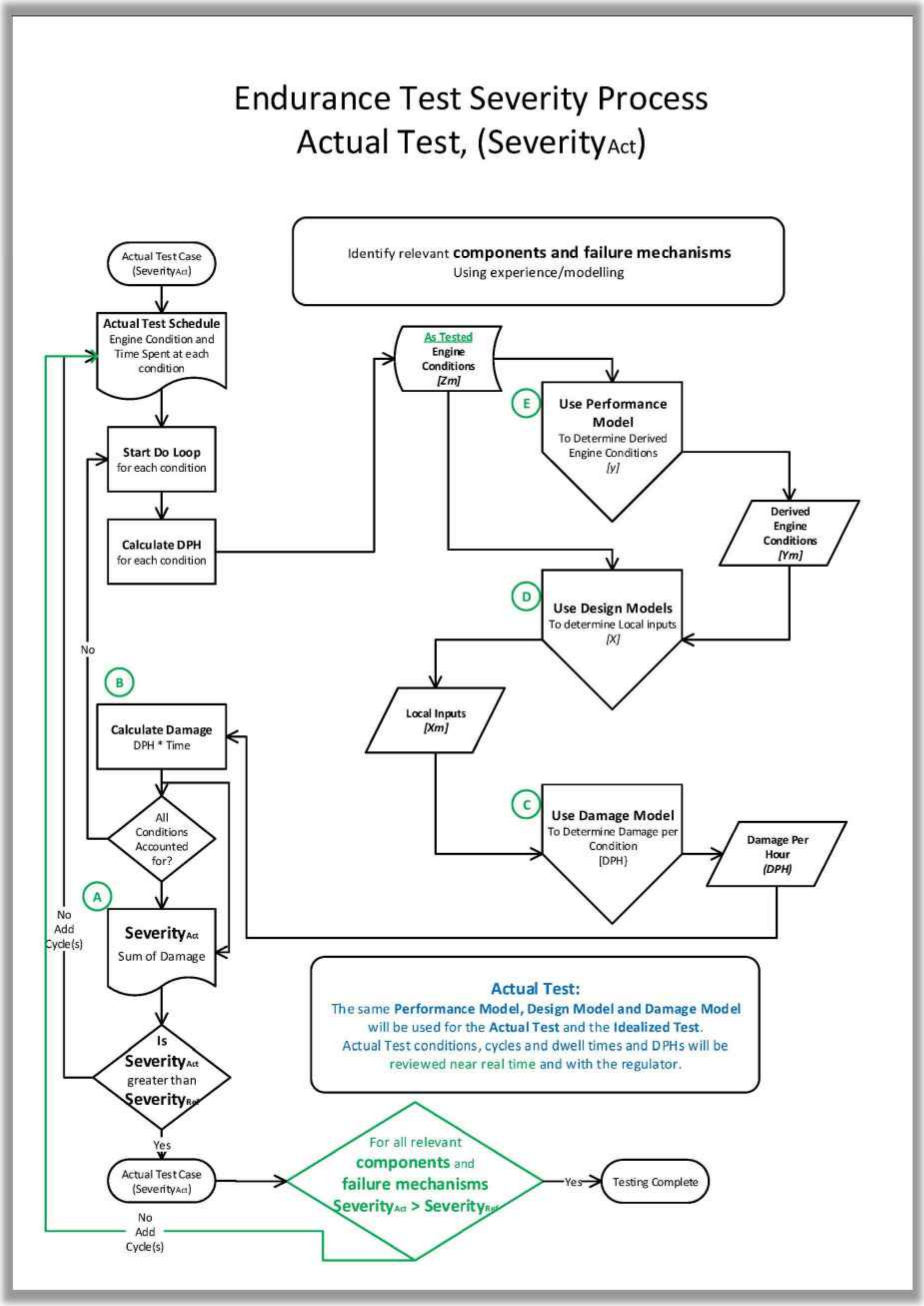


Figure 13.4 Endurance Test Severity Process – Planned Test (Severity$_{Plan}$)



Endurance Test Severity Process
Actual Test, (Severity Act)
Identify relevant components and failure mechanisms
Using experience/modelling
Actual Test Case (Severity Act)
Actual Test Schedule
Engine Condition and Time Spent at each condition
As Tested Engine Conditions [Zm]
Use Performance Model
To Determine Derived Engine Conditions [y]
Start Do Loop for each condition
Calculate DPH for each condition
Derived Engine Conditions [Ym]
Use Design Models
To determine Local inputs [X]
No
Calculate Damage
DPH * Time
Local Inputs [Xm]
Use Damage Model
To Determine Damage per Condition [DPH]
Damage Per Hour (DPH)
All Conditions Accounted for?
No Add Cycle(s)
Severity Act
Sum of Damage
Actual Test:
The same Performance Model, Design Model and Damage Model will be used for the Actual Test and the Idealized Test.
Actual Test conditions, cycles and dwell times and DPHs will be reviewed near real time and with the regulator.
Is Severity Act greater than Severity Ref
Yes
Actual Test Case (Severity Act)
For all relevant components and failure mechanisms Severity Act > Severity Ref
Yes
Testing Complete
No Add Cycle(s)

Figure 13.5 Endurance Test Severity Process – Planned Test (Severity$_{Act}$)

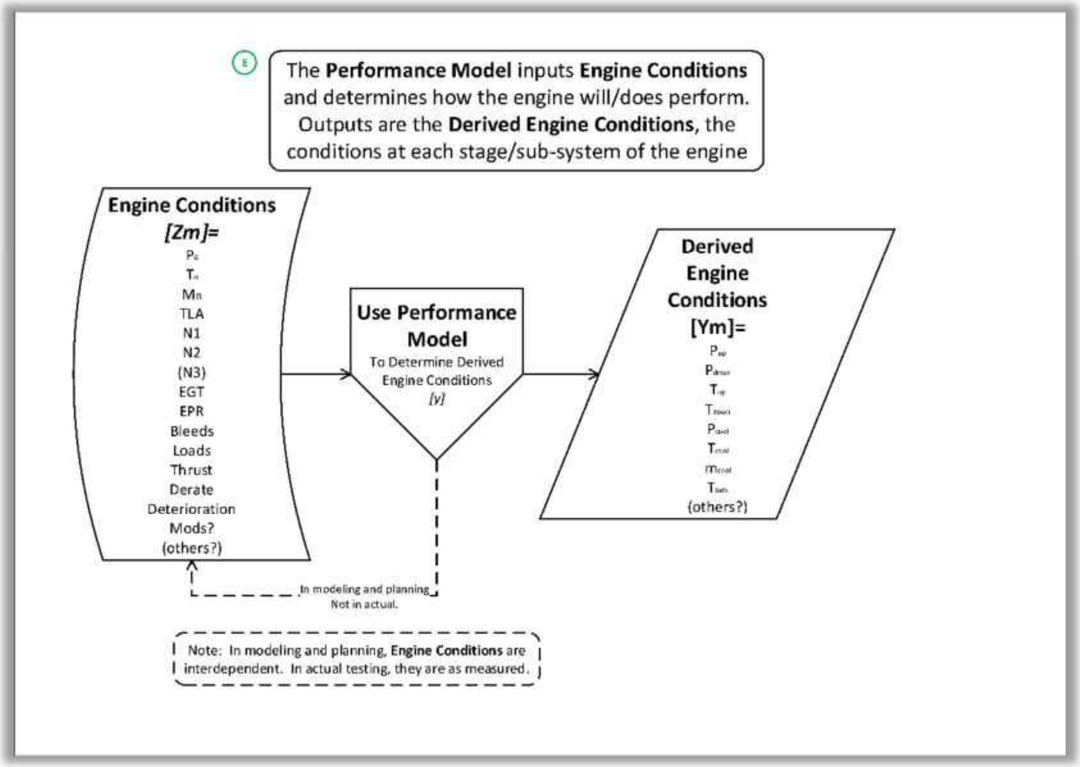


Figure 13.6 Performance Model

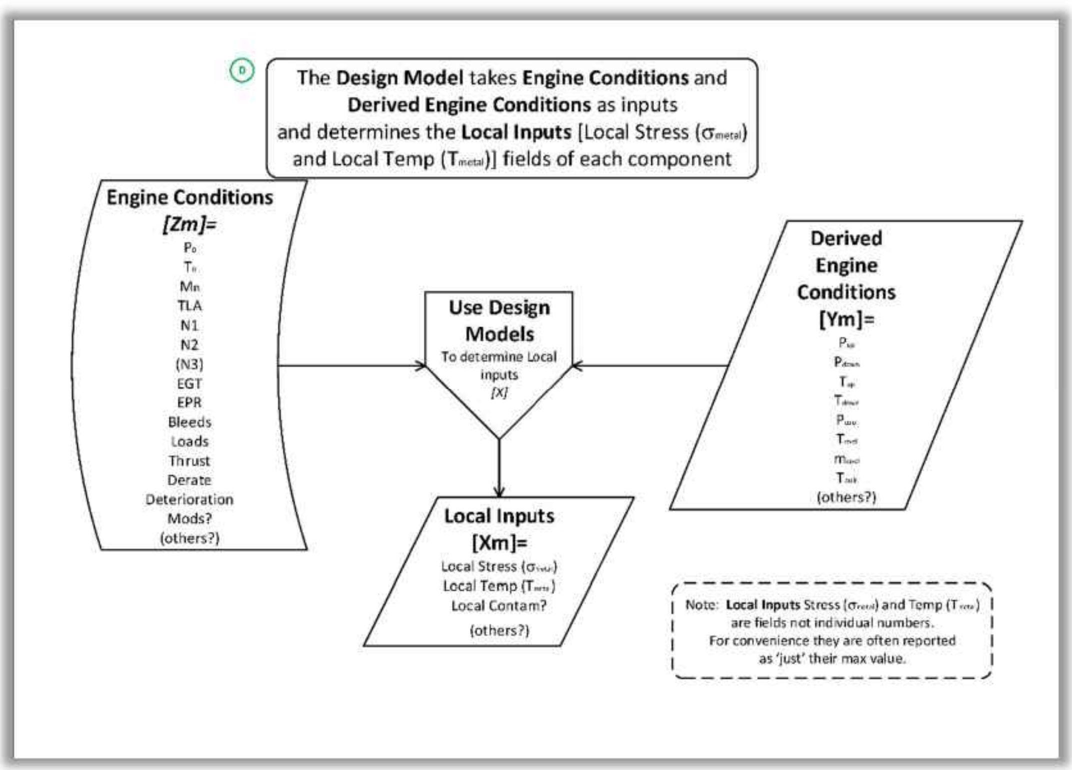


Figure 13.7 Design Model

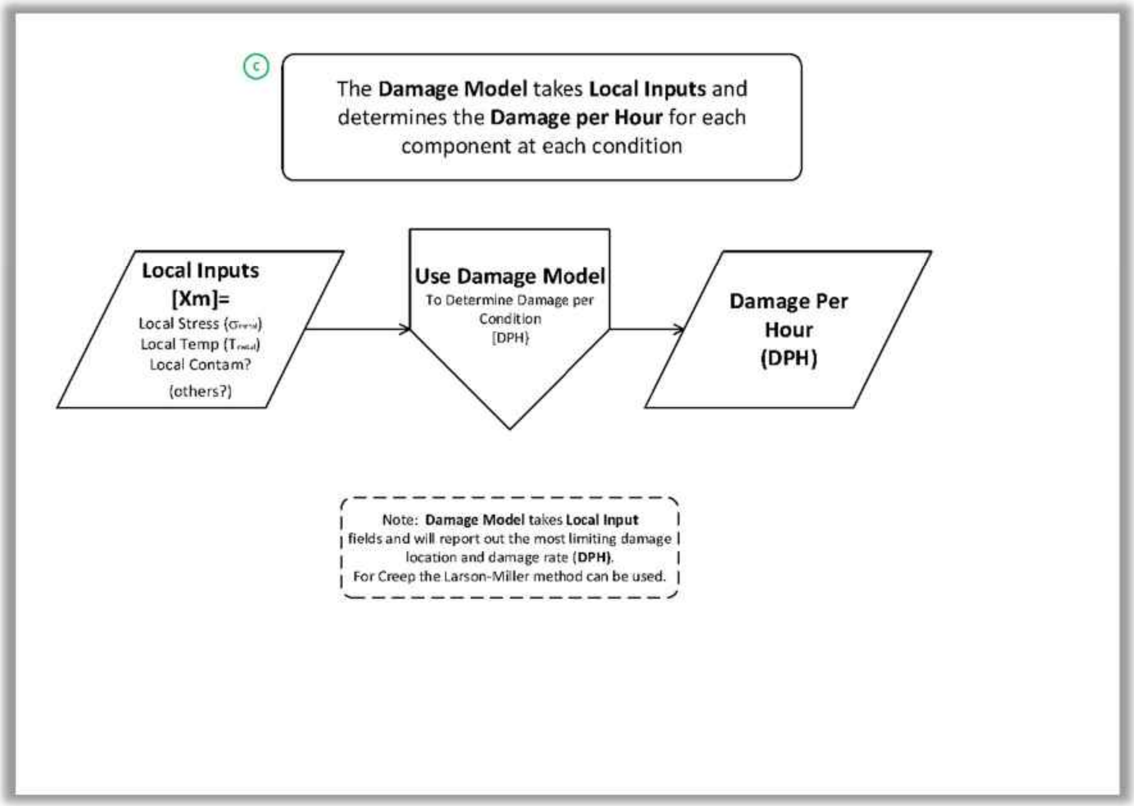


Figure 13.8 Damage Model

13.7 Errors Discussion

Ⓕ When calculating the local inputs (x_m), as stated above, multiple modeling techniques (calculations) may be used, (all of which may or may not have been validated). This culmination of calculations may introduce small errors ($\Delta x'_m$). We will identify primed variables as the ones with the small error.

$$x_m = x'_m - \Delta x'_m \quad or \quad x'_m = x_m + \Delta x'_m$$

$$x'_m \gg |\Delta x'_m|$$

Ⓖ These small errors are then included into the damage calculation.

$$Dph' = Dph'(x'_1, x'_2, x'_3, x'_4, .., x'_n) = Dph + \Delta Dph'$$

$$Dph' \gg [\Delta Dph']$$

These errors then roll up into Damage per cycle and ultimately Severity.

$$Damage' = \int Dph' dt \cong Dph' * t = (Dph + \Delta Dph') * t$$

$$Severity' = \sum_{k=1}^{k_n} Damage'_k = Severity + \Delta Severity'$$

$$Severity' \gg [\Delta Severity']$$

Ⓗ For the purpose of the Alternate Test, the applicant will be using the <u>same modeling techniques and calculations</u> for the idealized case ($Severity_{Ref}$), the planned case ($Severity_{Plan}$), and the actual case ($Severity_{Act}$). Therefore, the same type (and magnitude) of errors will be present in each calculation.

$$Severity'_{Ref} = \sum_{k=1}^{k_n} Damage'_{Ref_k} = Severity_{Ref} + \Delta Severity'_{Ref}$$

$$Severity'_{Plan} = \sum_{k=1}^{k_n} Damage'_{Plan_k} = Severity_{Plan} + \Delta Severity'_{Plan}$$

$$Severity'_{Act} = \sum_{k=1}^{k_n} Damage'_{Act_k} = Severity_{Act} + \Delta Severity'_{Act}$$

The goal/plan/requirement of the Alternate Test is that the planned (prior to testing) and actual Severities ($Severity_{Plan}$ and $Severity_{Act}$) should be equal to or greater than the idealized severity ($Severity_{Ref}$). (The following algebra will follow just the actual severity, but could be used for the planned severity.)

$$Severity_{Act} \geq Severity_{Ref}$$

$$Severity'_{Act} - \Delta Severity'_{Act} \geq Severity'_{Ref} - \Delta Severity'_{Ref}$$

$$Severity'_{Act} \geq Severity'_{Ref} - \Delta Severity'_{Ref} + \Delta Severity'_{Act}$$

Finally:

$$\frac{Severity'_{Act}}{Severity'_{Ref}} \geq 1 + \frac{\Delta Severity'_{Act} - \Delta Severity'_{Ref}}{Severity'_{Ref}}$$

Since the applicant will be using the <u>same modeling techniques and calculations</u> for the idealized case ($Severity_{Ref}$) and the actual case ($Severity_{Act}$), the errors ($\Delta Severity'_{Ref}$ and $\Delta Severity'_{Act}$) should be in the same direction and roughly the same magnitude.

$$\Delta Severity'_{Ref} \cong \Delta Severity'_{Act}$$

Therefore, on a comparative basis, the Severity errors will tend to cancel, especially when divided by $Severity'_{Ref}$.

$$\frac{\Delta Severity'_{Act} - \Delta Severity'_{Ref}}{Severity'_{Ref}} \cong 0$$

13.8 Main T_{metal} method flow charts showing Error references

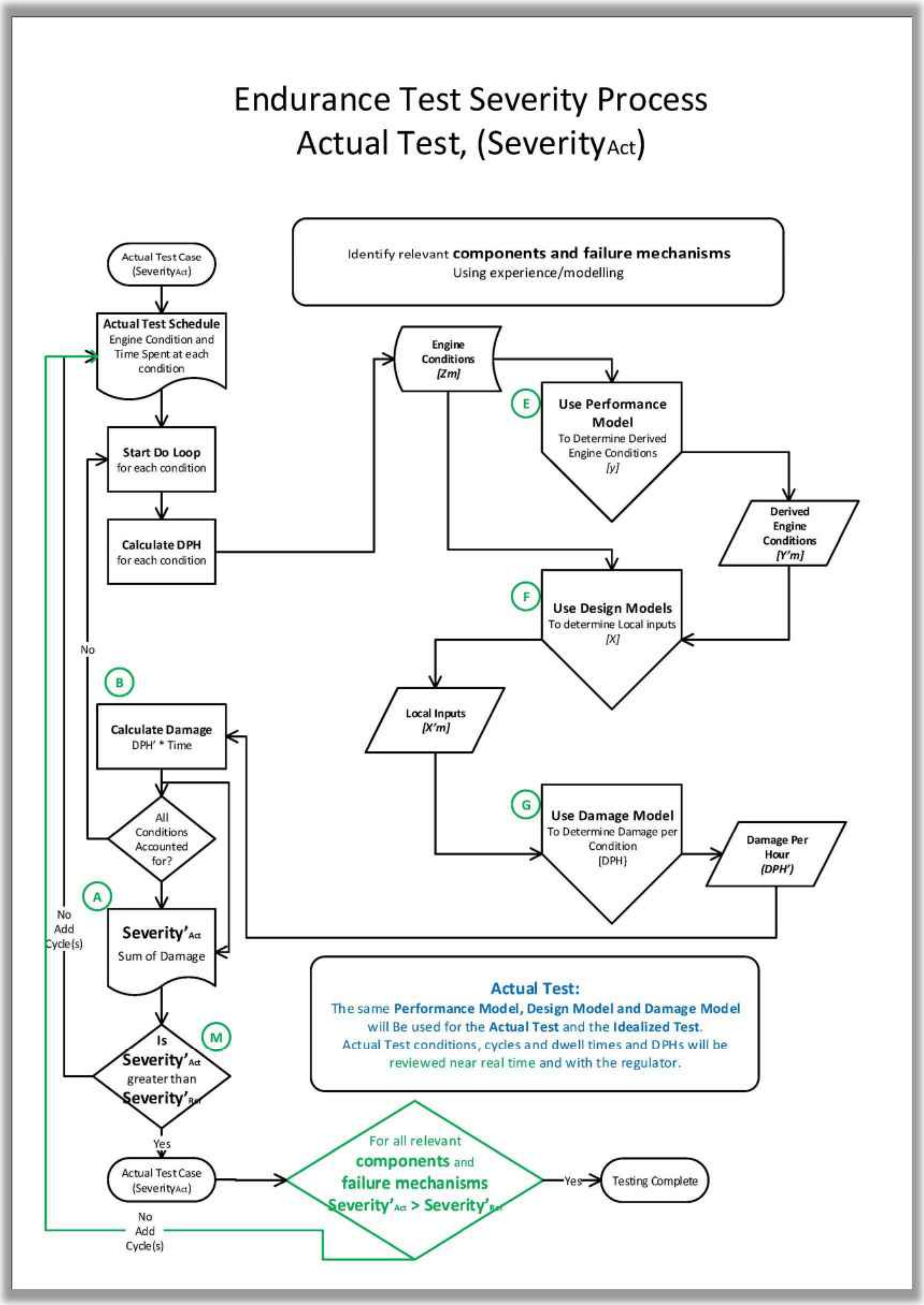


Figure 13.9 Endurance Test Severity Process – Actual Test (Severity$_{Act}$)

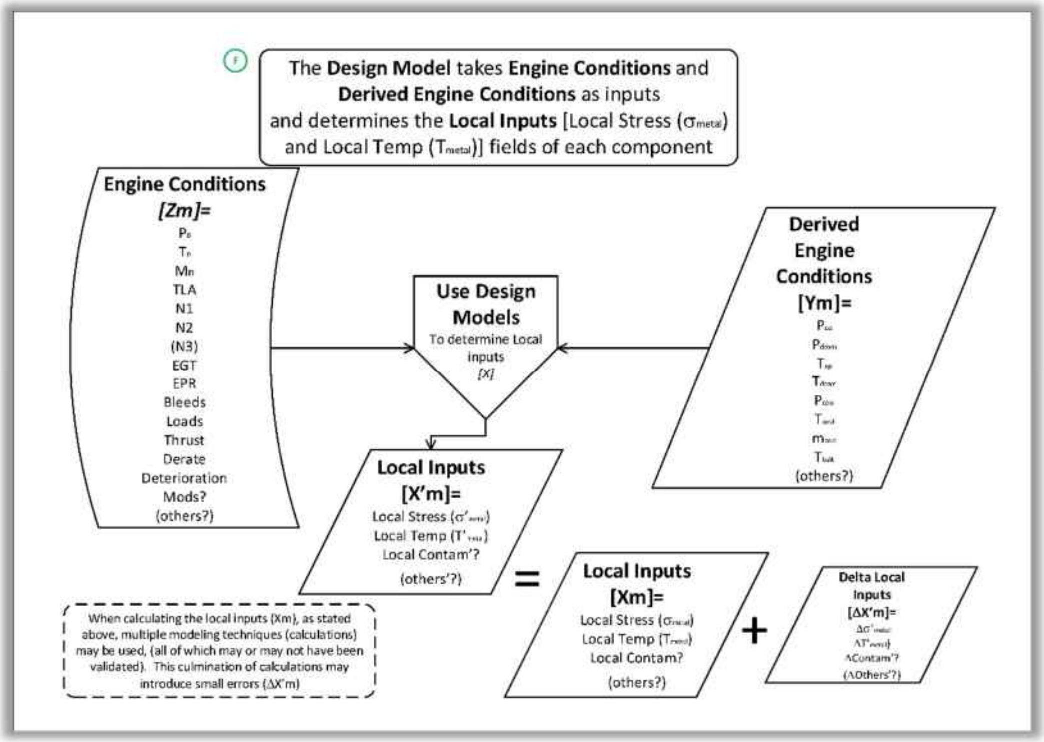


Figure 13.10 T_{metal} Method Design Model for Derived Conditions

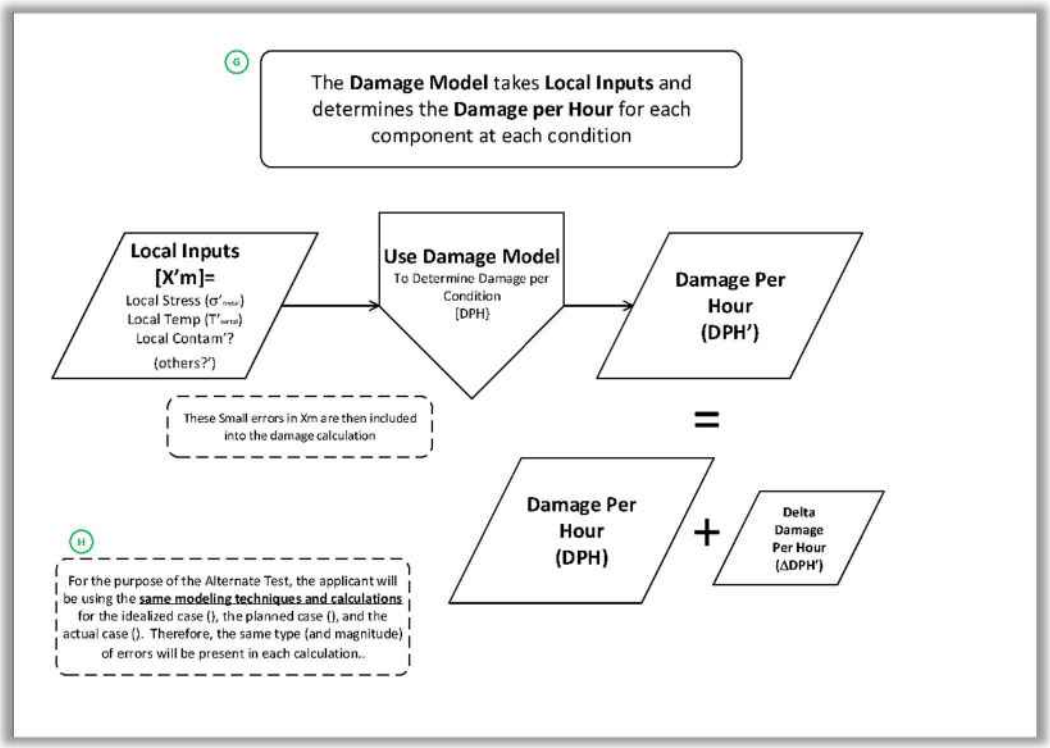


Figure 13.11 T_{metal} Method Damage Per Hour Calculation

13.9 Errors introduced by other Proxies

From the discussion above, Dph (Damage Per Hour) is calculated based on the damage mode specific inputs (x_m). Typical local inputs include, local stress (σ_{metal}), local temperature (T_{metal}) etc.

If the applicant were to use a different (less accurate, but easier to measure/calculate) input into the damage calculator…

$$Dph" = Dph"(x'_1, y_2, z_3, x'_4, .., x'_n)$$

instead of

$$Dph = Dph(x_1, x_2, x_3, x_4, .., x_n)$$

which when the errors are accounted for (identifying double primed variables as the ones with the small errors due to Proxy substitution):

$$Dph" = Dph"(x'_1, y_2, z_3, x'_4, .., x'_n) = Dph + \Delta Dph"$$

The errors introduced by the Proxy substitution may be larger than the errors introduced by the input modeling, but should still be significantly smaller than the Dph"

$$Dph" \gg [\Delta Dph"]$$

The math presented above would still follow for the " errors as they did for the ' errors. Skipping ahead:

$$\frac{Severity"_{Act}}{Severity"_{Ref}} \geq 1 + \frac{\Delta Severity"_{Act} - \Delta Severity"_{Ref}}{Severity"_{Ref}}$$

Since the applicant will be using the <u>same modeling techniques, Proxies, and calculations</u> for the idealized case ($Severity_{Ref}$) and the actual case ($Severity_{Act}$), the errors ($\Delta Severity"_{Ref}$ and $\Delta Severity"_{Act}$) should be in the same direction and roughly the same magnitude.

$$\Delta Severity"_{Ref} \cong \Delta Severity"_{Act}$$

Therefore, on a comparative basis, the Severity errors will tend to cancel, especially when divided by $Severity"_{Ref}$.

$$\frac{\Delta Severity"_{Act} - \Delta Severity"_{Ref}}{Severity"_{Ref}} \cong 0$$

13.10 EGT as a proxy for T_{metal}

A simplification to the T_{metal} approach is to run the test using EGT as a proxy for T_{metal}. The immediate benefit of this approach is that the EGT recorded for the test is accepted as the approved operating limitation, contingent upon substantiation of severity equivalence to the target severity. The drawback of the approach is that metal temperatures of some turbine components may be different (normally assumed to be higher, but theoretically lower) compared to a T_{metal} method when substantiating the same EGT RL value. Should the metal temperature be below the CPA calculated T_{metal} target the applicant will need to propose a means to address this (such as using the T_{metal} method, pushing the throttle to increase EGT, testing at conditions which generate a higher cooling air temperature, etc.). The test will be similar to the classic test with the exception that the target redline speed is not met during all Take-off and Maximum Continuous settings, hence the need for the severity equivalence assessment to establish the additional penalty running required. The applicant wanting to use the EGT method would need to justify that it would be equal to or conservative on T_{metal} relative to CPA conditions.

In this case EGT is being used as a proxy for T_{metal}. As explained above, the consistent use of processes in the severity equivalence assessment will provide error tolerance.

With regard to the process for this approach the following flow charts (Figures 13.12 – 13.15) illustrate the steps and provide a comparison to the T_{metal} process. As can be seen the modelling sequence is significantly simplified.

Note that the flowcharts indicate that the damage mechanism assumed by the EGT approach, as for the classic test, is creep. The assumption is taken because the process in this case, as for the classic test, does not demand that a specific component be identified. This does not rule out that an EGT based test could be assessed for severity of damage mechanisms other than creep.

13.11 Main EGT method flow charts

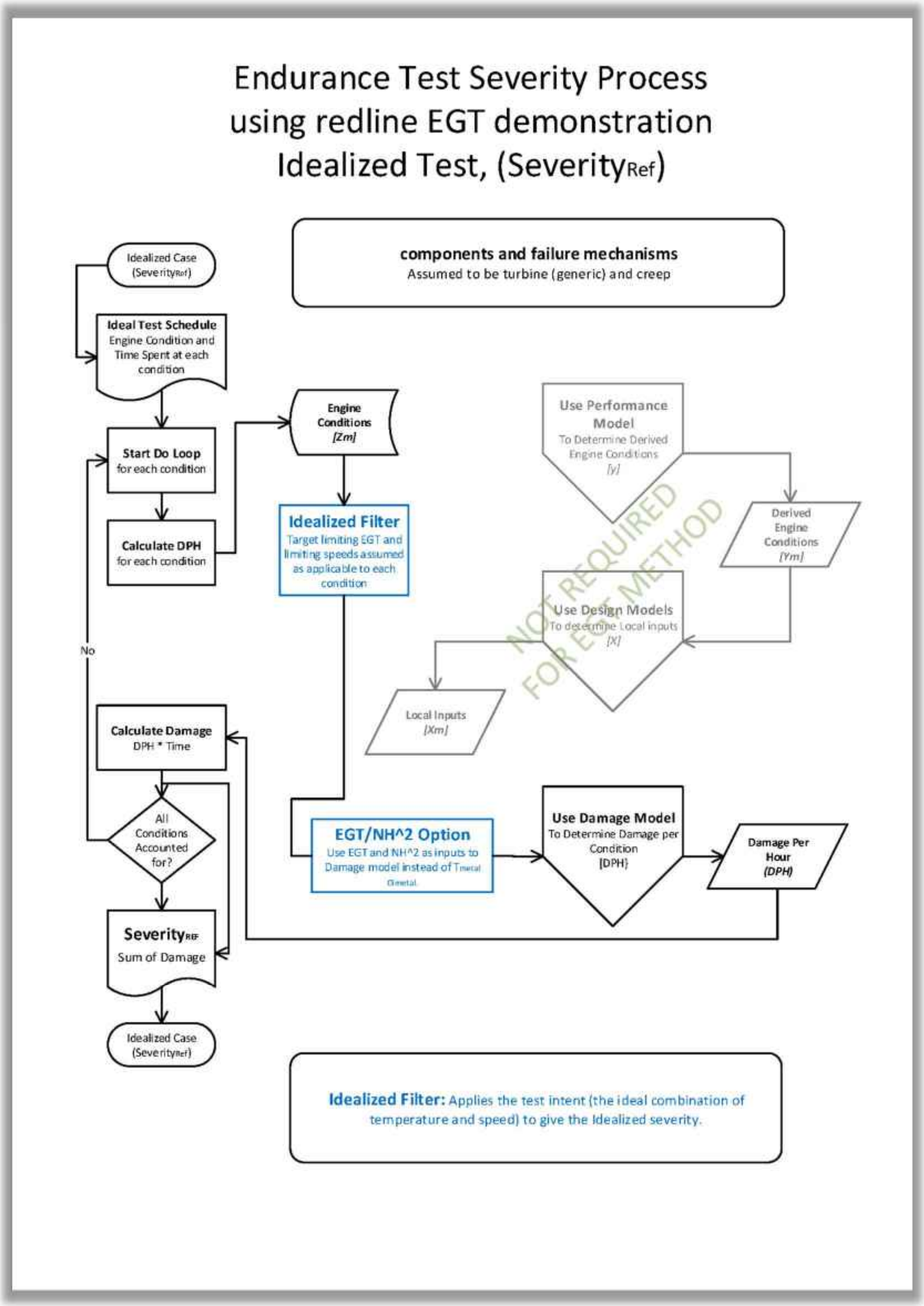


Figure 13.12 Endurance Test Severity Process using Redline EGT Demonstration – Idealized Test (SeverityRef)

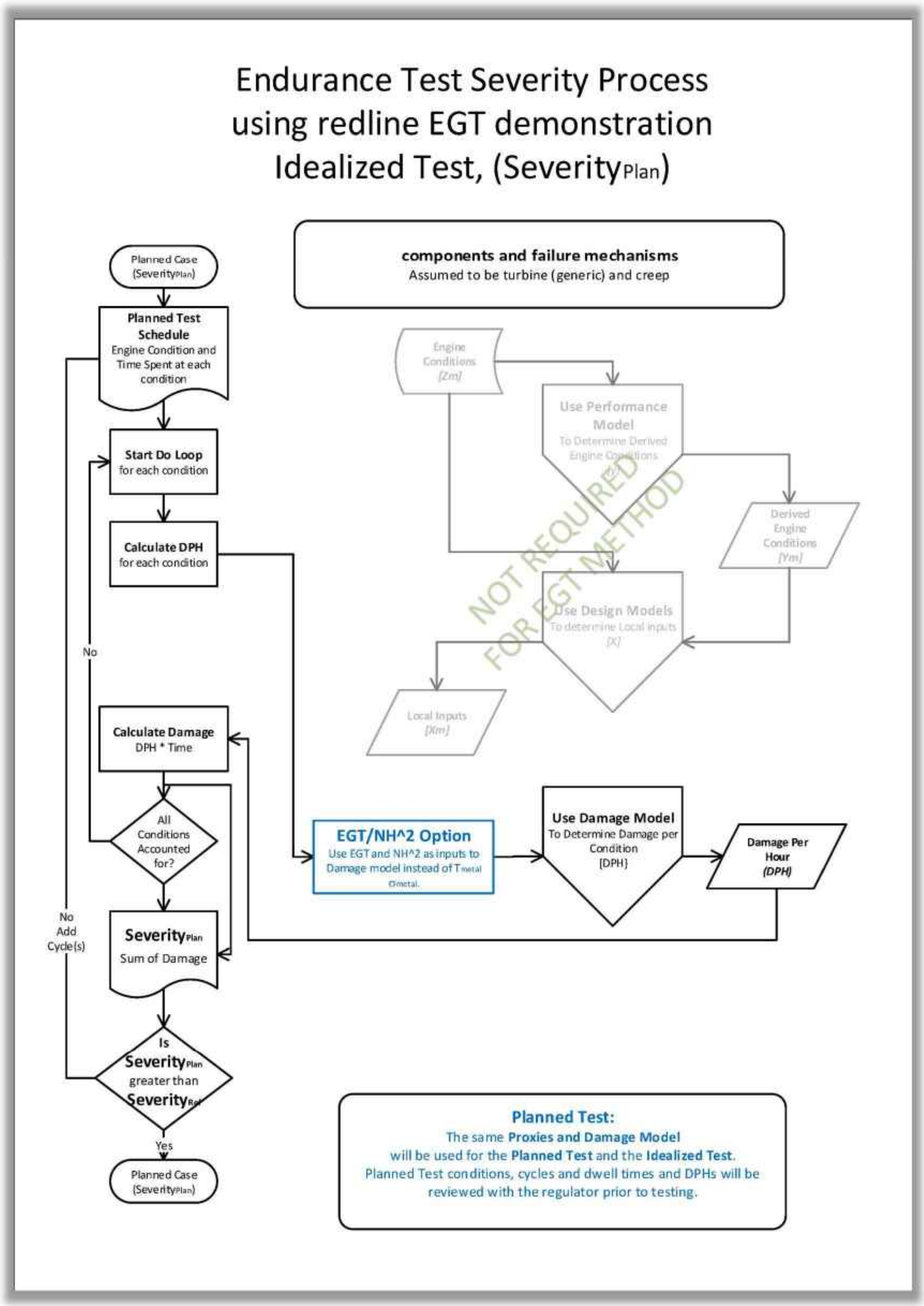


Fig 13.13 Endurance Test Severity Process using Redline EGT Demonstration – Idealized Test ($Severity_{Plan}$)

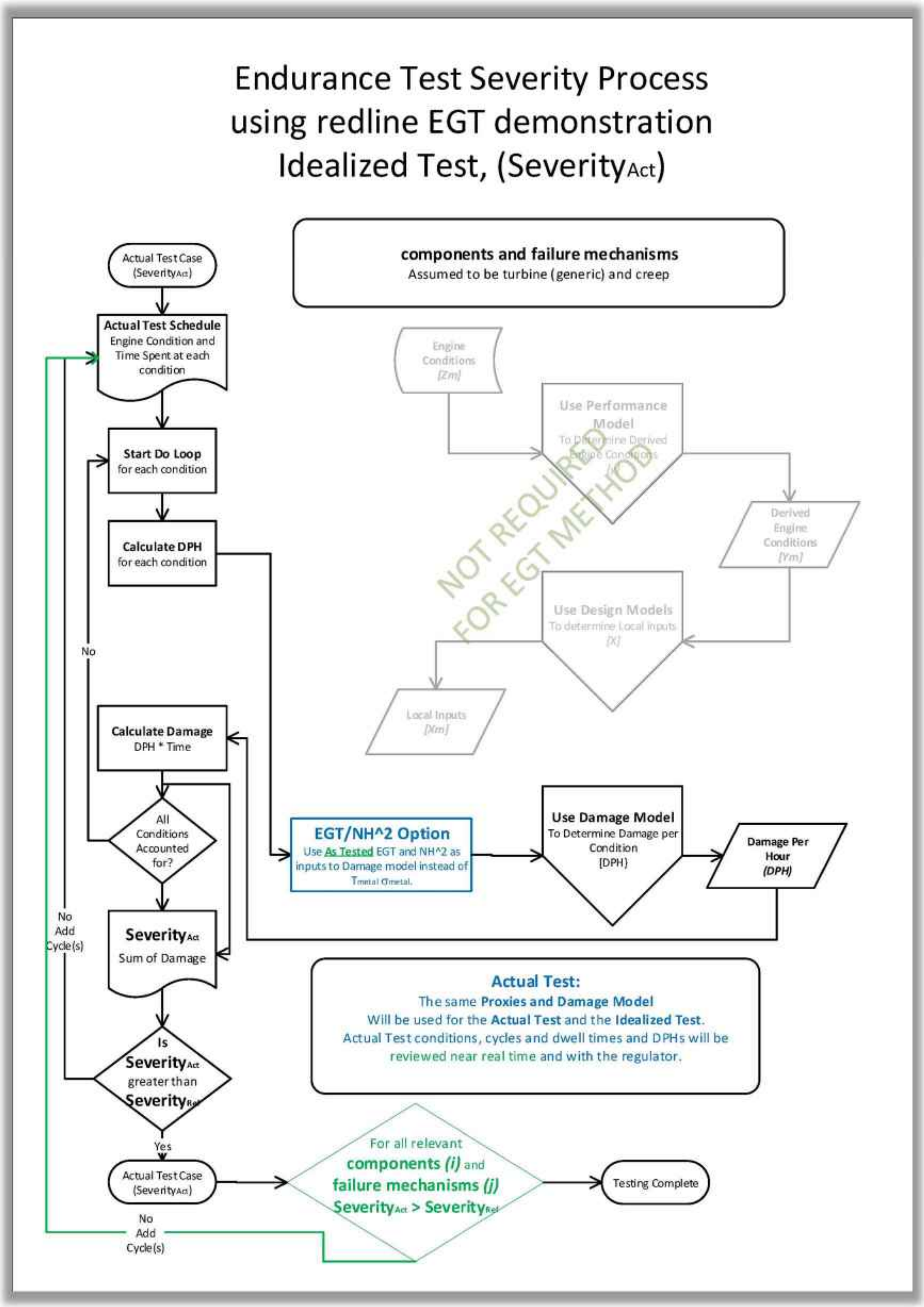


Figure 13.14 Endurance Test Severity Process using Redline EGT Demonstration – Idealized Test (Severity$_{Act}$)

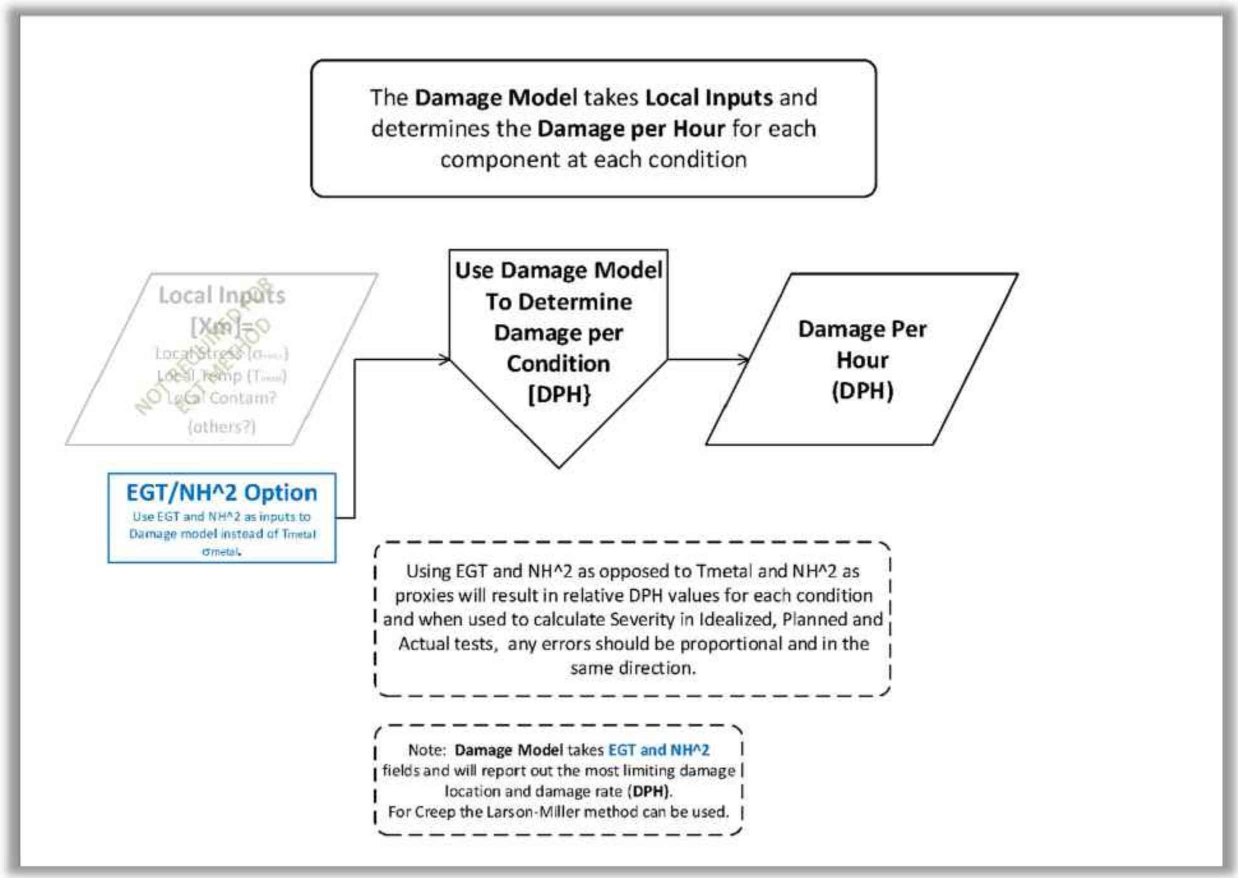


Fig 13.15 EGT Method Damage Model

13.12 Conclusion

For the 150 Hour Endurance Test, either Methods (1) currently-defined test, (2) Alternate (T_{metal} method), or (3) Alternate (EGT method) could be used. Each method has its benefits and drawbacks, however following each of the methodologies will result in an adequately severe test. The applicant will be required to discuss with the regulator which method they are planning on using before the start of the test.

Important to both Methods (2) and (3) are that the performance and damage calculation methodology MUST be consistent between the $Severity_{Ref}$ and $Severity_{Act}$ calculations. If during the testing, there is test data that requires an update to one of the modelling methodologies, then the $Severity_{Ref}$, would need to be recalculated with the new methodology as well.