

Policy Guidance for Fuel Tank Structural Lightning Protection

**Prepared by the
SAE AE-2 Lightning Committee**

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1 Overview

1.1 Background

The Federal Aviation Administration (FAA) recently released policy memo ANM-112-08-002 on the fuel tank safety provisions of Title 14, Code of Federal Regulations (14 CFR) 25.981(a)(3), as amended by Amendment 25-102, for 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 for some areas of structural design.

This document is intended to provide guidance to manufacturers who may apply this policy 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. Manufacturers should coordinate directly with their certifying 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 Process Overview

Application of the policy has been broken down into a number of process steps in this document. Figure 1.2-1 provides a general overview of the high level process to apply the policy. This figure is not intended to identify every significant step but only provide a general roadmap to the document – details are provided in each of the referenced sections. This process consists of the following major steps:

- a) Section 1.3 describes the initial assessment required to determine eligibility to apply the policy.
- b) Figure 2.0-1 provides a process flowchart for determining the regulatory path based on the options described in the policy. The three main options are direct compliance with § 25.981(a)(3), special conditions as defined in the policy or petitioning for an exemption using the criteria defined in the policy. The latter two options are dependent upon the level of flammability exposure in the design. Detailed process steps are provided in Section 2.
- c) Figure 3.0-1 provides a process flowchart for how to assess the design for fault tolerance. This flowchart includes the practicality assessment required if an element of the design cannot be made fault tolerant. Detailed process steps are provided in Section 3.
- d) For areas of the design where it is found to be impractical to provide fault tolerance, Figure 4.0-1 provides a process flowchart for how to conduct the required numerical probability assessment to ensure a fuel vapor ignition is extremely improbable. The detailed process steps associated with this are described in Section 4.
- e) Section 5 describes a step that addresses the analysis required to demonstrate that all practical measures have been incorporated into the design, manufacturing processes and instructions for continued airworthiness to prevent, detect and correct failures of structural lightning protection features.

- f) Section 6 describes typical data required for compliance to the exemptions and special conditions.

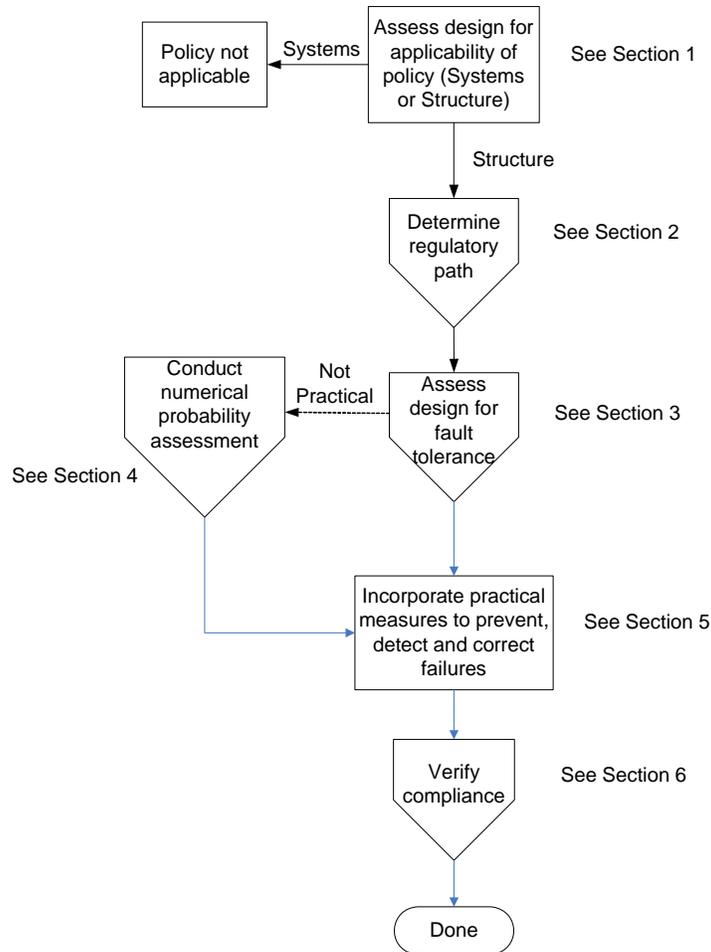


Figure 1.2-1: Overview of Policy Compliance Process

1.3 Assess Design for Applicability of Policy

The initial assessment for determining if the policy applies is to determine if the area of lightning protection design in question fits the criteria for fuel tank structure. The policy only applies to areas of fuel tank structure, and does not apply to lightning protection of systems components. From a lightning specialist’s perspective, an assessment of the overall fuel tank design should be accomplished against the requirements of § 25.954 and § 25.981(a)(3) which include both structure and systems installation designs. The first step relative to determining applicability of the policy is to identify if a design area under question is structure, systems or an element of systems installations that can be treated like structure. Per the policy, “fuel tank structure” includes structural members, such as airplane skins, joints, ribs, spars, stringers, and associated fasteners, brackets, coatings

and sealant. In addition, system supporting structure that is intended and expected to remain undisturbed for the life of the airplane uses many of the same construction techniques and presents some of the same impracticality issues, and is therefore eligible for consideration as an “area of fuel tank structure.” System components and system supporting structure that are likely to be disturbed if maintenance is required on a system (even if that system would not normally require maintenance) is not eligible under this policy and should be required to comply with § 25.981(a)(3). For these design areas, disassembly and reassembly of electrical bonding elements is considered to present a significant additional risk that a bond will be compromised during the life of an airplane, which generally does not exist for structure that is intended to be permanent.

Some examples of designs that may be considered fuel tank structure for purpose of this policy in addition to those listed above are:

- External or internal access doors – these are structural in nature despite not being “permanent” installations. Because of the likelihood of removal for inspections, they may require unique controls to ensure that any electrical bonding or other protection features are installed correctly after removal.
- Fuel pump housings where the housing itself is considered to be a permanent installation and where the fuel pump can be removed for maintenance without disturbing the housing installation.
- Fuel drain or vent installations where the installation is permanent and any maintenance can be accomplished without disturbing their installation.
- Brackets that mount system installations, such as transport elements, to structure. Typically these brackets are permanent installations whereas clamps attached to these brackets would potentially be removed for maintenance and therefore would not fall within the scope of this policy.

Some examples of designs that would not likely be considered fuel tank structure for purpose of this policy are:

- Fuel system components that may need to be removed or replaced.
- Transport elements such as tubing or wiring that may need to be disturbed in order to perform maintenance.
- Clamps holding transport elements to brackets or structure as noted above.

1.4 References

- ANM-112-08-002, “Policy on Issuance of Special Conditions and Exemptions Related to Lightning Protection of Fuel Tank Structure”, 26 May 2009
- § 25.981, “Fuel Tank Ignition Prevention”
- § 25.954, “Fuel System Lightning Protection”
- AC 20-53B, “Protection Of Aircraft Fuel Systems Against Fuel Vapor Ignition Caused By Lightning”, 5 June 2006
- AC 20-155, “SAE Documents To Support Aircraft Lightning Protection Certification”, 28 April 2006

- AC 25.981-1C, “Fuel Tank Ignition Source Prevention Guidelines”, 19 September 2008
- AC 25.1309-1A, “System Design and Analysis”, 21 June 1988
- ARP5412A, “Aircraft Lightning Environment and Related Test Waveforms”, February 2005
- ARP5414A, “Aircraft Lightning Zoning”, February 2005
- ARP5416, “Aircraft Lightning Test Methods”, March 2005
- ARP4761, “Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment”, December 1996
- ARP5150, “Safety Assessment of Transport Airplanes in Commercial Service”, November 2003
- DOT/FAA/AR-05/8, “Fuel Tank Flammability Assessment Method User’s Manual”, May 2008

2 Determine Regulatory Path

Figure 2.0-1 defines a process for determining the regulatory path based on the options described in the policy. The main steps in this process are defined in this section.

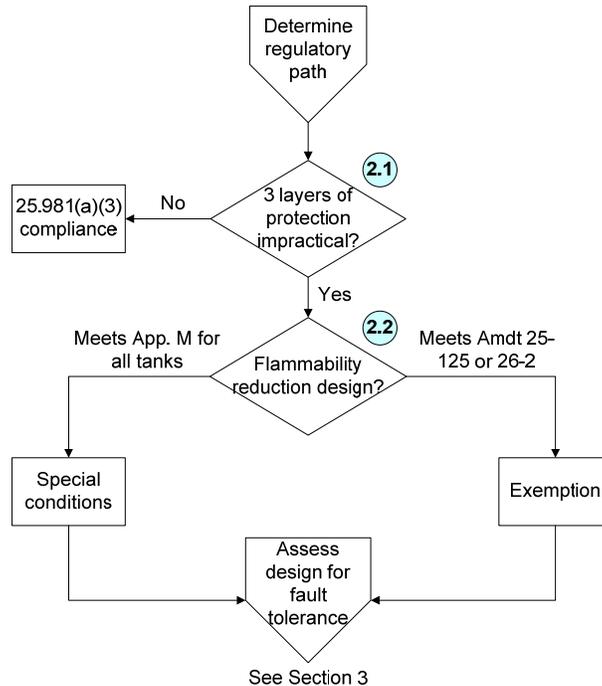


Figure 2.0-1: Determine Regulatory Path

2.1 Determine Practicality of Direct Compliance

Direct compliance with § 25.981(a)(3) typically implies that three independent, effective, and reliable protection features (or sets of features) be provided to prevent ignition sources for design areas that are addressed by this subparagraph. General guidance for compliance with § 25.981 is provided in AC 25.981-1C. The ANM-112-08-002 policy requires that direct compliance be demonstrated where it is practical. If direct compliance cannot be demonstrated, then either the Special Condition or Exemption routes to compliance may be considered in all or parts of the fuel tank structure.

The following are guidelines for establishing independent, reliable and effective protection features, or design features. For lightning, the threat conditions to assess for this include lightning direct attachment in Zones 1 and 2 and the associated conducted currents in the traditional Zone 3 definition that flow between attachment points. Lightning zones are defined in AC 20-155 via reference to ARP5414A. The fuel tank areas of concern with regards to potential lightning related ignition sources are joints that include fasteners penetrating to the exterior of the tank to lightning strike Zone 1 and 2

surfaces, and other mechanical joints in tank structures in Zone 3 which must conduct lightning currents between potential attachment points.

Note that external fasteners and skin in surface Zone 3 need not show direct compliance or apply the policy regarding multiple features of lightning protection for direct lightning attachment since the likelihood of lightning attachment to these surfaces has already been determined to be very low. In Zone 3, only one protection feature is required for direct lightning attachment.

Independent Features are those that are not subject to common cause failures that could also compromise the other protection feature (or features) relied upon to provide the fault tolerance.

Examples are:

- Sealant or other barrier covering a potential ignition source such as an external fastener, with sufficient robustness that failure of an underlying protection feature, such as an isolating washer does not allow voltage or thermal spark products to reach the flammable vapor space.
- An exterior fastener coating intended to prohibit direct lightning channel contact with the fastener, which, remains effective at preventing lightning channel contact with the fastener regardless of failure modes introduced by other aspects of the joint design
- A fastener sleeve intended to provide good electrical bonding to the surrounding hole, which if omitted or damaged, does not impair the protection effectiveness of other protection features such as sealants, or exterior fastener coatings.
- When one feature is misinstalled or not installed by mistake, the other feature(s) remain effective in preventing ignition sources.

An example of a protection feature that is not independent is a layer of sealant that if the fastener fails, will through that failure, remove or damage the sealant in a manner which eliminates it's ability to prevent arc products resulting from failure of the fastener.

Another example of a non-independent protection feature is an external protection feature, such as a fastener coating, which if failed or missing, allows a lightning strike to that fastener to overcome the effectiveness of internal protection features that are intended to contain arc products and prevent them from reaching the fuel vapor space.

Effective Features are those that are shown to adequately prevent ignition sources when exposed to the expected lightning current threat at that location. Effectiveness is typically determined as the result of testing. In some cases, single features alone can be demonstrated to be effective. In other cases, multiple features may be required to be combined to be effective so would be considered effective as a set. In the latter case,

failures that affect any features in the set may be sufficient to compromise the overall effectiveness of that set.

An example of a protection feature that is not effective is a layer of sealant that is insufficiently robust to contain the arc products resulting from failure of a second protection feature such as an interference fastener.

Reliable Features are those features whose failure modes and failure rates are such that they are not normally expected to fail during the life of an airplane or the life limit of the feature, when installed correctly per design. Some failures may be expected over a fleet life of airplanes but are not expected on the typical airplane.

Most structural features can be found to be reliable as long as they are designed with adequate margin, to ensure durability and robustness, and are installed with sufficient controls.

To determine practicality of direct compliance requires an assessment of each area of design along with an initial review of fault tolerant capability of the design. In general, where the design shows dual fault tolerance [i.e. two of three (or more) features have failed but the design remains effective against ignition sources,] direct compliance may be achieved. Where the design can only tolerate a single failure (or no failure) before there is an ignition source risk, additional design options should be considered to determine if dual fault tolerance can be achieved. If so, then this design feature (or features) should be added as long as it is practical to do so. If not, then the design cannot achieve direct compliance and the policy may be applied as long as the design area in question is within the policy definition of fuel tank structure. Examples of what may be considered practical or impractical along with some general criteria for how practicality is determined are provided in the policy. Determination of impracticality for a given design should be reviewed for concurrence with the appropriate regulatory authority.

2.2 Determine Special Conditions or Exemption Path

If the applicant demonstrates that direct compliance is impractical, an alternative approach for lightning protection of fuel tank structure may be used in accordance with the policy. Special Conditions or a partial exemption are options that are described per the policy.

In order to select the most appropriate compliance path amongst the alternate approaches, it is necessary to consider the structural and fuel system configurations, as well as coordinate closely with regulators.

Per the policy, the following factors would be considered by the FAA in the determination of the appropriate compliance path:

1. Fuel system architecture
 - a. If the fuel system employs a Flammability Reduction Means (FRM) for all tanks, Special Conditions could be pursued
 - b. If the fuel system relies upon conventional unheated aluminum wing or equivalent design, an Exemption could be pursued
2. Impact of compliance path selection
 - a. Selection of an Exemption for a new type design applicant presupposes that compliance with § 25.981(b) will be established
 - i. $\leq 3\%$ fleet average flammability exposure, or that of a fuel tank within the wing of the airplane model being evaluated, whichever is greater
 - b. Selection of a Special Condition for a new type design applicant requires additional demonstration of compliance with 14 CFR Part 25 Appendix M for all tanks
 - i. $\leq 3\%$ fleet average flammability exposure
 1. $\leq 1.8\%$ of this total may be when FRM is operational but tanks are still flammable
 2. $\leq 1.8\%$ of this total may be when FRM is not operational and tanks are flammable
 - ii. $\leq 3\%$ fleet average flammability exposure during ground and takeoff/climb flight phases on warm days ($\geq 80^\circ\text{F}$)

It should be noted that an exemption may be requested in lieu of applying the special conditions, even if the flammability exposure meets the special conditions requirements. However, only an exemption path is possible if flammability cannot be shown to meet the enhanced criteria required by the special conditions.

3 Assess Design for Fault Tolerance

Figure 3.0-1 defines a process for assessing the design for fault tolerance. The main steps in the process are described in this section.

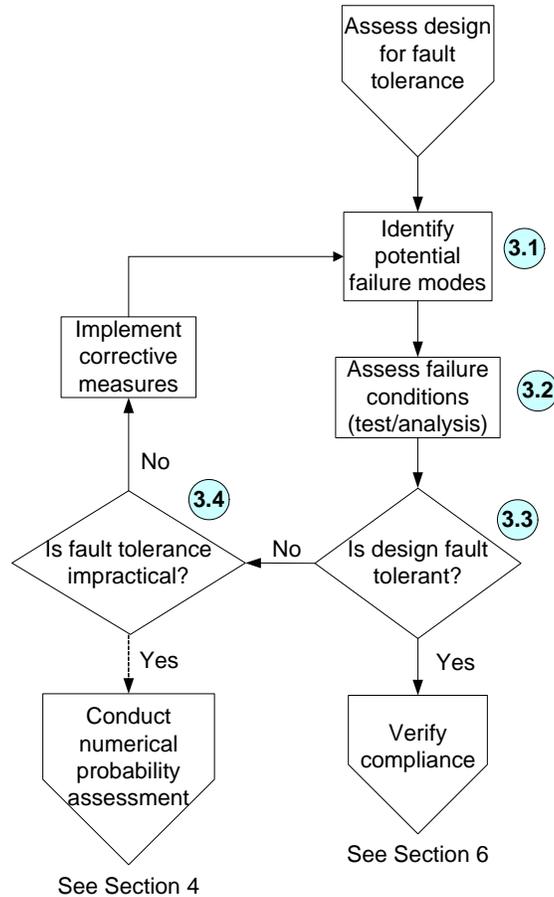


Figure 3.0-1: Assess Design for Fault Tolerance

3.1 Identify Potential Failure Modes

The applicant needs to consider the failure modes which may lead to the loss of one of the protection features or sets of features. Failure modes for structure and structural joints may be determined based upon a structured design review process which typically would include experts in lightning protection, materials and processes, structural 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. The use of “service history” to obtain a credit for the elimination of a specific failure mode must be based on a reliable system of data collection of the fleet and correlation to its possible occurrence during the life of the aircraft. 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. As part of the process of identifying potential failure modes, the following assumptions are made:

- 1) Basic design is sufficient to meet the requirements as defined within § 25.954 as designed. Guidance for compliance with § 25.954 is provided in AC 20-53B. Intolerance manufacturing variability and expected environmental operating conditions should be considered as part of the basic design compliance.
- 2) The policy is applicable to basic airframe structure and structural joint configurations (including systems installations not expected to be disturbed during aircraft life). These joints may be achieved via fasteners, chemical or metal/composite bonding, or a combination of both.

Typical failure Modes: The applicant needs to consider the failure modes which may lead to the loss of one of the protection features during the life of the aircraft so that these failures can be included in tests and/or analyses to establish whether the failures may cause ignition sources in the event of an aircraft encounter with lightning. Failure conditions to be considered may include:

- **Manufacturing quality escape conditions.** Typically these consist of the following types:
 - Misaligned fasteners,
 - Incorrect fastener size
 - Missing washers
 - Incomplete sealant or sealant that has not adhered properly to the surface
 - Missing cap seals
 - Incorrect fastener type or coating
 - Incorrect torque
 - Drilling issues (hole quality, failure to remove burrs, etc.)
 - Incorrectly installed electrical bonds
 - Missing or incorrect finishes
- **Other failures** that may reasonably be expected to occur as a result of intended operational and environmental conditions. Typically these consist of the following types:
 - Broken or cracked fasteners or rivets
 - Broken or cracked washer
 - Cracking or other degradation of insulating materials, sealants, caps
 - Disbonded stringer
 - Loss of fastener head coating
 - Loss of edge glow protection at holes or edges in composite laminates
 - Loose fasteners
 - Fatigue cracks in structure
 - Corrosion
 - Likely damage that could result from maintenance or inspections

Severity or types of failures 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 analysis or other certification analyses.

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 causes a second failure to occur, need to be considered as a single failure condition (i.e. a common cause failure). Failure rates for the failure conditions or combinations listed above are not required for fault tolerant features as long as the protection features can otherwise be shown to be reliable. Failure rates are required to conduct the numerical probability assessment for any non-fault tolerant feature failures (see 4.1).

Once the potential failure modes have been identified it is next necessary to determine if the design is fault-tolerant when a lightning strike occurs. In other words, the design must be free of ignition sources due to lightning even when one of the failure modes is present.

The following lists ignition source types and examples of how ignition sources might occur:

At Fastened Joints:

Voltage spark is defined in ARP5416 as an electrical breakdown of a gaseous dielectric between two separated conductors.

Thermal Sparks are defined in ARP5416 as burning particles emitted by rapid melting and vaporization of conductive materials carrying current through a point contact.

Voltage sparking might occur between the fastener and the hole or through an insulation layer between the base of a nut and a conductive surface. If this spark is exposed to fuel vapor an ignition may result.

Thermal sparking might occur when there is contact between the fastener and the adjacent hole material or between a collar or washer and an underlying surface. 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.

The resulting pressures from the 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.

At Electrically Bonded Joints:

Joints prepared so as to provide a low resistance current path are potentially vulnerable to incorrect preparation of the interfaces used to carry the current or use of the wrong materials or treatments. A build line bonding 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.

- Failure to prepare the surface correctly may result in an inadequate bond or even no electrical contact, which in turn may cause a voltage sparking hazard.
- Inadequate surface preparation or use of the wrong finishes may result in a thermal sparking hazard.

3.2 Assess Failure Conditions

This step is necessary to determine if the design is fault tolerant, meaning the design can withstand a lightning encounter free of ignition sources for each failure condition.

This assessment is usually done by lightning tests of representative joint specimens that contain the failure(s). The test object is exposed to arc entry (Zone 1 or 2) or conducted lightning current (Zone 3) conditions. Instructions for conducting the arc entry tests are found in Section 7.4.2 of ARP5416 and for the conducted current tests in Section 7.3.2 of the same standard. Methods for detection of potential ignition sources are found in Sections 7.7.1 and 7.7.2 of ARP5416. Where the possible ignition source is clearly visible the photography method of Section 7.7.1 is often used. When the source location is not visible to cameras or where the test result is not clear from photography the flammable gas method of Section 7.7.2 is used.

The lightning test currents applicable in each zone are defined in AC 20-155 via reference to ARP5412A.

Often the potential failure mode is at a fastened joint or other interface within a tank where only a portion of the total lightning current is to be expected. Thus test objects representing these internal joints should be tested with the appropriate scaling of the total lightning current. A fastener in the fuel tank skin may be exposed to the full currents, but the current flowing through the fastener to internal structural elements is usually not the full current. It is therefore important to establish the magnitudes of these internal currents since they must be represented in the tests.

Analyses (such as finite difference time domain) or tests of representative tank sections may be used to determine current magnitudes throughout a fuel tank due to lightning currents. This is especially important in composite tanks, where fasteners may transfer significant amounts of lightning current to interior structural elements. Internal structure currents are usually lower in tanks made completely of aluminum, and worst case

assumptions might be made of these currents in place of more sophisticated analysis methods. In either type of tank, the currents that are expected to be conducted through each part of the design need to be defined so that they can be conducted through test objects representing the design in a realistic manner. Care should be taken to consider effects of waveshapes on ignition sources, follow on current components and so forth in addition to just peak current scaling. Failure to do this may result in nonrepresentative currents/waveforms through the structural element of interest.

Where used, analyses should be validated by comparisons of analysis results with test results on structural elements that are similar to the tank structure to be certified. Key parameters include representative materials and thicknesses, joint connections, and significant bonding paths. Appropriate margins should be applied based upon the validation results.

Examples of currents that may be defined are shown in Figures 3.2-1 and 3.2-2.

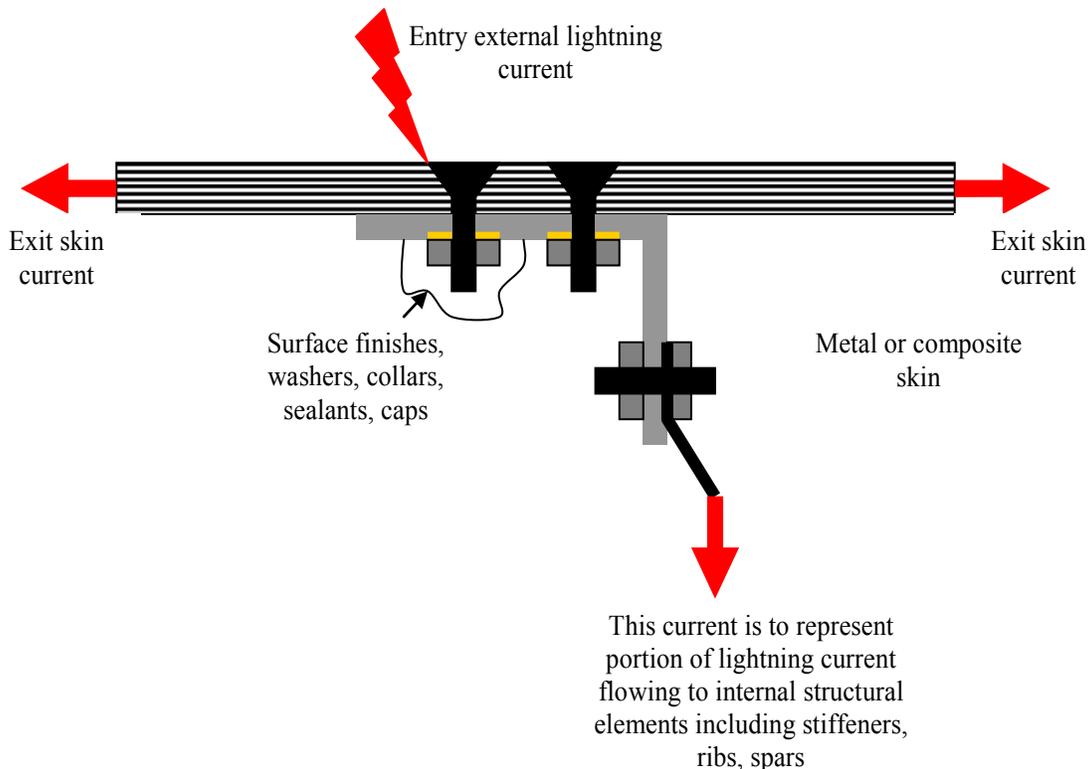


Figure 3.2-1: Test currents that need to be defined for assessments of failure conditions by test at external fastener installation

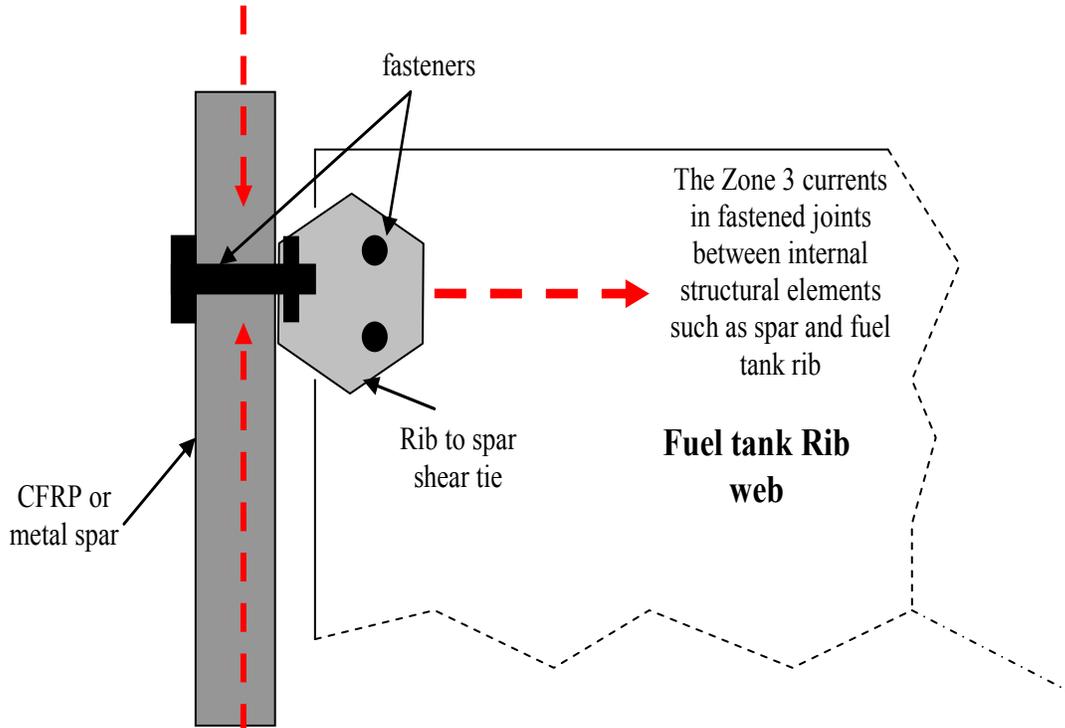


Figure 3.2-2: Test currents that need to be defined for assessments of failure conditions by test at a rib – spar interface

The potential failure modes that have been determined as described in Section 3.1 should be incorporated in the test objects, to see if the interface designs represented can tolerate these failure modes free of ignition sources. A group of failure modes which are analyzed to cause similar influence on a protection feature can be represented by one failure mode test that is analyzed as the worst case in the group.

The presence of two independent, effective and reliable features of protection against each of the sparking modes identified above must normally be demonstrated to meet the fault tolerant requirement. Alternately, it may be possible to demonstrate that a particular design is “intrinsically safe”, in which case the two features do not need to be demonstrated. This approach is described in more detail at the end of this section but the fault tolerance assessment approach is similar.

If two independent, effective and reliable features (or sets of features) cannot be identified in the design, and if there is a failure mode identified that demonstrates that the design is not intrinsically safe, then a numerical analysis must be conducted to demonstrate that the risk of ignition of fuel vapors resulting from this non-fault tolerant design is extremely improbable (see Section 4.)

In order to demonstrate fault tolerance, testing will be carried out first with one feature of protection artificially disabled (to reflect the failure mode), and then with the other

protection feature disabled. Non-sparking performance must be demonstrated in both cases to substantiate fault tolerance. If it is not possible to design a test with one feature of protection artificially disabled, then detailed analysis will be needed to demonstrate the effectiveness and independence of this feature.

It is also necessary to demonstrate that each feature of protection remains effective under normal manufacturing tolerances (e.g. levels of minor damage or contamination which would be considered acceptable within normal quality processes) and expected environmental and operating conditions.

In some cases it may be acceptable to demonstrate compliance with the requirements by alternative means. Typically this will be by similarity analysis from a test performed on a joint configuration shown to be similar (or more severe) from a sparking performance viewpoint. However, for every joint configuration, evidence must be provided of the presence, independence, and effectiveness of at least two features (or sets of features) of protection under each appropriate operating condition unless the design is shown to be intrinsically safe.

Fastened Joints - Recommended Means of Disabling Protection features

The following section describes acceptable (but not the only) means of disabling one feature of protection in order to demonstrate the effectiveness of the other feature (or set of features) by test. These are of necessity only examples:

- Where protection is provided by use of interference / close tolerance fastener fit in hole - test sample with equivalent clearance fit fasteners
- Where protection is provided by 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 protection is provided by sealant or other capping device over fastener – test sample with no sealant / capping device applied.
- Where protection is provided by a layer of insulation between nut & structure – test sample with that layer of insulation missing. Care should be taken to ensure that the resulting electrical connection is not so good as to provide a high quality electrical bonding path that may inadvertently act as an unintended protective feature.
- Where protection is provided by electrically bonding nut to metallic structure – test sample with an insulating coating or material in the bonding interface. Care should be taken to ensure that the insulative coating/material does not provide unrealistic and reliable insulation that may inadvertently act as an unintended protective feature.

While disabling one protection feature to demonstrate the effectiveness of the other addresses most failure modes, care should be taken to ensure that the actual functional effect from the failure mode is properly represented in the test configuration. In some cases, such as failure to remove burrs from a hole, the failure mode may change the ignition source or ignition source energy which may require an accurate representation of this effect in addition to or in lieu of a compromised feature.

Fastened Joints - Recommended Means of Achieving In-Tolerance or Expected Operating Conditions

Where expected operating conditions such as temperature, loading, moisture, etc., may affect the lightning performance of the design, the impact of these conditions should be assessed or the test should be conducted under representative conditions.

The following is a list of examples for assessing in-tolerance variability:

- Where protection is provided by use of interference / close tolerance fastener fit in hole, test with minimum level interference permitted by manufacturing standards
- Where protection is provided by nut/collar seal against structure, test each one or any likely combination of the following:
 - Lowest fastener preload which will occur over the airplane life
 - Worst case surface finish properties and thicknesses
 - Worst-case acceptable manufacturing damage (drill breakout, tool marks)
 - Maximum permissible fastener angle
 - Worst condition of fastener orientation (head or nut), when not specified by drawing
 - Worst condition of fastening hardware (e.g. nuts, collar, washers, self-aligning nuts)
- Where protection is provided by sealant or other capping device over fastener, test with:
 - Minimum permissible amount of sealant applied.
- Where protection is provided by a layer of insulation between nut & structure, test with:
 - Minimum permissible thickness of insulation feature and/or
 - Worst-case likely installation damage (scuffing etc)
- Where protection is provided by electrically bonding nut to metallic structure, test with:
 - Sample with surface not prepared for bonding.
 - Sample with only part of surface prepared (worst case that would pass post assembly production checks)

As noted above, it may be possible to show a design is fault tolerant without incorporating two or more features – in this case the design would be considered intrinsically safe. The term “intrinsically safe” is defined in AC 25.981-1C as being “incapable of releasing sufficient electrical or thermal energy under normal operating conditions, anticipated failure conditions, and environmental conditions which could cause an ignition source within the fuel tank.” For structural lightning protection, this concept essentially can be applied to designs that are demonstrated to tolerate all failure conditions free of ignition sources due to lightning – that is, there is no failure mode or

combination of failure modes that can result in an ignition source. The same basic process for demonstrating fault tolerance where two or more features are present is also required to be applied to determine a design is intrinsically safe. The difference is that, rather than disabling one feature at a time, the assessment would be based upon introducing a worst case combination of failure conditions to demonstrate that no combination of failures could result in an ignition source.

Examples of designs that might be shown to be intrinsically safe are:

- Fuel tank structural skins whose material and thickness are sufficient to ensure that hot spots or 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 cracks or delaminations caused by damage or fatigue.
- 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. Meaning of 'field fastener' is 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.

3.3 Determine Fault Tolerance

If the failure assessment results in demonstrating that the design is free from ignition sources after assessment of relevant single failure conditions, then the design is considered to be fault tolerant. If so, the next step is to verify protection adequacy as described in Section 5. If not, then further assessment is required per Section 3.4.

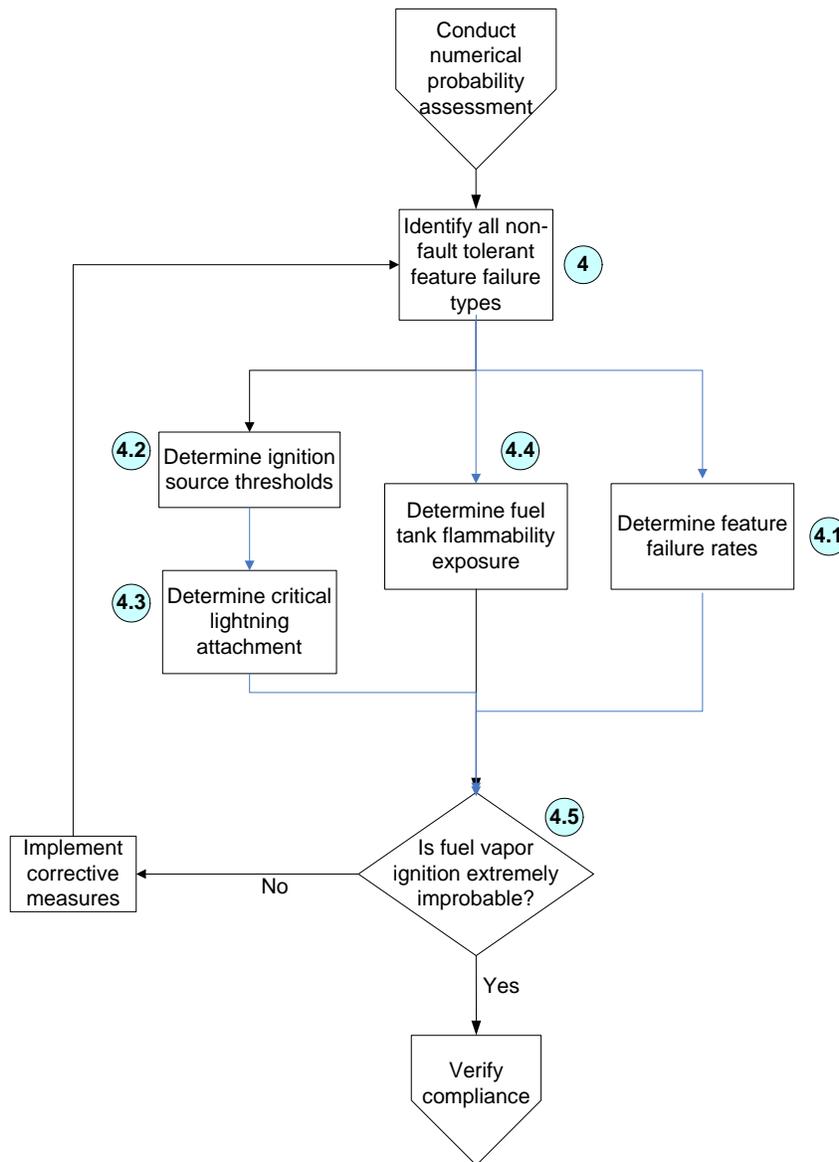
3.4 Determine Practicality of Providing Fault Tolerance

When a design has not been shown to be fault tolerant to an ignition source risk when exposed to lightning, an assessment is required to determine if there are practical design options to incorporate and make the joint fault tolerant. This assessment should identify design options that are available and each should be reviewed to determine if it is practical to incorporate that feature (or set of features) to provide fault tolerance. If so, then that design feature (or set of features) must be added to the design. Examples of what design options may be considered practical or impractical along with some general criteria for how practicality is determined are provided in the policy. As noted in the FAA policy, the determination of practicality is somewhat subjective and can be dependent on the proposed design and the “state of the art” at the time. Determination of impracticality for a given design should be reviewed for concurrence with the appropriate regulatory authority.

For joints that have failure conditions that are determined to be non-fault tolerant and impractical to make fault tolerant, all of the non-fault tolerant joints should be assessed by a numerical probability safety analysis to demonstrate that they have been minimized sufficiently such that fuel vapor ignition can be shown to be extremely improbable. Section 4 defines the process for conducting the required numerical probability safety assessment.

4 Conduct Numerical Probability Assessment

The purpose of this assessment, with a flow diagram shown in Figure 4.0-1, is to substantiate that it is extremely improbable that failures associated with non-fault tolerant features will lead to a fuel tank explosion. Extremely improbable is described in AC 25.981-1C as failure conditions so unlikely that they are not anticipated to occur during the entire operational life of all airplanes of one type. Numerically this is defined to be less than 1×10^{-9} events per flight hour. Therefore, the sum of all non-fault-tolerant feature failures must result in a numerical value less than 1×10^{-9} events per flight hour.



See Section 6

Figure 4.0-1: Conduct Numerical Probability Assessment

The relevant non-fault tolerant structural design features which may contribute to ignition sources inside the fuel tank when a failure occurs should be identified. Each type of non-fault tolerant feature failure (NFTFF) should be assessed and the result summed.

The characteristics of airplane fuel tank flammability, non-fault tolerant feature failures, and a critical lightning strike should be considered in this assessment. A general method for combining these characteristics in a numerical assessment is shown in Figure 4.0-2. The figure is based on the basic premise that a critical lightning strike, the flammability of the fuel tanks, and the presence of NFTFF(s) which could provide an ignition source are all independent events, and that the rate of critical strikes, $R_{L-CRITICAL}$, can be combined with the probability of the tanks being flammable, P_{FLAM} , and the probability that a given type of NFTFF(s) is present, $P_{STRUCT1}$, to obtain a rate for an ignition event, R_{IGN1} , for each given type of structural failure. These individual rates for each type of relevant structural failure are then summed to obtain an estimate for the overall catastrophic fuel ignition rate, $R_{IGNITION}$.

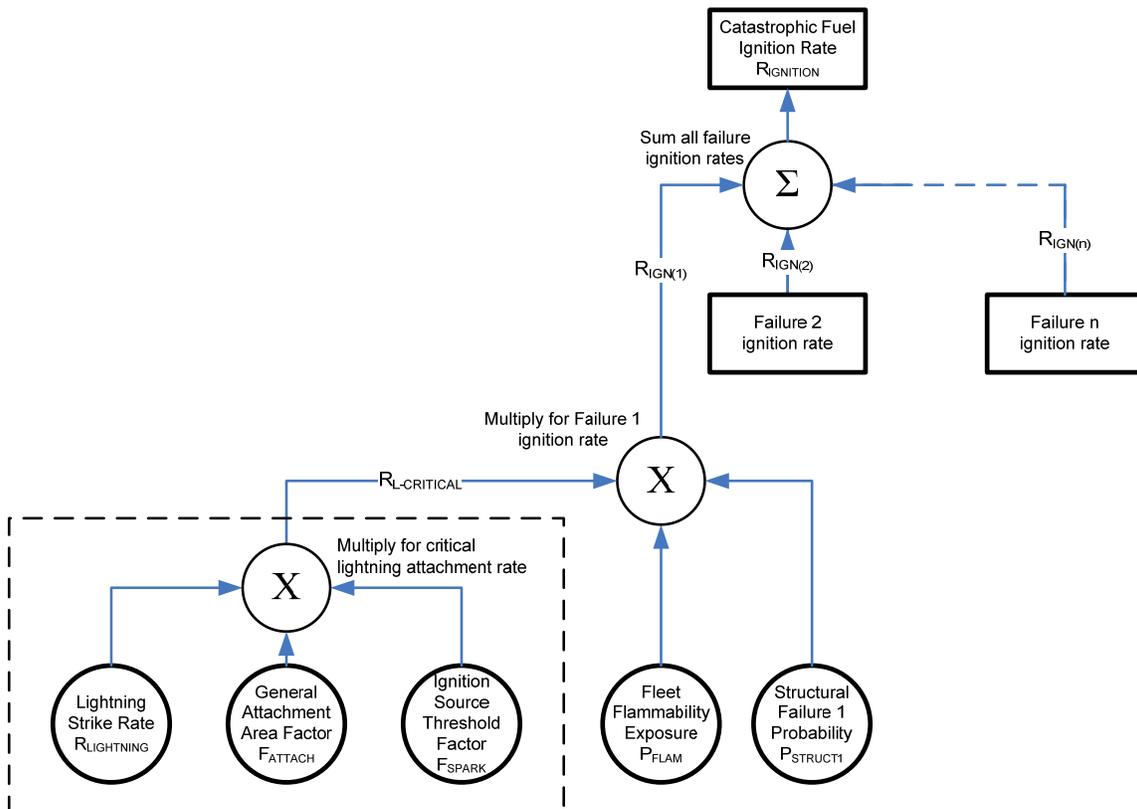


Figure 4.0-2: Sample Numerical Analysis Flow Diagram

4.1 Determine Failure Rates and Distribution

The purpose of section 4.1 is to present a simple discussion of how to estimate the probability of having structural failures of a given type, $P_{STRUCT1}$, present in the design

when those failures could provide ignition sources in the presence of a critical lightning strike. As Figure 4.0-2 shows, the approach presented herein needs a probability for the relevant structural failures. For this estimate:

- Determine the relevant area affected by a given critical strike.
- Determine the number of each type of structural elements in that area, where those failures could present an ignition source.
- Determine the percentage (or portion) of the structural items in each group that could be manufacturing or build escapes
- Determine the failure rate distribution, and therefore, probability distribution for the structural items in each group that were installed correctly.
- Use the specified inspection interval or the life of the airplane, as appropriate, to be the estimate of the probability of the presence of relevant structural failures.
- Calculate the probability of a given type of structural failure(s) being present, $P_{STRUCTI}$, by summing the “constant probability” of a manufacturing escape being present when the airplane is built and the probability of one or more failures occurring in the appropriate inspection, or life of the airplane, interval.

4.1.1 In-service failures

Once the non-fault tolerant feature failure types are identified, the structural feature failure rate and estimated probability of failure, $P_{STRUCTI}$, should be defined for each type of relevant structural failure. Relevant structural failures are those that could provide an ignition source in the presence of a critical lightning strike. Their failure rates and distributions can be determined using data from one or more of the following sources:

- Field service reports or databases
- Developmental engineering tests to determine durability of features, such as fatigue tests, thermal cycling tests, or corrosion tests.

Failure rates and their distributions for fuel tank structural elements are typically estimated from relatively few incident reports. Similarity of parts with a previously established data base may provide acceptable data. Engineering judgment may also be used to estimate failure rates where insufficient data exists. The determination of failure rates and their distributions in this manner should be based on conservative assumptions. In new designs, fatigue testing will normally be used to determine the various failure conditions and estimates for their failure rates. The failure characteristics of fasteners and other structural elements involved in lightning protection have been shown by fatigue testing to be time or cycle dependent, and hence, Weibull distributions rather than constant rate exponential distributions are considered to more accurately represent their failure probabilities. When data of the time-to-failure for the various structural elements is available, Weibull analysis, as described in SAE ARP 5150 Appendix F, have been used to estimate the failure characteristics for the various parts. An overview of Weibull analysis with some examples is provided below.

The probability of failure in a Weibull distribution is given by the equation:

$$P_{(\text{of failure of an item})} = 1 - e^{-(t/\eta)^\beta} \quad \text{Eq (1)}$$

(where ^ symbol means ‘to-the-power-of’)

In this equation, t is time, η is the mean-time-to-failure (MTTF) for the item, and β is used to characterize the change in the item’s failure rate with time.

The hazard or instantaneous failure rate at time t, $\lambda(t)$, is defined as $(dP/dt)/(1-P)$. For the Weibull distribution this is:

$$\lambda(t) = (\beta/\eta) * (t/\eta)^{(\beta-1)} \quad \text{Eq.(2)}$$

When β is greater than 1, the elements have a failure rate that starts at zero at time zero, and increases with time (or cycles, if cycles are the important parameter).

If n structural elements are of the same type and have failure probabilities rates characterized by a Weibull distribution with a given η and β , the probability of having one or more structural elements fail in the interval from time zero to time T would be:

$$\begin{aligned} P_{\text{STRUCTi}} &= P(\text{one or more elements failed}) = 1 - \text{Prob}(\text{none are failed}) \\ \text{Prob}(\text{none are failed}) &= e^{-n(T/\eta)^\beta} \quad \text{Therefore,} \\ P_{\text{STRUCTi}} &= 1 - e^{-n(T/\eta)^\beta} \quad \text{Eq.(3)} \end{aligned}$$

For example, for n = 5, T = 24,000 hours, $\eta = 10^7$ hours, and a β of 1.6:

$$P_{\text{STRUCTi}} = 0.00032$$

One item to note: If the structural failures are more accurately represented by Weibull distributions with a β greater than one, periodic inspections of the structural elements do not “zero time” those elements, as is the case with items having constant-with-time failure rates. If represented by Weibull distributions, the failure rates of the items will still be increasing with time, unless the item is removed and a new item is installed. Hence, many items will have an exposure period that is the life of the airplane. If this is the case and the airplane life is 80,000 hours, the estimated probability of failure for the 5 items in this example would increase to:

$$P_{\text{STRUCTi}} = 0.0022$$

The Weibull distribution is also one that includes the constant failure rate, exponential distribution. The simple exponential distribution is a Weibull distribution with a β of unity.

If $\beta = 1$, the instantaneous failure rate reduces to:

$$\lambda(t) = (1/\eta) = (1/\text{MTTF}) \quad \text{which is a constant number (i.e., not time dependent).}$$

For $\beta = 1$, replacing η with $(1/\lambda)$ in Eq.(1) yields the familiar constant rate, exponential failure probability equation:

$$P_{\text{STRUCT}i} = 1 - e^{-\lambda t} \quad \text{Eq.(4)}$$

In many systems, the times to failure of the elements may not be known. In these systems, the analyst may only have the number of failures and the total fleet time in which those failures occurred. In these cases, the analyst may choose to define the failure rate of the system as constant with time, and estimated as:

$$\lambda \approx (\# \text{ of failures})/(\text{fleet hours})$$

For constant failure rate elements, if there are n structural elements of a given type in the area of interest (i.e., the area affected by the critical lightning strike), the probability of one or more of those elements being failed in a given time period (or periodic inspection interval) T , would be calculated from the equation:

$$P_{\text{STRUCT}i} = P(\text{one or more elements failed}) = 1 - \text{Prob}(\text{none are failed})$$

$$\text{Prob}(\text{none are failed}) = e^{-(n\lambda T)} \quad \text{Therefore,}$$

$$P_{\text{STRUCT}i} = 1 - e^{-(n\lambda T)} \quad \text{Eq.(5)}$$

Repeating the first example: For $n = 5$, $T = 24000$ hours, and a constant failure rate for λ of 10^{-7} failures/hr for each element, the probability of a structural failure would be:

$$P_{\text{STRUCT}i} = 0.012$$

Note that this same group of 5 elements, where the elements are characterized by a constant failure rate distribution, have a probability of one or more failures occurring in a 24,000 hour period that is 5 times greater than the same group of elements with a β of 1.6 in the entire 80,000 hour life of an aircraft. Hence, the failure rate characteristics for the various structural elements are quite important and can have a large influence on the calculated results. Because of this, care should be taken to ensure that there is reasonable supporting data for justifying a value for $\beta > 1$, otherwise a constant failure rate should be assumed.

When the elements of concern have a constant failure rate rather than a failure rate increasing with time, the periodic inspection essentially “zero times” the system, and the probability of having one or more failures during a given fixed time interval (i.e., the periodic inspection interval) remains the same.

Additional factors that should be considered when determining failure rates include configuration or design specific details. For example, structural design may be driven by various loading conditions or have different margins applied in different locations. Fasteners and structure in certain locations may be sized by the maximum expected static

loads while other locations may be sized by fatigue effects. The likelihood of failures or types of failures that could occur may be different in each case. The failures could result from oversize or poor quality holes (resulting in poorer electrical contact), low joint clamp up forces (resulting in a degraded nut or collar seal), or a fastener shearing (resulting in either a fracture line or gap or a complete loss of nut or collar seal.) The failure rates associated with these effects may be different and could be dependent upon fastener/nut/collar material, type of fastening system, and the design margin.

Two examples for estimating/calculating failure rates are provided below:

Example 1:

The probability of failures assigned to structural elements could consider how compliance with structural requirements is achieved based on how structure performs in service. Compliance to the structural requirements of FAR 25 is based upon analysis and test data that substantiates that appropriate damage tolerance and durability is demonstrated. Part of this data is also used to substantiate structural inspection intervals. Accordingly, a reasonable probability for failures of the structural elements that can provide or affect lightning protection could be based on initial certification data, including fatigue test findings, and can account for inspection intervals. Also, data from in-service difficulty reports (SDRs) or similar structures and/or identical design features may be used to substantiate the failure rates. General experience from transport airplanes indicates that structural elements have an average failure rate on the order of 1×10^{-7} per flight hour. This average failure rate could be assigned to structural elements unless the above mentioned certification data or SDR for a particular manufacturer or model indicate otherwise. Such data should be obtained and appropriate average failure rates determined where possible.

It should be noted that the general experience noted above would only be valid for structural design elements that contribute to the structural integrity of the airplane, such as primary structure and associated fastened joints. This logic would not be applicable for design elements such as sealants or insulating materials, which would not be analyzed for structural effect nor would be a focus of structural inspections. For these kinds of design elements, data from zonal inspections or other sources may be more appropriate.

Example 2:

The method presented below is based on ARP5150, Appendix D – Quantitative Risk Assessment. Often, an aircraft failure or defect becomes an issue after it is actually observed in service. The data available for a probability evaluation is then the number of observed events and the number of flight hours operated on airplanes exposed to the problem.

When a probability calculation must be based on a small number of observed events, the results are subject to significant statistical uncertainty. Conservatism may be added any of several ways; in the assumptions used for the risk analysis, by a risk abatement plan more aggressive than the analysis might suggest or by adding a confidence bound to the results of the analysis.

The formula below is applicable for events where the probability can be treated as independent of product age. The statistical assumption is that the observed events arise from a Poisson process.

$$P_{\text{STRUCT}_i} \leq \chi^2[\alpha, 2(n+1)]/2t \quad (\text{Eq. 6})$$

where:

- χ^2 chi-square distribution
- t time in flight hours
- α selected statistical confidence level
- n number of observed events

The upper term in the formula represents the α^{th} percentile of chi-square (χ^2) probability distribution with $2(n+1)$ degrees of freedom, referenced in the upper bound.

For example, for a situation where no failures have occurred in an airplane fleet with 16 million flight hours, we calculate a 90% confidence bound using the parameter values:

$$t = 16,000,000 \text{ flight hours}$$

$$\alpha = 0.9$$

$$n = 0$$

From a table of the chi-square distribution, we find that:

$$\chi^2 [0.9, 2(0+1)] = \chi^2 [0.9, 2] = 4.61$$

Inserting into equation 6:

$$P_{\text{STRUCT}_i} \leq 4.605 / 2(16,000,000)$$

$$P_{\text{STRUCT}_i} \leq 0.144 \times 10^{-6}$$

That is, with no observed non-fault tolerant structural joint type failure in the considered fleet accumulated flight hours, the chi-square statistical distribution corresponds to a rate of 0.144×10^{-6} with a 90% confidence level.

4.1.2 Manufacturing Escapes

Another item of concern is manufacturing escapes. This term is used to identify manufacturing or airplane build failures in structural elements that were not detected in the manufacturing process but allow those elements to be ignition sources in the presence of a critical lightning strike. These failure conditions could be estimated from:

- Manufacturing records of escapes if available
- Manufacturing records for deriving escape rates based upon defects found

If these records or other data sources indicate that that a given percentage of structural elements are installed incorrectly and they could be ignition sources in the presence of a critical lightning strike, then the probability of these failures should be added – as a constant – to the probability of failures over time (i.e., Eq.(3)). For example, assume it is shown that 1 in 10,000 fasteners or structural elements of the same type is installed

incorrectly and is a potential ignition source. Then if there is an area where n elements of a given type are of concern, the probability of having one or more failures would be approximated as:

$$P_{(\text{STRUCTI})} = 0.0001*n + (1 - e^{-(n)(t/\eta)^\beta}) \leq 1.0 \quad \text{Eq.(7)}$$

where the first term represents the probability (or fractional estimate) of having a manufacturing or build escape at time zero, and the second term represents the probability of having a time dependent failure in one of the elements of interest. Needless to say, this build quality number can have a significant effect on the overall probability of having structural failures present in the design area of concern. Note that Eq.(7) cannot be greater than 1. If the number of the same type of structural elements of concern is large for a given area of concern, and the percentage of manufacturing and installation errors for those elements is large, such that it is expected that 1 or more ignition sources might be in-place after aircraft manufacture, the probability of an ignition source being present – as calculated by Eq.(7) – would simply be unity. It cannot be greater than unity.

4.2 Determine Ignition Source Threshold Factor

Most failed features within fuel tank structures will tolerate a certain amplitude of lightning current without producing ignition sources, such as thermal sparks or voltage sparks. Below these amplitudes, the failed feature will transfer current without producing ignition sources. The lightning peak current amplitude, charge transfer, or action integral that result in an ignition source can be determined by test using parts that incorporate the structural features in a failed condition.

SAE ARP 5416 Section 7.3.2 provides applicable tests where direct lightning attachment to external surface fasteners or skin installations is expected. Section 7.4.2 provides applicable tests where conducted lightning currents are expected. The test arrangements are similar to those described in Section 3.2 and illustrated in Figures 3.2-1 and 3.2-2.

More than one test object containing the failure condition needs to be tested to determine a reliable ignition source threshold. Typically this involves testing at increasing or decreasing test levels to converge on an approximate threshold. The number may range from as few as three when limited variability exists to more (e.g. 6 to 12) where the results are more variable. Applying statistical analysis methods to aid in establishing lightning performance thresholds may be applied, but it is generally not practical because it would greatly increase the number of tests per condition. Many of the other parameters in the numerical probability assessment are established by limited data or engineering judgment, therefore any increase in confidence or precision for ignition source threshold determination would be overcome by the uncertainty of the overall assessment. So it is acceptable to conduct a limited number of tests to converge toward an approximate threshold and then to repeat tests (typically three) at this threshold value to establish confidence in that value. The highest test current amplitude that did not produce an ignition source should be considered the ignition source threshold.

A simplifying assumption is that the ignition source threshold may be based on the peak current amplitude. This assumes that action integral and continuing current are scaled by the same factor as the peak current amplitude.

The lightning current exceedance distributions shown in Figures 4.2-1 and 4.2-2 may be used to determine the ignition source threshold factor F_{SPARK} , a unit-less value. The first return stroke data shown in Figure 4.2-1 should be applied for non-fault tolerant features in Zones 1 and 3, and the subsequent stroke data shown in Figure 4.2-2 should be applied for non-fault tolerant features in Zone 2. The distributions in these figures are based upon cloud to ground lightning measurements reported by Berger (1975) and Garbagnati (1982). Each of these papers provides log normal distributions of measured lightning parameters. Figures 4.2-1 and 4.2-2 show the combined peak current data for first return strokes and subsequent return strokes, respectively.

First Return Stroke (Zone 1)

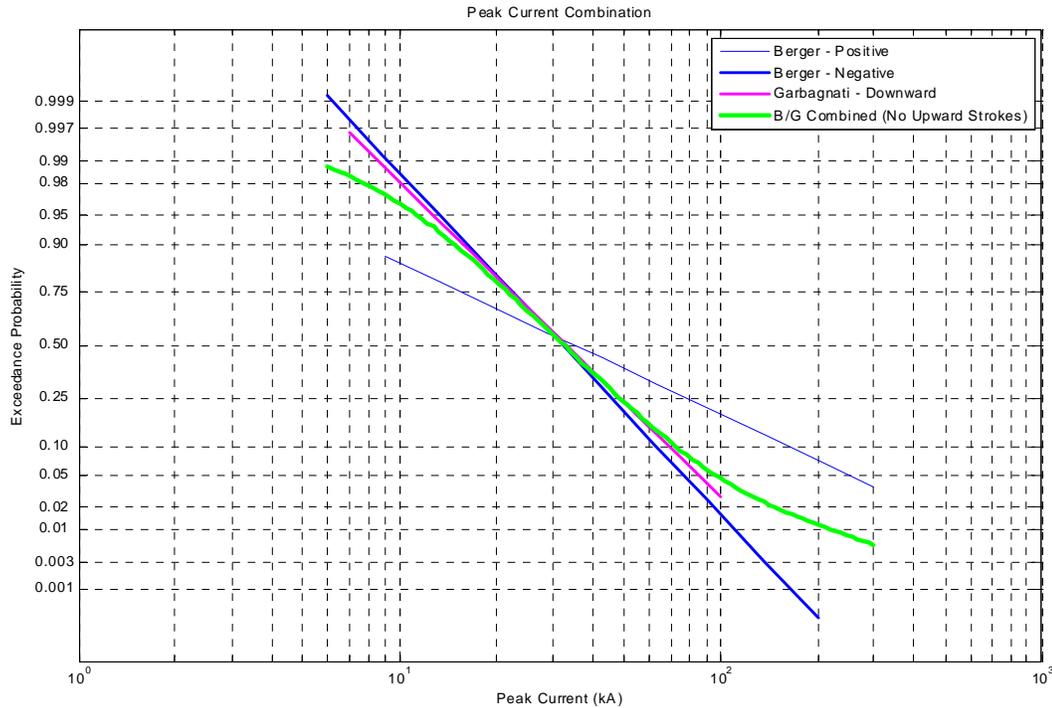


Figure 4.2-1: Lightning Exceedance Curve for Zone 1 and Zone 3 Areas

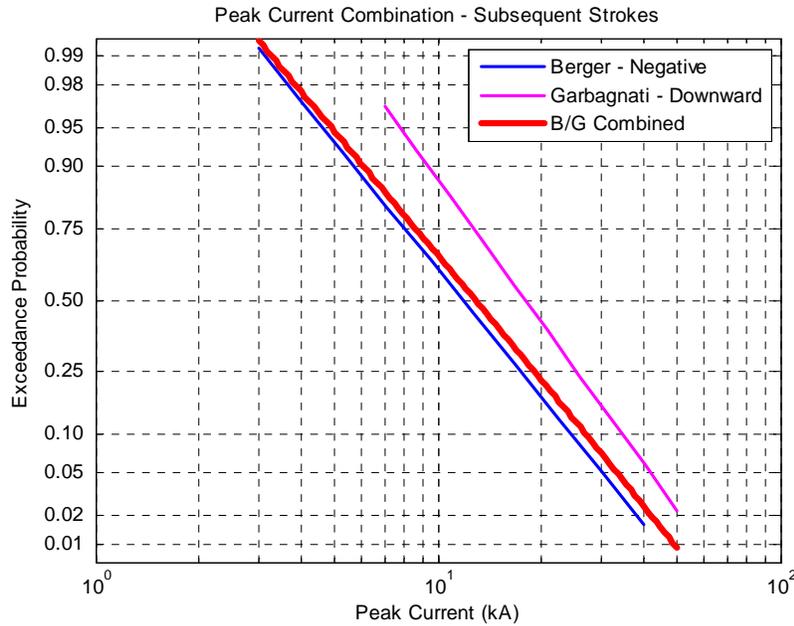


Figure 4.2-2: Lightning Exceedance Curve for Zone 2 Areas

The ignition source thresholds determined above should be compared with expected lightning current levels at the non-fault tolerant features. The combined Berger-Garbagnati (B/G combined) curves in Figures 4.2-1 and 4.2-2 should be used.

For example, the ignition source threshold in Zone 3 was shown to be 2 kA conducted current for a particular failed non-fault tolerant feature. The expected lightning current at this non-fault tolerant feature was 10 kA, for the specified conducted lightning current component A amplitude of 200 kA. The ratio of the ignition source threshold to expected lightning current is 0.2, so the lightning current amplitude that would cause an ignition source for the failed feature is 200 kA times 0.2, or 40 kA. The ignition source threshold factor F_{SPARK} from Figure 4.2-1 for the 40 kA first stroke amplitudes in Zone 3 is approximately 0.35.

As another example, assume that a failed non-fault-tolerant feature has an ignition source threshold of 40 kA when installed in a Zone 2 location where the specified lightning current component D amplitude is 100 kA. The ignition source threshold factor F_{SPARK} from Figure 4.2-2 for the 40 kA subsequent stroke amplitudes in Zone 2 is approximately 0.02.

4.3 Determine Rate of Critical Lightning Attachment

The rate of critical lightning attachment $R_{L-CRITICAL}$ should be determined for each type of non-fault tolerant feature, that is, for each family of similarly designed joints where the same failure condition would enable a potential ignition source when sufficient lightning current is present.

The probability of lightning current at a specific fuel tank fastener or joint installation exceeding the ignition source threshold depends on a combination of:

- The rate of lightning strikes to the airplane
- Lightning attaching to particular areas of the airplane fuel tank structure with failed non-fault tolerant features
- The lightning-related ignition source threshold factor for the failed non-fault tolerant features.

$R_{\text{LIGHTNING}}$ is the average lightning attachment rate per flight hour for the airplane, which according to SAE ARP5412A is likely to fall between one in 1000 hours to one in 20,000 hours. Using a rate on the order of one strike in 3000 hours (3.33×10^{-4} per flight hour) as a worldwide average is acceptable for this analysis.

F_{ATTACH} is the unit-less factor for lightning attachment to a general area of the airplane where failed non-fault tolerant features exist. The distribution of initial attachment locations can be obtained from manufacturers' data or the generic numbers in Table 4-1 can be used. The generic numbers in this table represent service experience from various manufacturers tabulated relative to general lightning attachment locations. The data provided consistently showed similar attachment distributions such that it is appropriate to apply it within the broad categories of airplane type. The table shows the fraction of lightning attachment in a general airplane area relative to the total number of lightning attachments to an airplane. While there can be several possible combinations of initial lightning attachment locations per lightning strike event, for purpose of this analysis only one pair of initial lightning attachment locations need be assumed per lightning strike for a particular non-fault tolerant feature failure. It is not required to consider more than one pair of attachment locations for one lightning strike event, however where a critical lightning strike could occur due to different attachment locations (e.g. wing tip to tail as one pair of attachment locations and engine to tail as another), these other lightning attachment locations should be considered as a separate lightning strike event.

Table 4-1: Generic Initial Lightning Attachment Location Distributions Factors

Airplane type	Nose/Fwd Fuselage	Wing Tip	Engine	Tail/Aft Fuselage	Landing Gear
Transport airplane with wing mounted engines	0.45	0.25	0.05	0.25	<0.01
Transport airplane with fuselage mounted engines	0.50	0.22	0.02, Zone 2 only	0.28	<0.01

For example, for an airplane with wing mounted engines, the lightning attachment factor for the wing tip would be 0.25 according to Table 4-1.

The critical lightning attachment rate $R_{\text{L-CRITICAL}}$ is the product of the lightning attachment rate $R_{\text{LIGHTNING}}$, the general attachment area factor F_{ATTACH} , and the ignition source threshold factor F_{SPARK} determined in 4.2, so that:

$$R_{L-CRITICAL} = R_{LIGHTNING} * F_{ATTACH} * F_{SPARK}$$

$R_{LIGHTNING}$ has values per flight hour, while F_{ATTACH} and F_{SPARK} are unit-less factors, so $R_{L-CRITICAL}$ results in values per flight hour.

4.4 Determine Flammability Exposure for Fuel Tanks

The flammability exposure P_{FLAM} should be determined for the fuel tanks where non-fault tolerant features exist. The requirements for fuel tank flammability exposure are defined in § 25.981(b) adopted in Amendment 25-125. The procedure for determining the likelihood that the vapor in a fuel tank is in a flammable state is defined in 14 CFR Part 25, Appendix N, Fuel Tank Flammability Exposure and Reliability Analysis. The desired numerical value to input for the lightning policy numerical analysis is the fleet average flammability exposure.

This fleet average flammability exposure is defined as a percentage of the total flight time, including from preflight through disembarking and unloading cargo, that the fuel tank ullage is considered flammable. Determination of flammability is based upon the range of fleet missions and world-wide environmental conditions and fuel properties included in the Fuel Tank Flammability Assessment Method spreadsheet. Incorporated into Appendix N by direct reference, the Fuel Tank Flammability Assessment Method User's Manual, dated May 2008, document number DOT/FAA/AR-05/8, provides guidance for determining flammability exposure for a particular aircraft. These documents can be downloaded from: <http://www.fire.tc.faa.gov/systems/fuel tank/FTFAM.stm>

Since applicability of the lightning policy is based on compliance with the relevant aspects of § 25.981(b), it is expected that most tanks under consideration will exhibit a flammability exposure no greater than 3%, or that of a fuel tank within the wing of the airplane model being evaluated, whichever is greater.

For this structural lightning numerical analysis, if an applicant has selected the Exemption compliance path, the analysis should use the flammability exposure for the airplane as defined in § 25.981(b).

If the applicant has chosen the Special Condition compliance path, the requirements of 14 CFR Part 25 Appendix M are applicable for all fuel tanks. These more stringent requirements include limiting fleet average flammability exposure to no more than 3% during ground or takeoff/climb flight phases on warm (80°F or greater) days, as well as limitations on flammability reduction means system reliability and availability. The flammability exposure P_{FLAM} should be expressed as a unit-less numerical value (not a percentage).

4.5 Determine Probability of Fuel Vapor Ignition

The probability of fuel vapor ignition per flight hour $R_{IGNITION}$ for a particular type of joint or feature is found by multiplying the fleet average flammability exposure, the fuel tank structure feature failure probability, and the critical lightning attachment rate. This should be done for each of the non-fault tolerant feature failure types, which will then be

summed to determine the probability that a fuel vapor ignition may result. To be compliant with either the special condition or exemption path as specified in the policy, this result should demonstrate that fuel vapor ignition is extremely improbable. Numerically, the risk of fuel vapor ignition should be less than 1×10^{-9} per flight hour.

$$R_{\text{IGNITION}} = (R_{\text{L-CRITICAL1}} * P_{\text{FLAM1}} * P_{\text{STRUCT1}}) + (R_{\text{L-CRITICAL2}} * P_{\text{FLAM2}} * P_{\text{STRUCT2}}) + \dots + (R_{\text{L-CRITICALn}} * P_{\text{FLAMn}} * P_{\text{STRUCTn}})$$

In these calculations, $R_{\text{L-CRITICAL}}$ is a rate per flight hour, while P_{FLAM1} and P_{STRUCT1} are unit-less probabilities. Therefore, the resulting R_{IGNITION} is an ignition rate per flight hour.

Ignition probability example: This example assumes that there are non-fault tolerant feature failures for structural features in four areas. The first two failures are subject to conducted lightning current when lightning attaches to a Zone 1 wingtip and conducts lightning current through fuel tank structure in Zone 3. The third failure is subject to direct lightning attachment in Zone 2 at the wing root. The fourth failure is due to a manufacturing escape, where the failure due to a manufacturing error is undetected when the airplane goes into service.

Failure 1

- The average time between lightning strikes was assumed to be 3000 flight hours, based on SAE ARP5412 guidance.
- Wing tip lightning attachment was determined to produce the worst case lightning conducted current for area 1. The general attachment area factor is 0.25 for a wing tip lightning attachment from Table 4-1.
- For fasteners in area 1 the expected Zone 3 conducted current is 10 kA per fastener, based on engineering analysis.
- The ignition source threshold was determined to be 2 kA for this type of non-fault tolerant feature failures, based on laboratory tests.
- The ratio of ignition source threshold at 2 kA to the expected conducted current at 10 kA is 0.2. The peak lightning current for Zone 3 is 200 kA, so this ratio of 0.2 would indicate that a lightning peak current of 40 kA will produce an ignition source for a failure at those non-fault tolerant fasteners. From Figure 4.2-1, this peak current has an exceedance factor of approximately 0.35.
- The fleet fuel tank flammability was determined to be 3% based on § 25.981(b) requirements and part 25 appendix N analysis.
- This area has 5 fasteners that would experience the Zone 3 current levels and are at risk for non-fault tolerant feature failures.
- The failure characteristics of these fastener features were determined to follow a Weibull distribution with a mean time to failure of 10 million hours and with β of 1.6.
- The inspection interval for these fasteners was set for every 24,000 flight hours, based on the airplane maintenance review board recommendations.

Failure 2

- The average time between lightning strikes was assumed to be 3000 flight hours, based on SAE ARP5412 guidance.
- Wing tip lightning attachment was determined to produce the worst case lightning conducted current for this area. The general attachment area factor is 0.25 for a wing tip lightning attachment from Table 4-1.
- For fasteners in this area the expected Zone 3 conducted current is 5 kA per fastener, based on engineering analysis.
- The ignition source threshold was determined to be 2 kA for this type of non-fault tolerant feature failures, based on laboratory tests.
- The ratio of ignition source threshold at 2 kA to the expected conducted current at 5 kA is 0.4. The peak lightning current for Zone 3 is 200 kA, so this ratio of 0.4 would indicate that a lightning peak current of 80 kA will produce an ignition source for a failure at those non-fault tolerant fasteners. From Figure 4.2-1, this peak current has an exceedance factor of approximately 0.08.
- The fleet fuel tank flammability was determined to be 3% based on § 25.981(b) requirements and part 25 appendix N analysis.
- This area has 10 fasteners that would experience the Zone 3 current levels and are at risk for non-fault tolerant feature failures.
- The failure characteristics of these fastener features were determined to follow a Weibull distribution with a mean time to failure of 10 million hours and with β of 1.6.
- The inspection interval for these fasteners was set for every 24,000 flight hours, based on the airplane maintenance review board recommendations.

Failure 3

- The average time between lightning strikes was assumed to be 3000 flight hours, based on SAE ARP5412 guidance.
- Nose lightning attachment that sweeps across the wing root was determined to produce the worst case lightning direct attachment for this area. The general attachment area factor is 0.45 for a nose lightning attachment from Table 4-1. Since this area of the wing root is one portion of the potential sweep path involving 60 degrees of the circumference in this vicinity, this factor was reduced further by a factor of 6, resulting in an attachment area factor of 0.08.
- For fasteners in this area the expected Zone 2 direct attachment current is 100 kA per fastener, assuming direct attachment to the fastener.
- The ignition source threshold was determined to be 40 kA for this type of non-fault tolerant feature failures, based on laboratory tests.
- The ignition source threshold at 40 kA results in an exceedance factor of approximately 0.03 from Figure 4.2-2 for subsequent strokes.
- The fleet fuel tank flammability was determined to be 3% based on § 25.981(b) requirements and part 25 appendix N analysis.
- This area has 100 fasteners that would experience the Zone 2 direct lightning attachment and are at risk for non-fault tolerant feature failures.

- The failure characteristics of these fastener features were determined to follow a Weibull distribution with a mean time to failure of 10 million hours and with β of 1.6.
- The inspection interval for these fasteners was set for every 24,000 flight hours, based on the airplane maintenance review board recommendations.

Failure 4

- The average time between lightning strikes was assumed to be 3000 flight hours, based on SAE ARP5412 guidance.
- Wing tip lightning attachment was determined to produce the worst case lightning conducted current for this area. The general attachment area factor is 0.25 for a wing tip lightning attachment from Table 4-1.
- For structural features in this area the expected Zone 3 conducted current is 5 kA per structural feature, based on engineering analysis.
- The ignition source threshold was determined to be 2 kA for this type of non-fault tolerant feature failures, based on laboratory tests.
- The ratio of ignition source threshold at 2 kA to the expected conducted current at 5 kA is 0.4. The peak lightning current for Zone 3 is 200 kA, so this ratio of 0.4 would indicate that a lightning peak current of 80 kA will produce an ignition source for a failure at those non-fault tolerant structural features. From Figure 4.2-1, this peak current has an exceedance factor of approximately 0.08.
- The fleet fuel tank flammability was determined to be 3% based on § 25.981(b) requirements and part 25 appendix N analysis.
- This area has five structural features that would experience the Zone 3 current levels and are at risk for non-fault tolerant feature failures.
- This structural feature failure is due to a manufacturing escape, where the failure occurs during the airplane manufacture, and the failure is not detected before the airplane goes into service. The escape probability in this example is one escape for 10,000 structural features of this type.

Table 4-2 shows the results of the failure probability calculations for this example. Note that the results are highly dependent on the number of non-fault tolerant feature failures, the ignition source threshold factor, the wear-out or failure probability for the non-fault tolerant feature, and the manufacturing escape rate.

Table 4-2: Example Fuel Ignition Rate Calculations

	Parameter	Description	Failure 1 Zone 3 Conducted Lightning	Failure 2 Zone 3 Conducted Lightning	Failure 3 Zone 2 Lightning Attachment	Failure 4 Zone 3 Conducted Lightning Manufact. Escape	Units
1	$t_{\text{LIGHTNING}}$	Average flight time between lightning strikes	3000	3000	3000	3000	flight hours
2	$R_{\text{LIGHTNING}}$	Lightning strike rate ($1/t_{\text{LIGHTNING}}$)	3.3E-04	3.3E-04	3.3E-04	3.3E-04	per flight hour
3	F_{ATTACH}	General attachment area factor	0.25	0.25	0.08	0.25	no units
4	F_{SPARK}	Spark threshold factor	0.35	0.08	0.03	0.08	no units
5	$R_{\text{L-CRITICAL}}$	Critical lightning attachment rate ($R_{\text{LIGHTNING}} * F_{\text{ATTACH}} * F_{\text{SPARK}}$)	2.9E-05	6.7E-06	8.0E-07	6.7E-06	per flight hour
6	P_{FLAM}	Fleet flammability exposure	0.03	0.03	0.03	0.03	no units
7	$n_{\text{STRUCT-ITEM}}$	Number of fasteners or structural items that, if failed, could be a spark source	5	10	100	5	no units
8	β	Wear-out characteristic	1.6	1.6	1.6		no units
9	η	Mean time to failure	1.0E+07	1.0E+07	1.0E+07		flight hours
10	$t_{\text{INSPECTION}}$	Inspection interval	24000	24000	24000		flight hours
11	P_{STRUCTn}	Failure n probability using Weibull cumulative distribution ($P[\beta, \eta, t_{\text{INSPECTION}}] * n_{\text{STRUCT-ITEM}}$) for in-service failures, or constant probability ($n_{\text{STRUCT-ITEM}} * P_{\text{STRUCTn}}$) for manufacturing escapes	0.00032	0.00064	0.00643	0.00010	no units
12	$R_{\text{IGN(n)}}$	Failure N ignition rate ($R_{\text{L-CRITICAL}} * P_{\text{FLAM}} * P_{\text{STRUCTn}}$)	2.8E-10	1.3E-10	1.5E-10	1.0E-10	per flight hour
13	R_{IGNITION}	Sum of probabilities for all failure types ($R_{\text{IGN1}} + R_{\text{IGN2}} + \dots + R_{\text{IGNn}}$)				6.6E-10	per flight hour

5 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 structural lightning protection features have been incorporated. This includes consideration of all failures due to manufacturing variability, aging, wear, corrosion, and likely damage.

5.1 Practical Design Measures

Practical measures to prevent failures of the structural 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 establish Critical Design Configuration Control Limitations (CDCCL) for the design 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.

5.2 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 & 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.

5.3 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.

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.

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 certification authority.

6 Verify Compliance

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 failure rates, lightning rates and flammability exposure that is used in the numerical analysis
 - Lightning ignition source threshold test data where credit is taken for lightning current amplitude
- 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 “Assessment of Design for Fault Tolerance Phase” (Section 3), 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 applicants’ position within the issue paper and agreed upon by the certification authorities.

In regard to the application of the design to the ANM-112-08-002 policy, both for exemptions and the special conditions, the design must be shown by means of testing to be fault tolerant or through numerical probability assessment that fuel 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 ARP5416 test methods.

The second phase of this is accomplished by performing the analysis using the guidance provided in Section 4, 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 applicants' 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 vapor ignition due to these failure modes must be shown to be extremely improbable. In order to accomplish this, the quantitative assessment of the overall probability of fuel vapor ignition must be included, along with all relevant data to support the probabilities determined in Section 4 of this letter.

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 3.2 of this letter, 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 5 of this letter 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