



AEROSPACE RECOMMENDED PRACTICE

ARP6205™

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Transport Airplane Fuel System Lightning Protection

RATIONALE

This document is intended to provide supplemental guidance beyond that provided in AC 25.954-1 and AMC 25.954 on acceptable means of compliance for applicants with regards to 14 CFR 25.954 at Amendment 25-146 (CS 25.954 at Amendment 26) and to encourage that a consistent compliance approach be applied across industry.

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1. SCOPE

1.1 Purpose

This document is intended to be a user's manual to AC 25.954-1 on acceptable means of compliance for applicants with regards to § 25.954 at Amendment 25-146 and to encourage a consistent approach to be applied across industry. This document is also intended to be a user's manual to AMC 25.954 on acceptable means of compliance for applicants with regards to EASA CS 25.954 at Amendment 26. The FAA *Advisory Circular* (AC) and the EASA *Acceptable Means of Compliance* (AMC) documents appear to provide equivalent guidance, using identical wording in most sections.

Applicants should coordinate with their certifying authority to ensure that their proposed approach is acceptable, and the means of compliance and compliance data planned are sufficient for certification. It is recommended that the applicant verify that use of the guidance in this document is acceptable to their certifying authority. Further recommendations regarding coordination with the certification authority are provided throughout this ARP.

The section numbering and titles of this document have been structured to match the main section numbers in AC 25.954-1 to allow the user to easily find the supplemental guidance for each individual section relative to the corresponding section of the AC. One exception was necessary; SAE requires that Section 2 of ARP be "References," whereas FAA uses Section 2 for "Applicability" (with respect to the AC itself). Guidance regarding "Applicability" of the FAA regulation and associated AC is located in 3.1.

The section numbering and formatting of the EASA document, AMC 25.954, is different than the AC and this ARP (ED), because the AMC has fewer major sections than the AC, however, the subsection numbering is similar. Where generic reference in this ARP (ED) to the AC and AMC is provided, both document numbers are generally shown. Where specific sections of the AC are referred to, the AMC number and applicable section are omitted; however, it appears to the writers of this document that the regulatory guidance from both the FAA and EASA is equivalent.

2. REFERENCES

See 3.1 for guidance regarding AC 25.954-1 Section 2 "Applicability."

2.1 Applicable Documents

The following publications form a part of this document to the extent identified herein. The guidance is based on the latest revision of the publications in effect on the date of the publication of this document, except where indicated. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP5412	Aircraft Lightning Environment and Related Test Waveforms
ARP5414	Aircraft Lightning Zoning (ARP5414A/ED-91 and ARP5414B/ED-91A apply to this ARP and are discussed further in 4.2.1 and 4.4)
ARP5415	User's Manual for Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning
ARP5416	Aircraft Lightning Test Methods

2.1.2 EUROCAE Publications

Available from EUROCAE Secretariat, 9-23 rue Paul Lafargue, "Le Triangle" Building, 93200 Saint-Denis, France, Tel +33 1 49 46 19 65, www.eurocae.net.

ED-84 Aircraft Lightning Environment and Related Test Waveforms (technically equivalent to ARP5412)

ED-91 Aircraft Lightning Zoning Standard (technically equivalent to ARP5414)

ED-105 Aircraft Lightning Test Methods (technically equivalent to ARP5416)

ED-158 User's Manual for Certification of Aircraft Electrical and Electronic Systems for the Indirect Effects of Lightning (technically equivalent to ARP5415)

2.2 Related Federal Aviation Administration Information

2.2.1 Federal Aviation Regulation Publications

Available from Federal Aviation Regulations, www.faa.gov or www.govinfo.gov. See the Federal Register (www.federalregister.gov) for specific updates.

Federal Aviation Regulations 14 Code of Federal Regulations Parts 25.581, 25.901, 25.954, 25.1309, and 25.1316

2.2.2 FAA Publications

The following Advisory Circulars (AC) may provide additional information. Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

AC 25.954-1 Transport Airplane Fuel System Lightning Protection

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

AC 25-19A Certification Maintenance Requirements, dated October 10, 2011

AC 120-97 Incorporation of Fuel Tank System Instructions for Continued Airworthiness into Operator Maintenance or Inspection Programs

2.3 Related European Aviation Safety Agency Information

2.3.1 European Aviation Regulations

Available from European Aviation Safety Agency, Postfach 10 12 53, D-50452 Cologne, Germany, Tel: +49-221-8999-000, www.easa.eu.int.

Certification Specifications 25.581, 25.954, and 25.1316

2.3.2 European Aviation Safety Agency Acceptable Means of Compliance

AMC 25.954 Fuel System Lightning Protection

2.4 Industry Publications

Fisher, F.A., Plumer, J.A., and Perala, R.A., *Lightning Protection of Aircraft*, Second Edition, 2004

Bane, S.P.M., 2010, *Spark Ignition: Experimental and Numerical Investigation with Application to Aviation Safety*

2.5 Definitions

ACTUAL ENVIRONMENT: The measured or simulated waveforms determined from lightning interaction with the aircraft or the aircraft specimen.

ANTICIPATED: Refers to events that have been observed in the past and/or are expected to occur during manufacture or operation in the life of the fleet based on reasonable and experienced engineering judgment.

ASSEMBLY: An assembly is comprised of multiple components. This may include fuel tubes with fittings, fuel pumps, portions of the wing structure, etc.

ATTACHMENT POINT: A point where the lightning flash contacts the airplane.

CASCADING FAILURE: When one failure mode or condition also causes a second failure to occur.

CERTIFICATION TEST: Test used for certification credit. Terms such as Certification Test, Compliance Test, etc., have been used to refer to these types of tests. For simplicity, this document uses “certification test” to refer to testing used for certification credit.

COMMON MODE FAILURE: An event (e.g., corrosion or manufacturing defect) which affects a number of lightning protection features otherwise considered to be independent.

COMPONENT: A component refers to any piece of a system (e.g., tube, bracket, valve, etc.) or structure (e.g., rib, bracket, bolt, etc.). In sections discussing lightning waveforms, the term component is used to refer to a current waveform that makes up part of the total lightning event.

CRITICAL CHARACTERISTIC: A lightning protection feature characteristic required to prevent catastrophic fuel vapor ignition.

CRITICAL LIGHTNING STRIKE: A critical lightning strike is a lightning strike that attaches to the airplane in a location that, when combined with the failure of any design feature or structure, could create an ignition source.

DESIGN ELEMENT: Components, assemblies, and any other part of the fuel system.

DESIGN FEATURE: A distinctive aspect of a design element, including processes, materials, and properties.

DEVELOPMENT TEST: Test used for data gathering, proof of concept, risk mitigation, etc. Terms such as Engineering Test, Company Test, Development Test, Research and Development Test, Margin Test, Threshold Test, etc., have been used to refer to these types of tests. For simplicity, this document uses “development test” to refer to these types of tests.

FAILURE EFFECT: A description of the impact on a lightning protection feature as the result of a failure (i.e., the consequence(s) a failure mode has on the function of the lightning protection feature).

FAILURE MODE: The way in which a failure occurs.

FAULT (or) FAILURE: An undesired anomaly in a design feature that can potentially compromise the function of the lightning protection.

FUEL SYSTEM: See definition in 3.1.1.

LIGHTNING PROTECTION FEATURE: A design feature within the fuel system that aids in the prevention of fuel vapor ignition caused by lightning.

LIGHTNING PROTECTION FEATURE CHARACTERISTIC: Aspect or attribute of a lightning protection feature that supports its performance capabilities and reliability.

LIGHTNING STRIKE: Attachment of the lightning flash to the airplane.

LIGHTNING STRIKE ZONES: Airplane surface areas and structures that are susceptible to lightning attachment, -dwell time, and current conduction. Refer to ARP5414 for additional guidance on airplane lightning zoning.

LIGHTNING WAVEFORM CHARACTERISTIC: Quantifiable aspect of a lightning waveform, including peak amplitude, action integral, charge transfer, and rate of rise.

MAINTENANCE ACTIONS: In-service inspections, tests, mandatory replacements, and repairs/alterations.

THREAT: The actual lightning environment or the verification lightning environment applicable to the area being assessed.

VERIFICATION ENVIRONMENT: Waveforms applied to coupons during ignition detection testing or during analysis to demonstrate compliance.

2.6 Abbreviations

§	Section 14 of the Code of Federal Regulations
14 CFR	Section 14 of the Code of Federal Regulations
A	Amperes
AC	Advisory Circular
AMM	Airplane Maintenance Manual
AWL	Airworthiness Limitation
AMC	Acceptable Means of Compliance
CDCCL	Critical Design Configuration Control Limitation
CFRP	Carbon Fiber Reinforced Plastic
CMM	Component Maintenance Manual
EM	Electromagnetic
EME	Electromagnetic Effects
FAA	Federal Aviation Administration
FMEA	Failure Mode and Effects Analysis
FOD	Foreign Object Damage/Foreign Object Debris
FRM	Flammability Reduction Means
FTA	Fault Tree Analysis
ICA	Instructions for Continued Airworthiness
kA	Kilo Amperes
LRU	Line Replaceable Unit
LTA	Lightning Transient Analysis

mA	Milli Amperes
MRB	Material Review Board
OEM	Original Equipment Manufacturer
QA	Quality Assurance
μJ	Micro Joules
WF1	Waveform (refer to ARP5412)

3. BACKGROUND

In 2018, FAA published Amendment 25-146 which moved the requirement for the prevention of lightning ignition sources from § 25.981, to a revised set of requirements in § 25.954. AC 25.954-1 paraphrases § 25.954 Amendment 25-146 requirements as:

- “Ensure catastrophic fuel vapor ignition is extremely improbable;
- Develop CDCCLs, inspections, test procedures, and mandatory replacement times for lightning protection design features; and
- Include the CDCCLs, inspections, test procedures, and mandatory replacement times in the Airworthiness Limitation section of the ICA.”

The wording of § 25.954 at Amendment 25-146 is:

§ 25.954 Fuel system lightning protection.

(a) For purposes of this section—

(1) A critical lightning strike is a lightning strike that attaches to the airplane in a location that, when combined with the failure of any design feature or structure, could create an ignition source.

(2) A fuel system includes any component within either the fuel tank structure or the fuel tank systems, and any airplane structure or system components that penetrate, connect to, or are located within a fuel tank.

(b) The design and installation of a fuel system must prevent catastrophic fuel vapor ignition due to lightning and its effects, including:

(1) Direct lightning strikes to areas having a high probability of stroke attachment;

(2) Swept lightning strokes to areas where swept strokes are highly probable; and

(3) Lightning-induced or conducted electrical transients.

(c) To comply with paragraph (b) of this section, catastrophic fuel vapor ignition must be extremely improbable, taking into account flammability, critical lightning strikes, and failures within the fuel system.

(d) To protect design features that prevent catastrophic fuel vapor ignition caused by lightning, the type design must include critical design configuration control limitations (CDCCLs) identifying those features and providing information to protect them. To ensure the continued effectiveness of those design features, the type design must also include inspection and test procedures, intervals between repetitive inspections and tests, and mandatory replacement times for those design features used in demonstrating compliance to paragraph (b) of this section. The applicant must include the information required by this paragraph in the Airworthiness Limitations section of the Instructions for Continued Airworthiness required by § 25.1529.

Consistent with the guidance in AC 25.954-1 (AMC 25.954), the primary objective of the fuel system lightning protection means should be to provide effective and reliable fault-tolerant ignition source protection resulting from lightning attachment to the aircraft.

Fault-tolerant means the design can preclude ignition sources even when a fault is present. The intent is to ensure protection is provided when each anticipated fault is considered independently. For example, a joint with multiple fasteners may be adequately shown fault tolerant by conducting the lightning-induced current without creating ignition sources when there is a single fault in one of the fasteners, or in some cases (e.g., low current densities) even a common mode failure affecting multiple fasteners may still be shown fault-tolerant. Section 4.7 and Appendix B provide more guidance regarding identification and testing of anticipated faults (including common mode failures and cascading failures).

In accordance with AC 25.954-1 (AMC 25.954), if fault-tolerant protection is not provided at specific locations, the applicant should demonstrate that all practical means have been utilized to provide protection and limit the likelihood of failures. Practicality is defined in AC 25.954-1 (AMC 25.954) as a balance of available means, economic viability, and proportional benefit to safety. A means to provide fault-tolerance against potential ignition sources that is possible with little economic impact is deemed practical even if the potential for catastrophic fuel vapor ignition may be shown to be extremely improbable without them. However, if the means would have a significant economic impact on production, operational, or maintenance costs, it is not necessary to use these means if it can be demonstrated that the failures that could lead to lightning-related ignition sources from that feature and all other non-fault-tolerant designs, when combined, are remote.

§ 25.954 Amendment 25-146 is harmonized with EASA CS 25.954 Amendment 25/26. FAA AC 25.954-1 is harmonized with EASA AMC 25.954, and this ARP is harmonized with EUROCAE ED-303.

3.1 Applicability

This section provides guidance regarding AC 25.954-1 Section 2.

3.1.1 Definition of Fuel System

Section 25.954 includes a specific definition for fuel system in § 25.954(a)(2) which says:

(a) For purposes of this section—

(2) A fuel system includes any component within either the fuel tank structure or the fuel tank systems, and any airplane structure or system components that penetrate, connect to, or are located within a fuel tank.

Previous regulations, guidance, and policy statements used other terms, such as ‘fuel tanks,’ ‘fuel tank structure,’ and ‘fuel tank systems.’ With this definition that is included in the regulation text, for the purposes of showing compliance with § 25.954, the definition supersedes all previous terms and definitions. Appendix A provides background information on the various definitions that are used in other regulations, guidance, and policy statements.

4. APPROACH TO COMPLIANCE

The activities described in AC 25.954-1 (AMC 25.954) and this document require an extensive, structured, and documented process for the fuel system lightning protection design, review and compliance data. Every fuel system component (e.g., valve, fastener, structural member, bracket, sealant, etc.) together with the relevant details of the components (e.g., material, finish, sealant type, etc.) and the relevant installation processes must be identified and documented (which can also be thought of as “catalogued”) by the applicant to show a full understanding and evaluation of the fuel system design. Lightning protection features within the fuel system must be included in the documentation. All anticipated faults for each identified feature must also be documented, along with applicable service history, MRB data, and cross functional engineering experience used to develop the list of faults. Once the lightning environment is defined, further documenting is necessary to associate the specific lightning environment for each fuel system element and interface. The specific lightning environments are compared to the lightning testing, similarity, or analysis data to show fault-tolerance for every catalogued element and interface, where fault-tolerance is practical. Further documentation is necessary to establish the reliability of all protection features, in manufacturing and in service. The primary purpose of these steps and documentation is the demonstration of fault-tolerance, and to establish reliability of the protection features. While this overview is not an exhaustive list of all required compliance activities, it illustrates the exhaustive documenting necessary to adequately show compliance.

Showing compliance involves dividing the design features for fuel system lightning protection into three categories: intrinsically safe, fault-tolerant, and non-fault-tolerant.

4.1 Summary

This document provides supplemental guidance beyond that provided in AC 25.954-1 and AMC 25.954. The guidance is provided using the same main section numbering and titles as the AC. In general, the information in the AC is not duplicated in this document, except where necessary to provide context. The section numbering of the AMC is different because the AMC has fewer major sections, but the subsection numbering is similar.

4.2 Compliance Tasks

Compliance demonstration to § 25.954 and/or CS25.954 to prevent catastrophic fuel vapor ignition due to lightning is required for the fuel system (see Section 2 for definition of “Fuel System”). Various methods are available to aid in demonstrating compliance. The activities described in the following subsections are one example of a structured approach to an ignition prevention certification program. In general, this approach consists of a documented assessment of each lightning protection design and lightning protection feature.

While the guidance herein focuses on new type certificate designs, specific guidance for modifications is detailed where appropriate. Applicants of modifications to existing airplanes may establish an arrangement with the type certificate holder to obtain baseline design/certification data, however the details throughout this document will help applicants who do not have or are not required to obtain such an arrangement. A certification plan proposed by the applicant may be assessed by the certifying authority taking into account the applicant's capability and knowledge of the original baseline design to verify the compliance of the lightning protection at an airplane level. AC 21.101-1B provides guidance regarding limited modifications to fuel tanks considering historical lightning fuel tank regulations and may help in defining the compliance approach within the certification plan. Appendix F provides a summary of the modification guidance contained in the main body of this document.

The recommended compliance tasks are listed below, along with the sections where detailed guidance is provided. The steps are from AC 25.954-1 (AMC 25.954), with the addition of the initial step to create a certification plan:

- Create a Certification Plan (4.2.1)
- Identify the design features and elements of the fuel system that require lightning assessment (4.3)
- Determine the lightning strike zones (4.4)
- Establish the airplane lightning environment (4.5)
- Develop a lightning protection approach and design lightning protection features (4.6)
- Identify potential failures of the design and protection features (4.7)
- Identify potential ignition sources associated with the design features and potential failures (4.8)
- Perform a safety assessment to determine fault-tolerance and non-fault-tolerance (4.9)
- Provide reliable fault-tolerant protection for lightning ignition sources (Section 5)
- Assess non-fault-tolerant protection for lightning ignition sources (Section 6)
- Establish airworthiness limitations (Section 7)

The primary objective in the compliance approach is to demonstrate fault-tolerance of the design. Two methods are presented, and the applicant can use one, or a combination of both methods. The choice of method(s) should be determined early in the program to ensure a robust approach to design and compliance:

- The first method is by demonstrating the fault-tolerance for each installed component and interface. The AC and the majority of the guidance in this document are written based on this general fault-tolerance approach.
- The second method (Fault-Tolerance by Redundancy) also demonstrates fault-tolerance but achieves this by demonstrating the redundancy provided by multiple, independent, and effective protection features within the design. The differences between this method and the general fault-tolerance method are discussed in subsections referring to “Fault-Tolerance by Redundancy.” The majority of the steps listed above for the general fault-tolerance method still apply when using the Fault-Tolerance by Redundancy method. The primary differences are:
 - When utilizing the Fault-Tolerance by Redundancy method the design focuses on providing redundant protection features for each ignition source. This method may be preferred when developing new aircraft with new design and manufacturing processes where it may be difficult to predict all potential fault conditions that will need to be addressed, due to the lack of in-service or manufacturing experience available at that time.
 - During compliance demonstration, the analysis or test is focused on showing that the redundancy provides effective and independent means of precluding ignition sources. Where providing redundant protection features is not achieved, the steps for compliance as described in Section 6 are utilized.

These differences, as well as other minor variations to the other steps are described in further detail in the sections identified by the phrase “Fault-Tolerance by Redundancy.”

4.2.1 Create Certification Plan

Although not discussed in AC 25.954-1 (AMC 25.954), the first step recommended toward demonstrating compliance is creating a certification plan. Aircraft certification applicants should describe the fuel system lightning protection approach and analytical procedures and/or qualification tests planned to show the effectiveness of the aircraft fuel lightning protection. The plan is submitted to the certifying authority. Coordination with the certification authority early in the program will help minimize risk. The certification plan should adequately communicate the compliance showing activities and should include, but not be limited to, the following general information:

- Description of the fuel system physical design (including both the fuel tank systems and fuel tank structure) and functional description of the fuel tank systems.
 - The description should explain the primary aspects of the design highlighting any unique characteristics.
 - Figures (figure, block diagram, etc.) are recommended as an aid to support this description.
- Description of the lightning zonings overlaid on the fuel system figure as well as specifying the applicable revision of ARP5414 (ED-91).
- Description of the lightning Zone 3 direct attachment applicability and associated considerations. This applicability is determined based on the revision status of the ARP5414/ED-91 for each particular certification program (see Table 1 in 4.4).
 - This selection may involve establishing the airplane as a “large transport” or “not large transport” category airplane or establishing those lightning protection design features that are considered as “new or novel” or not “new or novel.”
- Description of the process used to establish the applicable lightning environments for the fuel tank structure and fuel tank systems.
 - This should include the proposals for the utilization of test methods and analyses (including similarity to designs certified to the same airworthiness requirement if applicable) for the identification of the lightning environments.

- Description of the process for how the design features and elements are identified, grouped (as applicable), and evaluated. The process should be organized, comprehensive, and complete.
- Description of the process for identifying the potential failures of the design, ensuring the unique aspects of failures from manufacturing escapes, operational deterioration, and accidental damage are addressed.
- Description of the process for identifying the contribution of the potential failures to the development of an ignition source. The process should address how failures contribute to different types of ignition sources (voltage sparks, thermal sparks, edge glow, etc.) and how those contributions will be verified.
- Description of the process, format, and assumptions of the safety assessment to establish the fault-tolerance of the design features of the fuel system.
- Description of the process (testing and analyses) for demonstrating that the characterized fault-tolerance is effective and reliable, including the recording of assumptions used to identify worst-case failures. The process for evaluating the impact of the in-service considerations ensuring the fault-tolerance remains effective and reliable should be included.
 - Description of how development testing will be used to supplement certification testing, if applicable.
- Description of the assessment process for establishing that all practical measures will be taken to minimize any non-fault-tolerant designs, including all applicable assumptions that will be used.
 - Describe the analysis that will be used to establish the flammability in the area of the non-fault-tolerant designs.
 - Clearly delineate if a qualitative or quantitative approach will be utilized to identify the acceptability of the non-fault-tolerant designs. For quantitative analysis, the basis of the numerical data and the assumptions proposed to be included should be clearly documented.
- Description of the development of Airworthiness Limitations (AWL).
 - Description of the process for how the critical design features and elements will be identified and protected against damage to the integrity of the type design during aircraft production, operation, and maintenance.
 - Description of the process for establishing any mandatory replacement times and/or inspection intervals should be described.
 - The process should be organized, comprehensive, and complete.
- Description of the structured documentation process used to identify and document the compliance data.

Due to the complexity and large quantity of activities associated with this certification effort, the first submittal of a certification plan may not include all program details. It is recommended to include as much detail as is available initially and where necessary update the certification plan periodically.

4.3 Identify the Design Features and Elements of the Fuel System that Require Lightning Assessment

This section describes the initial step of the extensive documentation and cross functional reviews that are necessary to show compliance.

4.3.1 Identify the Design Features and Elements - General

All structural and system components and interfaces inside the fuel tank and all fuel system components outside but interfacing with the fuel tank structure must be considered for § 25.954 lightning ignition prevention requirements.

Compliance to § 25.954 is necessary for the fuel system, which is explicitly defined in the regulation as including any airplane structure or any system components (hydraulic, fuel, electrical, etc.) that “penetrate, connect to, or are located within a fuel tank.” It is relatively clear to identify what this includes inside the tank. For clarity, the following examples are provided for what the phrase “connected to” includes, and does not include, outside the tank:

- The structure used to contain fuel are included in the fuel system. This includes the structural tank walls (e.g., the skins, spars, tank end ribs, etc.) and all fasteners penetrating the tank walls are included in the fuel system. The adjacent structural elements (e.g., leading edge flaps, trailing edge flaps, ailerons, engine pylons, etc.) themselves are not included in the fuel system, however the lightning current flowing through them to the tank structure or connected systems installation must be considered (see 4.5). The volume within the adjacent areas (e.g., leading and trailing edge) are also not a part of the fuel system.
- Similarly, lines which are intended to contain fuel itself (e.g., engine and APU feed lines) and are connected to the fuel tank are included in the fuel system. The volume and physical elements surrounding these external fuel lines, including that enclosed by a shroud around the fuel line, are not considered a part of the fuel system. The lightning current flowing through these external lines to the tank must be considered (see 4.5).
- Wiring, electrical/electronic equipment, and associated interfaces directly connected to systems inside the fuel tank are a part of the fuel system.

For components in the areas adjacent to the fuel system that do not meet the definition of “fuel system” defined in § 25.954(a)(2), § 25.954 does not apply. It is noted that for areas adjacent to the fuel system compliance with § 25.863 is required and typically based on design methods including providing ventilation, drainage and minimizing the potential for ignition sources.

A detailed, documented, and thorough review of all fuel system installation drawings, assembly drawings, detail drawings, and process specifications is necessary. This review, together with identifying and documenting the design element grouping discussed below, should be started early in the design process and updated as the design evolves. The review process should be cross-functional including input from all design areas (e.g., lightning/EME, fuel systems, structures, electrical, hydraulic, etc.) involved in the elements that conduct lightning currents and provide protection from ignition sources.

Focus should be placed on interfaces in which filament heating, voltage dielectric breakdown, arcing (sparking or hot particle ejection due to excessive current flow through path), or hot spot formation could occur. These interfaces and components may include, but are not limited to the following:

- Structural interfaces
- Fastener installations
- Fuel system, inerting system and hydraulic system tubes and couplings
- Wiring and associated equipment
- Fuel quantity probes/fuel level sensors
- Fuel pumps
- Fuel valves
- Fuel vents
- Fuel and water drain valves
- Fuel tank access panels

The elements identified should be organized into groups based on similar lightning protection feature characteristics. Design features relevant to lightning protection performance can be used to identify design groups. These design features may include material properties, electrical contact area, fastener hole-size fit, material thicknesses, finishes (e.g., metallization, non-conductive coatings), fastener types and sizes, etc. Features affecting lightning current density, DC resistance, isolation, and other applicable characteristics should be considered when assigning structural and systems components and interfaces into design groups.

Skin attachments, support brackets, component interfaces, rib to spar interfaces, wing-mounted engine pylon mounts, and landing gear mounts/trunnion fittings, are examples of interfaces where lightning protection elements may exist in the fuel tank. Examples of fastener families/design groups for fastened joints and fastener types are provided below:

- Countersink head fasteners
- Protruding head fasteners
- Removable screws with a domed or riveted nutplate
- Removable screws with a threaded insert
- Solid aluminum rivet
- Blind, pull-type rivet
- Fasteners with swaged collars
- Fasteners with threaded nuts

The quantity of fastener design groups may be in the dozens, and the list above is for illustration purposes only. Multiple groups or sub-groups may be necessary due to basic installation differences. For example, within an overall group of protruding head fasteners, two sub-groups could be defined; one for different head contact areas, and one for installations with different levels of contact interference. When identifying testing, it may be shown that testing of one group will conservatively address another. For example, protruding head tension fasteners generally have larger mating areas than protruding head shear fasteners, thus test results for shear head fasteners, which have less mating area, may be used to conservatively demonstrate performance for tension head fasteners which have more mating area. In this example, the shear head fastener sub-group would be identified for testing and is sometimes referred to as “worst case.” It is important to provide a detailed discussion of every feature used to determine the design groups. This can help pre- and post-certification activities related to adding or changing fasteners, and to determine if additional testing is required or if similarity may be used.

When identifying design groups, it is prudent to think forward to the certification test program and the required test specimens. Grouping design elements with consideration of protection features may simplify the identification of test specimens to represent multiple items, and to minimize testing.

Examples of features to consider when developing design groups include:

- Similar materials, fastener types, and surface finishes
- Types of mechanical loading (i.e., load bearing purposes, tension, compression, shear)
- Similar lightning exposures, such as direct strike or conducted current only
- High or low conducted current densities
- Similar production processes (e.g., manual drilling, robotic drilling, pre-drilled versus drilling on assembly, etc.)
- Fuel tube fitting/coupler material, torque, geometry

An alternate method of grouping is by the lightning protection features, instead of the design features. This may facilitate grouping of test configurations.

Grouping by lightning protection features may include:

- Bond types
 - Fay surface electrical bond
 - Interference fit fastener bond
 - Spot face bond at fastener head/tail mating surface
- Arc containment feature
 - Fastener encapsulating seal
 - High torque fastening
 - Fillet seal around fuel tube fitting interface
- Insulation feature
 - Fuel tank primer at structural interfaces
 - Isolators on fuel or hydraulic tubing inside the tank
- Current diversion applied to external surfaces
 - Metallic foil on the wing skin
 - Insulating films on the wing skin along fastener rows

Groupings can be further defined (sub-groups) based on the lightning threat level. Low threat joints might perform adequately with smaller diameter fasteners or thinner gauge materials. If a higher than required current threat is applied to a joint that is smaller in fastener diameter or thinner gauge in order to reduce testing, the test approach adds risk of test failure. See 4.4 and 4.5 for further discussion of lightning threats.

Grouping may also need to account for different environments. For example, an installation in an external wing spar area may have much different aging characteristics than a similar installation inside the fuel tank or fuselage.

When developing design groups, it may be beneficial for the applicant to consider the design groups used on previous certification projects to facilitate compliance by similarity.

4.3.2 Identify the Design Features and Elements - Fault-Tolerance by Redundancy Method

As described in 4.3.1, a design review is performed to identify the fuel design interfaces and all possible locations where ignition sources could create a fuel vapor ignition hazard and therefore require lightning protection. Threat levels are identified as described in 4.4 and 4.5. The potential lightning ignition sources are described in detail in 4.8.2.

The difference when utilizing the Fault-Tolerance by Redundancy design approach is that early in the development of the design and protection features, the applicant should identify redundant independent protection methods for each applicable type of ignition source (see 4.8.2), unless the design is shown to be intrinsically safe as described in AC 25.954-1 (AMC 25.954) and 4.9.4.1 of this document.

4.4 Determine the Lightning Strike Zones

It is recommended that the zoning guidance provided in ARP5414 (ED-91) at the latest revision be utilized as it is based on the latest industry data and recommendations, unless agreed to by the certification authority to utilize an earlier revision of ARP5414 (ED-91).

Zoning of the aircraft is performed to identify the aircraft surfaces where lightning strike attachments are likely, and unlikely to occur. It is especially important to identify zoning and thus lightning attachment points for fuel tank structure and connections to the fuel tank, such as flight control surfaces, landing gear, wing-mounted engines, wing-mounted antenna, winglets, etc. High lightning conducted currents are associated with lightning attachments to these connections and should be carefully considered.

Identification of the lightning zones should be completed early in the design process, before locations of surface mounted system components (e.g., drain valves, vent outlets, filler caps, and other equipment potentially exposed to direct attachments) and design of structural attachments to the tanks (potentially paths for high density conducted currents) are finalized.

At the time of the publishing of AC 25.954-1, September 24, 2018, revision B to ARP5414 had not been finalized (released December 2018). AC 25.954-1 Appendix A Section A.8 references ARP5414A for zoning guidance. AC 25.954-1 Section 4.8.1 states:

“If the airplane uses novel or unusual materials, structure, or configurations, the applicant should evaluate fuel system fasteners, structure, equipment, and components on the outside surface of the airplane located in lightning Zone 3 using the nominal Zone 3 direct lightning attachment waveforms defined in SAE ARP5412. Use of materials for fuel tank structure that are not highly conductive is considered unusual. Lightning attachment in Zone 3 is defined as unlikely in SAE ARP5414, so the evaluation need not consider failures in combination with such an attachment but should demonstrate no catastrophic effect will occur when no failures are present.”

ARP5414 Revision B (ED-91 Revision A) includes the current industry recommended practices for lightning zoning. ARP5414 Revision B includes Zone 3 direct attachment requirements for all “large transport aircraft,” instead of for “new or novel” (ARP5414A), or “novel or unusual” (AC 25.954-1) designs. ARP5414 Revision B also includes significant changes to identification of Zone 2 areas. ARP5414 Revision B identifies that:

“Large transport airplanes should incorporate protection for direct lightning attachment to the exposed surfaces of the wing in Zone 3. Data for large transport aircraft in-service lightning strikes show that direct lightning attachments on large transport airplane exposed wing surfaces designated as Zone 3 occur infrequently. Because of the low rates associated with such attachments on large transport airplane wings, these attachments are unlikely. Therefore, the lightning protection for direct lightning attachment or associated conducted currents should not be required to demonstrate tolerance for faults or failures when considering direct lightning attachments on exposed large transport airplane wing surfaces designated as Zone 3.”

With the exception of “new or novel” designs, direct attachment in Zone 3 does not need to be considered when zoned per ARP5414A. With the exception of “large transport airplanes,” direct attachment in Zone 3 does not need to be considered when zoned per ARP5414B. Section 6.5 of this ARP provides details regarding exclusion or inclusion of faults during Zone 3 direct attachment and associated conducted currents, as defined in AC 25.954-1 and ARP5414/ED-91. Refer to ARP5414B Appendix A.1 for further information on what constitutes a “large transport airplane.” Applicants should identify in the certification plan whether their airplane is considered “large transport.”

It is also noted that at the time of the initial release of this document, ARP5412B, 6.4.1 defines the test levels for “direct lightning attachment in Zone 3 areas for new or novel designs.” This reference to Zone 3 direct attachment for “new or novel designs” was consistent with ARP5414A that was current at the time ARP5412B was published but does not supersede the current criteria for the zoning requirements defined in ARP5414B. ARP5412 defines test environments only. ARP5414 establishes the applicability of those test levels to the aircraft lightning zones.

Further, AC 20-155A Section 4 titled “Industry Documents on Lightning” states:

“The following industry documents define the characteristics of lightning flashes and how lightning attaches to aircraft. Aircraft and aircraft equipment designers should use these recommended practices when developing lightning protection for aircraft structures as well as fuel, and electrical and electronics systems.”

ARP5414B is listed in AC 20-155A, although at the time revision B was not yet published. Although the listing of Revision B for ARP5414 was premature, it is now an appropriate recommendation.

The following table summarizes the different lightning Zone 3 direct attachment considerations that the applicant must address, as part of the compliance demonstration process, depending on which revision status of the lightning zoning guidance document is agreed in the certification plan.

Table 1 - Zone 3

Zoning per ARP5414A (ED-91)	Consider Direct attachment in Zone 3?
New or novel design features	Yes
Not new or novel design features	No
Zoning per ARP5414B (ED-91A)	
Large transport airplanes	Yes
Not large transport airplanes	No

4.5 Establish the Airplane Lightning Environment

To demonstrate the lightning protection capabilities of the design, the applicant must assess the lightning environment. As lightning attaches to one aircraft location and exits another, the lightning current will distribute through many aircraft components. For the purposes of this document, the transient currents, voltages, and electromagnetic fields developed in the fuel system and the resulting effects make up the airplane lightning environment. These lightning transients include waveforms and amplitudes that must be determined for all design features and design groups of the fuel system requiring lightning protection. It is important to recognize that many different lightning current distributions could occur in the fuel system depending on the entry and exit points of the lightning channel. The transients need to be defined for all appropriate entry and exit locations. The airplane lightning environment is divided into two primary categories:

- Direct attachment environment
 - The lightning environments for direct attachment are provided as idealized waveforms in ARP5412 (ED-84). Idealized waveforms and amplitudes are to be considered for direct attachment in lightning Zones 1, 2, and potentially 3 as determined according to 4.4 on lightning zoning.
- Conducted current and voltage transient
 - Lightning currents flowing throughout the aircraft will create electromagnetic fields throughout the fuel system, with currents and voltages developing on internal structures and systems. Conducted currents include currents at external interfaces as well as currents at internal interfaces.

All design features should be assessed to establish likely attachments that could cause the most severe lightning environment. For example, if a feature is in a lightning Zone 3, but is next to a Zone 1 both the direct attachment Zone 3 currents and the conducted currents resulting from a nearby Zone 1 direct attachment should be considered when establishing the most severe environment for the feature. Approaches for assessing the current and voltage lightning environment waveform characteristics may include test, analysis, comparison with similar aircraft data, or some combination of these. Other options may be used, if adequate confidence can be achieved in the lightning environment definition and should be discussed in the certification plan. A combination of testing and analysis may provide the most thorough lightning environment definition throughout an aircraft fuel system with the least uncertainty.

For each design feature and group identified in 4.3, the applicant must determine the appropriate specimen and method for lightning environment definition. Details about aircraft specimen selection are covered in 4.5.1.2. The same environment definition method does not need to be used for all fuel system design features or groups. If using a combination of testing and simulation, some environments may be defined directly from the testing while some may rely on a simulation model that was validated with the same testing. There are practical and economic implications to the method chosen for establishing environment definitions. The applicant should carefully consider all options and decide what will provide the best solution for the aircraft being certified. Regardless of the technique used to determine the lightning environment, the applicant should be able to justify that the environment is appropriate for the design feature in question and be able to establish appropriate margins for the environment.

There are commonly two categories of environment definition in this process: the actual environment, and the verification environment. The actual environment is made of the measured or simulated waveforms determined from lightning interaction with the aircraft specimen. This typically involves measurements or probing at the design feature location in the specimen. Some evaluations about uncertainties or conservativeness of the actual environment determination technique should be performed. The actual environment is not typically used for verification coupon testing. There are margin development and waveform reduction activities that should be performed to convert from the actual environment to the verification environment. The verification environment are waveforms applied to coupons during ignition detection testing or during analysis to demonstrate compliance.

- Actual environment - The current or voltage waveforms determined from lightning interaction with the aircraft specimen considering the possible combinations of entry and exit points.
- Verification environment - The lightning waveforms that are used during coupon ignition detection testing to demonstrate compliance.

A thorough review of all fuel system components, interfaces, and lightning attachment points should be performed to ensure the appropriate lightning entry and exit locations are used for setting each design group's actual environment. The rationale for selecting entry and exit locations should be documented as part of the process as described in 4.4. The logical process for lightning environment definition, starting with the complete list of features identified in 4.3 and ending with the complete environment definition is illustrated in the Figure 1 flowchart.

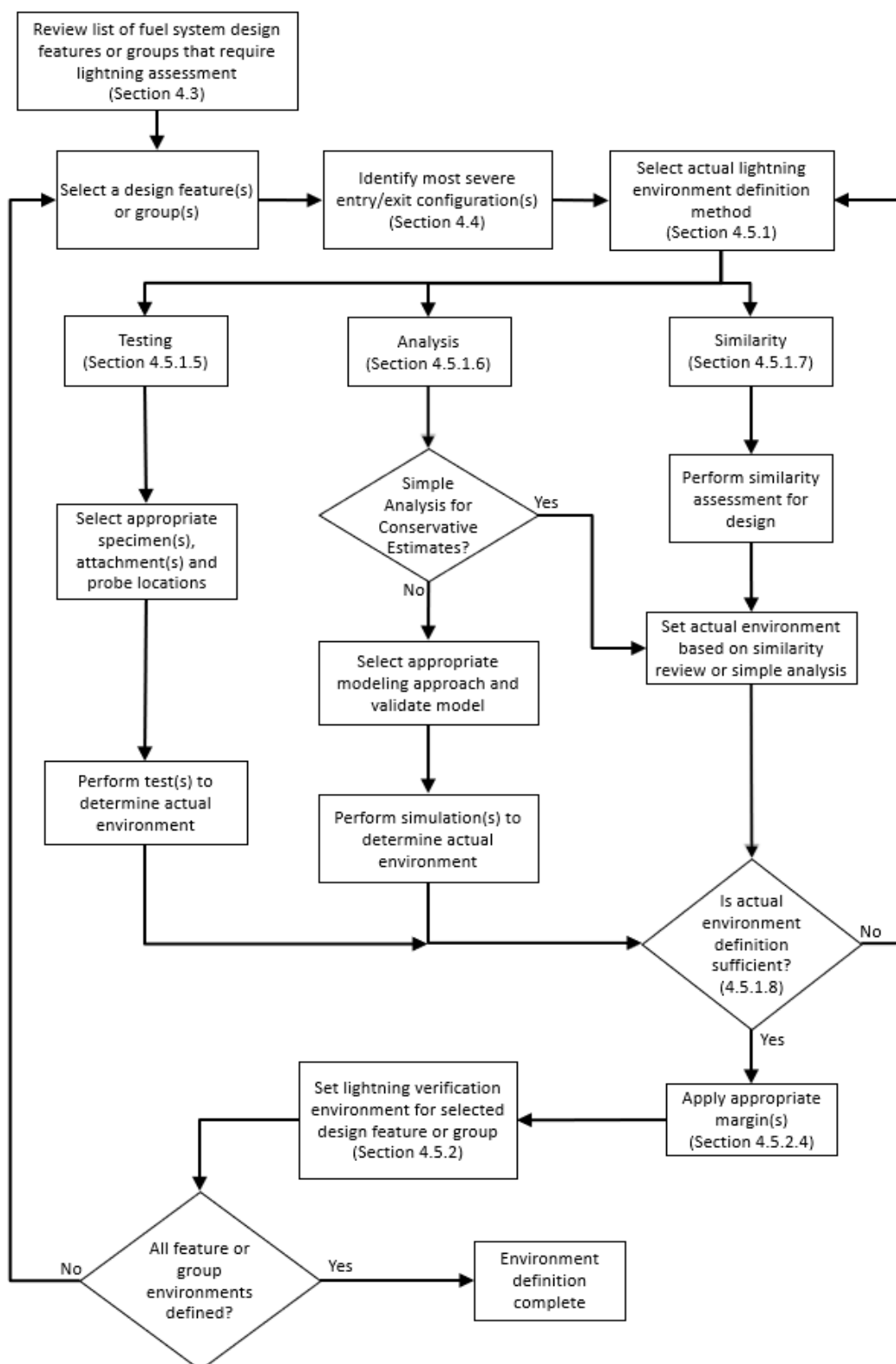


Figure 1 - Lightning environment definition process

4.5.1 Actual Environment Definition

There are three primary methods for determining the aircraft actual lightning environments: testing, analysis, or similarity. If establishing lightning environments from a similarity method, not all the steps outlined in this section may apply, but the applicant should ensure that the final verification environment is appropriately selected. If no prior lightning interaction data is available, the applicant will have to decide whether testing, analysis, or some combination of the two is most appropriate for each design feature. It is highly recommended that the design feature grouping performed in 4.3 is conducted in a way to minimize the total number of environment specifications required. It is also helpful to prioritize the features and identify locations in the fuel system that may be most severe for each design feature group. There are thousands of interfaces associated with aircraft fuel system and defining the specific lightning environment at every interface may not be practical.

4.5.1.1 Environment Definition Plan

It is important to establish an environment definition plan identifying which method will be used for environment definition, what specimen(s) will be used, and how uncertainties will be addressed. It is possible to have one environment definition plan that covers all fuel system design features or to make several different plans if multiple methods or specimens will be used. This environment definition plan should be reviewed with certifying authorities to gain concurrence before proceeding. It may be necessary to define individual test or numerical simulation plans that are separate from the overall environment definition plan. Some of the details covered in the environment definition plan might include:

- Environment definition objectives and applicability of results
- Design features covered in the plan
- Specimen(s) used for environment evaluation
- Approach(es) to environment definition/characterization
- Method used to determine lightning transients
- Lightning attachment scenarios
 - Lightning entry/exit locations
 - Lightning input waveforms
- Transient probe locations for specific design features
- Uncertainty characterization and validity of results assessment
 - Margin strategy may be part of this plan or addressed separately
 - Including aircraft specimen considerations
- Post processing or waveform reduction to set verification environment

4.5.1.2 Aircraft Specimen Considerations

Fuel system lightning environments may be determined on aircraft specimens of varying complexity. For each design feature, the applicant should select the appropriate specimen for determining the lightning environment and justify its relevance for the demonstration. If not using a full production aircraft, it may be necessary to have multiple specimens to adequately characterize the lightning environment for all design feature groups. It is important that manufacturing processes and materials are representative of the aircraft. This approach equally applies to all fuel tank structures and systems. Possible specimens in order of decreasing complexity may include:

- Full production aircraft
- Aircraft production standard components (e.g., full wing, center wing or full engine with pylon mounts)
- Large scale specimen (e.g., wingbox spanning several rib bays which may include fuel tank systems)
- Sub assembly specimens (e.g., skin to rib interface, panel to panel interfaces)

Additional details about how lightning environments are characterized for the various specimens are provided within testing and simulation sections below. There are several considerations applicants should balance when selecting appropriate specimens that may include:

- The larger the specimen, the greater the complexity associated with testing and simulations
- Large specimens may accurately represent EM response of aircraft to lightning, but transients may be difficult to capture inside the specimen and uncertainties may be difficult to quantify
- The smaller the specimen, the greater the uncertainty that the environment definition matches what would occur on a production aircraft
 - This uncertainty may be overcome if the specimen represents a severe configuration of the design feature in question
- Using smaller specimens may require multiple specimen tests or analyses. The number of specimens required depends on the number of design feature environments requiring definition and the scales of the specimen.

4.5.1.3 Approaches for Environment Definition

The lightning environment should be characterized to understand the most realistically severe environments for the aircraft. There are three common approaches to assess the fuel system lightning environment and justify the lightning environment is realistically severe. These approaches may apply to all environment definition methods and there may be some overlap in the approaches.

The approach selected for characterizing the environment influences the margin levels applied to actual lightning levels to arrive at the final verification environment.

4.5.1.3.1 Predictive Approach

The environment is determined for a specimen that matches the actual aircraft design. The goal is to obtain as faithfully as possible fuel system lightning transients that may exist for a single aircraft. Margins are added to the actual transients to ensure reasonably severe waveforms are used for verification.

While using a full production aircraft does ensure the most representative specimen is used for environment definition, there are complexities in testing or simulating a full aircraft. There may be little uncertainty that the specimen captures all pertinent electromagnetic aspects, but greater uncertainty in the method used to characterize the actual environment on that specimen. For testing, it may be difficult to measure lightning transients through large structural interfaces and there are many areas of the fuel system that are difficult to access with test equipment. As far as numerical simulation is concerned, it may be difficult to recreate all electric current paths that exist within the actual aircraft and to match the complex electromagnetic parameters associated with all aircraft materials and interfaces.

Although this predictive environment definition tends to accurately reflect all design features of the configuration it may not be able to evaluate the impact of the installation and design tolerance variabilities by itself. The applicant may have to perform some sensitivity analysis or account for these variabilities in the margin definition.

4.5.1.3.2 Conservative Approach

The environment determination is performed in a way that is ensured to be severe for the design feature in question. It is important to note that it may not be possible to construct a specimen that is conservative at all locations for all design features. Justification must be provided as to why the test configuration or model definitions are conservative for the design feature in question. The results using this technique may allow lower margins than those used for the predictive technique and depend on how convincing the justification is for conservatism. If significant conservatism is used in the environment determination, then the most severe environment is captured. It may be possible to use the conservative environments with this approach without applying additional margin.

Environment definition using the conservative approach may need to be complemented by supplementary analysis/small coupon tests to ensure a conservative approach in the environment definition. For instance, and in relation with 4.5.1.1, uncertainties due to non-linear behavior of the current distribution must be accounted for in relation with the way the test results are extrapolated and used in the compliance process.

4.5.1.3.3 Range Assessment

This approach is sometimes referred to as a sensitivity analysis where EM parameters of the specimen are adjusted within reasonable limits of aircraft product variances to understand the range and limits of lightning environment results. The output using this approach is the possible range of lightning transients that a design feature could experience. In a sense, this is another way of establishing conservative results but has the added benefit of understanding the range of results in a detailed way. Additional margins may not be applied to the results if sufficient justification is provided that the range of results covers reasonably severe cases. This approach is helpful for applicants needing to justify or quantify the ranges of transients associated with product variability.

4.5.1.4 Uncertainties in Environment Definition

Lightning interaction with aircraft is a complex phenomenon. There are uncertainties that applicants should consider when selecting appropriate specimens or methods for environment definition. There are uncertainties with testing and simulation techniques and the methods used to obtain fuel system environment transients. It may be appropriate to consider the following types of uncertainties when justifying an environment definition technique.

- $U_{demonstration}$: Uncertainty associated with techniques used to define the lightning environment and demonstrate accurate lightning characterization. This uncertainty reflects both the representativeness of the specimens employed to evaluate the environment and the accuracy of the methods used.
- U_{PVT} : Standard Product Variability/Tolerances Uncertainties - This variability/uncertainty type encompasses aspects such as normal fleet variation of aircraft parts, processes, production, environmental or aging effects. It may be difficult to evaluate multiple large or medium scale specimens to quantify this kind of uncertainty through testing. The applicant should have an understanding about the variabilities of their aircraft design but may be able to use a qualitative margin to cover this uncertainty.

It is not recommended to perform a complete characterization of all the sources of uncertainties for each certification process. In some cases, pre-existing robust and reliable test articles or simulation models may already be available and their validation for use as a certification means should have been previously established. In these cases, $U_{demonstration}$ can be considered negligible or significant up to a known level to define the set of margins required for certification.

The uncertainties associated with demonstration ($U_{demonstration}$) should be addressed during the specimen design, construction, and environment determination activities. The product variability type of uncertainty should be addressed as part of the aircraft design and manufacturing and may be an input to the specimen design and uncertainty evaluation.

Applicants should provide justification that the environment determined represents the actual aircraft behavior when exposed to the lightning threat. It is not the intention of the following uncertainty discussion to add unnecessary complexity to the certification process but to provide some background and explanations which can be used by applicants to understand uncertainties and justify margins. Additional details are provided in the next section to clarify the uncertainties listed above and discuss how they may be considered by the applicant.

4.5.1.4.1 Demonstration Uncertainty

When evaluating the lightning response of the aircraft, there are three primary concepts to consider when justifying the technique.

- How well does the specimen design selected for environment definition (either for testing or simulation) match the configuration?
- How well does the specimen built (physical test specimen or simulation model) capture the important electromagnetic properties of the aircraft design?
- How well does the selected method (test or simulation) produce the lightning environment in the actual specimen and determine the lightning transients throughout the specimen?

Using an unmodified production aircraft to characterize the lightning response of the aircraft minimizes uncertainty.

By considering the questions listed above, the applicant may perform evaluations of the specimen and assess the accuracy of the technique.

The environment definition specimen should include representative aircraft materials and manufacturing processes to capture current paths and appropriate electromagnetic coupling mechanisms. It may not be practical to include all aircraft details into a test or simulation article. If the environment evaluation article has variations from production quality parts or processes, it is appropriate to consider how these differences may affect the results. If justifiably conservative specimens are used, additional increase of the margin may not be necessary.

Once the specimen is designed, the actual build of the test article or simulation model should be carefully considered. For testing this relates to the physical materials, manufacturing, and assembly processes. This aspect of uncertainty may be lower when using testing because there is greater confidence that the physical specimen accurately captures the important EM features of the aircraft design. For numerical simulation, the uncertainty of the model build relates to component representation, CAD defeaturing, component connectivity and, material properties. It may be appropriate for simulation to use conservative values for EM parameters or perform sensitivity analysis to understand how simulation parameters impact the lightning environment definition.

The final uncertainty aspect in the demonstration process deals with how well the technique reproduces and characterizes the lightning environment in the specimen. For testing, there may be uncertainties associated with test and equipment setup, source, and noise generation, return network effects, probe positioning, modification of specimen geometry, and data acquisition. For simulation, uncertainty may be related to numerical technique, algorithm accuracy, source application, boundary conditions, probe positioning and data acquisition.

4.5.1.4.2 Standard Product Variability and Tolerances Uncertainty

The uncertainty with design tolerance and product variability (U_{PVT}) relates to how the aircraft response may vary across the fleet and its lifetime when exposed to lightning. Substantial differences exist between this source of uncertainty and the $U_{demonstration}$ described above. It should be noted that the $U_{demonstration}$ deals with uncertainties in techniques to quantify the lightning environment whereas U_{PVT} is a real feature of the product under scrutiny that is inherent to its design, fabrication and actual performance that cannot be determined from one specimen. U_{PVT} refers to the variability on design features that are consistent with the product specification. Examples of this variability are the requirements on maximum electrical resistance on bonding (any value acceptable below the established threshold) or on relative location of installation features (fuel pipes versus EWIS).

This uncertainty is not generated by the means used to establish the lightning environment (either test, simulation or both combined), but these means may be used to characterize the impact of this variability. To evaluate product variability, the applicant may perform some testing or simulation to understand the range of critical resistance parameters of their fuel system design and how the environment definition is sensitive to these parameters. This sensitivity analysis can be performed either via testing or simulation means but the best approach may be to use a combination of both techniques in order to maximize the reliability, versatility and completeness of the results.

4.5.1.5 Testing

Testing is one method for determining the airplane lightning environment. ARP5416 (ED-105) and ARP5415 (ED-158) provide guidance on performing these types of tests for full aircraft. ARP5416 (ED-105) also describes some tests on different fuel system specimens although many of these tests are meant to assess damage or perform pass/fail criteria testing. Lightning environment definition tests do not necessarily have pass/fail criteria and are meant to characterize the lightning environment on the fuel system. If some environment definitions are insufficient using testing alone, full aircraft testing may be supplemented by analysis.

As mentioned in the specimen scale considerations in 4.5.1.2, lightning testing may be performed on aircraft specimens of varying size and complexity. For each design feature, the applicant should select the appropriate specimen design to determine the lightning environment. It may be necessary to have multiple test articles to adequately characterize the lightning environment for all feature groups of the fuel system.

4.5.1.5.1 Test Plan

It may be appropriate to establish a test plan identifying how testing will be used for environment definition, approximations used, uncertainty characterization techniques and how margin strategy will be developed. The test plan should introduce test objectives, test setup, procedures, data acquisition and applicability of results to ensure an accurate and meaningful test outcome. The test plan should be reviewed with certifying authorities to gain concurrence. Some of the details covered in the test plan might include:

- Test objectives
- Specimen design(s)
 - Scale(s)
 - Configuration
- Injection scenarios
 - Injection technique (pulse or CW)
 - Lightning entry/exit locations
 - Lightning input waveforms and excitation method
- Data outputs
 - Probe locations
 - Results processing and waveform reduction
- Uncertainty characterization
 - Margin strategy
- Data applicability
 - Scope of validity, where test results may be used

An acceptable logical process for determining the test injection locations and appropriate test points is provided in the list of steps below.

- Identify all design features and groups that require environment definition (4.3)
- Review aircraft zoning to identify all direct attachment locations into the fuel tank (4.4)
- Identify highest current conduction paths into the fuel tank (i.e., main landing gear fitting, engine fittings, fastener attachment, wingtip distribution, inboard flap fitting, or aileron hinge attachments)
- Use direct attachment and severe conducted current conditions to determine which locations in the fuel system will be measured for each feature or group
- Define detailed measurement locations for inclusion in the test plan. Measurements may need to be taken for multiple entry/exit configurations to ensure the most severe environments are captured.

4.5.1.5.2 Full Aircraft Tests

Applicants may use a full production aircraft specimen for fuel system environment definition. As with the indirect effects LTA testing, these tests are typically performed with low-level current injections. Most of the test approaches and considerations identified in ARP5415 (ED-158) and ARP5416 (ED-105) for full aircraft tests are applicable to the full aircraft test performed for fuel system environment definition with the following notable exceptions:

- Lightning injection entry and exit points will differ
- Test measurements will generally occur on fuel tank structures and systems rather than exclusively on electrical harnesses
 - Current measurements occur on components such as fuel tubes, hydraulic tubes, stringer clips, rib shear ties, bonding jumpers, brackets connected to the external fuel tank structure, etc.
 - Voltage measurements are made at locations such as fuel quantity wiring to ribs or skins, pipe to rib voltages, across dielectric isolators, etc.
 - Magnetic field (B-dot) measurements are related to the current densities beneath the probe and can be used to determine magnetic field intensity above conductive structural components

Test current entry and exit points for all specimen types should be specified in the test plan and based on zoning. These entry and exit points should be selected to conduct test currents through those portions of the specimen that contain all design groups being considered. For example, on a full aircraft specimen, a measurement made on a fuel tube should consider the maximum 200 kA component A current flowing through the wing from a wingtip to wingtip strike. However, if that same fuel tube connects to a rib with a fastener in Zone 2A, it may be necessary to consider an entry point via a rib fastener. The test current would then be concentrated through portions of fuel system containing the design threat being measured, thereby inducing the maximum voltages or currents at this location. Table 2 defines some possible current entry and exit points that can be considered to stress the fuel system with different current distribution patterns. This list of entry/exit points is not mandatory and does not cover all possible scenarios.

Table 2 - Aircraft test entry and exit point examples

Entry	Exit
Zone 2A Wing Fastener	Tail
Zone 2A Wing Fastener	Landing Gear
Zone 2A Wing Fastener	Opposite Wing Tip
Wing Tip	Tail
LH Wing Tip	RH Wing Tip
Wing Mounted Engine Nacelle	Opposite Wing Tip
Wing Mounted Engine Nacelle	Tail
Nose	Wing Tip



The total number of measurements necessary to fully characterize the lightning environment in the fuel system will depend on the complexity of the applicant's approach. Using a conservative approach to grouping structural interface types may result in a large number of measurements. If the applicant has a greater number of design feature groups, a full environment definition may require many measurements.

Depending on the configuration of the structure and systems in the fuel tank, it may be difficult to take measurements to characterize all design feature environments. For example, it may not be possible to measure currents through several fasteners at a large structural interface or currents flowing between skins and stringers. The physical measurement approach may require intrusive probe connections around some structural and systems components which modify the natural lightning response and introduce added uncertainty to the measurement. These are not pass/fail tests, and the test plans should allow for aircraft modification and exploration of test probe locations during testing so that the maximum benefit of testing can be achieved.

4.5.1.5.3 Smaller Specimen Tests

If the applicant decides it is not practical to define all lightning environments on a production aircraft, it is possible to utilize smaller specimens. It is likely the applicant will have to generate numerous specimens to fully determine the fuel system lightning environment. In general, there is no set number of smaller specimens the applicant must test, but the number should be related to the design feature groups determined in 4.3. Many of the test details will be similar to those identified in 4.5.1.5.2 for the full aircraft testing.

Some benefits of smaller scale specimens are that modifications to the test specimen may be allowable whereas they would be not possible in a large scale production test article. These modifications might include holes drilled through components to accommodate test probes or adjusting the configuration to understand variances associated with the test specimen. Another benefit may be that some higher amplitude tests can be performed to raise the signal to noise ratio inside the test article to reduce uncertainty. The desired injected current levels may be derived from environment definition activities on larger scale test specimens or simply using different extrapolation values.

4.5.1.5.4 Test Uncertainties

All test methods should address uncertainties associated with test results. As described in the uncertainty discussion of 4.5.1.4, there are uncertainties associated with specimen design, specimen variance and the test methods used to determine the lightning environments. The test approach may utilize the most realistic specimens, including production aircraft, but there will always be aspects of the test process that have varying levels of uncertainties. Some of the test method uncertainties may include:

- Altering aircraft configurations, such as removing access panels or disconnecting pipes (to accommodate test instrumentation, for example), may impact the lightning response of the specimen.
- Tests are typically performed on the ground with a return array. This approach can replicate a natural inflight lightning distribution but may still have an effect near the ground plane or current concentrations near return array conductors.
- Test equipment itself could alter EM behavior if not properly considered. This includes scopes, probes, lead wires or attachment conductors. For example, if multiple, different sized braids are used to detach currents from the test articles in a distributed approach, the different dimensions and resistances can impact current distributions.
- Pulse generators cannot instantaneously turn on the current and there is an arc that typically occurs as the generator switch closes. This arc event may introduce noise into the article environment that is not a natural response of the aircraft to the idealized waveforms and can impact sensitive measurements. Noise effects on data should be considered and determined if they are a real response of the aircraft to the intended lightning environment or a product of the test approach.

- The test injection waveform will not exactly match the idealized waveforms of ARP5412 (ED-84). The test generators may produce a waveform that is satisfactory to represent the waveforms described in ARP5412 (ED-84), but there may be some features of the waveform that are not desirable to have in a validation effort including differing rise times, t_1 , decay times, t_2 , or oscillations not related to the test article. It may be possible to use the measured injection waveform as the simulation source.
 - Transfer function or Fourier analysis may be necessary to convert test environments to idealized environments of ARP5412 (ED-84). This approach is similar to the ARP5415 (ED-158) swept frequency discussion or the method described in ARP5416 (ED-105) full aircraft pulse test data processing section. Note, the use of transfer functions and Fourier analysis on results from nonlinear systems (tests or models) may lead to erroneous results, hence care should be taken to ensure both the source and the results waveforms do not contain discontinuities or cusps.
- Exact measurement locations may not be feasible (e.g., for measure individual fastener currents through large structural interfaces). If using nearby but accessible locations for probes, care must be taken to ensure the nearby environments or alternative measurement locations accurately capture the environment for the design feature being investigated.

The methods described in this section are used to establish an actual environment for the specimen being evaluated. The applicant will need to use uncertainty characterization, or some other justification based on the confidence of the testing to set margin levels when establishing the verification environment.

4.5.1.6 Environment Definition by Analysis

Analysis is another method for determining the fuel system lightning environment. This section describes two analysis techniques for evaluating the lightning environment. The first method involves calculations based on first principles and is referred to as a simple analysis. The second method involves computational electromagnetic (CEM) simulations to evaluate fuel system lightning environments.

4.5.1.6.1 Environment Definition by Simple Analysis

A simple analysis of airplane conducted lightning currents or voltages for selected fuel system features can be used if conservative assumptions are applied in the analysis. These conservative assumptions should result in a more severe actual lightning environment definition and therefore reduce uncertainty. The described simple analysis, developed with conservative assumptions that are easily justifiable, does not typically require additional margins. The use of simple analysis should be discussed in the certification plan. Here are some examples of simple assessments with conservative assumptions:

- A simple analysis could be used to cover conducted current scenarios with lower amplitudes using Zone 1 or 2 direct attachment testing.
- A simple analysis could be used to apportion the current conducted through a subset of the fasteners. As current usually concentrates towards the edge of a joint, distributing the overall current through only the fasteners located at the edges constitutes a conservative assumption. Assuming all the current of the joint goes through a reduced subset of fasteners increases conservatism.
- Using simplified analysis may be useful for modifications of a product already certified in which new parts are attached to the wing such as the installation of additional pylons or winglets.

4.5.1.6.2 Environment Definition by Simulation

Computer simulation methods are available to determine the entire aircraft fuel system lightning environment or focus on environment definition for a single design feature. Simulation can be performed on an initial design, updated as the design evolves, and can be accomplished prior to an aircraft or wing being built.

There are aspects of measuring fuel system transients related to design feature accessibility, probe placements and design variance that are not practical to evaluate by testing alone. In these cases, numerical simulations can help to fill voids in the environment definition process.

There are multiple ways to approach simulation model definition and scale selection, just like there is for testing. For each design feature, the applicant should select the appropriate specimen design and analytical approach to determine the lightning environment. It may be necessary to have multiple models to adequately characterize the lightning environment for all design feature groups of the fuel system. ARP5415 (ED-158) provides a detailed review of simulation approaches for lightning transient analysis modeling. As discussed in 4.5.1.5.2, there are many similarities between fuel system transients and electrical cable transient assessment and the descriptions in ARP5415 (ED-158) may be reviewed prior to selecting a modeling technique.

Regardless of the software or analysis technique used, all models should be based on the aircraft production design. An accurate simulation model requires accurate geometry representation, component connectivity, and parameter assignment. Additionally, the analysis may need to consider multiple lightning entry/exit configurations for each model if a single worst-case scenario is not identified for a given feature evaluation. Evaluating different current distribution scenarios through the fuel system helps to identify severe levels that should be used for environment definition. The aircraft zoning, as described in 4.4 should be used to determine which lightning current distribution scenarios are appropriate to consider.

A large scale simulation model may capture all the fuel system components in a single model. Alternatively, small simulation models may focus on a particular design feature or represent only a small portion of the fuel tank structure and/or system. If using smaller models, many models may need to be developed to represent all fuel tank structure and system design groups and to define all environments. There are several approaches and scales for developing simulation models that have benefits and drawbacks to consider. There are approaches to environment definition that may fall between the broad categories identified below or use combinations of categories to define all design feature environments.

4.5.1.6.2.1 Modeling and Simulation Plan

It may be appropriate to establish a modeling plan identifying where simulation will be used for environment definition, approximations used, validation techniques and how margin strategy will be developed. Similar to how a test plan will introduce test objectives, test setup, procedures, data acquisition and applicability of results to ensure an accurate and meaningful test outcome, this modeling plan should outline important aspects of the simulation process such as objectives, model setup approximations used, validation techniques, margin strategy and applicability of results. The modeling plan should be reviewed with certifying authorities to gain concurrence. Some of the details covered in the Simulation Plan might include:

- Simulation objectives
- Model specification
 - Scale(s)
 - Simulation technique
 - Model configuration
 - Key modeling parameters and properties
 - Boundary conditions
- Simulation scenarios
 - Lightning entry/exit locations
 - Lightning input waveforms and excitation method
- Model outputs
 - Probe locations
 - Results processing and waveform reduction

- Verification and validation
 - Validation plan
 - Uncertainty characterization margin strategy
- Model applicability
 - Domain of validity, where simulation results may be used

4.5.1.6.2.2 Large Scale Models

Large scale models may have the same level of fastener and connectivity details as the small and medium scale models but can consider the EM influence of all surrounding components contributing to the complex current distributions that can occur during a lightning event. Higher fidelity of aircraft representation may be needed in the localized areas where simulation measurements are being made. Lower fidelity may be acceptable at locations farther from the area of interest.

- Benefits
 - These models can accurately represent the entire fuel tank structure and/or system in a single model and consider the influence of all fuel tank structure and system components.
 - These models may be the best representation of the actual aircraft inflight response to lightning. Simulation on any sized article will have to include test equipment and setup that may alter the lightning response as compared to the inflight response. Simulation on small-medium sized articles may not capture some current distribution paths that are on the actual aircraft.
 - These models can consider many lightning attach/detach scenarios to evaluate the current distributions and ultimately define the lightning environments.
 - The simulation can capture hundreds of lightning currents or voltages in each simulation.
- Drawbacks
 - These models may take a long time to develop to incorporate all of the interfaces and material parameters to accurately reproduce the lightning environment.
 - These models may take a long time to simulate.
 - This modeling approach may require additional smaller test or simulation efforts to characterize the parameters of critical joints or regions.
 - It may be difficult to perform extensive sensitivity analysis due to the long simulation times. Refer to ARP5415 (ED-158) for an explanation on sensitivity analysis.
 - May require testing on a full aircraft or wing for model validation purposes.

4.5.1.6.2.3 Medium Scale Models

These models may involve several regions of the fuel tank structures and systems. It may consist of a section of the wing with several rib bays with skins, spars, ribs, stringers, access panels and some system components. These models may focus on specific areas such as the center tank, landing gear, pylon, or control surface interfaces to fuel tank structure and/or systems to understand maximum current distribution patterns.

- Benefits
 - By considering a region of the fuel tank structure and/or systems, the effects of and distribution of lightning currents across multiple components can be understood.
 - This type of configuration will be more representative of the actual aircraft than the small scale models.
 - These models will be significantly faster to create than large scale models but can still consider fine model resolution.
 - The validation article will be easier to test and characterize the lightning environment than a full aircraft or wing.
 - These models are highly amendable to sensitivity analysis for characterizing how varying EM parameters of the aircraft affect lightning environment.
- Drawbacks
 - Additional models will be required to capture all fuel tank structure and system environment definitions.
 - Some regions of the fuel system may not be validated with a single medium scale test article, and multiple validation tests may be required.
 - Higher margins may be required on the simulation results to account for uncertainties associated with how well the medium scale reflects all actual aircraft configurations.

4.5.1.6.2.4 Small Scale Models

Simulations can be performed to investigate localized lightning environments for the fuel tank structure and systems. These smaller, localized models may be representative of only a few components connected together or concentrated on critical interfaces or joints.

- Benefits
 - Models are easy to construct and validate with similarly configured test articles.
 - The parameters are easy to modify and understand the lightning response sensitivity to such parameters. Refer to ARP5415 (ED-158) for an explanation on sensitivity analysis.
 - Models can be used to bound or conservatively determine the environment for some design features.
- Drawbacks
 - Many models may be required to fully characterize the lightning environment for the entire fuel tank structure and systems.
 - These models may not be able to account for all surrounding components and their effect on the environment.
 - Determining, justifying, and implementing current injection/return configurations and amplitudes/waveforms may be difficult or may require additional simulation or test.
 - Smaller test articles may require higher margins to account for uncertainties about how the test article reproduces the aircraft lightning environment. In some cases, the model difference from the actual aircraft configuration may be too large to justify the results for environment definition.

4.5.1.6.2.5 Analysis Uncertainties and Validation

Whenever simulations are used to set fuel system lightning environment, justification or demonstration is necessary to show how modeling approaches, parameter selection and component connectivity can accurately determine the aircraft lightning response for the design features in question. This justification process has historically been called model validation. A validation effort may directly compare simulated results to measured test results for an appropriately selected aircraft specimen. Other validation methods may be used but must provide sufficient confidence that the simulation model and technique can accurately determine the lightning response for the aircraft being evaluated. The validation effort may help to establish levels of uncertainty or provide inputs for a margin strategy.

It is important to establish a validation plan, either in the modeling plan listed above or separately, identifying how evidence supporting model validation will be achieved. This may include dedicated testing and simulation plans outside of the modeling plan discussed in 4.5.1.6.2.1. These validation efforts may be used to demonstrate where simulations are applicable and how they may be used for environment definition.

There is no unique approach to modeling and from a first baseline electromagnetic model the applicant may select different options with different amounts of uncertainty. A baseline model can be established using average parameters, but the uncertainties and the robustness of the results, cannot necessarily be determined from a unique configuration unless test results for validation are available for a direct comparison, and hence an assessment of the predictive capability of the EM model. This test database may not be available, or measurement simply not practically achievable, such as for current flow on fasteners or groups of fasteners.

There is a trade-off to be established between the accuracy of the evaluation method of the local threat and the size or complexity of the specimen. The level of difficulty to predict the local environment on a spar or on a fastener is different, with different uncertainties. The margin on top of environment definitions may vary and for instance be larger for a threat defined at fastener level when compared to a threat defined at spar (or big parts) level. The use of conservative hypothesis will require smaller margins, and potentially no margin at all on top of the results if the conservatism is certain and demonstrated.

There are three primary approaches to simulation while considering uncertainty characterization mentioned in 4.5.1.3. Additional details as to how the applicant should consider uncertainties in the simulation methods are provided below. The applicant may choose to use a blend of approaches allowing for some conservatism while doing a sensitivity assessment or performing some sensitivity analysis while using a predictive approach. These groupings are not meant to be strict paths the applicant must follow. However, they give insight on how uncertainties with simulations may be understood and characterized to show that reasonably severe environments are captured for certification purposes.

4.5.1.6.2.6 Predictive Analysis

The model design is intended to match that of the actual aircraft design with geometrical representation and material assignment. The output of these models is a result that may be considered equivalent to the actual lightning transients one would achieve from testing. If a significant effort is devoted to understanding the fuel system lightning response through multiple entry/exit configurations with direct comparisons of tested and simulation waveforms the applicant may be able to conclude that simulation adequately captures the lightning response for all areas of the fuel system. This approach utilizes the predictive environment technique described in 4.5.1.3.1. This effort may include the following activities:

- Perform lightning testing on a large-scale article with multiple current distribution evaluations from multiple entry/exit configurations.
- Perform simulations that match the test article scale, setup, and probe locations.
- Compare the transient peak amplitude with respect to the overall amplitude range. Decide if the test and simulation results may be considered sufficiently similar in amplitude.
- Visually compare peak time and waveform. If results generally have similar peak times and overall waveshapes, the test and simulation results may be considered sufficiently similar.

The uncertainty in this approach is often characterized by quantitatively comparing test and simulation results of peak amplitudes or action integrals for a given specimen. The comparisons between testing and simulation results may be used to help set margin levels. It is important to understand that model validation does not necessarily mean the simulation results need to match testing results in all cases because there are reasons test results may not faithfully represent the aircraft coupling response. The quantitative comparison does not mean that whatever the largest discrepancy between simulation and testing is the margin that must be applied to the simulation results. The applicant should consider the results of simulation and test and form justifications for appropriate uncertainties. The uncertainties and evaluation margin to be added to the simulation results should be defined and justified for each type of observable (voltages between parts, current into parts, current densities on panels, etc.). As mentioned in 4.5.1.3.1, the predictive analysis may not provide any analysis of the impact of product variability and tolerances on the lightning environment definition.

4.5.1.6.2.7 Conservative Analysis

The model design and parameter assignment are performed in a way the lightning environment is ensured to be severe for the design feature in question. It is important to note that it may not be possible to construct a model that is conservative at all locations. With this approach some electrical properties are deliberately set to extreme values (e.g., perfect short-circuits and open circuits to maximize current flows at specific observation points) and the geometry can also be intentionally modified to maximize the exposure on some particular parts (e.g., elimination of some parallel current paths in the model or severe truncation of components). Justification must be provided as to why model definitions are conservative for the design feature in question.

The uncertainty that this approach matches the actual aircraft configuration may be high, but the uncertainty that this approach captures the most reasonably severe result for a design feature may be low. In this case the results will not require additional margin since the upper bound of the lightning environment is intentionally the target of choice. This approach may be similar to the simple analysis techniques described in 4.5.1.6.1 but uses CEM to determine the results.

4.5.1.6.2.8 Analysis with Sensitivity Assessment

The EM parameters assigned within the model are adjusted within reasonable limits associated with the aircraft product variances to understand the reasonable limits of lightning environment results. The output of these simulations are the possible ranges of lightning transients that a design feature could experience. This is an interesting and powerful option to justify margins. In most instances, the simulation process will take benefit of both a conservative approach and sensitivity analysis. Testing typically cannot afford this same type of parameter consideration due to prohibitive cost and implementation techniques. The results of a sensitivity analysis can be used to reduce uncertainty and therefore may reduce required margins. In theory, sensitivity analysis may be used on any sized model but may be difficult to implement in complex models that take a long time to simulate.

The uncertainty in this approach may be kept low if it is shown that the variability of the EM parameters encompasses the most reasonably severe levels. In a sense this is another way of establishing conservative results, but it has the added benefit of understanding the range of results in a detailed way. Some testing may be required to verify the EM parameters selected for the sensitivity analysis reflect the design. The modeling specimens should not be overly simplistic in their representation and the design should ensure important electromagnetic coupling mechanisms are not missed. Generally, the further a specimen deviates from actual aircraft design, the greater the uncertainty that the transient result matches the actual aircraft environment.

4.5.1.7 Environment Definition by Similarity

Environment definition by similarity is the process of utilizing the same currents and voltages developed in the fuel tank (fuel tank lightning environment) for a new aircraft that were used for a previously verified aircraft. The previously verified aircraft must be of demonstrably equivalent design, dimension, and construction in parts where similarity is claimed. The use of similarity, therefore, relies on the fuel tank lightning environment having been developed previously, on a fuel tank, by either testing or analysis. This is coupled with a systematic assessment of the difference between the previous fuel tank and the new fuel tank with respect to lightning electromagnetic effects. It is useful to tabulate the changes to the type design, description of the changes, and the associated impact.

This section provides general guidance and examples, which should not be considered requirements; each application is different and specific details should be considered.

Environment definition by similarity is possible by comparing the following items between fuel tanks. Note the guidance given here is specific to wing fuel tanks, but the same rationale can be applied to any fuel tank.

- Fuel Tank Structure

- Fuel Tank Geometry - Differences in chord length, wingspan, and thickness can affect current distribution. The greater the differences, the more difficult a similarity assessment becomes, unless the current densities are lowered. Generally, a larger wing fuel tank with a similar aspect ratio will have lower current densities at fastener interfaces and lower induced voltages. Differences in the spacing between ribs can also impact current distributions and should be considered.
- Materials - In order to utilize lightning environment data from one fuel tank to another, the fuel tank construction must be similar (i.e., metal to metal and/or composite to composite). Since metal versus composite structure can change current distributions, it is difficult to make a similarity claim from one material to the other. For currents or voltages coupled onto fuel tank systems components, such as tubing or wiring, metal fuel tanks are generally considered, all other things being equal, to be superior in regard to minimizing lightning coupling effects, assuming similar locations for the components within the fuel tank. The resulting waveforms coupled onto fuel tank system components may be different between a composite fuel tank and a metal fuel tank. The above discussion focuses on metal versus composite differences, however there can be an appreciable impact from changes to different types of metals, such as aluminum versus CRES, as well as changes to different types of composite, such as carbon fiber versus fiberglass. Given these issues, attempting to establish similarity between fuel tanks with appreciable material differences is not recommended. It may be acceptable to apply composite fuel tank coupled system component levels straight to metal fuel tank coupled system component levels, however structural interface environments may still be difficult to determine.
- Apertures - New or changed fuel tank apertures may affect the coupling of transients to wiring and tubing, as well as internal structural interfaces. Factors to consider include the locations, size and quantity of apertures (e.g., non-conductive or poorly bonded skins or doors), as well as the integrity of gaskets and electrical bonding of those apertures. Additional apertures to consider are wing to fuselage fairing access doors and electrical bonding methods, which can affect the fields surrounding the center tank area.
- Interface Impedances - Interface impedances at structural interfaces can impact how lightning currents are distributed through structure. The coating of fasteners may have an appreciable impact on the DC resistance across a structural joint. Types of fasteners (interference versus clearance fit) may also have an appreciable impact on the DC resistance across a structural joint. Given these issues, attempting to establish similarity between fuel tanks with appreciable interface impedance differences is not recommended. Laboratory bench tests could be performed to show the impedance is similar between interface types.

- Fuel Tank Systems

- Tubing and Wiring Lengths - As a general rule, shorter lengths results in lower coupled voltages. The resulting currents (if applicable) may be similar due to the tubing/wiring impedance which is proportional to length. A successful similarity analysis may be accomplished when tubing/wiring lengths are increased or decreased if sufficient enveloping and margins were applied in the original environment definition.
- Tubing and Wiring Routings - A review of the system routing should be conducted because the currents and voltages developed are dependent on current densities in the surrounding structure as well as proximity to apertures. Generally, current densities are higher near the outboard sections of wing fuel tanks. A successful similarity analysis may be accomplished when tubing/wiring routings is changed if sufficient enveloping and margins were applied in the original environment definition.
- Tubing and Wiring Configuration (external to fuel tank) - Tubing routing outside the fuel tank and electrical bonding methods at fuel tank penetrations can impact coupled voltages/currents on tubing inside the fuel tank. Generally, the impact of changes to tube routing outside the fuel tank are minimized by including robust electrical bonding methods at tubing fuel tank penetrations. Fuel quantity indication system (FQIS) wire lightning shielding is generally isolated from structure within the fuel tank but terminated on both ends outside of the fuel tank. The shield termination methods outside the fuel tank can have an impact on the coupled voltage levels within the fuel tank since the coupling length consists of the entire wire run. A review of the wiring/tubing construction and configuration should be conducted to ensure that the electrical properties are similar.

- Electrical Bonding/Grounding - A review of the electrical bonding techniques should be conducted to ensure that the fuel system components are bonded in a similar fashion between the two installations. Bonding techniques include direct metal to metal contact, interference fit fasteners, etc.
- Additional Considerations
 - Lightning Zoning - Zoning between the original fuel tank and the new fuel tank should be considered. Addition of winglets, location of wing mounted engines, and other differences can impact where direct lightning attachment and the resulting currents must be considered.
 - High Current Conduction Paths into the Fuel Tank - Differences in wing to fuselage fairing attachments, wing mounted engine attachments, landing gear fittings, flap fittings, aileron fittings, wing to fuselage fittings, etc., can impact where high currents enter the fuel tank and affect the resulting current distributions. If the original fuel tank lightning environment definition adequately characterized the current distributions surrounding the high current conduction paths, similarity may be a viable approach by adjusting the locations of the higher current densities due to location of these fitting/attachment points.

If the assessment shows that the changes decrease or do not appreciably increase the fuel tank lightning environment, then similarity may be used. A similarity assessment can show that there are changes where the associated impact is uncertain, or where the impact appreciably increases the lightning threat environment. In these cases, similarity may not be appropriate, and further analysis or testing would be required.

Environment definition by similarity can be simplified if the anticipated modifications of the new fuel tank are considered when verifying the original fuel tank. In this case, there are more options available to produce satisfactory verification by similarity, including:

- a. Perform an expanded set of simulations or test measurements dedicated at validating future modifications. The aim of these complementary measurements would be either to provide direct data for producing new fuel tank environment definition, or to validate a similarity approach to be used to justify future modifications.
- b. Incorporate additional margin in the basic aircraft certification, to allow increased fuel tank environment definition due to known future changes such as a wing to fuselage fairing material change.

4.5.1.7.1 Examples of Similarity Cases

This section contains a set of examples to determine whether a similarity case can be established. The examples incorporate changes to structure and system components.

For each example, the rationale in favor of, or against, the use of similarity is discussed. The criteria for determining if similarity can be utilized are whether the electromagnetic coupling mechanisms are significantly impacted and whether the associated coupling levels are significantly increased. The examples are presented in Table 3.

Table 3 - Examples of similarity cases

Example	Changes to Fuel Tank Structure	Changes to Fuel Tank Systems
#1	None	Equipment replacement, such as fuel level sensor
	This is the case of a simple equipment replacement (e.g., for an obsolete part or introduction of a new supplier). The fuel system coupling mechanisms and current distributions are not modified by the change. No changes to tubing or wiring. Note that changing a fuel quantity computer or signal conditioner may impact the lightning energy coupled onto FQIS wiring and should be considered. However, in this example, replacement of a fuel level sensor does not impact the lightning environment. Guidance: Original fuel tank lightning environment can be used directly, and similarity may apply.	
Example	Changes to Fuel Tank Structure	Changes to Fuel Tank Systems
#2	Addition of a winglet	None
	This is the case of adding a winglet. The fuel system coupling mechanisms and current distributions are not modified by the change, however, current distributions at the outboard end of the fuel tank are impacted. Lightning zoning may change as well as high current conduction entry points into the fuel tank. No changes to tubing or wiring. Guidance: Original fuel tank lightning environment can be used directly, and similarity may apply to areas away from the outboard end of the fuel tank. If the outboard end of the fuel tank is sufficiently away from the wing tip, the lightning environment in the outboard portion of the fuel tank may not be appreciably affected, however specific substantiation must be provided.	
Example	Changes to Fuel Tank Structure	Changes to Fuel Tank Systems
#3	None	Rerouting of tubing
	This is the case of tubing being rerouted from the inboard section of the fuel tank to the outboard section. The fuel system coupling mechanisms and current distributions are not modified by the change, however, coupling on the rerouted tubing is impacted. Guidance: Original fuel tank lightning environment can be used, but additional analysis would be required. If the original environment definition included coupling onto tubing routed to the outboard section, these levels can be applied to the rerouted tube. If the original environment definition did not include tubing routed to the outboard section, additional analysis and margin would be needed to account for the difference.	
Example	Changes to Fuel Tank Structure	Changes to Fuel Tank Systems
#4	Wing to fuselage fairing material change	None
	This is the case of wing to fuselage fairing panels changing from carbon fiber to fiberglass. Lightning strike protection plies (e.g., expanded copper foil) remain the same. The fuel system coupling mechanisms and current distributions near the center section of the fuel tank may be impacted by the change. No changes to tubing or wiring. Guidance: Original fuel tank lightning environment can be used, but additional analysis would be required. If the DC surface resistivity of the fairing panels is appreciably different, then current distributions from the fuselage to fuel tank will be affected. It may be necessary to assume the current densities on the other fuselage to fuel tank paths are increased. For example, wing to fuselage fitting currents will be increased.	

Example	Changes to Fuel Tank Structure	Changes to Fuel Tank Systems
#5	Aileron material change	None
	This is the case of an aileron changing from aluminum to carbon fiber with expanded copper foil lightning strike protection ply. The fuel system coupling mechanisms and current distributions are not impacted by the change. No changes to tubing or wiring. Guidance: Original fuel tank lightning environment can be used, but additional analysis would be required. Generally, the majority of lightning currents on ailerons from attachment and detachment combinations that don't involve the aileron, consists of the initial high dI/dt waveform front. DC resistance has a lower effect on high dI/dt waveforms, so the change may not have an appreciable impact on the current distributions near the aileron. Considering lightning attachment to the aileron, as well as Zone 3 conducted currents through the aileron, a laboratory bench test or analysis could be performed to show current distributions between the aileron hinge fittings are not appreciably impacted.	
Example	Changes to Fuel Tank Structure	Changes to Fuel Tank Systems
#6	Adding a pylon (small protrusion)	None
	This is the case of adding a pylon that meets the small protrusion requirements in ARP5414 and will not change lightning attachment points/zoning. Guidance: A detailed assessment of the lightning environment may not be necessary. However, the applicant should perform an initial analysis/investigation to justify not needing to do a detailed assessment. That outcome (not needing a detailed assessment) could be achieved through having an arrangement with the type certificate holder which can support that the modification will have no impact on the lightning environment identified in the original certification, or it could be through a localized conservative assessment. Applicable details are provided regarding simple analysis in 4.5.1.6.1.	
Example	Changes to Fuel Tank Structure	Changes to Fuel Tank Systems
#7	Adding a pylon (large protrusion)	None
	This is the case of adding a pylon that does not meet the small protrusion requirements in ARP5414 and will change lightning attachment points/zoning. Guidance: A detailed assessment of the lightning environment is necessary. Adding a new lightning Zone 1A, 1C, and/or 2A to an area of the fuel system that was previously Zone 3, may appreciably impact the lightning environment definition throughout the fuel system.	
Example	Changes to Fuel Tank Structure	Changes to Fuel Tank Systems
#8	Replacing a large portion of structure, such as a new engine pylon and interfacing attachment structure	None
	This is the case of a new engine type that requires a different structural design of the attachment or support of the engine pylon attached to the wing. Guidance: A detailed assessment of the lightning environment is necessary. The modification may appreciably impact the lightning environment definition throughout the fuel system.	