U.S. Department
of Transportation
**Federal Aviation
Administration**

Advisory Circular

Subject: Oxidation, Hot Corrosion, Thermal Fatigue, and Erosion Characteristics Testing to Support 14 CFR, Part 33, § 33.15, Compliance for Turbine Engines

Date: 9/23/14

Initiated by: ANE-111

AC No: 33-11

1. Purpose. This advisory circular (AC) describes an acceptable method, but not the only method, to support certain comparative assessment compliance findings to Title 14 of the Code of Federal Regulations (14 CFR) part 33, § 33.15, *Materials*, for turbine engine projects. Comparative assessment of certain data is often necessary to show the required functional and durability equivalencies between engine combustor and turbine section parts from different design or manufacturing processes, e.g., parts manufacturer approvals (PMA) versus type design parts. These equivalencies relate to oxidation, hot corrosion, and thermal fatigue and erosion characteristics in the engine environment. This data is necessary to support overall FAA design approval of turbine engine and auxiliary power unit (APU) parts approved under PMA, type certificate (TC) design change, supplemental type certificate (STC), or repair or alteration authority.

2. Applicability.

a. The guidance in this document is for applicants requesting FAA approval for PMA, TC design change, STC, or repair or alteration of turbine engine and APU parts. For the purpose of this AC, we will collectively refer to these parts as “replacement parts,” and the term “engine” is defined as a propulsion turbine engine or an APU. We intend this guidance to support comparative test and analysis design-approval projects. The guidance in this AC may also have application to other turbine devices such as turbochargers or superchargers.

b. This material is neither mandatory nor regulatory in nature and does not constitute a regulation. It describes acceptable means, but not the only means, for demonstrating compliance with the applicable regulations. We will consider other methods of demonstrating compliance that an applicant may elect to present. Terms such as “should,” “may,” and “must” are used only in the sense of ensuring applicability of this particular method of compliance when the acceptable method of compliance in this document is used. While these guidelines are not mandatory, they are derived from extensive FAA and industry experience in determining compliance with the relevant regulations. If we become aware of circumstances that convince us that following this AC would not result in compliance with the applicable regulations, we will not be bound by the terms of this AC, and we may require additional proof as the basis for finding compliance.

c. This material does not change, create any additional, authorize changes in, or permit deviations from existing regulatory requirements.

3. Reference. Advisory Circular 33-10, Statistical Analysis Considerations for Comparative Test and Analysis Based Compliance Findings for Turbine Engine and Auxiliary Power Unit Replacement, Redesign and Repaired Parts, dated August 28, 2014.

4. Background.

a. For comparative test and analysis design approval projects, materials validation (compliance with § 33.15) requires a detailed comparison of the proposed replacement part to the existing type design part. This work generally requires comparisons of a variety of physical and mechanical properties and characteristics associated with the materials and manufacturing processes involved. Development of replacement parts may arise from different factors, including durability or performance improvement, manufacturing process improvement, cost reduction, or other commercial reasons.

b. Combustor and turbine section gas path parts are exposed to a variety of effects when subjected to the extreme conditions associated with turbine engine operation. For gas path and certain main rotor parts, like combustors, disks, spools, spacers, turbine blades, vanes, cases, and their non-rotating seals, the effects of oxidation, hot corrosion, thermal fatigue, and erosion are of critical importance to the performance of these parts in service. Therefore, testing is often needed to reliably predict the behavior of parts and effectiveness of coatings (environmental and thermal barrier) in an engine. The testing normally needed is of a dynamic nature, because traditional static tests may not adequately replicate an engine environment. For example, the effects noted above can occur simultaneously in an engine environment and, therefore, cannot be evaluated by independent static tests. However, overall test methods (static/dynamic/engine) should be developed based on the function and operating environment of the part, and test objective. The specific test requirements will be determined during development of the approved compliance plan for the project. Test methods other than the burner rig method described in this AC, could be suitable alternatives to gathering the required information, depending on test objective. For example, alternative test methods could be acceptable where the dynamic characteristics of engine airflow are not significant to the test objective. Such proposals will be evaluated on a case-by-case basis.

c. This AC provides guidance for how burner rig testing may be used to show compliance to § 33.15 for comparative assessments, and describes an acceptable test method and criteria.

5. Comparative Tests. The comparative material tests described in the subparagraphs below may be necessary to adequately support compliance to § 33.15, for combustor or turbine section gas path replacement parts, where the base material, coating specifications, or braze/weld materials are not identical to the type design part, as determined by patent evaluation, formal material certification documentation, material reverse engineering, manufacturing processes, etc. These parts include, but are not limited to, rotor assemblies, combustor assemblies, turbine blades, turbine vanes, turbine cases, and their non-rotating seals. For these parts, applicants must show that the replacement part durability characteristics for oxidation, hot corrosion, thermal fatigue, and erosion are at least equivalent to the type design part when operated in an engine. Part durability characteristics can include both time-to-failure and the actual failure mechanisms.

Applicants can perform various tests to collect the data needed for this showing. Such testing most often uses material specimens (coupons), but could use actual parts in certain cases.

a. Part and Material Characteristics. Applicants must evaluate the following part and material characteristics, as applicable, in an engine operating environment:

(1) Corrosion. Corrosion is the deterioration of the surface coating or base metal of a part by chemical reaction with the various constituents of the engine core gas stream. Corrosion may also result from galvanic action between mating parts (e.g., mating of dissimilar metals at braze/weld joints).

(2) Oxidation. Oxidation is a form of corrosion that involves the chemical reaction of oxygen in the gas stream with the surface coating or base metal of the part. This chemical reaction creates oxide molecules as it consumes the coating or base metal. The oxides generally build up as a coating (oxide film) on the part surface, but can also be intergranular or below the external surface of the base metal. Oxidation will consume these materials at some rate and, in extreme cases, may prevent normal functioning or cause premature failure of the part. Oxidation is the most prevalent form of corrosion in aircraft engines.

(3) Hot corrosion. Hot corrosion is a special case of oxidation process that occurs when a normally protective oxide film layer is degraded or destroyed by a salt-based deposit (e.g., sodium sulfate), and is unable to reform or protect the base metal. Hot corrosion is a specific and important form of corrosion in turbine engines, and can occur at various operating temperatures between low and high power. There are various chemical mechanisms involved, which vary between coating, base metal, and gas constituent combinations. Hot corrosion typically occurs when salts form in the gas stream and react with protective oxide films on the part surface, then cause that protective layer to break down and not be able to reform. This results in a continuous chemical reaction of the base metal with oxygen and consumption of base metal structure until the part fails or no longer performs its intended function. Therefore, hot corrosion is an accelerated oxidation process that can have serious implications for engine operation and aircraft safety. Hot corrosion is the primary form of corrosion that attacks hot section turbine components. Phosphates and other gas path constituents can also contribute to hot corrosion, depending upon material selection. These can have effects similar to sodium sulfates.

(4) Thermal Fatigue. In an operating engine, thermal and mechanical stresses applied to a part can result in fatigue damage. For certain parts, thermally induced fatigue can be significant, and may result in cracking of a surface coating or base metal, or spalling of a protective oxide layer. The cracking or spalling results from the repeated application of thermally induced stresses due to rapid and non-uniform heating and cooling cycles during engine transients. Such effects can allow the gas stream to impinge on the base metal and accelerate the overall oxidation process, leading to part failure. These conditions are often responsible for thermal fatigue damage accumulation in hot section parts in service. This AC primarily addresses thermal fatigue concerns for protective coatings applied over the base metal of gas path parts to show coating durability and effectiveness.

(5) Erosion. Aircraft engines are subject to erosion damage by contaminants in the core gas stream. The erodents are generally small particles of sand, dust, or other airborne pollutants ingested from the surrounding environment. The shedding of particles from upstream engine components (e.g., combustor) can also be a source of particulate matter. Erosion can cause the

premature wear-out of protective coatings, degradation of protective oxide scales, or cause pitting damage to the base metal surface. These conditions could have a negative effect on the performance or durability of the replacement part.

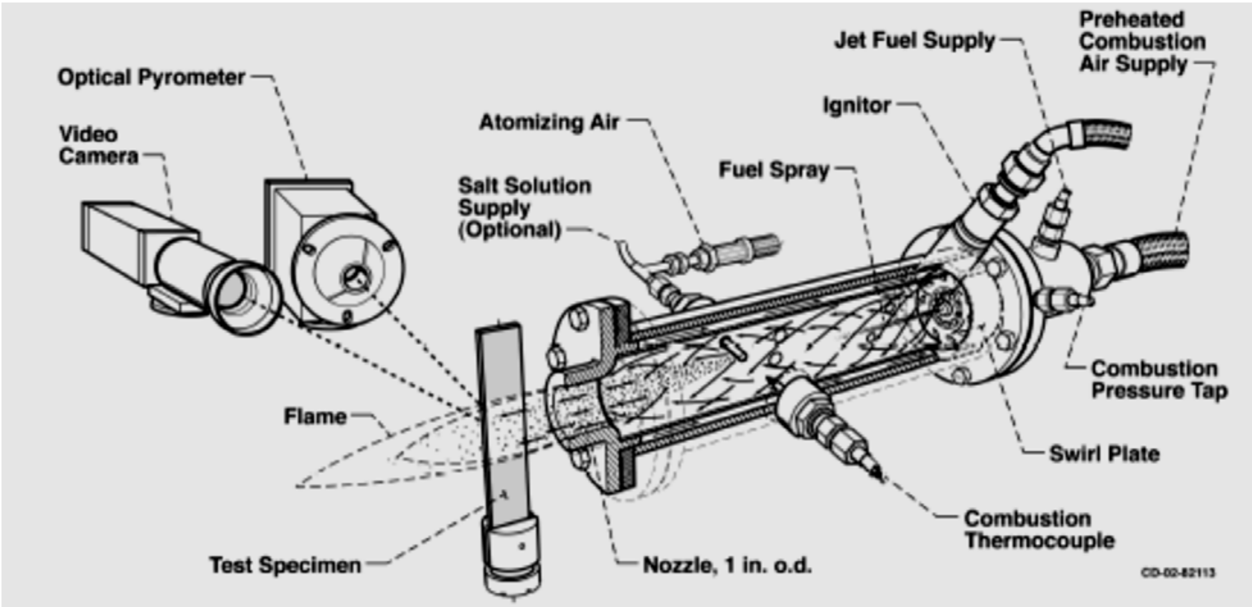
b. Burner Rig Test Method.

(1) The overall intent of this comparative test method is to generate adequate data to show that the proposed part is at least equal to the type design part relative to overall oxidation, hot corrosion, thermal fatigue, and erosion resistance when operated in an aircraft turbine engine. While the best method to evaluate these characteristics is during actual engine operation, in most cases, this will not be practical and simple static tests in air do not simulate an engine environment. Therefore, a fuel burner rig can be used to test material specimens or actual parts in an environment simulating that of an engine. Normally, these tests are conducted using material specimens and focus on either bare or coated metal. For testing using actual parts, the applicant will need to consider part size and how it is installed in the engine. For example, parts with complex cooling requirements may require a special test set-up to replicate its boundary conditions. Also, the burner needs to be sized to provide adequate coverage for the size of the test samples, whether they are specimens or actual parts.

(2) A fuel burner is a combustion device that generates a hot gas stream that attempts to simulate the mixing, flow, and chemistry of the core gas stream in an engine. However, such devices do not generally replicate the exhaust gas velocity or internal gas pressure found in a propulsion engine. Normally, a common commercial type jet fuel (e.g., Jet A) is used to power the burner. The test is conducted by placing a test specimen(s) in the exhaust gas of the fuel burner for the conditions defined in the approved test plan (e.g., time, temperature, gas flow constituents). Sometimes, multiple test specimens are used simultaneously and placed in a rotating carousel. The rotation assures that the temperature effects of the gas stream are averaged over all the test specimens throughout the test period. The gas stream can also have contaminants added to simulate hot corrosion or erosive environments. These contaminants can have significant effects on part function and durability; for example, a diluted and atomized sea salt solution can be introduced into the burner rig flow to test for hot corrosion. The test can also incorporate thermal cycles to simulate engine start, shutdown, or power transients to address associated thermal fatigue concerns.

(3) Figure 1 shows a typical set-up used at a number of commercially available laboratories. This figure shows the fuel burner, test specimen placement, temperature measuring devices, and various supply lines and other features of a typical test rig. Such a rig must be compatible with commercial jet fuels (e.g., Jet A), and have exhaust gas temperature and velocity ranges compatible with the intended engine application. For further reading, NASA Report No. NASA/TM-2011-216986 describes in more detail the design and function of a modern burner rig test facility having the capability to conduct the tests described in this AC. However, the information contained in the NASA report is for informational use only and does not describe the only possible test method.

Figure 1
Typical Burner Rig Set-Up



c. Test Planning. The applicable project compliance and test plans should include test conditions addressing oxidation, hot corrosion, thermal fatigue, and erosion. Back-to-back or simultaneous testing of samples of both proposed and type design parts, or test specimens, are necessary to compare part characteristics. The test plan should specify a sufficient number of test specimens to provide a statistically significant comparison of results (see referenced AC 33-10 for related information). Test specimens must be processed in the same manner as production parts with respect to coating thicknesses, substrate heat treatments, and other related parameters. For example, for coating performance testing, the test specimens must be designed to ensure that coating degradation occurs before base metal degradation. If base metal degradation occurs first, the test results may be invalid. Therefore, test specimens must reflect actual part processing in these areas to obtain meaningful comparisons. Test conditions must be representative of an engine operating environment, and typically include alternating heating and cooling periods. The test conditions must be of sufficient duration and severity so that representative degradation occurs. The test plan should address the following test conditions, as applicable:

(1) Oxidation. Include test conditions that evaluate part or specimen oxidation over the full range of engine operating conditions. This test must include sufficient time at an engine operating temperature, and sufficient thermal cycling to demonstrate oxidization characteristics and time to failure. Meaningful results may require gas streams of relatively high velocity (see paragraph 5.b(3) in this AC).

(2) Hot Corrosion. Include test conditions that evaluate part or specimen hot corrosion characteristics when the gas stream is contaminated with sodium sulfate. This test must include sufficient time at an engine operating temperature to demonstrate hot corrosion characteristics over the range of part features and engine operating conditions.

(3) Thermal Fatigue. Include test conditions that evaluate the durability of coatings (or in some cases base material) when exposed to thermally induced stresses. This can be accomplished by moving the test specimens in and out of the gas stream so as to create a steep temperature gradient in a manner representing engine operation. This test must include sufficient thermal cycling to demonstrate part resistance to thermal fatigue damage. Multi-layer coatings should generally be tested as a system, rather than layer-by-layer.

(4) Erosion. Include test conditions where the gas stream is contaminated with typical erodents found in a service environment. This test must include sufficient time in the erosive environment to demonstrate part or specimen erosion resistance.

d. Test Results and Equivalence Determination. The following comparisons are useful in showing equivalency:

(1) Oxidation and Hot Corrosion Resistance of Base Metal. Compare the type and thickness of oxide layers, and the overall rate of consumption of the base metal over exposure time. Look for overall mass accretion rate if the formed oxides are not removed by the gas stream. Using metallographic inspections look for granular or inter-granular oxidation (and penetration depth) and any local de-alloyed base material. This type of oxidation can have a significant effect on material mechanical properties and part function and durability. Pay particular attention to the effects of hot corrosion on oxide scale formation and durability, and on base metal integrity. In some cases, it may be necessary to perform post-test mechanical integrity evaluations to determine whether the oxidation has negatively affected part function or durability.

(2) Oxidation and Hot Corrosion Resistance of Protective Coating. Compare the type and thickness of oxide layers and the consumption rate of the coating over exposure time, including times to onset and coating failure. Look for cracking, spalling, or separation of the coating from the base metal.

(a) For separation, observe the effects on the base metal. Pay particular attention to the effects of hot corrosion on oxide scale formation and longevity, and the effects on base metal integrity. Differences in coefficient of thermal expansion between the oxide layer and the coating can accelerate spalling. Coating microstructure can vary significantly as a function of coating application method and can result in varying service lives.

(b) For thermal barrier coatings (TBC) that use a bond coat over the base metal, a key performance criterion is susceptibility to TBC spalling at the TBC/bond coat interface. Spalling of the TBC can lead to a significant increase in bond coat degradation rate and poor durability characteristics of the protective coating.

(3) Thermal Fatigue Resistance of Protective Coating. Look for cracking or spalling that result from the applied thermal stresses. For diffusion coatings, look for cracks propagating into the base metal. Observe corrosion resistance, as discussed in paragraphs 5.d(1) and (2) of this AC.

(4) Erosion Resistance. For base metal and coatings, look for surface wear, pitting, and other effects that consume material (e.g., loss of coating thickness); effects that could change the

part shape (e.g., airfoils); or effects that otherwise negatively affect part function or durability. The consumed material could be the base metal, the protective coating, or protective oxide scale.

(5) Other Criteria.

(a) Weight changes (positive/retention or negative/spalling);

(b) Visual inspection for surface damage;

(c) Phases of coating before and after oxidation;

(d) Examining for microstructure changes in coatings and base metal;

(e) Coating phase transformation and volume increase; and

(f) Associated cracking and/or spalling.

(6) The replacement part must show to be, at least, equal to the type design part for the above characteristics in terms of part or feature performance and durability.

6. Summary. The methods of compliance identified in this AC may be used to show compliance to § 33.15 for certain material characteristics using comparative assessment. If material specimen testing is used, sample size, specimen design, and test conditions must adequately represent the actual part in its operating environment.

If you have any suggestions for improvements or changes, you may use the template provided at the end of this AC.

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Appendix A. Advisory Circular (AC) Feedback Information

If you have comments or recommendations for improving this AC, or suggestions for new items or subjects to be added, or if you find an error, you may let us know about it by using this page as a template and 1) emailing it to 9-AWA-AVS-AIR500-Coord@faa.gov, or 2) faxing it to the attention of the AIR Directives Management Officer at 202-267-3983.

Subject: (insert AC number and title) Date: (insert date)

Comment/Recommendation/Error: (Please fill out all that apply)

An error has been noted:

Paragraph ____________________

Page ______

Type of error (check all that apply): Editorial____ Procedural____ Conceptual____

Description/Comments:____

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Recommend paragraph ______ on page ______ be changed as follows:
(attach separate sheets if necessary)

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In a future change to this AC, please include coverage on the following subject:
(briefly describe what you want added attaching separate sheets if necessary)

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Name: __________________________