Policy Guidance for Lightning Protection of Fuel Tank Structure and Systems

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1 Overview

1.1 Background
On May 26, 2009, the Federal Aviation Administration (FAA) released ANM-112-08-002, Policy on Issuance of Special Conditions and Exemptions Related to Lightning Protection of Fuel Tank Structure. The FAA developed this policy because they determined that compliance with current regulatory standards applicable to lightning protection of fuel tank structure may be impractical in some cases.

In the 2009 Policy Memo, the FAA also stated a plan to develop changes to the regulations to eliminate the need for Exemptions or Special Conditions for certification of fuel tank lightning protection.

Subsequently, the FAA chartered an Aviation Rulemaking Committee (ARC) to provide recommendations regarding fuel tank lightning protection regulations. The ARC provided their recommendations in a report to the FAA in May 2011.

On June 24, 2014, the FAA released PS-ANM-25.981-02, Policy on Issuance of Special Conditions and Exemptions Related to Lightning Protection of Fuel Tank Structure and Systems, which superseded the 2009 Policy Memo and incorporated the following recommendations of the ARC committee:

- Revision of the definition of practicality
- Replacement of the numerical assessment requirements with qualitative assessments when fault tolerance is impractical
- Expansion of applicability to include systems
- Modifications to the requirements for maintenance and continued airworthiness

This document is intended to provide guidance to applicants who seek to apply this 2014 Policy Statement to their type design programs and to establish criteria to encourage a consistent approach be applied across industry. The content of this document has been developed by the SAE AE-2 and EUROCAE WG-31 lightning committees. Applicants should coordinate directly with their airplane certification authority to ensure that their proposed application of this policy is acceptable and the means of compliance and compliance data planned are sufficient for certification.

1.2 Application of the Policy

The 2014 Policy Statement says,

“This policy may be applied to the design of lightning protection features in fuel tank structure and systems for which compliance with § 25.981(a)(3) is shown by the applicant and determined by the FAA to be impractical. However, all other potential fuel tank ignition sources must still be compliant with § 25.981(a)(3).”
Therefore the applicant must substantiate that it is impractical to comply with § 25.981(a)(3) for lightning protection of fuel tank structure and systems in order to apply the policy criteria to their design. Per the policy, “practicality” is defined as “a balance of available means, economic viability, and proportional benefit to safety.” If there is no means of providing direct compliance or if the only means of providing direct compliance would have a significant economic impact on production, operational or maintenance costs without providing a proportional benefit to safety, it is acceptable to utilize the alternate requirements of the policy.

The rationale and justification associated with it being impractical to directly comply with § 25.981(a)(3) should be outlined in the Exemption Request or Special Condition Issue Paper. Details and proprietary information would be included in the appropriate compliance documentation. This rationale would typically identify where there are no design options available that will achieve direct compliance and/or specific design options that were considered but dismissed as being “impractical” per the policy definition. This rationale should consider both fuel tank structure and systems.

The FAA will propose Special Conditions based on being appropriate in lieu of the existing regulations, as well as assuring an equivalent level of safety (for the public). Granting an Exemption is based upon providing an acceptable level of safety and being in the “public interest.” Therefore it is anticipated that the emphasis of the rationale for impracticality should be the public impact of additional design features, such as the fuel burn (and associated emissions) associated with higher design weights, operational and maintenance costs. Production costs are also a factor to the public travel costs, but may be a secondary factor when judging proportional benefit to public safety.

Regarding proportional benefit to safety, it is accepted that reducing risks to the level of Extremely Improbable at a system level will ensure an event is unlikely to occur in the life of a fleet. Once the airplane level risk of a catastrophic fuel tank vapor ignition event due to lightning is determined to be Extremely Improbable, any safety benefit from further reducing risk is negligible.

Under the new 2014 Policy Statement, the applicant has the opportunity to demonstrate that direct compliance to §25.981(a)(3) for systems, typically by providing three means of protection, is impractical based on a comparison of the associated safety benefits. The FAA has emphasized that the applicant must provide a clear justification to support the position that compliance is impractical, since recent certifications have been able to provide technical means for systems to comply. One approach to do this would be to demonstrate that two protection features (i.e. fault tolerant) each with an individual Remote failure rate, will ensure that the combined system level risk is less than Extremely Improbable (unlikely to occur in the life of a fleet). Considered together with all pertinent factors such as the likelihood of a lightning strike, lightning current amplitude, and flammability exposure, this would typically combine to far less probable than 1e-9 per flight hour. A risk that is already far less probable than the accepted standard for unlikely to occur in the life of a fleet does not justify any additional complexity, weight and cost to further reduce the risk. The same approach can be done qualitatively, based on combination of three Remote conditions (Remote likelihood of each of the two means of protection failing, together with the Remote combination of lightning and flammability). It would also be appropriate to identify that added complexity may have potential negative implications to overall
airplane safety, because of the increased chance for errors (installation or maintenance) and additional failure modes. For example:

- Installing multiple bond straps in parallel may provide additional redundancy, but it also doubles the likelihood of a failed jumper being present that may be a hazard. Or if slack in the installation allowed two jumpers to touch, the potential for sparking between them during a lightning event is a new hazard to address.
- Additional clamping may provide redundancy in ensuring wire separation from structure, but it also doubles the likelihood of support failures that may have unforeseen consequences.
- Additional sealant may contain potential sparking if both protection features in a fault tolerant design failed, but it also inhibits the ability to inspect for structural cracks. Having to remove sealant for structural inspections increases the potential for scratching or gouging the structure, which if not detected and corrected may lead to accelerated cracking after the inspection was just completed.
- Additional work inside the confined spaces of a fuel tank increases the risk for unidentified damage to other systems or structure inside the tank.
- Additional work and features increases the potential for foreign object debris (FOD) being left in the tank and causing engine feed issues or fuel transfers (clogged check valves or orifices).

It is difficult to quantify each of these risks that a more complex design causes, but they qualitatively support that adding complexity does not have a proportional benefit to safety when the risk with a less complex fault tolerant design is already Extremely Improbable (unlikely to occur in the life of the fleet).

The policy includes alternate requirements for Special Conditions and Exemptions. Special Conditions may be proposed by the FAA where there is a flammability reduction means that enables the proposed design to meet the Appendix M criteria for all fuel tanks. Alternatively, applicants may petition for an Exemption following the process defined in §11.81 and include the rationale and justification above for why it is impractical to directly comply, as well as how they plan to apply the alternate safety requirements of the policy to enable the FAA to find that it provides an acceptable level of safety.

### 2 Compliance Demonstration Process

If the applicant demonstrates that direct compliance with §25.981 (a)(3) at amendment 25-102 or 25-125 is impractical, an alternative approach for lightning protection of the fuel structure and systems may be used in accordance with the Policy Statement PS-ANM-25.981-02.

In general this approach will consist of an assessment of each lightning protection design and/or design feature for fault tolerance and, where designs are not fault tolerant, that they must be shown to be impractical to make fault tolerant along with an assessment confirming the likelihood of lightning related fuel tank vapor ignition due to the combination of these non fault tolerant designs being
Extremely Improbable. The following eleven steps describe the basic process for demonstrating compliance to the relevant requirements determined by the selected compliance path:

**Step 2.1:** Identify the fuel system design features and associated lightning protection  
**Step 2.2:** Determine the lightning strike zones for the aircraft  
**Step 2.3:** Establish the aircraft lightning environment of the design  
**Step 2.4:** Identify potential failure modes of the design features  
**Step 2.5:** Identify potential ignition sources associated with the design features and potential failure modes  
**Step 2.6:** Perform safety assessment to determine fault tolerance  
**Step 2.7:** Assess the combined risk of all non-fault tolerant conditions  
**Step 2.8:** Develop supporting data for lightning protection performance  
**Step 2.9:** Develop Instructions for Continued Airworthiness, Maintenance and Surveillance Programs  
**Step 2.10:** Incorporate practical measures to prevent, detect and correct failures  
**Step 2.11:** Verify compliance to the requirements

Further explanation of each of the eleven steps as applied to Special Conditions or Exemptions is provided below.

### 2.1 Identify the fuel system design features and associated lightning protection

The fuel system requiring lightning assessment should be identified along with the means of lightning protection. The following are examples of the type of detailed documentation that should be provided:

- Details of each structural member or categories of members and fasteners exposed to direct attachment including the pertinent information needed to assess the ability to prevent fuel tank vapor ignition sources during attachment.
- Details of each structural joint or categories of joint and fasteners exposed to conducted currents resulting from lightning attachment including the pertinent information needed to assess the ability to prevent fuel tank vapor ignition sources.
- Details of each systems installation exposed to direct attachment or conducted current including the pertinent information needed to assess the ability to prevent fuel systems ignition sources.

Pertinent information can include, but is not limited to: material properties, thicknesses, and finishes (metallization, non-conductive coatings), fastener sizes, fit, and quantities, manufacturing tolerances, bonding or isolation, wire routing and shielding, etc. Typically this information is synthesized into a set of design groups or families that share similar characteristics relative to lightning protection performance. For each of the designs the lightning protection design features can also be identified and documented. This categorization organizes the designs and/or lightning protection design features into groups to aid with the evaluations identified below.
2.2 Determine the lightning strike zones for the aircraft

Determine the lightning zoning for the aircraft and particularly the fuel tank and fuel system regions using the zoning process defined in ED-91/ARP5414 document.

2.3 Establish the aircraft lightning environment of the design

The way the local lightning environment of the design is defined must be consistent with the principles that are used to verify the lightning protection performance of the design. Indeed, the definition of the threat determined at this step of the process must enable a direct correlation with the threat that is developed during a lightning test on a test sample and should be aimed at verifying the performance of the design.

The correlation can be done at different levels of aircraft design e.g. large object (wing), assembled joint/interface, group of fasteners or even at the fastener level itself. In the case where the protection principle is evaluated at the fastener level, for example, then the local lightning environment has to be established at the same scale for enabling correlation.

External surfaces of the aircraft are exposed to the external lightning environment, as defined in ED91/ARP5414 and ED84/ARP5412. All internal structural and system elements are exposed to the conducted currents resulting from lightning attachments in Zone 1 or Zone 2 regions.

Regardless of whether an area is exposed to a direct attachment, the lightning environment must also consider the worst case localized conduction current at the location of each and every component and interface inside the fuel tanks due to any lightning attachments to the aircraft. Historically similar design and manufacturing methods have been used in Zone 3 areas as in Zone 2, hence the design will generally provide effective lightning protection at most locations in the event of an unlikely attachment.

Determination of these threat levels requires an assessment of the worst case external attachment scenarios based on an appropriate combination of Analysis, Tests and Similarity:

**Analysis and Tests:**

There are several options available for approaching such a structural/systems assessment to derive appropriate lightning threat levels for the type of test samples selected for the compliance demonstration. Indeed there are also several choices available for test sample complexity. One can consider, for example, the component parts of a typical structural “test pyramid.”

One means, but not the only means, of proceeding is as follows:-

- For each design or design feature choose the preferred "test pyramid level" for compliance demonstration. (Note this equally applies to systems and equipment installations as well as structural components)
  - Aircraft Production standard components.
  - Large scale demonstrators (e.g. wing box).
  - Sub assembly components (e.g. rib bay demonstrator).
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- T-joints
- Multi fastener lap joints
- Individual fastener joints

Based on the test level choice decide whether an analytical approach or physical measurement approach (or combination of both) can best be employed to most accurately determine the worst case lightning threat levels.

- The analytical approach could consist of calculations from first principles through to 2D and 3D computational electromagnetic modeling.
- The physical measurement approach may require intrusive connections around some structural and systems components to determine localized current densities, peak values and resultant waveforms.
- Both methods have their respective constraints and limitations and these should be taken into account. Current flow computations must take into account that the size of the cell might influence the results specifically in complicated zones or near the edge of parts. Such numerical modeling therefore requires some level of validation. It is important that computations be performed at a similar scale as that used for the verification test. Manufacturing variations of parameters such as fastener contact resistances and structural seam impedances may also influence the current distribution.

- The worst case internal lightning threat levels for each design and protection feature, based on all potential direct attachment scenarios to the aircraft in question, can therefore be defined by this process.
- For all analyses, tests, and/or similarity, appropriate margins to determine test current levels must be addressed.

**Similarity:**

It is possible to establish the lightning environment based on prior test or analysis data from similar previously certificated airplane designs. The applicant may provide a comparative analysis to a previously certificated airplane, which would include a detailed assessment of the design features and details that affect susceptibility to failure, exposure time to the lightning hazard, service experience, and any applicable analyses and data.

### 2.4 Identify potential failure modes of the design features

The applicant must consider the failure modes and design sensitivities which may lead to the loss of effective lightning related ignition source protection. Failure modes to consider include those that may occur because of manufacturing errors and escapes, maintenance errors, repairs or alterations, aging, wear, corrosion, or likely damage. Design sensitivities to consider are those resulting from design variations such as those associated with skin thickness, finish application to parts and structure, part variability, etc. Sensitivities that could degrade the effectiveness of lightning protection are typically identified through analysis or test.
Failure modes may be determined based upon a structured design review process which typically would include experts in lightning protection, manufacturing processes, materials and processes, structural design, systems design, reliability and maintainability, etc. Sources of information to aid in identifying failure modes should include manufacturing process data assessment, service history records, and developmental test data. Failure modes that should be considered are those that may occur during the life of an airplane or a fleet of airplanes of a particular model.

Specific failure modes are related to aircraft specific tank structure and systems. The design must consider the failure modes which may lead to the loss of lightning related ignition source protection during the life of the aircraft. These design features may then be included in tests and/or analyses to establish whether the failure modes may cause ignition sources. Failure modes which should be considered include those that occur due to manufacturing quality escapes, operational deterioration, and accidental damage.

**Manufacturing Quality Escapes**

Typical examples of structural manufacturing quality escapes include fastener selection issues (incorrect fastener size, type, finish, or coating), fastener assembly issues (misalignment, incorrect torque, hole size or quality, missing or extra washers), and installation issues (inadequate or improperly adhered sealant, missing cap seals, incorrectly installed electrical bonds).

Typical examples of manufacturing quality escapes on systems include design installation issues (incorrect fasteners, wrong or missing clamp or bracket, inadequate or improperly adhered sealant, missing or incorrect finishes), electrical bonding issues (missing or improperly installed electrical bond or wiring shield), and clearance issues (insufficient tube or wiring clearance to adjacent systems or structure).

**Operational Deterioration**

Typical examples of structural failures due to deterioration during intended operations include broken or cracked elements (fasteners, rivets, nuts, or washers), corrosion, degradation of applied materials (sealants, fastener head coating, edge glow protection, or bonded joints), and fatigue issues (loose fasteners or structural cracks).

Typical examples of systems failures due to deterioration during operations include failures of support features (loss of fasteners, brackets, or clamps supporting tubes, wiring or components) and degradation of electrical bonds, wire insulation or shielding due to corrosion, aging, or wear.

**Accidental Damage**

Typical examples of structural or systems failures due to accidental damage include impact from FOD or inadvertent damage incurred during maintenance or inspection.
Severity or types of failures should be defined and can be based upon service history, where appropriate, or laboratory test data. Failure severity should be consistent with, or bounded by, assumptions made for structural and systems certification analyses. Severity or types of failures due to manufacturing escapes should be based upon factory history and/or manufacturing process robustness.

In-tolerance manufacturing variability and environmental conditions should be considered in conjunction with failures, but stacking of worst case conditions for all parameters is overly conservative and not necessary.

Failures due to operating or environmental conditions outside of those required to support certification need not be considered.

Possible combinations of failure modes, as when one failure mode or condition also causes a second failure to occur, need to be considered as a single failure condition (i.e. a common cause or cascading failure). Combinations of independent failure modes do not need to be considered.

2.5 Identify potential ignition sources associated with the design features and potential failure modes.

The applicant should assess the fuel system design and associated failure modes to identify potential lightning-related ignition source threats. This assessment should cover all normal aircraft operating modes, stages of flight, and operating conditions.

Following is a list of common ignition source types and examples of how ignition sources might occur:

Voltage Spark

A voltage spark is defined in ED105/ARP5416 as an electrical breakdown of a gaseous dielectric between two separated conductors. Voltage sparking might occur for example between the fastener and the hole or through an insulation layer between the base of a nut and a conductive surface. Or, a voltage spark could occur between a system tube and adjacent structure if the separation is insufficient or the bonding to minimize the voltage potential has failed. If this spark is exposed to fuel vapor an ignition may result.

Note: Electrically bonded joints are prepared to provide a low resistance current path but are potentially vulnerable to incorrect preparation of the interfaces used to carry the current or use of the wrong materials or treatments. A bonding resistance check may not detect all these faults, either because of the use of multiple redundant bonding paths or because the fault is only apparent at very high current and/or voltage levels.
Thermal Spark

Thermal sparks are defined in ED105/ARP5416 as burning particles emitted by rapid melting and vaporization of conductive materials carrying current through a point contact. Thermal sparking might occur for example when there is contact between the fastener and the adjacent material, surface to surface contact, or between a collar or washer and an underlying surface. Thermal sparking could also occur if a point contact or edge contact in either a structural joint or a system installation exists and is exposed to a high enough current flow. The current density through such contacts may be sufficient to cause local heating. Beyond a critical level of current density the contact materials melt or burn, releasing gas that may be an ignition source. Surface coating, fastener fit and bonding surface roughness may influence the threshold of ignition source generation. Where sealing is used to contain potential sparking, the resulting internal pressures from the heat of thermal sparks may be sufficient to force a path past the sealing of the fastener or disrupt the material of the joint giving rise to a jet of sparks into the fuel vapor area.

Edge Glow

Edge glow may occur at the edges of carbon fiber composite material where a voltage or thermal spark can occur because of breakdown of resin between fibers or contact between fibers.

2.6 Perform safety assessment to determine fault tolerance

2.6.1 Fault tolerance assessment

A safety assessment is performed to determine if the design is capable of providing fault tolerant fuel systems lightning protection given the environment in conjunction with design sensitivities and potential failure modes identified in the previous steps. Fault tolerant means the design can withstand a lightning encounter free of ignition sources for each failure condition. For many designs, this assessment can be accomplished by a design review or analysis based on engineering knowledge or previous testing of the effects of a failure mode.

An FMEA (Failure Modes and Effects Analysis) is one means of evaluating and documenting the safety assessment. FMEAs are discussed in ARP4761. In the case of fuel systems lightning protection, the FMEA may consist of a table of the fuel systems design elements identified in Step 2.1, the lightning environment at those locations identified in Steps 2.2 and 2.3, the failure modes identified in Step 2.4 and the potential ignition sources identified in Step 2.5.

It is possible to simplify the FMEA by grouping together similar structural and systems components and/or associated potential failures that might occur into families as stated in Step 2.1. The FMEA can also be used to identify analyses and/or testing that will be necessary to verify that ignition sources will not occur.

It should be noted that designs can be fault tolerant without incorporating multiple protection features. This concept essentially can be applied to basic designs that exhibit no failure mode or combination of
failure modes that can result in an ignition source. This may be due to an inherent robustness of the design and/or due to very minimal exposure to the lightning environment.

Examples of such designs might include:

- Fuel tank structural skins whose material and thickness are sufficient to ensure ignition sources cannot be present on the tank side opposite a lightning attachment. This normally would require some built in design margin to account for failure conditions that could compromise performance, such as incorrect application of finishes or delaminations caused by damage or fatigue.

- A field fastener or joint where the current density from a likely lightning attachment location (i.e. Zone 1 or 2) is so low that an ignition source will not result even when a failure condition is present. The meaning of “field fastener” is a skin-through fastener used to fasten a part primarily attached to the skin only. Examples are a skin-stringer joint fastener and a skin-doubler joint fastener.

If the safety assessment results in demonstrating that each design is free from ignition sources after assessment of relevant single failure conditions and possible common cause effects, then that design is considered to be fault tolerant. If, however, any designs do not demonstrate fault tolerance, then design changes to provide fault tolerance must be evaluated. When a design has been modified to become fault tolerant to a particular fault, it is necessary to ensure that any failure modes associated with the modification have also been considered.

2.6.2 Determination of impracticality to provide fault tolerance

The intent is to provide fault tolerance wherever practical, where practical is defined as a balance of available means, economic viability, and proportional benefit to safety. A means to provide fault tolerance that is possible with little economic impact is practical even if the conditions would be Remote without them. However, if the means would have a significant economic impact on production, operational or maintenance costs, it is not necessary to utilize these if it can be determined that the ignition source conditions would be Remote.

Determination of impracticality for a given design should be reviewed for concurrence with the appropriate airplane certification authority.

2.7 Assess the combined risk of all non-fault tolerant conditions

2.7.1 General

The purpose of this non-fault tolerant assessment is to substantiate that fuel tank vapor ignition due to all non-fault tolerant features, when their fuel tank vapor ignition event probabilities due to lightning are combined, is shown to be Extremely Improbable.

One means to accomplish this is to first evaluate the likelihood of lightning attachment during flammable conditions. Industry data shows that the occurrence of lightning attachment to an aircraft is low (typically between 1e-3 and 1e-4 strike events per flight hour). In addition, Part 25 regulatory requirements require an applicant to demonstrate that the flammability exposure for fuel tanks is 3% or less (e.g. on the order of 1e-2). Both of these factors are independent of each other, as well as independent of the failure of lightning protection means. The combination of these two factors
(lightning attachment and flammability) occurring simultaneously is Remote. Therefore, one means of assessing the risk of a potentially catastrophic event due to failures of non-fault tolerant features is to demonstrate that lightning related ignition sources due to these failure conditions are Remote. It is accepted that two independent Remote conditions are unlikely to occur together in the life of a fleet, and therefore are Extremely Improbable.

Note: Remote failure conditions are defined in FAA Draft AC 25.1309-1X, System Design and Analysis, Arsenal draft dated June 2002 paragraph 5.B.2: “Qualitative Probability Terms are those unlikely to occur to each airplane during its total life, but which may occur several times when considering the total operational life of a number of airplanes of the type.”

The assessment of non-fault tolerant failure conditions should consider the robustness of the design to limit failures, the other conditions necessary for a failure to result in an ignition source, and any means utilized to limit the occurrence or latency of a failure. Robustness of the design includes the ability to safely conduct the lightning current or prevent the lightning current flow, as required by the particular design.

A qualitative non-fault tolerance assessment should also consider possible in service conditions (e.g. vibration, humidity, temperature change, maintenance activity, latent conditions) when determining that an ignition source resulting from lightning strikes to the aircraft is Remote.

Determining that non-fault tolerant conditions when combined are Remote can be a qualitative assessment utilizing knowledgeable engineering judgment. The qualitative assessment should consider the likelihood of the failures, the likelihood of other conditions necessary for the failure to result in an ignition source and any means utilized to ensure the combination of conditions will be unlikely. As discussed above, the basis of this approach is that flammability and lightning attachment are independently also Remote. The qualitative assessment of ignition sources therefore cannot consider the likelihood of lightning attaching to the airplane or the flammability of the fuel tanks. It can include the likelihood of lightning current threat levels that would lead to an ignition source for that particular structural or system failure. It should also be noted that quantitative data supporting the non-fault tolerant assessment can be utilized in support of qualitatively demonstrating ignition sources are Remote, where well supported data exists. Such a non-fault tolerance assessment should include the following activities listed in Figure 1 below and detailed in the following sections.
2.7.2 Consider robustness of the design to minimize faults

The first task is to evaluate the robustness of the design to failures through a detailed assessment of the lightning protection features of the design along with precautions taken during manufacturing and maintenance and as detailed in associated operator procedures. In addition, the robustness of the installation from the perspective of whether it is relatively straightforward to install and hence less
prone to installation errors, or is a more difficult installation where an error or manufacturing escape might be possible, should also be evaluated. This assessment may include:

- Lightning testing relevant to specific or similar design features
- Dielectric strength testing of insulating materials and structures such as brackets, clamp cushions, air gaps and wire harness insulation
- Field service reports or databases related to the non-fault tolerant condition being assessed
- Engineering tests to determine durability of features, such as fatigue tests, thermal cycling tests, or corrosion tests
- Engineering judgment based on experience may also be used to estimate the likelihood of failures. The determinations should be based on conservative assumptions
- Service experience records of manufacturing or maintenance escapes if available
- Manufacturing records for defects found

It may also be possible to demonstrate that a new or changed design or design feature will perform similarly to a previously certificated design or design feature under lightning threats. If applicable, provide a comparative analysis of similar design features and details on a previously certificated airplane. The comparative analysis would include a detailed assessment of the design features and details that affect susceptibility to failure, exposure time to lightning environment, service experience, and any applicable analyses and test data.

2.7.3 Consider how many locations non-fault tolerant conditions exist
Next, assess the potential for the failure condition to occur in multiple locations on an airplane. While a failure at any individual place in an airplane could be unlikely, if the potential for this failure exists in many locations and is latent for long periods of time (e.g. the life of the airplane), the potential for a failure manifesting itself in an individual airplane could be significant.

2.7.4 Consider robustness of design with faults present to tolerate lightning threat levels without creating an ignition source
Evaluate the likelihood of lightning attachment conditions causing a current or voltage threat of sufficient amplitude to cause an ignition source to be present at the failure condition location.

Appropriate factors to consider include:

- The possibilities of lightning attaching to places on the exterior surface of the airplane close to the failed non-fault tolerant features.
- The lightning-related ignition source threshold current for the failed non-fault tolerant features. This is the amount of lightning current that would have to pass through or adjacent to a failed non-fault tolerant design feature to produce a voltage spark or thermal spark.
- The amplitude of the external lightning current that would be necessary to produce an internal current that would exceed the ignition source threshold current.

Failed features within fuel systems will usually tolerate some amount of lightning current or voltage, until a threshold is reached, without producing an ignition source. This threshold can be determined by test using test specimens that incorporate the system or structural features in a defined fault condition.
2.7.5 Consider measures used to detect failures and limit latency where practical
Consideration should be given to any practical means that may already be present or could be introduced to detect potential failure conditions and therefore limit the time duration that such a fault may be present. For example, where practical a specified inspection interval that may detect the failure may be proposed. Or additional production and/or in service measures may be implemented to minimize the occurrence of defects and escapes.

2.7.6 Assess whether the combination of all non-fault-tolerant failure conditions which could result in an ignition source is Remote
The final qualitative assessment must consider all the potential non-fault tolerant features and determine if the combination of potential for ignition sources due to failures of these features is Remote. As noted previously, this qualitative standard means that an ignition source resulting from all non-fault tolerant failures will not be expected to occur on a typical airplane in its total life but could occur several times in a fleet of airplanes of that type.

This demonstration evidence shall be documented and typically would include a combination of mitigating circumstances which show that condition is unlikely. Some examples of such mitigating circumstances are as follows:

- Where a failure might result from manufacturing or maintenance errors, the design is simple and/or an incorrect installation would be detected and rejected.
- Where a failure might result from aging, wear or corrosion, the design has been shown to be resistant to such effects through service history or by representative environmental and durability testing.
- The number of potential failures which might result in ignition sources when exposed to lightning currents for a common lightning strike condition (e.g. a wingtip attachment) is limited.
- Where non-fault tolerant conditions will only become a potential ignition source for relatively high lightning current amplitude, action integral and/or charge transfer conditions such that it would require severe lightning conditions to make a failure at the non-fault tolerant location become an ignition source.
- The failure condition itself is detectable before the condition might result in an ignition source.
- The failure condition itself has a low probability of occurrence.
- Effective inspections or maintenance processes have been implemented that provide high confidence in limiting any latent exposure or preventing the failure from occurring at all.
- Effective manufacturing process and quality controls have been implemented to minimize the risk of manufacturing errors from occurring.

2.8 Develop supporting data for lightning protection performance

Demonstrating compliance requires that the applicant provide supporting analysis, testing, and/or similarity to previous testing and/or analysis to support the safety assessment prepared in Sections 2.6 (and 2.7 if required). The safety assessment usually relies upon data from lightning tests of representative structural joint or system installation specimens that contain the failure(s) of most
interest. For design groups or families where compliance data addressing similar configurations and failure conditions already exists, a similarity assessment between the proposed design and the applicability of the previous compliance data may be sufficient. Performing numerical or physical analysis to establish the sparking performance of a proposed design, however, can be very challenging due to the lack of well established fundamental understanding and characterization of factors which may contribute to sparking. Also challenging is the analytical criteria to apply for simulating failure conditions and establishing when an ignition source results. Therefore, using analysis for this purpose will most likely be limited to very simple configurations (e.g. to confirm a wing skin is thick enough to prevent a hot spot from forming due to lightning attachment) or will require very thorough validation of the predictive ability relative to the design configurations and failure modes of relevance. In addition, margins appropriate to the uncertainty of the analysis should also be substantiated and applied.

Where lightning testing is selected, the most challenging aspect is to determine the relevant configurations to test to ensure adequate substantiation data in support of the assumptions in the safety assessment. Given the large number of permutations of structural joints, system installations and potential failure modes for each, analysis or engineering judgment is typically applied to reduce the test configurations to a manageable yet sufficient set of test conditions. The following steps outline an approach for identifying appropriate test configurations.

1) All relevant areas of design were grouped into families that share similar lightning protection characteristics in Section 2.1. This step determines how to simplify the design family into a common configuration for the purpose of testing. For example, the key elements of the configuration are assessed to identify a bounding configuration for the purpose of testing using criteria like the following for the fastener:
   - Smallest diameter of fasteners
   - Lowest fastener preload
   - Thinnest materials in stack up
   - Lowest conductivity of fastener material
   - Lowest contact area under the head of fastener

   Where hypotheses such as these require justification, it can be obtained by analysis, engineering judgment or test as part of the applicant’s background data or from existing and published data bases.

2) Sort the failure modes identified in Section 2.4 into faults that affect the lightning protection effectiveness for each design group or family and select bounding faults to test. Similar to the design groups or families, the hypotheses for selecting the dominant failure conditions require justification which can be by engineering judgment, analysis, similarity or test. By selecting the most vulnerable assemblies in combination with the most hazardous failure modes a test matrix can be derived.

3) Apply the current levels and waveforms defined per Section 2.3 to the design groups or families. Test panel attachment and conducted current test levels would typically be based on these. However, there may be some additional analysis required where potential failure modes could
affect the current distribution associated with the design group or family and should be considered. Examples of currents translated into test are shown in Figures 2 and 3.

Figure 2: Test currents that need to be defined for assessments of failure conditions by test at an external fastener installation (lightning entry points and which fasteners are nominal or exhibiting failures will depend upon specific test plans)
Figure 3: Test currents that need to be defined for assessments of failure conditions by test at a rib – spar interface (lightning entry points and which fasteners are nominal or exhibiting failures will depend upon specific test plans)

4) Conduct testing for compliance using the current levels and waveforms from step 3 and/or incremental testing independent of the specific threat (while considering potential conditioning of the sample) to determine the sparking threshold of the assembly. These tests should be conducted in accordance with the test methods referenced by AC20-155A and ARP5416A/ED105A. It is strongly recommended to seek early coordination with the airplane certification authority to achieve concurrence with the proposed compliance test program.

The previous steps have established the configurations to test. The next challenge is to define the specific test configuration, in particular the method for implementing the fault condition for each test. Normally, only one fault will be included with each test, unless there is a common or cascading failure that requires more than one fault to represent a single failure condition. It is also necessary to consider the effects of in-tolerance manufacturing variability and expected environmental and operating conditions, but it is not necessary to stack worst case tolerances in conjunction with a defined fault condition.

The following gives examples for how faults could be represented in a test article:

**Structural joints**

- Where the design incorporates fastener interference fit in a hole, test the sample with equivalent clearance fit fasteners.
• Where the design incorporates a nut/collar seal against structure, the seal can be compromised by relaxing torque, introducing an angled shim in the joint, or creating a slot in the structure or nut/collar.

• Where the design incorporates sealant or other capping device over a fastener, test the sample with no sealant / capping device applied.

• Where the design incorporates a layer of insulation between a nut and structure, test the sample with that layer of insulation missing. Care should be taken to ensure that the resulting test configuration is representative of the worst anticipated case of a defective assembly such that the testing is representative of the potential fault.

• Where the design incorporates electrical bonding to metallic structure, test the sample without surface preparation or with an insulating coating or material in the bonding interface. Care should be taken to ensure that the insulating coating/material does not provide unrealistic and reliable insulation that may inadvertently act as an unintended protective feature.

**Systems installations**

• Where the design incorporates electrical bonding to structure, perform analysis or testing with the bonding missing or degraded to the worst case anticipated in-service.

• Where the design incorporates wire bundle shielding, perform analysis or testing with the shield missing or the ground degraded to the worst case anticipated in-service.

• Where the design incorporates dielectric protection of a component or wire installation, perform analysis or testing with the worst case voltage threats that exist when other protection means have failed.

The following is a list of examples for implementing design/manufacturing in-tolerance variability in test:

**Structural joints**

• Where the design incorporates use of interference / close tolerance fastener fit in hole, test with minimum level interference permitted by manufacturing standards.

• Where the design allows in-tolerance variability in the nut/collar seal against structure, test each one or any likely combination of the following:
  o Lowest fastener preload which will occur over the airplane life
  o Representative surface finish properties and thicknesses
  o Representative acceptable manufacturing damage (drill breakout, tool marks)
  o Maximum permissible fastener angle
  o Representative fastener orientation (head or nut), when not specified by drawing
  o Representative fastening hardware (e.g. nuts, collar, washers, self-aligning nuts)

• Where the design incorporates sealant or other capping device over fastener, test with minimum permissible amount of sealant applied.

• Where the design incorporates a layer of insulation between nut & structure, test with:
  o Minimum permissible thickness of insulation and/or
• Representative allowable or likely (for anticipated conditions that processes do not control) installation damage (scuffing, etc.)

• Where the design incorporates bonding nut to metallic structure, test the sample with only part of surface prepared (representative case that would be expected given quality standards and pass post assembly production checks).

System installations

• Where the design incorporates sealant or other capping device, test the sample with no sealant / capping device applied.

• Where the design incorporates a layer of insulation between the system and structure, test with:
  o Minimum permissible thickness of insulation and/or
  o Worst-case allowable or likely (for anticipated conditions that processes do not control) installation damage (scuffing, etc.)

• Where the design incorporates electrical bonding the system to metallic structure, test the sample with only part of surface prepared (worst case that would be expected given quality standards and pass post assembly production checks).

It may also be possible to show a design is fault tolerant without incorporating additional protection. For fuel system lightning protection, this concept essentially can be applied to designs that exhibit no failure mode or combination of failure modes that can result in an ignition source.

Examples of such designs might include:

• Fuel tank structural skins whose material and thickness are sufficient to ensure that unacceptable hot spots or other ignition sources cannot be present on the tank side opposite a lightning attachment. This normally would require some built in design margin to account for failure conditions that could compromise performance, such as incorrect application of finishes or delaminations caused by damage or fatigue.

• Structural cracks exposed to conducted currents where the current density from a likely lightning attachment location (i.e. Zone 1 or 2) is so low that the single fault condition will not result in an ignition source. The probability of direct or local attachment to a crack is itself Remote, and it is likely that the capability of aluminum structure with a crack will safely conduct lower currents without sparking.

• A field fastener in a Zone 3 surface area where the current density from a likely lightning attachment location (i.e. Zone 1 or 2) is so low that any combination of failure conditions will not result in an ignition source.

For cases where a design cannot be shown to be fault tolerant, testing will also typically be required to establish that the design, without a failure, still provides effective lightning protection to support the safety assessment required in Section 2.7. While these cases do not require a fault to be implemented in the test, the design should consider the effects of in-tolerance manufacturing variability and environmental and operating conditions.
At the time of writing this guidance, no examples were identified where systems fault tolerance was not practical, though perhaps a unique situation could exist (e.g. a unique repair).

2.9 Develop Instructions for Continued Airworthiness, Maintenance and Surveillance Programs

Inspections or other procedures must be established to prevent development of lightning-related ignition sources within the fuel systems. These inspections or procedures must include any airworthiness limitations for non-fault-tolerant features, and caution information for lightning protection features that may be altered by maintenance and repairs. Addressing the effects of aging, wear, and corrosion as both a design and continuing airworthiness consideration is necessary to ensure reliable protection over the life of the aircraft.

Maintenance and surveillance for non-fault tolerant and fault tolerant protection features that need consideration include the following:

- Caution information, which identifies the lightning protection features of the fuel system, must be defined in order to minimize the potential for inadvertent damage or disruption to the features. This information must be included in the applicable airplane maintenance documents and be acceptable to the Administrator. These cautions, if required by Special Conditions or Exemptions, must be included as CDCCL, and must be included in the Airworthiness Limitations section of the Instructions for Continued Airworthiness and in the maintenance documentation and approved by the Administrator.

- For non-fault tolerant lightning protection features which are identified in support of certification, scheduled maintenance or inspections to preclude the development of unsafe conditions must be developed and identified as Airworthiness Limitations in the Instructions for Continued Airworthiness (ICA) and approved by the Administrator.

- Maintenance and/or inspections to validate the in-service integrity of fault tolerant lightning protection features that are likely to degrade must be included in the Instructions for Continued Airworthiness, and be acceptable to the Administrator. The likelihood of degradation and the reliability of protection features must be established in support of certification and approved by the Administrator. Dedicated maintenance and/or inspections are not required for those lightning protection features that are considered inherently reliable.

- In order to verify the in-service integrity of lightning protection features that are not expected to degrade, maintenance and/or inspections may be utilized and be accepted by the Administrator, or sampling and surveillance programs may be utilized and approved by the Administrator.
2.10 Incorporate practical measures to prevent, detect and correct failures

An analysis must be performed to show that all practical measures to prevent, detect, and correct failures of lightning protection designs have been incorporated. This includes consideration of failures due to manufacturing variability, aging, wear, corrosion, and likely damage. As noted elsewhere, “practicality” is defined as “a balance of available means, economic viability, and proportional benefit to safety.”

2.10.1 Practical Design Measures
Practical measures to prevent failures that compromise the lightning protection features begin with the design itself, and a structured engineering design review should be incorporated to ensure fault tolerance wherever practical and to provide early identification of critical areas and processes. The intent of this review is to minimize failure modes and identify design elements which can be verified within a process control framework. In order to facilitate identification of failure modes, a review of service history records is advisable. Once critical areas and processes are identified, this review should include establishing engineering drawing signoff requirements to ensure that designs critical to structural lightning protection cannot be modified without the authorization of the appropriate individuals cognizant of the requirements of this policy. As an example, it is critical that during the design phase, aging and wear of the sealant is accounted for and the proper sealant selected that will withstand the anticipated environmental conditions during aircraft operation. Furthermore, signoff authority for the drawing that specifies the sealant must include individuals who are cognizant of the critical nature of its structural lightning protection features.

2.10.2 Practical Manufacturing Measures
An engineering review of manufacturing processes should also be performed, including consideration of failure modes that may occur due to manufacturing variability, including errors or escapes. Practical quality control and manufacturing processes should be established, such as those already employed on other critical areas of the aircraft. One quality control example would include requiring inspection of critical features by a person other than the person that performed the manufacturing work. Manufacturing examples to ensure fastener interference fit would include automatic hole drilling and fastener insertion, manual fastener insertion with tooling to confirm interference fit, or fastener specific certification for installation personnel. Examples to ensure sealant integrity during initial application would include specific Zone 1 and 2 sealant application certification for shop personnel, and direct application of sealant followed by a “sealant cap” to provide a visual means to verify the continued integrity of the sealant.

Defining processes that are simple and minimize reliance on mechanic unique skill can also improve manufacturing consistency. Examples are use of a sealant application tool or parts for ensuring a consistent sealant amount and void free installation, or use of plastic parts like a sealant cap or insulation layer parts whose shapes are pre-molded before installation to ensure better consistency and minimize defects. Other methods of improving consistency are use of visible-indicating parts such as
self-locking type nuts, providing visible means for easy inspections (such as putting a carved seal of part type, size and/or part number), or designing the shape of parts to prevent incorrect installation.

It is also recommended that special manufacturing inspection techniques such as NDI or eddy current measurements be employed to ensure that all fasteners in areas of concern are carefully inspected by trained and certified inspectors to preclude quality escapes.

2.10.3 Practical Maintenance Measures
A thorough review of maintenance practices is also required to ensure that proper repair techniques are used. When evaluating repair techniques, the repair must restore the type design to a functional equivalent of the original design. This means that any approved repair methods must restore a fault tolerant design to an equivalent fault tolerant design. Any cases where this is not possible in service must be handled through appropriate FAA processes and are not addressed by the Policy Statement.

When developing field maintenance and service inspection techniques, a review of similar aircraft designs and their service history should be conducted to focus on areas where past experience has shown there is a potential for failures of concern. If established field repair techniques result in failures of concern, these must be considered in the failure mode cases to be tested or analyzed, or the field repair technique must be modified to ensure continued structural lightning protection adequacy. In this case, practical measures should be taken to designate the new procedure as a critical controlled process, much like the drawing signoff process controls previously discussed.

2.10.4 Practical Airworthiness Limitations Measures
Any identified CDCCL must be documented in the airworthiness limitations section of the instructions for continued airworthiness, as well as any life limitations or repetitive inspections determined to be necessary to establish either fault tolerance or compliance with the quantitative analysis. An example might include an inspection interval to visually inspect sealant integrity on fasteners within a lightning Zone 2 region of the aircraft.

The analysis discussed above should be documented and provided within the compliance report and reviewed and approved by the airplane certification authority.

2.11 Verify compliance to the requirements
Data must be provided to substantiate compliance with the requirements for Exemptions or Special Conditions. Typical compliance data would include the following:

- Definition of the design areas or joints where the alternate requirements defined by the policy are being applied
- Definition of failure modes for the lightning protection features and associated assessment of effects
- Lightning test data to substantiate effective lightning protection with and without failure conditions introduced
• Description of the processes and measures taken in design, manufacturing and maintenance to prevent, detect and correct failures of the lightning protection features

• For any design areas that cannot be shown to be fault tolerant:
  - Substantiation for why it is impractical to achieve fault tolerance
  - Substantiation for the data and/or assumptions used in the qualitative assessment
  - Lightning ignition source threshold test data where credit is taken for actual lightning current threat levels

• If the Special Condition criteria is applied, substantiation that the flammability exposure meets or exceeds the requirements of Part 25 Appendix M for all fuel tanks

During the “Perform safety assessment to determine fault tolerance” (Section 2.6), a design should have been identified through engineering testing and/or analysis that showed:

1) Basic design is sufficient to meet the requirement as defined within § 25.954.
2) Design is shown to be fault tolerant and/or shown through testing/analysis to be non-fault tolerant and impractical to make fault tolerant.

Designs must be tested and shown to be compliant to the requirements of § 25.954 as designed, without the requirement to assess fault tolerance. This must be accomplished by means of testing or similarity analysis. It is critical that this is clearly stated within the applicant’s position within the issue paper and agreed upon by the certification authorities.

In regard to the application of the design to the PS-ANM-25.981-02 Policy, both for Exemptions and Special Conditions, the design must be shown by means of testing to be fault tolerant or through qualitative assessment that fuel tank vapor ignition is Extremely Improbable.

The first phase of this is accomplished by taking the finalized designs of representative joint specimens that contain the fault tolerant failure(s) developed during the assessment phase and conducting compliance testing. To ensure that all data that is gathered during this testing may be used to support compliance, it is critical that procedures defined in FAA order 8110.4C are adhered to, in regard to certification plans, test plans, conformities, test reports, etc. Testing should be conducted in accordance with ED105/ARP5416 test methods.

The second phase of this is accomplished by performing the analysis using the guidance provided in Section 2.7, “Assess the combined risk of all non-fault tolerant conditions,” for joints determined to be non-fault tolerant. This analysis should be supported by testing or analysis of joint sparking thresholds using methods similar to those used for the joints that are shown to be fault tolerant. The usage of this type of analysis must be contained as part of the applicant’s position within the issue paper and agreed upon by the certification authorities.

Failure modes of structural components for which fault tolerance has been shown to be impractical must also be addressed in the compliance report, and the overall likelihood of fuel tank vapor ignition due to these failure modes must be shown to be Extremely Improbable. In order to accomplish this, the
qualitative assessment of the overall risk of fuel tank vapor ignition must be included, along with all relevant supporting information.

In addition, for those joints that cannot be made fault tolerant, supporting data must be provided to show why it is impractical to achieve fault tolerance. This may include a list of design options available or considered along with the rationale or justification for why it is impractical to apply them or why these options will not result in fault tolerance.

Once the testing and/or analysis is completed, verification of the adequacy of design features to provide their intended lightning protection function should be documented in a compliance report format. This report should address each identified failure condition, providing the substantiation and/or test data for each test or analytical case determined in Section 2.8 of this document, and establishing the robustness and independence of each feature of protection.

The data required to substantiate that all practical measures have been taken to prevent, detect and correct failures of lightning protection features as discussed in Section 2.10 of this document would typically include description of and/or reference to:

- design process controls, such as drawing signoff by a lightning protection engineer or any other design assurance or change controls implemented
- manufacturing process controls, such as utilization of automated drilling and fastener installation or independent QA checks to confirm lightning protection features are properly installed
- maintenance process controls, such as special instructions for restoring lightning protection features during maintenance activities
Appendix 1 Related Documents


   a. Part 25, Airworthiness Standards: Transport Category Airplanes:

      § 25.581 Lightning protection

      § 25.954 Fuel system lightning protection

      § 25.981 Fuel system explosion prevention

      § 25.1316 Electrical and electronic system lightning protection

      § 25.1529 Instructions for continued airworthiness

      § 25.1729 Instructions for continued airworthiness, EWIS

      Appendix H, Instructions for continued airworthiness

2. Federal Aviation Administration (FAA) Advisory Circulars (AC), Users manuals, reports and policies. You can access copies of the following ACs at www.faa.gov/regulations_policies/advisory_circulars/.

   Note: The ACs referenced in this document refer to the current revisions.

      a. AC 20-155A, Industry Documents to Support Aircraft Lightning Protection Certification, July 16 2013

      b. AC 1309-1X, System Design and Analysis, Arsenal draft dated June 2002


3. Industry Documents.

   a. ARP4761, Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment

   b. ARP5412, Aircraft Lightning Environment and Related Test Waveforms

   c. ARP5414, Aircraft Lightning Zone

   d. ARP5416, Aircraft Lightning Test Methods

   e. ED-84, Aircraft Lightning Environment and Related Test Waveforms

   f. ED-91, Aircraft Lightning Zoning

   g. ED-105A, Aircraft Lightning Test Methods

   Note: The industry documents referenced in this document refer to the current revisions. Refer to AC 20-155A for information regarding additional accepted industry documents.
## Appendix 2 Definitions

The following definitions apply in this guidance document:

<table>
<thead>
<tr>
<th>TERM</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attachment Point</td>
<td>A point where the lightning flash contacts the aircraft.</td>
</tr>
<tr>
<td>Extremely Improbable</td>
<td>As defined in AC 25.1309 Arsenal version paragraph 5.B.2, Qualitative Probability Terms, “extremely improbable failure conditions are those so unlikely to occur that they are not anticipated to occur during the entire operational life of all airplanes of one type.”</td>
</tr>
<tr>
<td>Fault tolerant design</td>
<td>Fault tolerant means the design can preclude fuel systems ignition sources even when a fault is present.</td>
</tr>
<tr>
<td>Fuel Systems</td>
<td>The term fuel systems in this rule and AC refers to all positions of the fuel system including the fuel tank structure (defined below) and all systems (defined below) associated with the fuel tank installation.</td>
</tr>
<tr>
<td>Lightning Strike</td>
<td>Attachment of the lightning flash to the aircraft.</td>
</tr>
<tr>
<td>Lightning Strike Zones</td>
<td>Aircraft surface areas and structures that are susceptible to lightning attachment, dwell time, and current conduction. See AC 20-155A, which references documents that provide additional guidance on aircraft lightning zoning.</td>
</tr>
<tr>
<td>Lightning Stroke (Return Stroke)</td>
<td>A lightning current surge that occurs when the lightning leader (the initial current charge) makes contact with the ground or another charge center. A charge center is an area of high potential of opposite charge.</td>
</tr>
<tr>
<td>Practicality</td>
<td>Practicality is defined as a balance of available means, economic viability, and proportional benefit to safety.</td>
</tr>
<tr>
<td>Remote</td>
<td>As defined in AC 25.1309 Arsenal version paragraph 5.B.2, Qualitative Probability Terms, “remote failure conditions are those unlikely to occur to each airplane during its total life, but which may occur several times when considering the total operational life of a number of airplanes of the type.”</td>
</tr>
<tr>
<td>Structure</td>
<td>Structure includes fuel tank structural members such as airplane skins, joints, ribs, spars, stringers, and associated fasteners, brackets, coatings and sealant.</td>
</tr>
<tr>
<td>Systems</td>
<td>Systems include tubing, components, and wiring that are penetrating, located within, or connected to the fuel tanks.</td>
</tr>
</tbody>
</table>