U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
ARC Charter

Effective Date:
08/20/2009

SUBJ: Large Airplane Fuel System Lightning Protection Aviation Rulemaking Committee

1. Purpose of this Charter. This charter creates the Aviation Rulemaking Committee (ARC) for Fuel System Lightning Protection according to the authority of the Administrator of the Federal Aviation Administration (FAA) under section 106(p)(5) of Title 49 of the United States Code (49 U.S.C. 106(p)(5)). This charter also outlines the committee's organization, responsibilities, and tasks.

2. Audience. This charter applies to members of the Large Airplane Fuel System Lightning Protection ARC, including aviation industry organizations and employees within the Office of the Associate Administrator for Aviation Safety. The audience for this charter also includes employees of the Office of Chief Counsel and the Office of Aviation Policy and Plans.

3. Where to Find this Charter. You can find this charter on the FAA website at http://www.faa.gov/about/committees/rulemaking/

4. Background. Prior to Amendment 25-102 to Title 14, Code of Federal Regulations (14 CFR) 25.981, the lightning protection requirements for fuel tanks were contained in § 25.954. Section 25.954 applied to system components as well as airplane structure. That regulation required prevention of ignition of vapors in the fuel tank, but it did not take into account anticipated design failures, age, wear, or maintenance errors.

a. In May 2001 the FAA issued Amendment 25-102. This amendment added specific ignition prevention requirements and a new flammability minimization requirement to § 25.981. The amendment contained specific ignition prevention requirements in § 25.981(a)(3) that included consideration of factors such as age, wear, and maintenance errors, as well as the existence of single failures, combinations of failures, and latent failures, that might cause ignition sources in fuel tanks. These requirements applied to fuel tank systems in addition to structural components of fuel tanks.

b. Systems with potentially catastrophic failure modes would typically meet the requirements of § 25.981(a)(3) by providing at least triple-redundancy in their protective features with periodic inspections, or dual-redundancy with continuous system monitoring, to reduce the latency period. Dual-redundant designs could only comply with § 25.981(a)(3) when combined with either regular inspections at very short intervals or a monitoring device, to verify the functionality of the protective features. Inspection of the various design features might be difficult or impossible if the feature is covered by airframe structure.

c. To prevent all sources of ignition in a fuel tank, the design had to be "fail-safe," meaning that hidden (latent) component failures should not cause an ignition source when combined with another failure. An acceptable design must provide a third protective design feature. As it applies to fuel tank lightning protection for certain airframe structures (airplane skins, joints, ribs, spars, stringers, and associated fasteners, brackets, and coatings), applicants have argued that both adding a third independent protective feature and providing sufficient monitoring to detect latent failures in a dual-protective feature are impractical for certain areas of airplane wing structure. Incorporating three independent hardware protective features to control structural ignition sources might become too expensive to produce and maintain using currently available technology.

d. Confirming the continued effectiveness of these design features is difficult due to the impracticality of providing continuous monitoring of the features and the limited capability of inspecting the features. These design features are typically integral to the fuel tank structure or internal to the fuel tanks. Inspection of design features inside fuel tanks requires access to the fuel tanks, which is usually only scheduled once or twice during the life of the airplane. Increasing the frequency of internal fuel tank inspections could also increase the possibility of damaging the lightning protection features during the inspection process. Because of these issues, we issued two exemptions that were found to be in the public interest and are developing a special condition for another applicant with a composite fuel tank.

e. We now believe it is appropriate to re-examine §§ 25.954 and 25.981 to address these and other issues that have surfaced during application of the requirements of Amendment 25-102 to the design of lightning protection of fuel tanks. We wish to establish a balanced approach to ensure that airplane designs provide an acceptable level of safety, while allowing manufacturers to use designs that are economically viable in terms of design, manufacture, and operation. Regarding structural components, the new standards should require the applicant to develop a design as free of ignition sources as practical. In addition, the applicant must consider fuel vapor flammability in developing a design with an acceptable level of safety.

f. We issued policy number ANM-112-08-002, "Issuance of Special Conditions and Exemptions Related to Lightning Protection of Fuel Tank Structure," on May 26, 2009, as a temporary means to address the above issues. This policy memo will remain in effect until rulemaking to address the practicality issues with § 25.981(a)(3) is completed.

5. Organization and Administration of the Fuel System Lightning Protection ARC. We will set up a committee of members of the aviation community, including airplane lightning protection design specialists representing diverse viewpoints. FAA participation and support will come from all affected lines-of-business. Where necessary, the committee may set up specialized work groups that include at least one committee member and invited subject matter experts.

a. The committee sponsor is the Manager, Transport Airplane Directorate, who:

(1) Appoints members or organizations to the committee, at his sole discretion;

(2) Receives all committee recommendations and reports;

(3) Selects industry and FAA co-chairpersons for the committee; and

(4) Provides administrative support for the committee, through the Aircraft Certification Service .

b. The co-chairpersons will:

(1) Determine (with other committee members) when a meeting is required (a quorum is desirable at committee meetings, but not required);

(2) Arrange notification to all members of the time and place of each meeting;

(3) Draft an agenda for each meeting and conduct the meeting;

(4) Keep meeting minutes; and

(5) Provide status updates to the Manager, Transport Airplane Directorate, at 6 months and 12 months from the effective date of this charter.

6. Committee Membership. The committee will consist of about 20 members, representing airplane manufacturers, fuel tank lightning protection specialists, FAA and other aviation industry participants. Members will be selected based on their familiarity with fuel tank lightning protection, analysis and regulatory compliance. Membership will be balanced in viewpoints, interests, and knowledge of the committee's objectives and scope. Committee membership is limited to promote discussion. Active participation and commitment by members is essential for achieving the committee's objectives. Attendance is essential for continued membership on the committee. The committee may invite additional participants as subject matter experts to support specialized work groups.

7. Public Participation. Persons or organizations outside the committee who want to attend a meeting must get approval in advance of the meeting from a committee co-chairperson or designated federal representative.

8. Committee Procedures and Tasks.

a. The committee advises and provides written recommendations to the Manager, Transport Airplane Directorate, ANM-100.

b. Committee tasks include, but are not limited to, the following:

(1) Determining whether the approach to fuel tank safety related to lightning protection should be focused on fuel vapor ignition, ignition sources, or a combination of both.

(2) Determining whether the lightning protection regulation changes should apply to the complete fuel system, or just to the fuel tank structure.

(3) Determining what type of safety assessment approach should be used (e.g.; SAE Document ARP5577 or § 25.1309). Define content and procedures of the safety assessment.

(4) Determining whether a probabilistic approach, prescriptive pass/fail criteria, or a combination of both using qualitative analysis, should be applied to structure or the complete fuel system lightning protection. If a probabilistic approach is used, determine if flammability exposure should be considered. Determine how single failures should be addressed. Determine what types of single failures are impractical to preclude. Finally, determine what probabilistic distribution of lightning amplitudes would be acceptable as an industry standard.

(5) Establishing which components and installations must be addressed and which failure modes (including possibility of cascading failures) should be considered. Determine if all foreseeable, likely, or a specific set of failures should be addressed in determining adequate structural lightning protection. If a probabilistic approach is used, determine the criteria that should apply for the standard. Identify acceptable data to support the safety analysis (e.g., supporting failure rates).

(6) Determining a means to address manufacturing variability, age, wear, corrosion, and likely damage to lightning protection features.

(7) Determining criteria associated with instructions for continued airworthiness and any needed modifications to processes defined in Revision 3 to the Maintenance Steering Group (MSG-3) document.

(8) Considering the effect of reducing the flammability below the criteria of § 25.981(b), Amendment 25-125, in adjusting the other tasks listed above.

(9) Identifying compliance guidance that might be required to facilitate showing compliance with the recommendations above.

c. The committee may propose additional tasks as necessary to the Manager, Transport Airplane Directorate, for approval.

d. The ARC will submit a final report detailing recommendations within 15 months from the effective date of this charter. The Manager, Transport Airplane Directorate, may extend this deadline for up to 6 months if it is in the interest of the FAA to do so.

9. Cost and Compensation. The estimated cost to the Federal Government of the Fuel System Lightning Protection ARC is $60,000, annually. All travel costs for government employees will be the responsibility of the government employee's organization. Non-government representatives serve without government compensation and bear all costs of their committee participation.

10. Availability of Records. Under the Freedom of Information Act, 5 U.S.C. 522, records, reports, agendas, working papers, and other documents made available to, prepared for, or prepared by the committee will be available for public inspection and copying at the FAA, Transport Airplane Directorate, 1601 Lind Avenue SW., Renton, WA 98057-3356. Fees will be charged for information furnished to the public according to the fee schedule in 49 CFR part 7.

11. Committee Term. This committee becomes an entity on the effective date of this charter. The committee will remain in existence for a term of 15 months unless its term is ended sooner or extended by the Administrator.

12. Distribution. This charter is distributed to the Office of the Associate Administrator for Aviation Safety, the Office of the Chief Counsel, the Office of Aviation Policy and Plans, and the Office of Rulemaking.

Administrator

Effective Date:
11/19/2010

SUBJ: Large Airplane Fuel System Lightning Protection Aviation Rulemaking Committee

1. Purpose of this Charter. This charter renews the Aviation Rulemaking Committee (ARC) for Fuel System Lightning Protection according to the authority of the Administrator of the Federal Aviation Administration (FAA) under section 106(p)(5) of Title 49 of the United States Code (49 U.S.C. 106(p)(5)) . This charter also outlines the committee's organization, responsibilities, and tasks.

2. Audience. This charter applies to members of the Large Airplane Fuel System Lightning Protection ARC, including aviation industry organizations and employees within the Office of the Associate Administrator for Aviation Safety. The audience for this charter also includes employees of the Office of Chief Counsel and the Office of Aviation Policy and Plans.

3. Where to Find this Charter. You can find this charter on the FAA Web site at http://www.faa.gov/about/committees/rulemaking/

4. Cancellation. This document cancels the original charter, Large Airplane Fuel System Lightning Protection Aviation Rulemaking Committee, dated 08/20/2009.

5. Background. Prior to Amendment 25-102 to Title 14, Code of Federal Regulations (14 CFR) 25.981, the lightning protection requirements for fuel tanks were contained in § 25.954. Section 25.954 applied to system components as well as airplane structure. That regulation required prevention of ignition of vapors in the fuel tank, but it did not take into account anticipated design failures, age, wear, or maintenance errors.

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6. Organization and Administration of the Fuel System Lightning Protection ARC. We have set up a committee of members of the aviation community, including airplane lightning protection design specialists representing diverse viewpoints. FAA participation and support comes from all affected lines-of-business. Where necessary, the committee may set up specialized work groups that include at least one committee member and invited subject matter experts.

a. The committee sponsor is the Manager, Transport Airplane Directorate, who:

(1) Appoints members or organizations to the committee, at his sole discretion;

(2) Receives all committee recommendations and reports;

(3) Selects industry and FAA co-chairpersons for the committee; and

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b. The co-chairpersons:

(1) Determine (with other committee members) when a meeting is required (a quorum is desirable at committee meetings, but not required);

(2) Arrange notification to all members of the time and place of each meeting;

(3) Draft an agenda for each meeting and conduct the meeting;

(4) Keep meeting minutes; and

(5) Provide status updates to the Manager, Transport Airplane Directorate, at six months from the effective date of this charter.

7. Committee Membership. The committee consists of about 20 members, representing airplane manufacturers, fuel tank lightning protection specialists, FAA and other aviation industry participants. Members were selected based on their familiarity with fuel tank lightning protection, analysis and regulatory compliance. Membership is balanced in viewpoints, interests, and knowledge of the committee's objectives and scope. Committee membership is limited to promote discussion. Active participation and commitment by members is essential for achieving the committee's objectives. Attendance is essential for continued membership on the committee. The committee may invite additional participants as subject matter experts to support specialized work groups.

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should be considered. Determine how single failures should be addressed. Determine what, if any, types of single failures are impractical to preclude. Finally, determine what probabilistic distribution of lightning amplitudes would be acceptable as an industry standard.

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(8) Considering the effect of reducing the flammability below the criteria of § 25.981(b), Amendment 25-125, in adjusting the other tasks listed above.

(9) Identifying compliance guidance that might be required to facilitate showing compliance with the recommendations above.

c. The committee may propose additional tasks as necessary to the Manager, Transport Airplane Directorate, for approval.

d. The ARC will submit a final report detailing recommendations by May 20, 2011.

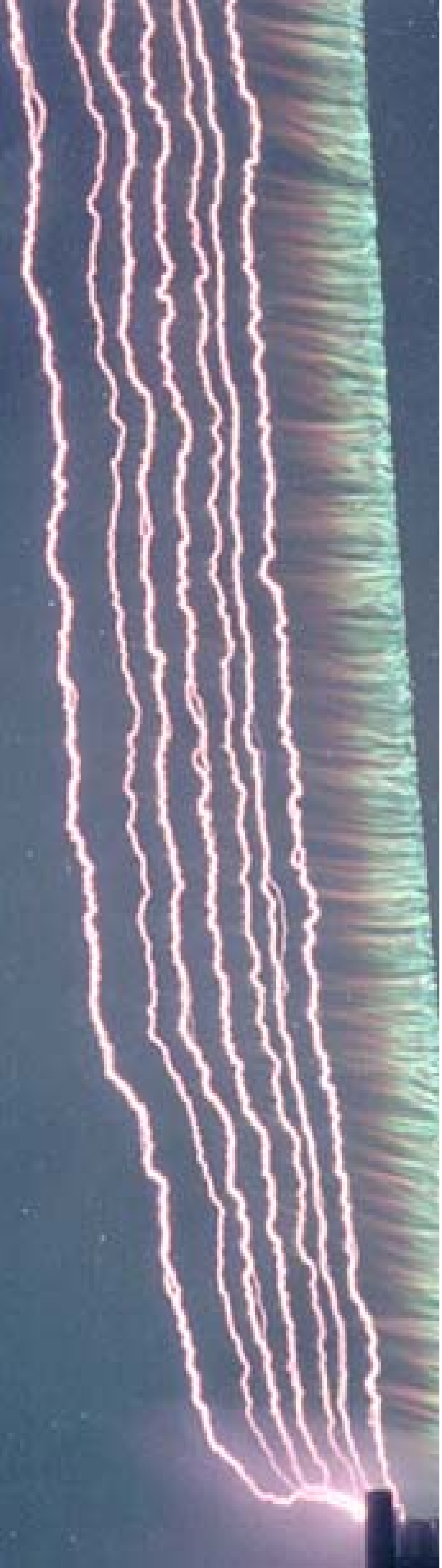
10. Cost and Compensation. The estimated cost to the Federal Government of the Fuel System Lightning Protection ARC is $60,000, annually. All travel costs for government employees will be the responsibility of the government employee's organization unless otherwise agreed among their organizations. Non-government representatives serve without government compensation and bear all costs of their committee participation.

11. Availability of Records. Records, reports, agendas, working papers, and other documents made available to, prepared for, or prepared by the committee will be available for public inspection and copying at the FAA, Transport Airplane Directorate, 1601 Lind Avenue SW., Renton, WA 98057-3356, consistent with the Freedom of Information Act, 5 U.S.C. 522. Fees will be charged for information furnished to the public according to the fee schedule in 49 CFR part 7.

12. Committee Term. This committee remains an entity as of the effective date of this charter. The committee will remain in existence until May 20, 2011.

13. Distribution. This charter is distributed to the Office of the Associate Administrator for Aviation Safety, the Office of the Chief Counsel, the Office of Aviation Policy and Plans, and the Office of Rulemaking.

/s/
J. Randolph Babbitt
Administrator



Large Airplane Fuel System Lightning Protection Rulemaking Recommendations

May 2011

**Federal Aviation Administration
Large Airplane Fuel System
Lightning Protection
Aviation Rulemaking Committee**

Cover photo courtesy of University of Florida International Center for Lightning Research and Testing

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FOREWORD

All proposals and discussions contained in this Final Report have been reviewed and unanimously accepted by the members of the Large Airplane Fuel System Lightning Protection Aviation Rulemaking Committee (Lightning ARC) as accurate and comprehensive representation of the committee deliberations that occurred from August 2009, to May 2011.

EXECUTIVE SUMMARY

The Federal Aviation Administration (FAA) chartered the Large Airplane Fuel System Lightning Aviation Rulemaking Committee (Lightning ARC) to re-examine Title 14, Code of Federal Regulations (14CFR) sections 25.954 and 25.981 to address the impracticality of complying with § 25.981 at Amendments 25-102[5] and 25-125[6] for fuel tank lightning protection.

The Lightning ARC included industry members that are the leading aircraft lightning protection design experts in the world, along with the leading regulatory experts working in the lightning area. The Lightning ARC charter identified nine committee tasks. To complete those tasks, the Lightning ARC held ten face-to-face meetings, one full-committee web-based meeting, and over 30 international teleconferences. In between meetings, detailed technical evaluations were developed by Lightning ARC members to complete the Lightning ARC Charter tasks and prepare this report. In addition, a subcommittee made up of airplane manufacturer structural experts was established by the Lightning ARC to address structure-specific issues, such as the occurrence of cracks and fastener failures. The Lightning ARC also commissioned a specific study of lightning current distribution at structural cracks and fasteners, including the evaluation of lightning-related sparks at these cracks and fasteners. The results of the special studies are presented in appendices. The Lightning ARC findings and recommendations are included in this report.

Lightning ARC recommendations based upon its findings are:

1. Prevention of fuel vapor ignition due to lightning should be the objective of the regulations, achieved through both flammability control and ignition source prevention. Existing Part 25 regulations provide adequate flammability requirements. Thus, lightning-specific requirements should focus on ignition source prevention.
2. Both structure and *systems* should be addressed in the same fuel system lightning protection rule with the same requirements.
3. A prescriptive approach requiring single fault tolerant designs should be mandatory. If fault tolerance is impractical, a qualitative assessment, such as the Lightning Hazard Assessment recommended in SAE ARP5577[12], should be conducted to ensure that the combination of non-fault-tolerant failures resulting in an ignition source is remote.
4. Manufacturing variability, aging, wear, corrosion and likely damage should be addressed by design, manufacturing processes and/or by instructions for continued airworthiness (ICA).
5. Caution information for critical lightning protection features should be incorporated into instructions for continued airworthiness to minimize accidental or likely damage to these features during performance of maintenance, alteration or repairs.

6. Inspections and procedures required for non-fault-tolerant designs should be included in the Airworthiness Limitations section of the instructions for continued airworthiness, whereas fault tolerant designs should utilize tasks developed by the MRB or a sampling program where appropriate.
7. Changes should be made to Air Transport Association (ATA) Maintenance Steering Group (MSG) document MSG-3[20] to support instructions for continued airworthiness for fuel tank lightning protection. Addition of a new section specific to fuel tank lightning protection is recommended.
8. No requirement for lower flammability should be included in the lightning regulations.
9. New guidance material should be developed and existing guidance material should be revised to ensure a consistent approach to fuel system lightning protection is applied across industry.

Proposed Rulemaking

The Lightning ARC recommends §§ 25.954, 25.981 and Appendix H be revised to read as follows:

§ 25.954 Fuel system lightning protection.

(a) The fuel system must be designed and installed to prevent catastrophic fuel vapor ignition due to lightning.

(b) The fuel system lightning protection design must be fault-tolerant for failures that result in lightning-related ignition sources.

(c) Fault tolerance is not required for any specific design feature if:

(1) providing fault tolerance is shown to be impractical for that feature, and

(2) the failures that lead to lightning-related ignition sources from that feature and all other non-fault-tolerant features, when combined, are shown to be remote.

(d) Inspections or other procedures must be established as required by Sec. 25.1529 to prevent development of lightning-related ignition sources within the fuel tank system pursuant to paragraphs (b)(c) of this section. Caution information for critical lightning protection features shall be incorporated into instructions for continued airworthiness required by Sec. 25.1529 to minimize accidental or likely damage to these features during performance of maintenance, alteration or repairs. Required inspections and procedures for non-fault-tolerant features in paragraph (c) of this section must be included in the Airworthiness Limitations section of the instructions for continued airworthiness required by Sec. 25.1529.

§ 25.981 Fuel Tank Ignition Prevention
(a) No ignition source may be present at each point in the fuel tank or fuel tank system where catastrophic failure could occur due to ignition of fuel or vapors. This must be shown by:

> (3) *Except for ignition sources due to lightning subject to Sec. 25.954*, demonstrating that an ignition source could not result from each single failure, from each single failure in combination with each latent failure condition not shown to be extremely remote, and from all combinations of failures not shown to be extremely improbable. The effects of manufacturing variability, aging, wear, corrosion, and likely damage must be considered.

§ H25.x Fuel System Lightning Protection Instructions for Continued Airworthiness
(a) The applicant must prepare Instructions for Continued Airworthiness (ICA) applicable to fuel system lightning protection including the following:

> (1) Mandatory maintenance or inspections necessary to preclude the development of unsafe conditions due to non-fault tolerant lightning protection features shall be identified as Airworthiness Limitations and approved by the Administrator.
> (2) Sampling programs, maintenance and/or inspections for fault tolerant lightning protection features, included in the manufacturer's recommended airplane maintenance program and acceptable to the Administrator.
> (3) Caution information which identifies the lightning protection features of the fuel system design, to minimize the potential for inadvertent damage or disruption of lightning protection features, included in the applicable airplane maintenance documents and acceptable to the Administrator.

The Lightning ARC also recommends that the preamble for the rule should clarify that fuel system lightning protection be excluded from rules of general applicability such as §§ 25.901 and 25.1309.

Required interpretation and intent for the § 25.954 rule is provided in the Recommendations section of this report.

1.0 INTRODUCTION

Prior to Amendment 25-102[5] to Title 14, Code of Federal Regulations (14CFR) section 25.981, the lightning protection requirements for fuel tanks were contained in § 25.954 of that same Title. Section 25.954 applied to system components as well as airplane structure. That regulation required prevention of ignition of vapors in the fuel tank, but it did not take into account anticipated design failures due to manufacturing variability, aging, wear, corrosion and likely damage.

In May 2001 FAA issued Amendment 25-102[5]. This amendment added specific ignition prevention requirements and a new flammability minimization requirement to § 25.981. The amendment contained specific ignition prevention requirements in § 25.981(a)(3) that included consideration of factors that might cause ignition sources in fuel tanks. The factors requiring consideration included manufacturing variability, aging, wear, corrosion and likely damage, as well as evaluation of single failures and combinations of failures, including latent failures. These requirements applied to fuel tank systems and fuel tank structure.

Systems with potentially catastrophic failure modes would typically meet the requirements of § 25.981(a)(3) when they provided at least triple-redundancy in their protective features, or dual-redundancy with continuous system monitoring to reduce the latency period. Dual-redundant designs could only comply with § 25.981(a)(3) when combined with either regular inspections at very short intervals or with a monitoring device to verify the functionality of the protective features. Inspection of the various design features might be difficult or impossible if the feature is covered by airframe structure.

To prevent all sources of ignition in a fuel tank, the design had to be fail-safe so that a hidden or latent failure when combined with another failure would not cause an ignition source. An acceptable design must provide a third protective design feature. Applicants have argued that adding a third independent lightning protection feature or providing sufficient monitoring to detect latent failures in a dual-redundant protection feature are both impractical for certain areas of airplane wing structure, such as airplane skins, joints, ribs, spars, stringers, and associated fasteners, brackets, and coatings. Incorporating three independent protection features to control structural ignition is not technically possible for some designs or is too expensive to produce and maintain using currently available technology.

It is impractical to continuously monitor or inspect the protection features. These protection features are typically integral to the fuel tank structure or inside the fuel tanks. Inspection of design features inside fuel tanks requires access to the fuel tanks, which is usually only scheduled once or twice during the life of the airplane. Increasing the frequency of internal fuel tank inspections could increase the possibility of damaging the lightning protection features during the inspection process. Because of these issues, FAA developed policy related to exemptions and special conditions for § 25.981(a)(3).

FAA decided it is appropriate to re-examine §§ 25.954 and 25.981 to address these and other issues that have surfaced during application of the requirements of Amendment 25-102[5] to fuel tank lightning protection design. The FAA's intent is to establish a balanced approach to ensure that airplane designs provide an acceptable level of safety, while allowing manufacturers to use economically viable design, manufacture, and operation. The new standards should require the applicant to develop structural component designs that are as free of ignition sources as practical. In addition, the applicant must consider fuel vapor flammability in developing a design with an acceptable level of safety.

FAA chartered the Aviation Rulemaking Committee (Lightning ARC) with members that include airplane lightning protection design specialists and aviation airworthiness authorities that represent diverse viewpoints. FAA participation and support came from all affected lines-of-business. The Lightning ARC was directed to set up specialized work groups, where necessary, that include at least one Lightning ARC member plus invited subject matter experts from industry and government.

The Lightning ARC sponsor was the FAA Transport Airplane Directorate Manager.

The names of Lightning ARC members, observers and contributors are listed in Appendix A.

1.1 Lightning ARC Tasks

The Lightning ARC charter (Appendix B) included the following tasks:

1. Determining whether the approach to fuel tank safety related to lightning protection should be focused on fuel vapor ignition, ignition sources, or a combination of both.
2. Determining whether the lightning protection regulation changes should apply to the complete fuel system, or just to the fuel tank structure.
3. Determining what type of safety assessment approach should be used (e.g.; SAE Document ARP5577[12] or § 25.1309). Define content and procedures of the safety assessment.
4. Determining whether a probabilistic approach, prescriptive pass/fail criteria, or a combination of both using qualitative analysis, should be applied to structure or the complete fuel system lightning protection. If a probabilistic approach is used, determine if flammability exposure should be considered. Determine how single failures should be addressed. Determine what types of single failures are impractical to preclude. Finally, determine what probabilistic distribution of lightning amplitudes would be acceptable as an industry standard.
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7. Determining criteria associated with instructions for continued airworthiness and any needed modifications to processes defined in Revision 3 to the Maintenance Steering Group (MSG-3) document.
8. Considering the effect of reducing the flammability below the criteria of § 25.981(b), Amendment 25-125, in adjusting the other tasks listed above.
9. Identifying compliance guidance that might be required to facilitate showing compliance with the recommendations above.

1.2 Task Group Organization

In order to accomplish the tasking defined in its Charter, the Lightning ARC was divided into major task groups, with each group organized around similar subject matter tasks.

The Task Groups are the following:

TASK GROUP 1:

Andy Plumer, Co-Chair
Rod Graham, Co-Chair

Regulatory Scope for Fuel System Lightning Protection. Task Group 1 addressed tasks 1, 2, 8 and 9 from the Lightning ARC Charter. This task group was primarily focused on the overall general application and intent of the current rule and how it might be revised to accomplish the overall safety of the airplane fuel system without driving complexity to the point where the requirements for the design become impractical. In addition, the Task Group was assigned the work of defining the compliance guidance that needs to be developed or revised to support the revision to the regulatory requirements.

TASK GROUP 2:

Dale Winter, Co-Chair
Dave Walen, Co-Chair

Safety Assessment for the Fuel System Lightning Protection. Task Group 2 addressed tasks 3, 4, and 5 from the Lightning ARC Charter. This Task Group was primarily focused on the overall approach to safety assessment and application of the compliance requirements in terms of either a probabilistic or a prescriptive approach.

TASK GROUP 3:

Peter Bootsma, Co-Chair
Helio Librantz, Co-Chair

Manufacturing and Continued Airworthiness Considerations. Task Group 3 addressed tasks 6 and 7 from the Lightning ARC Charter. This Task Group was primarily focused on the overall approach of how to address manufacturing, aging and continued airworthiness in regard to the protection used for fuel system and structure with respect to the lightning threat.

The Task Groups gathered background information, reviewed relevant history and developed sections for a first draft of the Lightning ARC Report. Once that was accomplished, all further report development, review, and approval were accomplished by the entire Lightning ARC.

2.0 BACKGROUND

2.1 Lightning Effects on Airplanes

Lightning strikes to airplanes occur regularly; on an order of once per year for a commercial transport, particularly to airplanes operating in instrument meteorological conditions. When lightning strikes an airplane, high transient current is conducted in the airplane structure. The transient current can melt, burn, and deform airplane parts and structure where the lightning attaches to the airplane. The high lightning current is also conducted through airplane structure between the lightning attachment points on the airplane. The conducted lightning transient current can also induce voltage and current on airplane wiring, tubes and control mechanisms. Melting, burning, arcing, or sparking due to conducted lightning current or voltage can result in fuel vapor ignition if they occur in a flammable environment.

Methods for preventing ignition sources due to lightning strikes are mature and are based on years of research into natural lightning characteristics and effects upon airplane structures and systems. The results have been documented in a wide body of literature and formalized into standards such as SAE documents ARP5412[16], ARP5414[21] and ARP5416[22]. Use of these standards has been accepted by FAA through Advisory Circulars AC 20-53B[3] and AC 20-155[23]. Much of the supporting research has been published by the International Conference on Lightning and Static Electricity (ICOLSE), National Aeronautics and Space Administration (NASA), the European Organization on Commercial Aircraft Equipment (EUROCAE), and in other industry forums. A high degree of communication among airplane lightning specialists worldwide assures that designers and certification authorities are continually informed of advances in lightning protection technology and application of this technology to new designs.

2.2 Lightning-Related Accidents

On June 26, 1959, a Lockheed L-1649A Constellation was struck by lightning and experienced explosions in two of its fuel tanks, resulting in a crash. This airplane was fueled with aviation gasoline. Prior to the time of this accident there had been research conducted into the possible effects of lightning on airplane fuel tanks but the scope of this had been limited to integral fuel tank skin melt-through and hot-spot formation.

Fuel vapor ignition due to lightning was the probable cause for the Boeing 707 accident that occurred near Elkton, Maryland on December 8, 1963.[1] At the time of its certification, the 707 was not required to demonstrate effective lightning protection for fuel systems. Following the 707 accident, substantial research was performed to determine the factors that could result in lightning-related fuel ignition. However, most of this research focused on lightning burn-through for metal fuel tank structure, and lightning-related fuel vapor ignition for fuel vents.

On December 23, 1971, a Lockheed L-188A Electra suffered a lightning strike which led to a fire and separation of the right wing. Since the L-188A was certified by FAA in 1958 the type did not benefit from the additional attention given to airplane fuel tanks after 14CFR 25.954 was published in 1967. The fuel type on board could not be determined by the Lightning ARC.

On May 9, 1976, a Boeing 747 crashed following a lightning strike to the airplane.[2] The investigation for this accident presented evidence that fuel vapor ignition could have been caused by lightning-induced sparking at a motor-driven fuel valve.

In three of the four accidents noted above, investigations found that the airplane fuel tanks contained either aviation gasoline or a mixture of Jet A kerosene-type fuels and higher volatility Jet B/JP-4 fuels. The fuel type involved in the 1971 Electra accident was not identified. The investigations for the other three accidents determined that the fuel mixtures would be flammable at the temperatures and altitudes that the airplanes were flying in at the time of the lightning strikes. During the 1980s the use of Jet B/JP-4 fuels began to decline, becoming nearly obsolete in the 1990s.

Since the last lightning-related airplane fuel tank explosion, the understanding of lightning effects on airplane fuel tanks and systems has increased significantly, and no further events have occurred even though the number of flight hours since the 1976 accident (approximately 1-billion flight hours) is more than eight times that which preceded that event (less than 120 million flight hours).

2.3 Fuel Systems Lightning Protection Regulations, Policy and Advisory Material

Following the Boeing 707 Elkton[1] accident, FAA adopted new fuel system lightning protection regulations. These regulations were implemented for transport category airplanes in § 25.954, *Fuel system lightning protection*.

§ 25.954 states:

> *The fuel system must be designed and arranged to prevent the ignition of fuel vapor within the system by –*
>
> > *(a) Direct lightning strikes to areas having a high probability of stroke attachment;*
> > *(b) Swept lightning strokes to areas where swept strokes are highly probable; and*
> > *(c) Corona and streamering at fuel vent outlets.*

This regulation explicitly requires lightning protection regardless of the likelihood that lightning would strike the airplane. This regulation is prescriptive in requiring effective protection, and there is no acknowledgement that the lightning protection features could fail or become ineffective. There is no requirement for fault-tolerant fuel system lightning protection or for any evaluation of probabilities of failures related to the lightning protection.

Following the 1976 Madrid Boeing 747[2] accident, further guidance for airplane fuel system lightning protection was developed. Specifically, FAA revised Advisory Circular AC 20-53, *Protection of Airplane Fuel Systems Against Fuel Vapor Ignition Due to*

Lightning,[3] along with its corresponding User's Manual[4]. The Advisory Circular has been revised twice since its original issue. These documents added emphasis for lightning protection of fuel system components such as fuel tubes, fuel quantity systems, and fuel filler caps.

There have been no transport airplane accidents related to fuel vapor ignition caused by lightning since 1976. Transport airplanes designed and certified today meet § 25.954, following the guidance in AC 20-53[3].

On July 17, 1996, a Boeing 747 operating as TWA Flight 800 was involved in an in-flight breakup after takeoff. The ensuing investigation determined that the center wing fuel tank exploded due to an unknown ignition source. Following the Flight 800 accident, FAA adopted Amendment 25-102[5] which revised § 25.981, *Fuel tank ignition prevention*. This amendment incorporated § 25.981(a)(3) requiring that the fuel tank ignition source prevention design must address failures within the fuel system.

§ 25.981(a)(3) states:

> *"(a) No ignition source may be present at each point in the fuel tank or fuel tank system where catastrophic failure could occur due to ignition of fuel or vapors. This must be shown by: … (3) Demonstrating that an ignition source could not result from each single failure, from each single failure in combination with each latent failure condition not shown to be extremely remote, and from all combinations of failures not shown to be extremely improbable. The effects of manufacturing variability, aging, wear, corrosion, and likely damage must be considered."*

While lightning was not listed as a probable cause of the Flight 800 accident, potential ignition sources due to lightning must be considered as part of compliance with this regulation, as lightning was mentioned in the rulemaking preamble and the associated Advisory Circular AC 25.981-1C[27]. This regulation effectively requires lightning protection that is fault tolerant to two independent failure conditions. This is because failures of lightning protection features could remain latent for a long time between inspections. Typically these latent failure conditions could not be shown to be extremely remote.

When Amendment 25-102[5] was adopted, FAA did not consider it practical to set specific limits for fuel tank flammability. The amendment adopted regulation § 25.981(c) that required minimizing the flammability of airplane fuel tanks. This regulation did not specifically require fuel tank inerting, nor did the regulation state specific fuel tank flammability limits. When amendment 25-102[5] was adopted, FAA stated in the preamble:

> *"The FAA does not concur that mandating fuel tank inerting technology has been shown to be feasible at this time. This was discussed in detail in the preamble to the notice. We are continuing to evaluate further safety improvements, and are conducting research and development to*

> *investigate the feasibility of incorporating nitrogen inerting on both in-service and new type design airplanes. As noted previously in this preamble, we tasked the ARAC on July 14, 2000 (65 FR 43800), to evaluate both on-board and ground-based fuel tank inerting systems. If further improvement is found to be practicable, we may consider initiating further rulemaking to address such improvements."*

However, following the implementation of Amendment 25-102[5], active fuel tank flammability reduction systems were developed and installed that could practically limit fuel tank flammability. Subsequently, FAA adopted Amendment 25-125[6], which set specific limits for fuel tank flammability. This Amendment modified § 25.981(b) to set specific limits for fuel tank flammability, expressed in terms of the fleet average flammability exposure.

Following the adoption of Amendment 25-102[5], several applicants found that it was impractical to achieve dual fault tolerance for fuel tank structure lightning protection.[7] [8] [9] [24] [25] [26] FAA agreed with the applicants that applying § 25.981(a)(3) for fuel tank structure may be impractical. As a result, FAA issued a policy memorandum to standardize the process for granting exemptions and issuing special conditions for fuel tank structure lightning protection. FAA Policy Memorandum ANM-112-08-002[10] defined requirements that would be applied through special conditions or exemptions. These requirements included both prescriptive requirements and requirements based on likelihood of occurrence.

3.0 TASK EVALUATION

3.1 Task 1

Determine whether the approach to fuel tank safety related to lightning protection should be focused on fuel vapor ignition, ignition sources, or a combination of both.

3.1.1 Evaluation of the Issue

The Lightning ARC considered several options during its evaluation of the top level requirement for fuel tank lightning protection. After some discussion, it was realized that the three options listed in the Charter for Task 1 (fuel vapor ignition, ignition sources, or a combination of both) are actually two options because fuel vapor ignition is already the combination of ignition sources and flammability.

The options we considered were:

Option 1: Retaining the current ignition-source-only focused philosophy of 14 CFR 25.981(a), or;

Option 2: Focusing on the prevention of fuel tank vapor ignition as has been the § 25.954 requirement which takes into consideration both ignition source prevention and fuel tank ullage flammability.

Consideration of further reduction in fuel tank flammability beyond the present requirements of § 25.981 Amendment 25-125[6] will be discussed in Task 8.

Ignition Source Prevention

The prevention of all potential ignition sources in fuel tanks due to lightning is an ideal requirement and the goal of all lightning protection designs. Airplane manufacturers have demonstrated, and FAA has concurred, that in certain areas of the fuel tank it is impractical to provide a design that can demonstrate compliance to § 25.981(a)(3), let alone eliminate all ignition source possibilities, especially when considering the potential for latent failures and human error.

From the FAA Policy Memorandum ANM-112-08-002[10] Page 6:

> *"…the FAA has now determined that application of § 25.981(a)(3) to fuel tank structural lightning protection can be impractical for certain areas of structural design, and is therefore inappropriate for design features where the applicant shows compliance is impractical."*

In practice, the presence of a potential ignition source alone does not directly result in a fuel tank explosion, as a flammable environment must also be present. Therefore, complete elimination of potential ignition sources is not necessary to ensure a safe design.

Fuel Vapor Ignition Prevention (combination of ignition and flammability protection)
Preventing fuel vapor ignition has been the over-arching requirement in § 25.954 for over forty years. The § 25.954 requirements and event history are provided in Section 2 of this report. The designs certified to § 25.954 requirements have demonstrated outstanding safety. A contributor to the safety record is the almost complete elimination of the use of high-flammability wide-cut fuels.

Fuel vapor ignition prevention can be achieved by limiting or eliminating flammability exposure, or eliminating ignition sources. As noted above, eliminating absolutely all ignition sources is impractical. Similarly, eliminating all flammability exposure with current fuels and technology is also impractical. An effective approach would use practical means to limit both the likelihood of ignition sources and flammability to prevent fuel vapor ignition. A combination of flammability and ignition control was used in FAA Policy Memorandum ANM-112-08-002[10] and the FAA charter for this Lightning ARC states that the "*applicant must consider fuel vapor flammability in developing a design with an acceptable level of safety*."

Fuel tank flammability exposure was studied by the 1998 Fuel Tank Harmonization Working Group following the TWA Flight 800 accident. The resulting Aviation Rulemaking Advisory Committee (ARAC) report recommended limiting flammability exposure to levels that typically occur in unheated wing tanks fueled with Jet A type fuels. FAA incorporated that recommendation via Amendments 25-102[5] and 25-125[6], which now prescriptively limit flammability exposure to less than 3%, or equivalent to a conventional, unheated, aluminum wing tank, and provide specific means for assessing flammability exposure. Other protection means to address flammability, such as those allowed in § 25.981(c) to mitigate the effects of vapor ignition, are also considered sufficient for limiting flammability to prevent fuel vapor ignition.

3.1.2 Findings

The Lightning ARC found that the top requirement should be to prevent fuel vapor ignition and that this could be achieved by an effective combination of flammability reduction and ignition source prevention. Given that § 25.981(b) amendment 25-125[6] already directly controls the flammability aspects, the Lightning ARC found that establishing requirements for fuel tank lightning protection could address ignition sources only while still considering the top event as fuel vapor ignition. The Lightning ARC found that this combination of protection means can provide an acceptable level of fuel tank lightning protection, and assure that no lightning-related fuel vapor ignition would be expected to occur.

3.2 Task 2

Determine whether the lightning protection regulation changes should apply to the complete fuel system, or just to the fuel tank structure.

> Note: The term *fuel system* is often used to refer to all of the airplane features related to fuel storage (i.e. tank structure), fuel plumbing, fuel related mechanical components (e.g. pumps and valves) and electrical wiring associated with fuel, such as wiring to components, and the fuel quantity indication system (FQIS). In the context of this section and many places elsewhere in the document, the word *systems* (often highlighted in Italic font), refers to the non-structural part of the *fuel system,* such as plumbing, components, FQIS, and electrical wiring.

3.2.1 Evaluation of the Issue

3.2.1.1 Background

The Lightning ARC reviewed the background material discussed in Section 2 that is relevant to consideration of any revisions to existing regulations and policy applicable to lightning protection of fuel tank structures and *systems*.

The Policy Memorandum ANM-112-08-002[10] applies only to tank structure, not *systems*. In the comments to the draft Policy Memorandum, industry recommended the Policy also apply to fuel *systems* lightning protection. FAA did not incorporate this recommendation, partly based upon the concern that maintenance to systems presented a significant additional risk. Further, FAA stated that applicants had shown compliance of fuel *systems* lightning protection to § 25.981(a)(3), thus demonstrating that compliance was practical. In response to the industry comment, FAA stated:

> "*In developing the proposed policy, the FAA determined that relief from the requirement of § 25.981(a)(3) was warranted for areas where it was shown to be impractical to meet that regulation, and where it could be shown that an acceptable level of safety would be provided by meeting a different standard. The FAA agrees that, from an electrical bonding standpoint, there is not a clear line between structural elements and systems elements, and many of the same design challenges exist for both structural bonding and the bonding of systems elements. The extension of the proposed relief to systems elements and systems supporting structure was carefully considered. One of the significant factors that led the FAA to arrive at the proposed scope for the alternative standard was the expected level of maintenance (disassembly and reassembly) for these design areas. Disassembly and reassembly of electrical bonding elements is considered to present a significant additional risk that a bond will be compromised during the life of an airplane, which generally does not exist for structure that is intended to be permanent*."

The Lightning ARC reviewed the technical aspects of lightning interactions with fuel tank structure and fuel *systems*, and the techniques that are available for protection. The Lightning ARC found that similar protection techniques are used for *systems* and tank structures. The lightning protection design techniques include electrical bonding, insulation and isolation, arc containment, and current diversion.

The Lightning ARC reviewed the history of activities related to *systems* lightning protection compliance to § 25.981, the majority of which are projects from our Lightning ARC members companies. There are few projects that have demonstrated lightning protection compliance of fuel tank *systems* with § 25.981(a)(3) using the rigorous systems-level assessment that the current FAA interpretation of § 25.981(a)(3) requires. While some designs have achieved compliance, or anticipate agreement on compliance in the near term, many of the features incorporated to achieve dual fault tolerance add complexity and are not needed to provide a safe design in which events would be extremely improbable. The Lightning ARC questions the benefit of introducing the complexities needed to demonstrate dual fault tolerance for lightning threats relative to overall fuel tank safety.

3.2.1.2 Options

In our evaluation of whether the lightning protection regulation changes should apply to the complete fuel system, or just to the fuel tank structure, two options were considered.

Option 1: Changes should address the tank structure alone.

Option 2: Changes should address the tank structure and the fuel *systems*.

During our consideration of these options the following relevant factors, each discussed beneath a bold headline, became evident:

The lightning environment and effects are similar for both *systems* and structures. Lightning currents that enter internal system components and structural elements are driven by the same mechanisms. These include:

- Direct lightning attachment to structure or system components located in areas of likely attachment.
- Lightning currents conducted into exterior and interior structural elements such as tank skins, stiffeners, spars, ribs, fuel pipes and system components.
- Transient voltages and currents induced into structure, plumbing and electrical wiring within the fuel tanks for equipment such as fuel probes, fuel pumps, and fuel valves.

When an airplane is struck by lightning it becomes part of the lightning current path. The lightning current typically attaches at one location on the airplane, such as a wing tip, and flows through the structure to an attachment location on another extremity of the airplane. If one of the initial lightning channel attachment locations is at a forward extremity such as the nose or an engine nacelle, the airplane flies through the lightning channel which re-attaches to other locations aft of the initial attachment location. Lightning doesn't differentiate between *systems* and structures; it only sees conductive paths, loops, resistances and installations.

For more information on the interaction of aircraft and lightning, including fuel tanks and systems, see Section 3 of SAE ARP5416[22] or the handbook *Lightning Protection of Aircraft* [11].

Lightning protection means for mechanical systems and structure are similar. Airplane lightning protection is achieved by understanding the behavior of lightning currents throughout the airplane, and addressing each of the effects of these currents with robust protection designs. For fuel tank structures and *systems*, protection design begins with making the airframe as inherently safe as possible by selecting appropriate materials and assembly methods, and adding dedicated protection features where necessary. These protection features include electrical bonding to enable safe conduction of current, isolation of hazardous current paths, and provision of barriers between potential ignition sources and fuel vapors. The same approaches used for lightning protection of a fuel pump installation are used for preventing ignition sources at fuel tank skin, rib and spar joints. Designs are based on industry standards that define the airplane lightning environments, and adequacy of protection is verified by a combination of analysis and tests done in accordance to industry standards. These standards are referenced by FAA advisory circulars and are under constant review by SAE Committee AE-2 and EUROCAE Working Group 31 with participation by FAA and other airworthiness authorities.

When a *system* component is expected to be removed for inspection or replacement, the design features have to ensure that the protection effectiveness is preserved in the replaced component. To effectively achieve this, the design must be simple to remove and reinstall as well as be tolerant to installation errors.

Failure modes of lightning protection for *systems* and structure are similar. Because the lightning protection methods and many of the features for *systems* and structure that implement the lightning protection are similar, the failure modes which could lead to potential ignition sources will also be similar. Failures can result from aging, wear, corrosion, manufacturing defects, and maintenance errors. Such failures and the lightning current densities or voltage potential differences sufficient to produce ignition sources may appear in both *systems* and structures.

Analysis and test tools that are utilized to quantify lightning effects and verify designs are similar.
The tools used to determine the magnitudes of lightning currents in fuel tank structural elements are fundamentally the same as those tools used to determine the lightning voltages and currents in *systems* and installations. The physics are the same whether the objective is managing current in internal tank structural elements or voltage induced in FQIS wiring. Commonly used tools such as finite difference time domain codes have been employed to compute fuel tank fastener and structural element currents, as well as voltages appearing across insulated fuel pipe sections and between fuel probes and

adjacent tank structure. Also, the same lightning test equipment and standards that are used to look for ignition sources within fuel tank structural components are used for testing fuel *system* installations. The standard for these tests is SAE ARP5416[22], which defines similar methods for both structural and system ignition source evaluations. Lightning laboratories and their engineers and technicians perform lightning tests on both *systems* and structures.

The ability to provide additional layers of protection for *systems* is not a justification for requiring their implementation.
The additional layers may have no commensurate safety benefit, yet their complexity can lead to additional failure modes. In the disposition of comments to the Policy Memorandum ANM-112-08-002[10], FAA stated that applicants had shown compliance of fuel *systems* lightning protection to § 25.981(a)(3), thus demonstrating that compliance was practical. The Lightning ARC reviewed this position and concluded that the ability to implement more complex designs does not mean it is practical from the perspective of achieving a commensurate benefit. In fact, a more complex design will usually have additional failure modes or increased risk of errors that can reduce overall safety, rather than enhance safety. A different requirement for *systems* than for structure, based solely on the availability of technology to implement additional layers of protection, is not appropriate justification for a different standard.

One example of a more complex, but potentially less safe system installations is where three parallel stand-off clamps are used to provide dual fault-tolerant insulated support for a fuel pipe. While achieving a requirement for three independent, effective and reliable supports for the fuel pipe, the probability of insulation failure due to breakage, contamination or material defect has been increased by a factor of three. It may be better to consider one or two mechanically robust clamps with plenty of insulation instead of three smaller clamps.

Fuel pipe isolators may be used to prevent lightning currents from flowing in the pipes and couplings. One such isolator with sufficient capability is better than two or three such isolators in series which might be utilized to meet a dual fault tolerant requirement but provide no more lightning protection than a single isolator. There may also be common-cause failures that could defeat all of the isolators such that dual fault tolerance is not really achieved by adding additional isolators. The additional components may even introduce new ignition source risks For example, if bond straps used to ground the resulting intermediate conductive pipe couplings become loose or are omitted during maintenance, a potential ignition source due to static discharges might result. Further, additional plumbing joints within a fuel system increase the potential for fuel leaks which can lead to engine fuel feed problems.

In another example, multiple parallel bond straps may be installed across a pipe coupling to achieve a dual-redundant electrical bonding path. Additional bond straps increase the possibilities of strap and associated clamp failures, which, depending upon the design, might lead to arcing during a lightning strike. Parallel bond straps can create unwanted induced current loops, resulting in the straps and clamps becoming potential ignition sources, themselves requiring dual fault tolerant designs. There is also the possibility of multiple bond straps making inadvertent contact with each other, resulting in an electrical arc source. While the design intent would have been to ensure that an original threat is precluded, additional potential failure modes leading to potential ignition sources are introduced. A robust design that achieves the desired level of safety without these additional complexities is superior.

The addition of designs with multiple layers of protection in small spaces may result in less robust individual designs. Examples are small volume spaces such as fuel collector or sump tanks where there are many components in close proximity to each other. The need to fit additional features in a tight space may introduce unexpected hazards. This is especially true for smaller Part 25 airplanes, such as business jets, but is true for areas in large transport airplanes as well.

Multiple redundant features increase the potential for installation and inspection errors, both in the factory and during maintenance.

A significant factor in the omission of *systems* from Policy Memorandum ANM-112-08-002[10] was the distinction between those components or elements which are expected to remain in place for the life of the airplane versus those which are expected to be removed and reinstalled. Although maintenance activity can increase the likelihood that a disturbed lightning protection feature is rendered ineffective, the risk of ineffective lightning protection can be greater with multiple redundant lightning features on removable components because all features must be disconnected and reconnected in order to replace the component. An example is a fuel pipe that is electrically bonded using multiple redundant bond straps in order to comply with the requirement. This means that the installer and inspector would have up to three separate opportunities for making a mistake, resulting in multiple potential installation configurations which are incorrect and less safe for every one correct combination. This situation is not the result of an inadequate design, but the inevitable consequence of additional redundancy in the context of a common mode factor such as lightning, which affects every protection feature simultaneously.

In contrast, a single robust lightning protection feature has only one opportunity for improper installation, and the probability of a mistake can be readily reduced by proper maintenance and inspection procedures. This approach results in equivalent effective lightning protection while dramatically reducing the potential for erroneous installations.

The existing regulation § 25.954 and associated AC 20-53B[3] address both structural and *system*s lightning protection with common requirements and guidance.

Section 25.954, *Fuel System Lightning Protection*, has been used to demonstrate compliance for both *systems* and structural lightning protection since 1967. The history of lightning protection for airplanes certified to these requirements has been excellent (one event noted in Section 2). While the 1967 wording for the subparts to the rule do not emphasize *systems*, the associated advisory material AC 20-53B[3] includes the need to assess lightning effects on both *systems* and structure. For example, AC 20-53B[3] states the following regarding *systems*:

> ***"2. SCOPE***
> ***b.*** *We address ignition hazards caused by direct effects on main and auxiliary fuel tanks, fuel tank components and plumbing, and the indirect effects (upset or damage) on analog or digital electronic and electrical systems that could lead to ignition hazards on wires or equipment such as fuel quantity probes located in a fuel tank cavity containing fuel vapor."*
>
> ***"5. LIGHTNING EFFECTS ON FUEL SYSTEMS***
> ***c.*** *All or some of the lightning current may be conducted through fuel tanks or fuel system components. It is important to determine where the current flows through the aircraft to allow for adequate design measures to protect the fuel system."*
>
> ***"6. FUEL SYSTEM LIGHTNING PROTECTION***
> ***b.*** *When designing the fuel system lightning protection, consider the following factors:*
> > ***(6)*** *Lightning currents flowing in the internal components of the fuel system (such as fuel and vent lines, conduits, or internal structural parts) may produce electrical sparks and ignite flammable vapors.*
> > ***(7)*** *Lightning currents flowing in the airframe produce voltage differences between adjacent parts or structure. The lightning electromagnetic fields can induce transient voltage and current in the electrical wiring and components of the fuel system."*

Using the same design standard for both structure and *systems* is more likely to ensure all elements are considered.

If both *systems* and structure are considered together beginning with the initial design on through lightning effects assessment, protection design and verification there will be less likelihood that some potential ignition sources are overlooked. A coordinated approach to structure and *systems* avoids the possibility of conflicting protection designs, such as isolation and electrical bonding at a *system*/structure interface.

Addressing structure and systems avoids the need to establish an artificial boundary.

Questions about differentiating which design features comprise part of the *system* and which comprise the tank structure would continue if an artificial boundary is utilized. An example is a permanent vent stringer installation with associated removable plumbing for climb ports, which combines a structural function (wing strength) with a system function (venting). The demonstration of compliance is unnecessarily complex because of different requirements. Avoiding the artificial boundary would provide a clear and simplified compliance path that avoids duplication or omissions.

Another example of the problem with different requirements for *system* and structure can be shown with a pump installation. The FAA Policy Memorandum ANM-112-08-002[10] accepts that certain pump housings are installed for the life of the airplane, and, hence, considered part of the structure. However, one portion of the lightning protection may be pump wire shielding via a shield that grounds the wiring connector shell to the pump housing. Clearly the wiring connector is removable and thus would be categorized as *systems*, but does this mean the housing is now a part of *systems* because the housing is a part of the *system* ground? To keep *systems* and structure separate, a design might tend to use a separate pigtail wire for the shield. This is a less effective shield termination design than one using the connector backshell for shield grounding, resulting in a less robust design than might be necessary to keep the pump housing from being considered a part of *systems*.

Fuel Quantity Indicating Systems (FQIS)

In the discussions about whether *systems* and structures should have a common set of requirements, FQIS was a major topic of *systems* discussion. The Lightning ARC review determined that, unlike the lightning protection certified under the existing § 25.954 requirement which did not require fault tolerance for either structures and *systems*, redundant protection from power-induced ignition sources affecting FQIS has been the design standard for decades. FQIS are designed to be intrinsically safe by assuring that system power is limited to less than that required for ignition in both normal operating and failure conditions. In addition, physical probe separation from structure within the fuel tank made this system dual fault tolerant for internal system electrical power faults. But many early FQIS designs did not include even fault tolerant designs for lightning protection. Basic lightning protection was provided by probe gaps and separation from structure, with no wire bundle electromagnetic shielding. Hundreds of millions of safe operating hours have been achieved with these designs. The adoption of § 25.981 Amendment 25-102[5], which requires the assumption of latent failure conditions being present unless extremely remote, as well as considerations of other faults such as external electrical shorts, has generally led to a need for FQIS changes to achieve compliance for both electrical power faults and lightning. The question is whether this FQIS *systems* precedent justifies that a difference in *systems* and structures requirements is necessary for lightning protection.

The Lightning ARC found that the same justifications for a common requirement for *system* and structure also apply to FQIS. All of the factors noted above apply to the FQIS, the other fuel *system*s, and fuel tank structure. There is no need for different lightning protection requirements for fuel *systems*, including FQIS, and fuel tank structure. Applying a revised standard for lightning protection to FQIS will not negate the need to provide dual fault tolerant protection necessary to achieve compliance to § 25.981(a)(3) for non-lightning threats. The other aspects of the fuel system safety assessment for FQIS will still be subject to the requirements of § 25.981(a)(3).

3.2.2 Findings

The Lightning ARC determined that changes in the regulations should address both fuel tanks structure and *systems* with a common standard.

The findings are based upon the following summary of Section 3.2.1.2:

- The lightning environment, interaction mechanisms and effects assessment methods are the same for structures and *systems*.
- It is difficult, subjective and unnecessary to create an artificial delineation between *systems* and structure with respect to lightning protection.
- Historic lightning protection requirements in § 25.954 and guidance material have utilized a common standard for structure and *systems*.
- The availability of means to implement additional layers of protection for *systems* is not justification for a different requirement than structure. The additional design complexity that would result from additional layers of protection will have no commensurate safety benefit and may introduce unforeseen negative safety consequences, including design, installation and maintenance errors.

3.3 Tasks 3, 4 and 5

Evaluation of Safety Assessment Approaches

Tasks 3, 4, and 5 in the Lightning ARC Charter require evaluation of fuel tank lightning protection safety assessment approaches and the kinds of failures or other conditions that must be part of the assessment. The task statements are listed below.

Task 3 - Determine what type of safety assessment approach should be used (e.g.; SAE Document ARP5577[12] or § 25.1309). Define content and procedures of the safety assessment.

Task 4 - Determine whether a probabilistic approach, prescriptive pass/fail criteria, or a combination of both using qualitative analysis, should be applied to structure or the complete fuel system lightning protection. If a probabilistic approach is used, determine if flammability exposure should be considered. Determine how single failures should be addressed. Determine what types of single failures are impractical to preclude. Finally, determine what probabilistic distribution of lightning amplitudes would be acceptable as an industry standard.

Task 5 - Establish which components and installations must be addressed and which failure modes (including possibility of cascading failures) should be considered. Determine if all foreseeable, likely, or a specific set of failures should be addressed in determining adequate structural lightning protection. If a probabilistic approach is used, determine the criteria that should apply for the standard. Identify acceptable data to support the safety analysis (e.g., supporting failure rates).

These three tasks are interrelated, so are discussed together in this section. The fundamental question to address as part of Tasks 3, 4 and 5 is the method of safety assessment that should be applied to fuel system lightning protection. Two basic safety assessment approaches have been identified for consideration as part of Task 3 – a hazard assessment, similar to that described in ARP5577[12], and a risk assessment, similar to that described in AC 25.1309-1A[13].

The focus of a hazard assessment is to ensure that the protection design can effectively mitigate the hazards that may result when the airplane is struck by lightning. Since lightning protection is not the primary focus of the basic airplane design, this assessment technique works well for identifying where specific lightning protection features must be added to the basic design to mitigate potential lightning hazards. This hazard assessment would typically be done early in the design phase to ensure that adequate lightning protection is incorporated. Tests or analysis are then typically conducted to confirm that the required lightning protection is effective in eliminating the hazards.

On the other hand, the focus of a risk assessment is to evaluate the design functionality, including effects of potential failure conditions, and show that the residual risk of an undesirable event is mitigated to an acceptable risk level. For example, where there is potential for a catastrophic effect, the likelihood of that event must be shown to be extremely improbable. This risk assessment approach has been used for evaluating complex systems architectures, which are part of the basic design of the airplane, to ensure that functionality is maintained to appropriate levels when component failures occur.

3.3.1 Evaluation of the Issue

The existing regulations that apply to fuel system lightning protection, § 25.954 and § 25.981(a), currently drive different approaches for assuring adequate lightning protection design. The requirements of § 25.954 have driven the fuel system lightning design for the vast majority of Part 25 airplanes flying today. For § 25.954, the focus is strictly on demonstrating effectiveness of the lightning protection design - it does not require consideration of failure conditions that may compromise that effectiveness. This approach has resulted in an outstanding safety record in the fact that there has been no lightning-caused ignition of fuel tank vapors since 1976, as noted in Section 2. The Amendment 25-102[5] requirements of § 25.981(a) have only been in place since 2001, with very limited certification activity, so the industry experience is mostly associated with implementing the requirements in the design and demonstrating compliance. These requirements drive a rigorous assessment of failure conditions and combinations of failure conditions, but have been found to result in designs that are, at best, complex and challenging and, at worst, impractical to implement. FAA has acknowledged the impracticality of complying with this rule for fuel tank structural lightning protection in the FAA Policy Memorandum ANM-112-08-002[10]. As requested in the Lightning ARC charter, these rules will be re-examined in conjunction with addressing the system safety assessment tasks with a focus on achieving a balanced approach between an acceptable level of safety and economic viability in design, manufacture and operation.

Airplane Fuel System Lightning Hazard Considerations

The rulemaking projects that resulted in Amendments 25-102[5] and 25-125[6] were intended to prevent catastrophic fuel vapor ignition. For lightning to cause catastrophic fuel vapor ignition, the following conditions must exist:

1. Lightning must strike the airplane; and
2. The fuel tank ullage (air space in fuel tank) must be flammable; and
3. The lightning amplitude and energy must exceed the severe definition used for the airplane protection design; or
4. The lightning protection must have failed.

These conditions must exist when considering lightning-related fuel vapor ignition for both fuel tank structure or fuel *systems*.

First: Lightning strikes to airplanes are common in an airplane fleet, but not frequent for any single airplane. Certain atmospheric conditions lead to higher likelihood of airplane lightning strikes. For example, airplane lightning strikes are most common when the airplane is operating in clouds with precipitation and the atmospheric temperature is near freezing. Airplanes fly through these conditions frequently, but lightning strikes occur on only a small number of airplanes in these conditions.

Second: Fuel tank ullage in transport airplanes operating with typical fuel types (Jet A or similar) is not often flammable. Amendment 25-102[5] added regulations to minimize fuel flammability, and the subsequent Amendment 25-125[6] added quantitative fuel tank flammability requirements for new transport airplane designs. The requirements in Amendment 25-125[6] set limits to the percentage of time that the airplane fuel tanks can contain flammable vapors, based on the flammability performance of conventional unheated aluminum wing fuel tanks. These flammability requirements significantly reduce the likelihood of fuel vapor ignition, independent of the lightning protection elements.

The lightning-related accidents on the Boeing 707 and 747 described in Section 2 had fuel tanks that contained highly volatile JP-4 type fuels. High-volatility fuels such as JP-4 are not generally available and are not allowed on most transport category airplanes certified since the early 1990s. High-volatility fuels are unlikely to be approved for use for airplanes that must demonstrate compliance to Amendment 25-125[6]. FAA is currently pursuing Airplane Flight Manual (AFM) limitations to preclude use of high-volatility fuel types unless no other fuel is available.

The likelihood of lightning strikes to an airplane is independent from and unlikely to coincide with flammable fuel tanks operating with Jet A type fuels. Fuel tank flammability is dependent on the temperature of the fuel. Fuel tanks that are exposed to warm days (air temperature of greater than 80°F at takeoff) have higher likelihood of having a flammable ullage. However, lightning strikes to airplanes occur when the outside air temperature or atmospheric temperature is near freezing. While airplane lightning strikes occur at a range of temperatures around freezing, there is no correlation between airplane lightning strikes and higher atmospheric temperatures. Figure 3.3-1 was developed from a review of a set of pilot reported lightning strike reports and illustrates this point. Figure 3.3-2 uses the same pilot reports but makes a comparison to the ground temperature at the airport nearest to where the lightning strike was reported, which shows the independence of lightning strikes relative to warm days on the ground. Review of other published data[14] [15] also supports this conclusion.

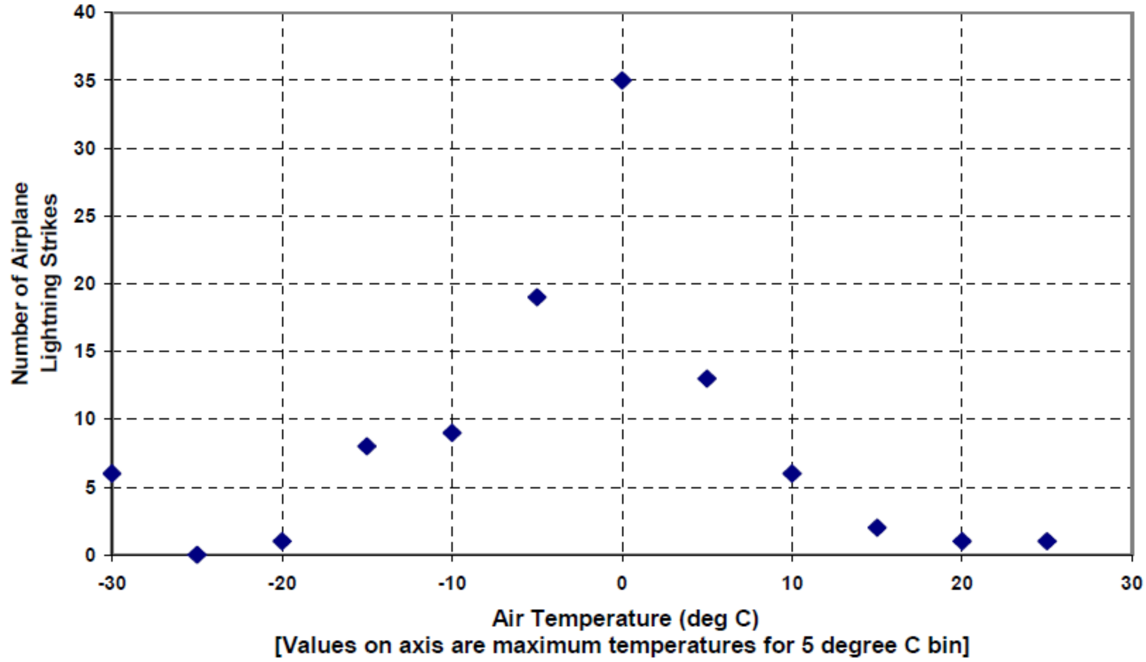


Figure 3.3-1 Static Air Temperature at Time of Airplane Lightning Strike

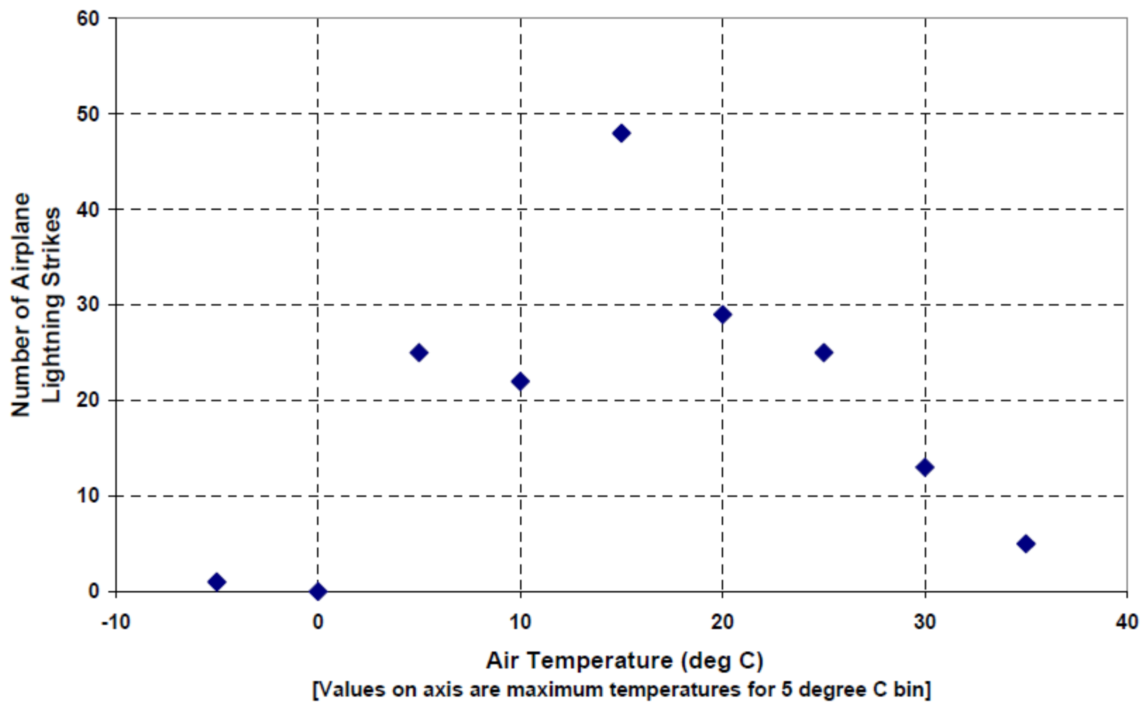


Figure 3.3-2 Air Temperature at Closest Airport at Time of Airplane Lightning Strike

Third: The characteristics of lightning vary widely from one lightning flash to another, so that the range of lightning energy, current amplitude, duration, number of current pulses, and timing of the pulses vary widely. However, these characteristics are independent of the airplane that is struck by lightning. When lightning strikes an airplane, the airplane does not change the characteristics of lightning.

Because of the widely-varying characteristics of lightning and the difficulty and complexity associated with measuring actual lightning characteristics, it is impractical for individual airplane lightning protection engineers to develop their own definition of lightning characteristics. Industry, regulatory, and military aircraft lightning specialists collaborated to consider the variability associated with lightning and airplane lightning strikes. The specialists, meeting in working groups such as the SAE AE-2 Lightning Committee, defined lightning environments that could be used to demonstrate effective airplane lightning protection. [15]

The aircraft lightning protection specialists, both from industry and governments, agreed to define specific, severe airplane lightning environments. The defined lightning environment reflects relatively rare conditions for peak current amplitude, energy, and flash duration. While the likelihood of the severe airplane lightning environment is not specifically defined, the lightning standards consider it to represent on the order of the highest one percentile lightning flash characteristics.

These three factors – widely-varying characteristics of lightning, frequency of airplane lightning strikes, and fuel tank flammability exposure – are all independent and are not directly related to the airplane fuel tank structure and fuel system design. But all three contribute to the overall lightning-related fuel system safety record for modern transport airplanes; which under previous design requirements did not incorporate fault-tolerant fuel tank lightning protection.

Fuel System Lightning Protection Design Elements

Fuel system lightning protection design must address the airplane fuel tank structure and all equipment, wiring, components and parts that are exposed to fuel or fuel vapor under normal conditions. The structure and equipment include the fuel tank skins, spars and ribs, hydraulic lines which are routed inside tanks, fuel system lines, fuel pumps, fuel valves, fuel quantity indicating parts and systems, in-tank wiring, fuel temperature probes, fuel caps, and vents. The lightning protection design must also address fuel lines which may contain fuel vapor and are installed outside the fuel tank. Areas of the airplane that may be exposed to fuel or flammable vapor due to leaks or other failures are not considered part of the fuel system, since fuel vapor would be present in such areas only following a failure of the fuel boundary sealing. Examples are areas adjacent to fuel tanks, space between walls of twin-wall pipes, and equipment adjacent to the tanks. Protection for flammable leakage zones is addressed by § 25.863.

Fuel tank structure and systems lightning protection design elements include structural materials, fasteners, skin thickness, primer, paint, sealant coatings, electrical bonding straps, fuel and hydraulic tube fittings, wire bundle shields, transient suppression devices, etc. Many of these lightning protection design elements serve also as system or structural elements, and lightning protection is not their sole function.

This situation where the lightning protection design elements serve as system or structural elements leads to designs that are generally reliable. Environmental qualification and structural integrity tests typically determine if the protection design elements are reliable over the expected operating conditions for the airplane. If reliable lightning protection designs are implemented for fuel tank structure and systems, then these designs should achieve the intent of ensuring that failure of lightning protection elements will occur infrequently during the operational life of each airplane.

Lightning Protection Element Failures
The Lightning ARC reviewed prior data on fuel tank failures to assess the in-service reliability of lightning protection features. Those reviews are summarized below.

The first set of data reviewed were 220 airworthiness directives (AD) related to airplane fuel tank ignition sources issued following Special Federal Aviation Regulation (SFAR) 88 assessments. This review found there were no cases where structural fasteners or sealant were the cause of the AD. Therefore, those failure conditions were either not found or were not determined to be a lightning hazard if any were present.

A second set of data reviewed was the Aircraft Fuel System Safety Program (AFSSP) report[17]. This report, which documented the results of a voluntary industry inspection program, gathered information about the overall integrity of the fuel system design and maintenance of the in-service airplane fleet. Over 100,000 labor-hours were expended performing airplane fuel system inspections of the world fleet. Inspections were completed on 990 airplanes operated by 160 air carriers in diverse operating environments on six continents.

Various criteria for inspections were used but all included elements for inspecting tank structure, sealant, components and transport elements. Overall, the fuel tanks inspected were generally found to be in good to excellent condition unless subject to initial manufacturing error or subsequent modification or damage. There were a few isolated reports of sealant missing or separating from structure and some isolated foreign object debris, but these were classified as insignificant in the report. Beyond this, the majority of findings related to degradation were associated with chafed wiring, missing or broken bonding jumpers, component electrical bond resistance above installation specification maximum value requirements and access doors with minor corrosion or seal issues. The few areas that were thought to potentially affect airworthiness out of these inspections were addressed as they were found or through follow-on actions.

Failure modes that have been considered for lightning protection under § 25.981(a) and the related exemptions include those that may reasonably be expected to occur as a result of intended operational and environmental conditions or those that may be expected to occur as a result of a manufacturing quality escape. Possible cascading effects from any failure mode have also been considered in addition to the direct consequences of the failure. Assessments considering these failure modes have shown lightning protection features to be reliable.

Structural Failures Study

A team of structural specialists from transport category airplane manufacturers and FAA were asked by the Lightning ARC to evaluate the potential for structural failures that could degrade the fuel tank lightning protection. The specialists considered the current Part 25 structural design regulations, the airplane structural design methods and processes, and in-service fuel tank structure failures to assess the risks related to structural failures that could degrade the fuel tank lightning protection. Of particular interest was also understanding the risks involved with increasing use of composite structures, where limited service experience exists.

The airplane structural specialists reported that structural integrity for transport airplanes is established by complying with discrete requirements. The design of safe structures is based on approaches such as fail-safe, primary/secondary path, and safe-life designs. In all these cases, a reliance on a robust design and inspection program is part of the compliance demonstration. Probabilistic failure analysis is not used. This is due in part to the difficulty in assessing the variability in design, manufacturing methods, and operational environment which, in the structural specialists' opinion, makes a probabilistic approach unreliable and unsuited for structural failure evaluation. This approach has led to successful airframe designs in transport airplanes, including the prevention of fuel vapor ignition due to lightning. Instead of analyzing the probability of failure, the current structure design regulations and airplane manufacturer design guidelines minimize the occurrence of structural failures.

Robust fuel tank structure that results from these design approaches and guidelines will retain its functionality, structural integrity and dimensional stability throughout the airplane service life. This will be the case regardless of whether the basic airframe materials are primarily aluminum, composite or some other material. The robust fuel tank structure will also help to ensure that lightning protection features inherent within the fuel tank structure will be reliable. A given design can be engineered to provide significant safeguards against identified sources of potential structural degradation.

The structural specialists noted that compliance with existing structural regulations results in robust fuel tank design, where structural failures have been minimized. This is supported by in-service reports of structural failures from airplane operators.

There are continuing improvements in structural design processes and analyses, material selection and processing, manufacturing, and inspection methods. This results in a more robust fuel tank structure with respect to cracks, broken fasteners, corrosion and wear for airplanes designed and certified today compared to existing airplane designs. Although manufacturing escapes and engineering errors still occur, the test and inspection methods are effective at detecting these early in the airplane life cycle. Composite structures are less likely to have structural cracks than aluminum structure, which is one of the driving forces behind the expanded use of composite structures in new designs.

The existing prescriptive approach for the evaluation of structure is appropriate because it mitigates the chance of structural failure and incorporates analysis and material improvements as they evolve.

The structural specialists' findings stressed that it is not appropriate to use probabilistic analysis methods to demonstrate that a structural failure that could cause an ignition source is extremely remote. Probabilistic analysis methods are inconsistent with structural design methods, and the large scale of testing to provide numerical data to support the probabilistic analysis adds no value to the evaluation of structure.

Another factor that reduces the risk associated with structural failures are mandated inspections. The continued airworthiness instructions as required by 14 CFR Part 25 result in detecting degradation to maintain the integrity of the airplane structures. The structural airworthiness limitations and routine inspection tasks detect occurrence of cracks prior to reaching a length critical to affecting structural integrity. The interval for each inspection task takes into account the possibility of not detecting the deficiencies in the initial inspections. The inspection intervals are developed in order to ensure that if a crack occurs, it would not reach a critical length even if not detected during initial inspections.

A fatigue test program representing multiple lives of the airplane with a representative flight mission is performed as an integral part of the basic type certification. This fatigue test program investigates the behavior of the structures and detects structural degradation in advance of similar service experience. The rigor imposed by the industry and the authorities ensure that once a critical structural failure is found in a fatigue test, design solutions are introduced for production airplanes as well as development of repairs for the in-service airplane regardless of whether such a failure is found in service. Interim measures such as routine inspections are imposed until the terminating design action is implemented.

The structural specialists concluded that existing structural regulations drive processes, tests and analyses that will ensure a high level of robustness is inherent in the design, which should also minimize risk of failures that affect lightning protection. This conclusion applies whether or not the structure is primarily made from metal or composite materials. More detail is provided in the structural specialists report in Appendix D.

Service Reports for Structural Failures

Certification applicants that have addressed compliance with § 25.981(a), special conditions, or exemptions related to fuel tank structure lightning protection have identified specific failure conditions where fault tolerance may not be practical. Two conditions identified are: 1) cracked or broken fuel tank structure, where the crack could be a potential ignition source if subjected to lightning, and 2) broken structural fasteners, where the broken fastener could possibly compromise or defeat remaining lightning protection features such as sealant.

To better understand these failure conditions, the Lightning ARC requested information from the airplane manufacturers represented on the Lightning ARC to determine how frequently these conditions occur on the existing airplane fleet. The structural specialists validated this information.

Each airplane manufacturer represented on the committee provided data to the Lightning ARC. The information collected represents the reported structural cracking conditions associated with fuel tanks of both small and large transport class airplanes. A summary of the data is provided in Table 3.3-3. As shown, some structural cracks do occur in the fuel tanks. However, fuel tank cracks are only a subset of cracks associated with wings overall – many cracks associated with the wing are associated with leading and trailing edges. These cracks have generally been attributed to design or manufacturing errors, non-conformity of parts, accidental damage, or deterioration due to unexpected environmental or operational conditions.

Table 3.3-3 Airplane Manufacturer Report Structural Cracks

Model	Flight Hours	Accumulated Flight Cycles	Fleet Size	Structural Cracks - Wing Fuel Tanks	Structural Cracks - Non-Wing Fuel Tanks	Unique Conditions*	Potential Lightning Ignition Source**
1	32,000,000	16,000,000	821	174	3	23	3
2	90,000,000	50,000,000	4485	56	-	15	2
3	31,000,000	6,000,000	1118	443	5	19	1
4	488,578	419,639	362	1	-	1	1
5	4,930,941	4,794,160	1336	4	-	4	0
6	6,329,989	4,752,138	745	1	-	1	0
7	2,494,180	1,935,291	325	1	-	1	1
8	40,129,904	6,286,294	694	14	34	11	0
9	24,401,623	5,126,324	882	29	-	8	0
10	53,300,000	28,200,000	3200	4	-	3	0
11	48,000,000	19,200,000	1000	7	-	1	0
12	55,100,000	15,800,000	993	16	-	5	0
13	9,298,510	10,688,040	332	17	-	8	7
14	17,208,716	14,466,369	877	0	0	0	0
15	1,933,168	1,305,371	347	4	-	4	0
16	2,653,894	1,965,027	308	0	-	0	0
17	15,000,000	12,000,000	2000	14	4	-	0
18	3,441,253	1,710,666	486	5	-	1	-
19	944,469	411,469	192	14	-	-	-
20	433,767	162,665	272	2	-	-	-
21	2,309,333	2,548,418	327	5	-	1	0
22	19,542,309	23,727,972	672	115	-	1	1
23	757,764	-	359	0	-	0	0

*Unique Conditions - this column distinguishes between the total number of reported cracks in fuel tank structure and the number of causes of the cracks. For instance, if there was a service bulletin for a specific design condition that was sent out, there may have been many reports of cracks at that location but the root cause of all of those cracks was the same.
**Potential Lightning Ignition Source – this column assesses the locations of the cracks relative to possible exposure to high enough lightning current that an ignition source may be possible

Section 121.703(a)(15), *Service Difficulty Reports*, requires that the certificate holder report "*Cracks, permanent deformation, or corrosion of airplane structures, if more than the maximum acceptable to the manufacturer or the FAA*". The number of unique cracking conditions, meaning all common cause events that were found across multiple airplanes within a given model (such as may have been subject to a specific service bulletin) have been combined to represent just one condition, to provide a sense of the number of failure conditions that have resulted in the cracks.

Data was also requested from airplane manufacturers regarding the in-service failure experience of fasteners or rivets. Fewer reports were received on cracked or broken fasteners, so the data was not tabulated. It appears that broken or cracked fasteners are less likely than cracked structure. The reports showed a small number of isolated events and a few common cause events associated with particular parts types that were subsequently corrected or eliminated. In each case, these reported failures were less frequent with less exposure than for the cracked structure.

The in-service reports on fuel tank structural cracks and broken bolts are relatively rare, which is an indication of the robustness of airplane wing structure. The absence of fuel ignition due to lightning for these airplanes indicates that structural cracks and broken bolts are not significant lightning strike ignition sources.

The data in Table 3.3-3 is primarily from airplanes with aluminum fuel tank structure, although it includes a small number of transport airplane models with fuel tanks built using carbon fiber composite structure. In addition, the airplane manufacturers that have experience with primary structure built from carbon fiber composite materials were asked to provide their experience relative to cracks or similar failure conditions, even if the composite materials were not used for fuel tank structure. No reports of structural cracks in composite structures were found. The airplane manufacturers also reported that laboratory testing of composite materials with small cracks incorporated showed no propensity for the cracks to grow. The structural specialists also reported that cracks in composites were not expected as the design approach taken for composites is typically to keep operating strains below levels where cyclic damage will lead to deterioration over the life of the airplane. Some airplane fatigue testing has demonstrated this has been effective over multiple airplane lifetimes. Also, composites are not prone to failures due to corrosion effects from environmental exposure.

Lightning Risks Associated with Structural Cracks and Broken Bolts

As noted above, structural cracks and broken bolts are mitigated by structural design methods and analysis. This results in robust structure that minimizes failures that will occur. Mandatory inspections are defined to look for cracks that also aid in minimizing their exposure should they occur. In service data indicates that cracks and broken bolts are relatively rare in fuel tanks, as noted in Table 3.3-3. However, despite the structural methods employed that lead to robust structure, cracks and broken bolts still can occur. As shown from service experience, their occurrence has not resulted in an ignition of flammable fuel vapors when the airplane is struck by lightning, even after over one billion flight hours of potential exposure.

Still, the Lightning ARC reviewed these failure conditions and resulting implications when lightning strikes an affected airplane to understand the risk they may pose. For instance, small cracks originating at fastener holes will be covered by fastener hardware (such as collars) or sealant, which protects the fuel vapor from exposure to an ignition source if it were to result. For larger cracks or those cracks initiated away from fasteners, lightning analysis and tests were conducted to assess the risk of an ignition source resulting from lightning. This assessment is described in Appendix E.

The lightning tests indicate that high current densities (on the order of 100,000 A/m) are needed before representative structural cracks will arc or spark. These current densities would only be expected at or very near attachment points on skins. For conducted currents in aluminum structure, these current densities are much greater than what would be found internal to the tank (maximum values on the order of 10,000 A/m away from a direct attachment).

Similar to cracks, broken bolts would also not immediately result in an ignition source hazard in an aluminum fuel tank. Where significant lightning currents are expected, sealant could be applied that would provide a level of fault tolerance to prevent ignition sources from these failures. However, in some cases, such as for highly-torqued bolts, the sealant could be compromised by the energy released due to the bolt fracturing. In those cases, tests indicate that it may require 1,000s to 10,000s of amperes to result in an ignition source, depending upon the fastener installation. For locations internal to aluminum fuel tanks, these current levels will not occur through fasteners. So again it is expected that the fasteners most at risk would be skin fasteners exposed to lightning attachment, although there may be some tank penetrating fastener locations where a conducted current threat may be sufficient to result in an ignition source if the sealant is compromised and a large enough amplitude and energy is present in the lightning strike. Even then, the latent exposure of these installations will be limited as broken bolts in these locations that compromise the sealant will also compromise the integrity of the fuel tank and allow fuel to leak, which would likely be found within a few flights.

Given the service experience and the data assessment, the risk of cracks or broken bolts resulting in an ignition source due to lightning is very small in conventional aluminum fuel tanks. The Lightning ARC does not see this as significant enough to warrant changes to structural design practices in an attempt to prevent cracks altogether, which would likely only further reduce but not eliminate the risk. Nor does the Lightning ARC recommend modifying inspection programs to find smaller cracks sooner as the increased risk of damage caused during inspections would likely offset the risk caused by these cracks. The most relevant data to support the Lightning ARC position that the risk is very small is the service experience, where these conditions are known to have been present with no lightning caused fuel vapor ignitions resulting from them. In addition, when they are present, lightning test and analysis indicates that very few installations would be at risk of seeing enough lightning current even under severe lightning conditions to be a hazard.

Composite Fuel Tank Design Considerations

The majority of transport category airplane fuel tanks are constructed primarily of aluminum. Therefore, the in-service experience that could be utilized within the Lightning ARC tasks is primarily based upon airplane design with aluminum structure. However, there are transport category airplanes with carbon fiber composite fuel tanks that were certified to lightning protection requirements of § 25.954. Given this experience coupled with the increasing use of carbon fiber composite materials in new airplane fuel tank construction means the implications of lightning protection design associated with the use of these composite materials must also be considered.

There are transport category airplane models in service with carbon fiber fuel tanks. No specific safety issues were identified related to composites fuel tank construction following the SFAR 88 fuel tank safety assessments. There is substantial experience with carbon fiber primary structures in general. As noted in Appendix D, general service experience has shown increased robustness to certain failure modes associated with aluminum that are relevant to lightning protection, such as corrosion and fatigue cracking. In addition, the design and analysis methods used by structures are also expected to result in robust structure for new designs as the use of composites expands to even more structural applications.

The civil airplanes with composite fuel tank structure along with military airplane have served to identify lightning protection issues associated with composite fuel tanks. Some of these issues are addressed in guidance such as the handbook *Lightning Protection of Aircraft* [11]. However, past design efforts have focused on effectiveness of the protection and have not typically addressed implications of failures or manufacturing variability as is now required by FAA Policy Memorandum ANM-112-08-002[10] for Part 25 applications.

There are also a few Part 25 projects in work at the time of this Lightning ARC activity that incorporate composite fuel tanks, but none have been certified for lightning protection based upon the FAA Policy Memorandum ANM-112-08-002[10] at the time of this report. The details of these designs are not publicly available, and sensitivity of the associated intellectual property has limited the Lightning ARC's ability to engage in detailed discussions regarding specific failures or effects of manufacturing variability. However, some general points can be made to identify potential implications of composite fuel tanks relative to Lightning ARC recommendations.

Use of carbon fiber composite structures in fuel tank design introduces some different lightning protection design considerations than conventional aluminum designs. This is driven by some of the basic characteristics of typical carbon fiber composites noted below.

1. Composite materials used for transport airplane fuel tanks at this time are fabricated as laminates. The laminate displays anisotropic current flow locally along the direction of the fibers at the ply level and also has intermittent contact between fibers within a ply or between plies. This inhibits the ability for current to flow well at faying surface interfaces or through the thickness of the laminate. Where there are cut edges of composite, a phenomena that been referred to as edge sparking or edge glow in industry literature can occur.
2. The effective quasi-isotropic conductivity of the carbon fiber composite laminate is typically on the order of 1000 times less than aluminum which results in increased current locally in joints and overall in joints internal to the fuel tank. Addition of meshes or foils in the skins can help to reduce the current that flows into the joints or internal tank, but do not produce conductivity comparable to aluminum.
3. The resins used in the laminate are dielectric and typically designed to cure at relatively low temperatures compared to the local heating that can be created by lightning currents. When the material is subjected to those lightning currents (particularly at interfaces or joints), it can either pyrolize (vaporize) the resin over a small volume or at least cause the resin to soften or flow locally at interfaces due to rapid heating of the fibers and/or other conductive materials that carry the lightning current in that area. For interfaces where there is some resin or other

dielectric between conductive elements, voltages driven by the lightning currents are enough to potentially break down locally through those dielectric interfaces with current flow resulting from that breakdown.

Lightning protection design concepts are somewhat independent of the tank material, but the materials introduce different methods for implementing those concepts with different levels of effectiveness.

Aluminum fuel tank skins are inherently very conductive and allow only relatively small currents to flow internal to the tank. As noted above, the material conductivity difference between aluminum and composites typically requires that composite designs add features like metal foils or meshes to partially compensate for this difference. These add-on features cannot provide the laminate with an equivalent effective conductivity comparable to aluminum skins because they are only very thin conductive layers. This results in higher current in many joints and associated fasteners, both at skin interfaces and internal tank joints. The higher current places more of a burden on other design features in order to achieve effective lightning protection.

Widespread use of fasteners to assemble structure remains normal practice today, even with composite tanks. Achieving interference fit of those fasteners can be a contributor to lightning protection. It is relatively easy to implement interference fit fasteners in aluminum structures and is desirable in order to efficiently conduct lightning currents through joint interfaces. However, it is a challenge to do this in composite structures because the insertion force of the metallic fastener as it transitions through a hole smaller than the fastener diameter can result in delamination of the composite structure at the hole interface. A similar challenge exists regarding removal of those fasteners for rework or repair. Most composite designs therefore have used fasteners installed in clearance holes to avoid the issues with interference fit installations. This results in more heating and associated sparking/pitting in that interface, which places more burden on other features in the design. The use of sleeves, bushings or grommets to enable interference fit can minimize the risk of delamination during installation and improve the electrical interface with the composite material. However, these also introduce additional interfaces in the joint which can increase the variability of the lightning current path through the joint and add more potential sources of sparking. They also complicate the manufacturing installation process which can affect the robustness of that process.

The mix of electrically conductive and insulating elements in the composite laminates limit the ability to get high quality electrical bonds through faying surface interfaces as can be done with aluminum interfaces. They also can add variability to electrical connection in the interfaces due to presence of dielectric material from the resin. Electrical bonding of composites is typically achieved through fastened interfaces because of this, but those suffer from the fastener interface issues noted above. Some processes have been developed to sand off resin to expose the carbon fibers for achieving faying surface bonds but this approach can introduce other variability, such as consistency in the fiber exposure due to sanding as well as introducing the potential for damaging the fibers or compromising their protection against local environmental conditions such as moisture intrusion or contamination.

Achieving electrical bonding through rework or repair also has challenges as adhesives or resins used in typical field applications (both factory and airline operations) can result in relatively thick dielectric interfaces between the repair material and the parent laminate. An alternate approach to electrical bonding taken sometimes with composites is to introduce intentional insulating materials at certain interfaces to positively prevent current flow at those interfaces and direct it elsewhere. These can be effective in some applications but must be able to withstand voltages that might be present at those interfaces during lightning conditions as well being reliant on the other design aspects to adequately handle the higher current densities that result. Care must also be taken to ensure that electrostatic sensitivities are not introduced by use of insulators in the tank.

One design feature that is comparable between aluminum and composite installations is the application of sealants to contain sparking. However, because of the other factors noted above, the sealant may be required to handle higher pressure stresses as part of a composite design as compared to an aluminum design so the relative effectiveness may be less in some cases.

Existing industry lightning protection standards and practices were reviewed to assess the implications to composite fuel tanks. Given the conductivity differences to aluminum there has been a lot of analytical modeling development work done across industry to provide better understanding of lightning current distributions through structure and systems for composite structures. This development is especially significant for fuel tank lightning protection design because of the higher internal tank currents coupled with some of the design issues noted above, which require a higher resolution in understanding what levels of conducted currents may be present in joints throughout the fuel tank from various lightning attachment locations.

The design issues noted previously coupled with assessment of failures and manufacturing variability associated with candidate designs has resulted in designs that have been difficult to make fault tolerant under some conditions. In most cases for those conditions where fault tolerance could not be achieved, these designs have relied upon use of sealant to ensure effective protection. Continuing technology development as well as a better understanding of the physical effects and the interrelationships between environment, in-tolerance variability and failure conditions that can result in lightning caused ignition sources should enable eliminating these kinds of non-fault tolerant conditions as time goes on. Certifying a composite fuel tank to criteria such as required by the FAA Policy Memorandum ANM-112-08-002[10], may result in non-fault tolerant design conditions without practical means to make them fault tolerant. The current FAA policy has provisions for addressing these designs via numerical probability analysis but, as is noted elsewhere in this section, there are a number of issues with applying this approach to lightning protection design of fuel tanks and it is even more difficult in this case given the limited experience with composite fuel tank designs.

In summary, there is limited experience with designing lightning protection for composite airplane fuel tank structure, particularly since the publication of Amendment 25-102[5] introduced the concept of failure assessment and manufacturing variability considerations for lightning protection certification. Technical challenges introduced with composite material fuel tank design drive the need for additional features beyond conventional aluminum designs. Composite tank design experience suggests there is increased variability relative to assessing lightning protection performance, and there are challenges achieving fault tolerant designs under some conditions. Technology development and general maturity of the knowledge base is expected to eliminate the non-fault tolerant conditions over time but it is not always practical to do that today. In most cases these non-fault tolerant conditions are reliant on sealants to ensure effective lightning ignition source protection. While the current policy accounts for this via a requirement to demonstrate that a catastrophic fuel vapor ignition of a tank is extremely improbable, it is not practical to acquire the data needed to perform the required probabilistic analysis. The Lightning ARC has estimated that the current challenges with composite tanks are likely short term. While it may require more design effort and testing to demonstrate that the lightning protection features are effective for composite designs, the Lightning ARC has not identified any need for a difference in requirements for composite designs.

Numerical Analysis Considerations

Quantitative analyses have traditionally been used as a tool where complex systems are evaluated. For example, if the loss of a function is classified to be catastrophic, normally three independent and reliable systems would be required to meet the top level criteria of no catastrophic effect in one billion flight hours. The three channels would be checked prior to each flight and if one of the channels could fail in a latent manner, an AFM procedure or a routine certification maintenance requirement would be imposed. The probability of failure of one system is typically on the order of once in ten thousand flight hours during the life of the airplane. There is no requirement to improve the typical reliability of one system/channel.

Structures evaluations on the other hand have traditionally relied upon implementing fail-safe, safe-life, and damage-tolerance concepts, supported by routine inspection tasks. The structural specialists who assisted the Lightning ARC indicated that a numerical probability analysis approach is inappropriate for structures due to the difficulty in assessing the variability in design, manufacturing methods, and operational environment which makes a probabilistic approach not viable. This is documented in Appendix D. Some issues with conducting numerical probability assessments relative to lightning protection are summarized below.

Fuel system lightning protection design elements do not have defined lifetimes or wear-out characteristics that are typically associated with moving mechanical systems or with electronic components. Therefore the lightning protection design element reliability cannot be evaluated using the safety assessment techniques and handbook values normally applied to electrical and electronic systems, or moving mechanical systems.

Lightning protection for airplane fuel tanks and systems involves specific characteristics of a number of parts and components, such as structural fasteners, wing skins and underlying structure, bonded structural interfaces, fuel tubes, bonding jumpers and access panels. For each class of part or component, there are many variations in their characteristics that could affect the lightning protection performance. For example, structural fasteners have a wide range of shank diameter, length, material and coating, any of which could affect the lightning protection performance. Therefore, the lightning protection must consider a large number of detailed characteristics of these parts. Typically these parts are designed to last the life of the airplane, but generally there is no numerical value for the mean time to failure for these features. Any protection approach that relies on a numerical safety assessment will require failure rate data for hundreds of parts with a wide range of characteristics.

System safety assessments have traditionally been based on military handbook data to provide base failure rates for components. However, no such data source exists for structural components. Structural certification has generally been based on the concept of demonstrating strength and fatigue margins based on airplane life and mechanical stress levels. Probabilistic failure rates have never been considered for this type of component.

Similarly, there is no data for rates of occurrence of undetected manufacturing escapes or maintenance errors. The data that is available related to detected escapes or errors is not meaningful in this context.

There are also relatively few fuel system lightning protection design concepts even though there are many potential detailed features that implement these concepts. The relatively limited experience using numerical safety analysis for lightning protection as driven by § 25.981(a) or the FAA Policy Memorandum ANM-112-08-002[10] has shown that the primary value of these assessments was achieved when identifying potential protection element failure scenarios. The numerical safety analysis results typically do not change the fundamental lightning protection design approach.

The fuel system lightning protection cannot be effectively analyzed using the traditional system safety assessment tools. In most cases, the functions of the fuel systems are not related to lightning protection. For example, the function of fuel pumps and tubes is to provide fuel to the engines, so failure of the fuel pumps and associated plumbing could result in loss of engine thrust. The lightning protection for these fuel pumps and plumbing is not directly related to the function of providing fuel to the engines, and is typically not addressed as part of the fuel system safety assessment.

The redundancy approaches typically used for electrical and electronic systems, or moving mechanical systems are not effective for lightning protection either, particularly fuel tank lightning protection. For many lightning protection features such as structural fasteners, redundancy of the fasteners does not provide redundant lightning protection. For other lightning protection elements, the lightning protection is not improved by adding more of the same element. For example, adding another layer of fuel sealant over existing sealant does not provide lightning protection redundancy for that feature, because degradation of the adhesion between the sealant and structure may compromise all layers of sealant. Another example is the addition of multiple bonding straps to an installation where common failures, such as corrosion, could degrade or disable all of them. Finally, adding redundant add-on features such as multiple bonding straps can also lead to a greater chance of exposure to damage or improper reinstallation during routine maintenance, increasing the risk of possible ignition sources. The history of lightning protection design has shown that the simplest design implementations are typically the best.

These characteristics of lightning protection make evaluation using numerical safety assessment techniques normally applied to electrical, electronic or mechanical systems inappropriate. Instead, the lightning protection effectiveness has generally been evaluated using standardized lightning tests, some following exposure to other environmental conditions such as temperature and humidity. The use of standardized lightning tests in combination with standardized environmental tests provides prescriptive lightning protection compliance demonstrations.

The approach of defining specific, severe airplane lightning environments result in airplane lightning protection engineers focusing on the specific lightning protection features that would be incorporated into the airplane design. With this approach the airplane designers and the regulatory authorities emphasize the airplane lightning protection design adequacy based on specific lightning environment definitions, rather than focusing on the statistics and probabilities associated with the lightning environment.

Safety Assessment Considerations

As noted previously, the widely-varying characteristics of lightning, frequency of airplane lightning strikes, and fuel tank flammability exposure are all important factors relative to the likelihood of lightning causing a catastrophic fuel vapor ignition. They are all independent factors not directly related to the airplane fuel tank structure and fuel system design. Any qualitative or quantitative safety analysis would use similar factors for lightning characteristics, airplane lightning strikes rates, and fuel tank flammability exposure. Because these factors significantly reduce the risk of fuel vapor ignition, their contribution to safety should be considered and factored into defining acceptable criteria for the lightning protection design. The only factor that significantly changes the likelihood of lightning-related fuel ignition sources is the specific airplane lightning protection design, so that could be the focus of a practical design safety assessment.

The contribution to catastrophic fuel vapor ignition by the factors that are independent of the airplane fuel system design can be considered numerically. The worldwide transport airplane lightning strike rate is on the order of once in several thousand flight hours.[18] The fuel system flammability exposure is controlled by transport airplane regulation. Section 25.981(b) limits the fleet average flammability exposure to three percent of the flammability exposure evaluation time, or that of a conventional unheated aluminum wing tank. Using at least 3000 flight hours between lightning strikes to each airplane, and less than three percent flammability exposure, any lightning strike to an airplane during a flammable condition is expected less than once in 100,000 flight hours. These two factors are not dependent on the fuel system lightning protection design. Using the terminology from the draft Advisory Circular 25.1309-1X Arsenal version, these conditions would be considered remote, or unlikely to occur to each airplane during its total life.[19]

Lightning protection ineffectiveness results in a threshold where lightning of a certain amplitude and energy will result in an ignition source. Lightning strikes have wide range of amplitude and energy distributions, with most strike amplitudes significantly lower than the lightning environment specified for evaluating fuel system lightning protection. Since the amplitude and energy of lightning is statistically variable, the lightning strike to the fuel tank structure or system feature with ineffective lightning protection must exceed the ignition source threshold for that feature at the location where the ineffective lightning protection exists.

The result is that, if a quantitative safety assessment for fuel tank structure and systems lightning protection is used, it only needs to address the probability of ineffective lightning protection features experiencing a lightning strike amplitude or energy that exceeds its ignition source threshold at its location, not the probability of flammability and airplane lightning strike rates. An acceptable level of safety is to show that catastrophic fuel vapor ignition is extremely improbable, typically expressed numerically as a probability of less than once in a billion flight hours. If the probability of an airplane lightning strike in combination with flammable fuel vapors is expected to be less than once in 100,000 flight hours, then the residual risk related to ineffective lightning protection in combination with a lightning strike that exceeds the ignition source threshold needs to be less than once in 10,000 flight hours. Using the terminology from the draft Advisory Circular 25.1309-1X Arsenal version, a probability per flight hour that is less than one in 10,000 flight hours is considered probable, or anticipated to occur one or more times during the entire operational life of each airplane.

As noted earlier, lightning protection designs have been shown to be generally reliable. If reliable lightning protection designs are implemented for fuel tank structure and systems, then these designs should achieve the intent of ensuring that failure of lightning protection elements will occur infrequently during the operational life of each airplane. Airplane designs that comply with § 25.954 have prevented lightning-related fuel ignition when the airplanes operate with lower-volatility Jet-A type fuels, even though § 25.954 does not require fault tolerance for the lightning protection.

If fuel tank and fuel system lightning protection features and elements are reliable, then implementing fault-tolerance for these features and elements will effectively minimize the residual risk so that lightning-related catastrophic fuel vapor ignition is extremely improbable. The approach of fault-tolerant fuel tank and fuel system lightning protection is consistent with other transport airplane regulations and the FAA Policy Memorandum ANM-112-08-002[10].

3.3.2 Findings

In reviewing the data presented above and in response to the specific tasks statements of Task 3, 4, and 5 in the Lightning ARC Charter, the Lightning ARC recommends the following:

- A reliable single fault tolerant fuel system lightning protection design should be applied as a prescriptive requirement.
  - Failures leading to ineffective lightning protection do not result in a catastrophic fuel vapor ignition unless they are combined with the remote event of a lightning strike of enough amplitude or energy to result in an ignition source and fuel vapors in the tank are flammable. This alone makes a catastrophic fuel vapor ignition unlikely with a lightning protection design that has reliable features. A reliable single fault tolerant design will ensure that such an event will not happen.
- A qualitative hazard assessment approach similar to that described in ARP5577[12] should be used for conducting the fuel system lightning safety assessment.
- The safety assessment should include the following content and procedures:
  - Identify the elements of the fuel systems lightning protection
  - Identify each failure condition that potentially affects lightning protection, including cascading effects caused by the root failure.
  - Assess and substantiate the effectiveness, robustness and independence of the lightning protection relative to the expected lightning threat at each design location, with and without failure conditions.
- A probabilistic safety analysis should not be applied to fuel system lightning protection because the significant contributors to the top level event are independent of the fuel system design. In addition, failure data relevant to lightning protection to support a meaningful probability analysis is not readily available or easily obtained.
- Specific single failures (structural cracks or broken fasteners) leading to ineffective lightning protection have been determined to be rare and impractical to preclude for new type design. These failures are effectively mitigated by structures regulations, design processes, and mandated inspections. Even when they do occur, they may only result in an ignition source in aluminum fuel tanks if lightning attaches immediately in their vicinity. Because the combination of the crack or broken fastener with a lightning attachment in the immediate vicinity is remote, the residual risk of catastrophic fuel vapor ignition is negligible and they can, therefore, be excluded from the safety assessment for aluminum fuel tanks.
  - While the Lightning ARC focused on the above specific non-fault tolerant modes identified in past designs, if an applicant identifies other improbable single failures that are impractical to preclude, it would be reasonable for the applicant to demonstrate via the same qualitative assessment process, that these represent a negligible risk.

- Because a probabilistic safety analysis is not recommended, there is no need to provide a probabilistic distribution of lightning amplitudes. The use of standardized specific and severe airplane lightning environments as defined in ARP5412[16] is consistent with other lightning regulations and focuses the design emphasis on the effectiveness of the lightning protection rather than on the variability of the lightning environment.
- Composite fuel tanks typically require more features and result in greater variability in lightning protection performance than aluminum fuel tank designs. Given the maturity of these composite tank designs and associated technologies, applicants working new certification projects have found it difficult to provide fault tolerant designs under some conditions. Expectations are that over time and with continued technology development and maturity of industry knowledge related to variability and failures of lightning protection in composite designs, fault tolerant designs will become practical for all conditions. Therefore, the Lightning ARC finds that these composite design challenges today should not influence the other safety assessment recommendations.
- Requirements for single fault tolerant lightning protection should be applied to all components and installations in the fuel tank structure and systems, with the exception of the specific single failures identified above. Failure modes, including cascading failures and those attributable to manufacturing errors, should be considered in the safety assessment with the exception of the specific structural failures regarding cracked structure or broken fasteners in aluminum fuel tanks identified above. The failure modes to include would be those that may reasonably be expected to occur as a result of intended operational and environmental conditions or those that may be expected to occur as a result of a manufacturing quality escape.

3.4 Task 6

Determine a means to address manufacturing variability, age, wear, corrosion and likely damage to lightning protection features.

3.4.1 Evaluation of the Issue

This section of the Lightning ARC report addresses the effects of manufacturing variability, aging, wear, corrosion and likely damage. While the term "age" is listed in the Task, the term "aging" is used in § 25.981(a). The ARC believes the intent was to evaluate "aging", although little difference between the evaluation of the two terms was identified.

Review of Existing Regulations

Prior to Amendment 25-102[5] to § 25.981, the lightning protection requirements for fuel tank structures and systems were contained in § 25.954. This regulation required prevention of vapor ignition in the fuel tank, but the regulation did not contain wording requiring the airplane manufacturer to address manufacturing variability, aging, wear, corrosion and likely damage. Advisory Circular AC 20-53A[29] did not provide any specific guidance material with respect to manufacturing variability, aging, wear, corrosion and likely damage. Advisory Circular AC 20-53B[3] introduced section (8) entitled "*Maintaining Fuel System Lightning Protection*" and states in (8c): "*Where possible, do not use devices susceptible to corrosion, fretting, flexing cycles, or other life limiting design features. However, when using those types of devices, you must publish their replacement cycles in your instructions for continued airworthiness manual*".

Section 25.981(a)(3) specifically requires the airplane manufacturer to address these issues within the regulation by stating "*the effects of manufacturing variability, aging, wear, corrosion and likely damage must be considered…"*. Sections 25.981(b) Amendment 25-102[5], 25.981(d) Amendment 25-125[6] and SFAR 88 also introduced the use of Critical Design Configuration Control Limitations (CDCCL) as a means of managing and controlling the configuration of ignition protection features. The CDCCL notation is designed to preserve the integrity of ignition protection features during configuration change that may be caused by design changes, alterations, repairs or maintenance activity (likely damage).

The 2006 advisory material for § 25.954 briefly addresses aging, wear, and corrosion as part of continuing airworthiness while § 25.981 requires the airplane manufacturer to address these areas as well as manufacturing variability and likely damage within the regulation.

Review of Service History Pertaining to Manufacturing Variability, Aging, Wear, Corrosion and Likely Damage

In order to identify a means to address the effects of manufacturing variability, aging, wear, corrosion and likely damage it is appropriate to review the service history of the world aviation fleet. The most comprehensive source of information is provided in the AFSSP report[17] previously described in section 3.3.1. Overall, the fuel systems inspected were generally found to be in good to excellent condition unless subject to initial manufacturing error (a subset of manufacturing variability) or subsequent modification or damage (likely damage). There were no findings to suggest that the world aviation fleet exhibited systemic problems associated with aging, wear and corrosion.

Options

The Lightning ARC considered the following options for determining a means to address manufacturing variability, aging, wear, corrosion and likely damage of lightning protection features.

Option 1: Address manufacturing variability, aging, wear, corrosion and likely damage during the design and certification of lightning protection features.

Option 2: Address manufacturing variability, aging, wear, corrosion and likely damage with reliable manufacturing, quality and process controls.

Option 3: Address manufacturing variability, aging, wear, corrosion and likely damage using instructions for continued airworthiness (ICA).

Option 4: Address manufacturing variability, aging, wear, corrosion and likely damage by providing maintenance personnel with information that will minimize accidental or likely damage to lightning protection features during performance of maintenance, alterations and repairs.

Aging, Wear and Corrosion

As discussed in section 3.3, the objective is to design reliable lightning protection features that are not expected to degrade when exposed to the anticipated effects of aging, wear and corrosion. A reliable design can reduce the need for maintenance inspections required to verify the protection design, which, in turn, reduces the possibility of likely damage or disabling of lightning protection features that may occur during operations and scheduled and unscheduled maintenance activity.

The effects of aging, wear and corrosion can be addressed during the design/certification phases with lightning protection features that promote a design that is reliable. As outlined in the AFSSP report[17], the fuel tank systems inspected were generally found to be in good to excellent condition. There were no findings to suggest that the world aviation fleet exhibited systemic problems associated with aging, wear and corrosion. A reliable lightning protection design can be achieved by utilizing designs with a good service history, supplemented by lightning and environmental testing, where applicable.

The objective is to design reliable lightning protection features that are not expected to fail when exposed to the anticipated effects of aging, wear and corrosion. However, there may be cases where it is not practical to implement a lightning protection design that is completely immune to the anticipated effects of aging, wear and corrosion. In such cases, the instructions for continued airworthiness can be used to identify the appropriate maintenance tasks and intervals to verify, restore or replace the lightning protection features.

The Lightning ARC reviewed the Options listed above and determined that an optimum means to address aging, wear and corrosion of lightning protection features may be a combination of Options 1 and 3 where the objective is to design reliable lightning protection features that are not expected to fail when exposed to the anticipated effects of aging, wear and corrosion. In cases where lightning protection features may degrade, the airplane manufacturer could identify appropriate inspection tasks and intervals in the instructions for continued airworthiness to maintain the integrity of the lightning protection features.

Likely Damage

Likely damage refers to damage that may occur to lightning protection features during operations and scheduled or unscheduled maintenance activity of the fuel tank structures and systems.

Likely damage was identified as a significant finding within the Aircraft Fuel System Safety Program (AFSSP) [17], and usually occurs during maintenance activity. One means to address likely damage is to provide maintenance personnel with awareness of the fuel tank lightning protection features which can help prevent likely damage and accidental removal or disabling of lightning protection features during maintenance activity. Sections 25.981(b) Amendment 25-102[5] and 25.981(d) Amendment 25-125[6], use Critical Design Configuration Control Limitations (CDCCL) as a means of managing and controlling the configuration of ignition protection features and require that CDCCL information be included in the Airworthiness Limitations section of the instructions for continued airworthiness as required by § 25.1529. Incorporating the CDCCL information into the Airworthiness Limitation section may not be the most effective approach to minimize likely damage. The Lightning ARC determined that these instructions would be more effective if they are published in the maintenance documents that are directly used by the maintenance personnel during operations and scheduled or unscheduled maintenance activity.

As an alternative to using the CDCCL designation, the applicant could incorporate applicable Caution information (notes) associated with critical lightning ignition source prevention features directly into the maintenance documentation including the Airplane Maintenance Manual (AMM), the Structural Repair Manual (SRM) and manuals that provide maintenance personnel with standard practices such as standard wiring practices. The Lightning ARC determined that Caution information for critical lightning protection features could be incorporated into instructions for continued airworthiness required by § 25.1529. This is a similar approach to Part 25 Appendix H25.5 (a)(1)(vi) which requires the applicant to provide protection and Caution information that will minimize contamination and accidental damage for Electrical Wire Interconnection System (EWIS).

Incorporating Caution information into the maintenance requirements and incorporating this information into the appropriate maintenance documentation can provide maintenance personnel with an awareness of the fuel tank lightning protection features which can help prevent likely damage and accidental removal or disabling of lightning protection features. For example, during scheduled or unscheduled maintenance within the fuel tank, in addition to identifying the lightning protection features, maintenance personnel could be advised to perform a final inspection prior to closing the fuel tank to ensure the lightning protection features have not been disturbed. In cases where a lightning protection feature has been the subject of the maintenance activity, maintenance personnel could be advised to verify that the lightning protection feature has been restored and verified by the appropriate procedure.

Another means to address likely damage is to carry out an engineering evaluation of lightning protection features for susceptibility to likely damage during the airplane design/certification phase. The evaluation can include a review of manufacturing records, quality records and operational history of similar designs that include production and maintenance induced errors (likely damage).

Manufacturing Variability

As outlined below, manufacturing variability as currently interpreted by the FAA for § 25.981(a) includes both manufacturing tolerances as well as manufacturing errors.

- *Manufacturing Tolerances* that are expected to occur during normal manufacturing and allowed per the manufacturing and quality control processes
- *Manufacturing Errors* which can be further subdivided into *manufacturing errors* or non-conformances that are detected and dispositioned during the airplane build process and *manufacturing escapes* which leave the factory undetected

Manufacturing tolerances associated with the fabrication of lightning protection features are expected to occur during the normal manufacturing and quality control processes. These tolerances may have an impact on the effectiveness of the lightning protection design. Manufacturing tolerances can be addressed during the design of lightning protection features and substantiation of the design tolerances can be carried out during the lightning protection verification program. Examples of manufacturing tolerances include the tolerances associated with the fastener installation in fuel tank structure, the tolerances associated with sealant used as a spark barrier or the maximum allowable pipe alignment angle when evaluating a pipe-to-pipe electrical bonding path.

Manufacturing Errors including Non-conformances and Escapes. Manufacturing non-conformances are manufacturing errors that are detected during the manufacturing or inspection process when it is determined that the production build does not conform to the engineering definition. There may be cases when a manufacturing error involves a fuel tank lightning protection feature. Manufacturing errors are anticipated to occur during the manufacturing/production build of the airplane. Non-conformance(s) associated with fuel tank structures and systems should be brought to the attention of the fuel tank lightning protection design authority and dispositioned to restore the fault tolerant lightning protection design intent.

Manufacturing escapes define a condition where an error has occurred during the manufacturing process such that the production build of the airplane does not conform to the engineering definition. Furthermore, the manufacturing error is not detected and the airplane leaves the factory and enters service. Manufacturing escapes are anticipated to occur during the manufacturing/production build of the airplane. There may be cases when a manufacturing escape involves a fuel tank lightning protection feature.

Manufacturing errors can be mitigated by reliable manufacturing operations, processes and inspections. In some cases, manufacturing processes can be selected which are reliable and repeatable, such as many automated processes. In cases where manufacturing operations rely on human skill factors, proper training and reliable production processes can minimize or preclude manufacturing errors. It may also be possible to review manufacturing and in-service records of similar designs to determine if such escapes have occurred and incorporate production line inspections for areas where records indicate a potential for errors/escapes.

Manufacturing errors can be minimized or precluded during the design and certification of lightning protection features. Implementing a design where the lightning protection feature is not just an “add on” feature but is part of the functionality of the fuel system means that a manufacturing error involving a lightning protection feature would also manifest itself as a failure during the fuel system functional test procedure.

Finally, designs may be able to mitigate manufacturing errors by the use of additional protection features to compensate for a compromise in lightning protection performance. This would be the objective of a fault tolerant design where the additional feature protects against the failure caused by the manufacturing error. An example would be the application of sealant over the collar or nut of a fastener installation.

3.4.2 Findings

The Lightning ARC has evaluated the means to address the effects of manufacturing variability, aging, wear, corrosion and likely damage to lightning protection features. The findings are summarized below:

- The Lightning ARC found that addressing the effects of aging, wear and corrosion as both a design consideration and continuing airworthiness consideration will ensure a reliable design as supported by the findings of the AFSSP report[17].

- The Lightning ARC found that the optimum means to address likely damage would be a combination of addressing the susceptibility of lightning protection features to likely damage during the design/certification phase and publishing Caution information in the appropriate maintenance documentation to help prevent likely damage and accidental removal or disabling of lightning protection features.

- The Lightning ARC found that the optimum means to address manufacturing tolerances associated with lightning protection features is addressing manufacturing tolerances during the design and certification phase.

- The Lightning ARC found that an optimum means to address manufacturing errors is a combination of manufacturing, quality and process controls to minimize manufacturing errors, plus use of fault tolerant design features to mitigate the impact of manufacturing escapes.

3.5 Task 7

Determining criteria associated with instructions for continued airworthiness and any needed modifications to processes defined in Revision 3 to the Maintenance Steering Group (MSG-3)[20] document.

3.5.1 Evaluation of the Issue

This section of the Lightning ARC report proposes criteria associated with the instructions for continued airworthiness (ICA) and provides a review of ATA MSG-3[20] for developing and documenting the instructions for continued airworthiness.

Review of Existing Regulations

Prior to Amendment 25-102[5] of § 25.981, the lightning protection requirements for fuel tank structures and systems were contained in § 25.954. This regulation required prevention of fuel vapor ignition in the fuel tank, but the regulation did not specifically address ICA. The applicable regulation for continued airworthiness is contained in § 25.1529 and Appendix H. Although § 25.1529 and Appendix H are applicable to all Part 25 regulations, including § 25.954, § 25.1529 did not specifically address continued airworthiness as related to fuel tank lightning protection. Advisory Circular AC 20-53B[3] introduced section (8) entitled "*Maintaining Fuel System Lightning Protection*" which briefly discusses the need to monitor and maintain lightning protection features.

The introduction of § 25.981 at Amendment 25-102[5] and subsequently Amendment 25-125[6] specifically required the applicant to address continued airworthiness by stating in the regulation *"…inspections or other procedures must be established as necessary to prevent development of ignition sources within the fuel tank system"*.

Sections 25.981(b) Amendment 25-102[5], 25.981(d) Amendment 25-125[6] and SFAR 88 also introduced the use of CDCCL as a means of managing and controlling the configuration of lightning protection features. These regulations also mandated CDCCLs, inspections and procedures by stating *"…these CDCCL, inspections and procedures must be included in the Airworthiness Limitation section of the Instructions for Continued Airworthiness required by § 25.1529."*

Options

The Lightning ARC considered the following options for determining criteria associated with instructions for continued airworthiness.

Option 1: Retain the approach § 25.981 at Amendments 25-102[5] and 25-125[6]which requires the applicant to address continued airworthiness and also mandated that maintenance inspections, deemed "as necessary", in the Airworthiness Limitation section of the Instructions for Continued Airworthiness.

Option 2: Adopt a more definitive approach to continued airworthiness, where the maintenance inspections are determined by specific criteria as defined within the regulations.

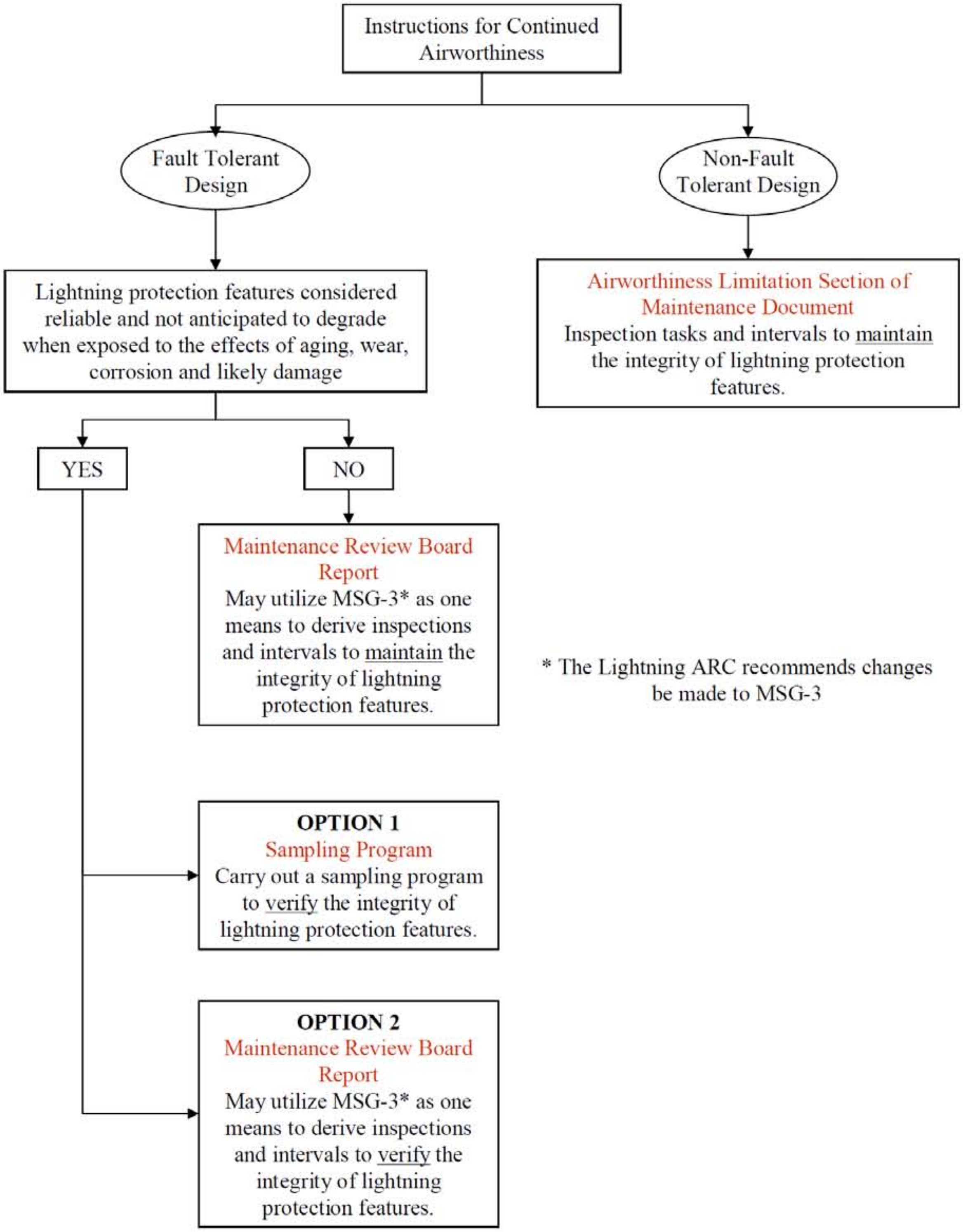
Industry experience indicates the thoroughness of continued airworthiness instructions for fuel tank lightning protection has varied from applicant to applicant. This may be due in part to the limited information regarding fuel tank lightning protection ICA in the regulatory language and guidance material of §§ 25.954 and 25.1529. Providing a more definitive approach to continued airworthiness within the proposed fuel tank lightning protection regulation can help ensure ICA are addressed by the applicant.

However, the Lightning ARC is concerned with the § 25.981 regulatory language which states, *"…inspections or other procedures must be established, as necessary, to prevent development of ignition sources within the fuel tank systems. These CDCCL, inspections and procedures must be included in the Airworthiness Limitation section of the Instructions for Continued Airworthiness required by § 25.1529."* The interpretation of the regulatory language and specifically the phrase "as necessary" has resulted in some confusion as to what inspections and procedures are deemed necessary and as a result what inspections must be incorporated into the Airworthiness Limitation section of the ICA.

Section 3.3 discusses that most lightning protection features are considered reliable and thus not expected to degrade when exposed to the anticipated effects of aging, wear and corrosion. A reliable design can reduce the need for maintenance inspections required to verify the protection design which in turn reduces the possibility of likely damage or disabling of lightning protection features that may occur during operations and scheduled or unscheduled maintenance activity. A review of the data regarding the overall integrity of fuel tank design and maintenance, including the AFSSP report[17] indicates that the fuel systems inspected were generally found to be in good to excellent condition unless subject to subsequent modification or damage (likely damage). Since likely damage was considered a significant finding within the AFSSP report[17], and usually occurs during operations and scheduled and unscheduled maintenance activity, the Lightning ARC determined that it would be beneficial to adopt a continued airworthiness approach which can minimize the frequency of fuel tank maintenance activity and consequently reduce the risk of accidental or likely damage. In addition, if a fault tolerant design is implemented fuel tank entries can be minimized.

The Lightning ARC developed a definitive approach (see Figure 1) for determining criteria associated with instructions for continued airworthiness, as suggested by Option 2. This approach proposes inspections and procedures for non-fault tolerant features be included in the Airworthiness Limitations section and procedures for fault tolerant designs may utilize sampling programs or the MRB process (via a modified MSG-3[20]) to derive the maintenance tasks. A more definitive approach will avoid the confusion associated with the "as necessary" terminology of § 25.981 and, together with a reliable fault tolerant design, will minimize the need for fuel tank entries.

FIGURE 1


Instructions for Continued Airworthiness
Fault Tolerant Design
Non-Fault Tolerant Design
Lightning protection features considered reliable and not anticipated to degrade when exposed to the effects of aging, wear, corrosion and likely damage
Airworthiness Limitation Section of Maintenance Document
Inspection tasks and intervals to maintain the integrity of lightning protection features.
YES
NO
Maintenance Review Board Report
May utilize MSG-3* as one means to derive inspections and intervals to maintain the integrity of lightning protection features.
* The Lightning ARC recommends changes be made to MSG-3
OPTION 1
Sampling Program
Carry out a sampling program to verify the integrity of lightning protection features.
OPTION 2
Maintenance Review Board Report
May utilize MSG-3* as one means to derive inspections and intervals to verify the integrity of lightning protection features.

The Lightning ARC has also reviewed the wording in § 25.981 at Amendments 25-102[5] and 25-125[6],"…*visible means to identify critical features of the design must be placed in areas of the airplane where maintenance actions, repairs, or alterations may compromise the critical design configuration limitations (e.g. color-coding of wire to identify separation limitation). These visible means must also be identified as CDCCL.*"

Fuel tank lightning protection may utilize several approaches including fastener type/installation, sealant used as a spark/arc barrier, sealant used to prevent corrosion of lightning protection features, electrically bonded interfaces to safely conduct the lightning current, electrically insulating interfaces to prevent voltage breakdown/current conduction, adequate clearances between fuel systems and structure as well as cable shielding. The present wording in 25.981 regarding "visible means" can be widely interpreted. One possible interpretation would require the applicant to place visible means, such as placards, in areas of the fuel tank to identify all the fasteners, sealant applications, conductive and insulating components that may be used in the fuel tank to prevent ignition sources. In addition, the placards themselves would then be defined as a CDCCL item requiring mandatory inspections to ensure their integrity. The Lightning ARC reviewed and discussed the application of visible means to identify fuel system lightning protection features, but found no options that were considered practical or beneficial.

Review of ATA MSG-3[20] as a Means of Developing and Documenting the Instructions for Continued Airworthiness.

Part of Task 7 is to identify any recommended changes to the ATA MSG-3[20] logic process should this process be used to derive maintenance tasks and intervals associated with fuel tank lightning protection features.

As outlined in the previous sections, the Lightning ARC proposes a definitive approach that utilizes sampling programs, Airworthiness Limitations and the Maintenance Review Board (MRB) process for documenting the instructions for continued airworthiness.

In general, developing the instructions for continued airworthiness can be derived using a number of approaches including the following:

- Tasks that are derived by engineering specialists during the certification process such as CMRs and Structural Airworthiness Limitations. This process can also be used to derive tasks for fuel tank lightning protection features.
- Tasks that are developed within the Maintenance Review Board process using the structured approach of ATA MSG-3[20].

The Maintenance Review Board report contains ICA that are developed through the logic-based analysis process provided in ATA MSG-3[20], *Operator/Manufacturer Scheduled Maintenance Development,* prepared by the Air Transport Association. The latest version of the document is MSG-3 Revision 2009.1[20]. The tasks and intervals are developed by coordinating the efforts of specialists from the airplane Operators, Airplane Manufacturer and Regulatory Authorities. The airplane manufacturer utilizes the guidelines from the ATA MSG-3[20] document and produces a Policy and Procedures Handbook (PPH) outlining the processes and any assumptions made by the airplane manufacturer to derive the scheduled maintenance program.

The working portions of the ATA MSG-3[20] document are contained in the following four sections. A brief overview of each section is provided below, as well as the suitability of each section to derive instructions for continued airworthiness as related to fuel tank lightning protection features.

- Section 2-3: Systems /Powerplant Analysis Procedure
  This section identifies Maintenance Significant Items (MSI) based on consequences of failure, evaluates functional failure to determine failure effect category (safety, economic or operational) and takes into consideration the failure cause to derive maintenance tasks. This section presently contains a note (section 2.3.1) added in 2005 regarding fuel tank systems safety as related to ignition sources, including lightning.

  The ARC determined that this section may be used to derive maintenance tasks and intervals. However, section 2-3 would require changes to ensure the analysis in this section can be applied effectively. A number of potential shortcomings are summarized below.

The existing note contained in section 2-3-4 regarding *"fault tolerant systems"* is inconsistent with a fault tolerant design requirement and requires review by MSG-3[20] specialists. Confusion can exist when applying the logic questions contained in MSG-3[20] section 2-3 as outlined below:

- The terms "Function", "Functional Failure" and "Failure Effect" may require clarification as they apply to a fault tolerant design subject to a lightning event.
- There may be ambiguity when asking and understanding the logic questions such as the Level 1 Question 3: *"Does the combination of a hidden functional failure and one additional failure of a system related or back up function have an adverse effect on operating safety?"* At the present time, it is not clear how to respond to this question for a fault tolerant design in the event of a lightning strike.
- It is not clear that the analysis process within this section can derive a maintenance task to restore the fault tolerant design where one lightning protection feature has failed.
- It is not clear that the analysis process within this section can derive the tasks required to verify the integrity of lightning protection features of a fault tolerant design where the protection features are not anticipated to fail.

The note added to section 2-3-1 logic analysis in 2005 refers to "*lightning protection of the fuel tank system"* and references the one example of: *"the electrical bonding subsystem."* This information is very limited and does not provide an adequate description of fuel tank lightning protection features especially if both fuel tank structures and systems lightning protection is adopted.

- Section 2-4: Airplane Structural Analysis Procedure
  This section identifies Structural Significant Items (SSI) based on their contribution to carrying flight, ground, pressure and control loads. Structural components are evaluated for susceptibility to Accidental Damage (AD), Environmental Damage (ED) and Fatigue Damage (FD) when deriving the maintenance tasks. There is presently no reference to fuel tank lightning protection features.

  The Lightning ARC did not identify any means to use this section for evaluation of fuel tank lightning protection features.

- Section 2-5: Zonal Analysis Procedure
  The airplane is divided internally and externally into zones. Structures and systems located within each zone are evaluated for likelihood to AD and ED. Standard zonal analysis derives tasks where only general visual inspections (GVI) are adequate to check for security and general condition. Enhanced zonal analysis (EZAP) applied to areas which contain wiring and have potential for combustible material being present.

  The Lightning ARC determined that this section could be used to derive GVI of fuel tank lightning protection features provided the required task meets the criteria to become a GVI and provided the GVI is an adequate task to check for security and general condition. For example, this section may be appropriate to specify a GVI for structural conditions that may have lightning implications. In addition, the EZAP applied to areas which contain wiring may be appropriate to derive tasks and inspections for wiring located within the fuel tank.

- Section 2-6: Lightning/High Intensity Radiated Fields (HIRF) Analysis Procedure
  This section identifies lightning/HIRF protection systems and components such as wire shielding, pigtail terminations, backshells, bonding straps, raceways, metallic meshes, conductive gaskets, and conductive coatings. Protection components are evaluated for likelihood to AD and ED and asks the question*," Will the failure condition due to the expected degradation in combination with a Lightning/HIRF event prevent the continued safe flight and landing of the aircraft?"* There is presently no specific reference or examples associated with fuel tank lightning protection features.

  The ARC determined that this section could be used to derive maintenance tasks and intervals since the basis of the analysis in this section evaluates the components for susceptibility to AD and ED. However, section 2-6 would require significant changes since there is presently no specific reference or examples associated with fuel tank lightning protection features. In addition, the analysis process would have to be revised for a fault tolerant lightning protection design requirement.

3.5.2 Findings

The Lightning ARC identified a number of findings during the assessment of criteria associated with continued airworthiness which could improve and promote a consistent approach to ICA for fuel tank lightning protection.

- Adopt a definitive approach to continued airworthiness where inspections and procedures for non-fault tolerant features would be included in the Airworthiness Limitations section of the instructions for continued airworthiness required by Sec. 25.1529, and inspections and procedures for fault tolerant designs may utilize sampling programs or task developed through the MRB process.

- The use of visible means for identifying lightning protection features is impractical.

The ARC identified a number of findings related to potential modifications to ATA MSG-3[20]. Revisions could be incorporated into Section 2-3, Section 2-6 or into a new Section 2-X dedicated to fuel tank lightning protection. Any specific modifications to the MSG-3[20] document would require specialists in the MSG-3[20] logic process along with the support of fuel tank lightning protection specialists.

- The existing note contained in ATA MSG-3[20] Section 2-3-4, Systems/Powerplant Analysis Procedure, regarding *"fault tolerant systems"* discourages the use of this analysis process where fault tolerant designs are required for certification. If this section were to be used, this information would require revision for fuel tank lightning protection as a result of fault tolerant design being implemented.

- The note added to ATA MSG-3[20] section 2-3-1, Systems/Powerplant Analysis Procedure, in 2005 refers to "*lightning protection of the fuel tank system"* and references the one example of, *"…the electrical bonding subsystem."* This information would require revision to identify additional examples for both fuel tank structures and systems lightning protection, or deletion if a new section 2-x were to be used.

- ATA MSG-3[20] section 2-3, Systems/Powerplant Analysis Procedure, would require revision if used to develop ICA for a fault tolerant fuel tank lightning protection design, to provide additional information and examples on the most appropriate method of using the analysis in this section. This includes information and clarification regarding "Function", "Functional Failure" and "Failure Effect"; as well as information and clarification to ensure the MSG-3[20] user understands the logic questions such as the Level 1 Question 3.

- ATA MSG-3[20] section 2-6, Lightning/High Intensity Radiated Fields Analysis Procedure, would require significant revision to include fuel tank lightning protection features supported with examples and a dedicated process flowchart and to ensure appropriate tasks can be derived for a fault tolerant lightning protection design.

- A new ATA MSG-3[20] section 2-x, Fuel Systems Lightning Protection, could be prepared to develop ICA for fuel tank lightning protection features supported with examples and a dedicated process flowchart and to ensure appropriate tasks can be derived for a fault tolerant lightning protection design. This approach is preferred by the Lightning ARC as extensive rewording to the other sections would likely cause difficulty for other uses.

3.6 Task 8

Consider the effect of reducing the flammability below the criteria of § 25.981(b), Amendment 25-125, in adjusting the other tasks listed above.

3.6.1 Evaluation of the Issue

With the release of the Fuel Tank Flammability Reduction Rule at Amendment 25-125[6], two distinct levels of flammability criteria have been established: those pursuant to the standard set in § 25.981(b) & (b)(1), as defined by Appendix N to Part 25, and those pursuant to the higher standard set in § 25.981(b)(2), as defined in Appendix M to Part 25. It is these new flammability reduction standards that FAA Policy Memorandum ANM-112-08-002[10] uses as a basis for allowing alternate requirements for the ignition prevention standards of § 25.981(a)(3) applied to fuel tank lightning protection.

In considering the effect of reducing the flammability below the Amendment 25-125[6] criteria, the impact on each of the previous Lightning ARC tasks was examined.

Effects of Further Flammability Reduction

1. **<u>Impact to Task 1</u>**
   Task 1 was to determine whether the approach to fuel tank safety related to lightning protection should be focused on fuel vapor ignition, ignition sources, or a combination of both. Prior to the 2001 Amendment 25-102[5] revision to § 25.981, fuel tank ignition protection was based solely upon ignition source prevention. In the preamble to the Fuel Tank Flammability Reduction Rule, as well as in FAA Policy Memorandum ANM-112-08-002[10], FAA stated the following:

   > *"Predicting the effectiveness of ignition prevention actions is challenging, since many ignition sources are the result of human error, which cannot be precisely predicted or quantitatively evaluated. Despite extensive efforts by the FAA and industry to prevent ignition sources, we continue to learn of new ignition sources. Some of these ignition sources are attributable to failures on the part of engineering organizations to identify potential ignition sources and provide design changes to prevent them. Others are attributable to actions by production, maintenance, and other operational personnel, who inadvertently compromise wiring and equipment producing ignition sources. Regardless of the causes, we believe that ignition prevention actions, while necessary, are insufficient to eliminate ignition sources."*

   The same inherent limitations found in the design, production, maintenance, and operation of a protection means based solely upon ignition source prevention, would exist for a design based solely on a Flammability Reduction Means (FRM). Just as it is not practical to eliminate all potential ignition sources, it is not practical to eliminate all possible failure conditions which could contribute to flammability exposure. The overall efficacy of the FRM is dependent not only upon its own performance, but also its reliability and the reliability of the systems supporting the FRM, such as electrical power, and pressurized air systems. A design based entirely on precluding flammability would require a flight critical means of flammability control. Achieving flight critical availability requires levels of redundancy which render the system impractical. A top level requirement based upon a balance of both flammability reduction and ignition source prevention is the practical solution, as found in Task 1.

2. **Impact to Task 2**
Task 2 was to determine whether the lightning protection regulation changes should apply to the complete fuel *system* or just to the fuel tank structure. The ARC did not identify any potential impact that additional flammability reduction would have on whether the same lightning protection regulation changes should apply to the complete fuel system (*systems* and structure), or just the fuel tank structure.

3. **Impact to Tasks 3, 4, & 5**
Tasks 3, 4 and 5 were to:

   Task 3 was to determine what type of safety assessment approach should be used.

   Task 4 was to determine whether a probabilistic approach, prescriptive pass/fail criteria, or a combination of both using qualitative analysis, should be applied to structure or the complete fuel system lightning protection. If a probabilistic approach is used, determine if flammability exposure should be considered. Determine how single failures should be addressed.

   Task 5 was to establish which components and installations must be addressed and which failure modes (including possibility of cascading failures) should be considered.

The reduction of fuel tank flammability beyond the established criteria could impact the determination of the appropriate fuel tank lightning protection safety assessment method. Flammability exposure would need to be considered in the analysis if credit for additional reduction were sought by an applicant. If such a reduction were practically established, this could potentially affect the finding of Task 3, 4 and 5 regarding the requirement to demonstrate fault tolerance.

To achieve an equivalent level of enhanced lightning protection, replacing the recommended requirement to demonstrate fault tolerance would have to be justified by an equivalent increase in the prevention of flammability. As discussed in Tasks 3, 4 and 5, a robust means of providing fault tolerance would mean the probability of a failure being present would be rare (e.g. less than 1 in 1000). Therefore, an equivalent decrease in the flammability exposure would mean the capability of the FRM would have to increase by multiple orders of magnitude. This would require not only lower flammability levels from the performance of the FRM design, but also an increased criticality of the operation of the FRM throughout the lifetime of the airplane. The availability of the FRM is dependent upon both the reliability of the FRM components, and the significant number of systems and subsystems which support or affect the FRM operation.

Based upon technology available today, a far more capable FRM is not feasible. Although the ARC did not do extensive studies of FRM which was outside the scope of the committee, the experts familiar with FRM know of no system currently available which they believe could demonstrate this level of flammability prevention.

4. **Impact to Task 6 & 7**

Task 6 was to determine a means to address manufacturing variability, aging, wear, corrosion and likely damage to lightning protection features.

The Lightning ARC reviewed Task 6 and found that further reduction of flammability exposure would not alter the means to address manufacturing variability, aging, wear, corrosion, or likely damage to the lightning protection designs.

Task 7 was to determine criteria associated with instructions for continued airworthiness and any needed modifications to processes defined in Revision 3 to the Maintenance Steering Group (MSG-3)[20] document.

The Lightning ARC reviewed the finding of Task 7, and did not find that the recommended criteria associated with determination of whether inspections were needed (and the associated maintenance intervals if required) would be based upon an assessment including the flammability exposure levels. The only impact the ARC identified that further flammability reduction might have on Tasks 6 and 7, would be if the recommendation for providing fault tolerance was replaced entirely by lower flammability exposure requirements. Given that this was not found to be practical above, the ARC found no impact on Tasks 6 and 7 if flammability exposure were reduced below Amendment 25-125[6].

3.6.2 Findings

The Lightning ARC found that further reduction in flammability exposure beyond that of § 25.981(b) Amendment 25-125[6] would not affect the findings of Task 1. A balance of both flammability reduction and ignition source prevention is the practical solution. Absolute prevention of flammability exposure is not feasible with current technology, nor recommended as an only means of protection.

The Lightning ARC found that flammability exposure had no impact on Task 2 regarding whether regulation changes should apply to the complete fuel system (*systems* and structure), or just the fuel tank structure.

The Lightning ARC found that a further reduction in flammability exposure might affect the safety assessment approach used (numerical assessment vs. prescriptive requirements). However, for a further reduction in flammability exposure to allow a reduction in the recommended ignition source prevention means (i.e. replacing the Task 3, 4 and 5 recommendation for demonstrating fault tolerance), a far more capable FRM would have to be available. This level of flammability prevention is not available today, nor does it appear to be practical in the near term. Accommodating different levels of ignition source prevention based upon different levels of flammability exposure would result in multiple tiers of compliance criteria and increased complexity in the regulation. Therefore, the Lightning ARC found that the regulation changes should not include different ignition source requirements based upon the potential for further reduction in flammability exposure beyond 25.981 Amendment 25-125[6]. Based upon this finding, no impact to Tasks 3, 4 or 5 were identified.

Regarding any impact of Task 6 and 7, the Lightning ARC found that further reduction of flammability exposure would not alter the means to address manufacturing variability, aging, wear, corrosion, or likely damage to the lightning protection designs, nor the criteria or processes associated with the determination of whether inspections were needed.

3.7 Task 9

Identify compliance guidance that might be required to facilitate showing compliance with the recommendations above.

3.7.1 Evaluation of the Issue

The evaluation of potential changes to compliance material is based on the following summarized findings /recommendations of Tasks 1 through 8:

- Prevention of fuel vapor ignition due to lightning strikes should be the overarching requirement of the future rulemaking.
- Fuel systems as well as tank structures should be addressed by the same rule.
- A prescriptive approach of fault tolerant protection designs should be adopted (for both *systems* and structures), coupled with existing flammability requirements.

The guidance material presently provided in AC 25.981-1C[27] and AC 20-53B[3] will need to be updated. Specific findings related to updating of the advisory circulars and other guidance materials are provided in the following paragraphs. The ARC also found many updates to these ACs are needed even if no changes to the regulations were implemented, to reflect the current regulation interpretations and the 2009 FAA Policy Memorandum ANM-112-08-002[10].

Updated guidance material should address the following topics:

- Means to evaluate the fuel tanks and system designs. This would include guidance for identifying possible failure modes and evaluating practical fault tolerant features by test. Also guidance should be provided on evaluation of fault tolerance for conducted currents in all areas, whereas fault tolerant protection for direct attachment would only need to be demonstrated for Zone 1 and 2 areas. Guidance material will need to be provided so that this process can be consistently applied.

- Means to identify and assess the potential for ignition sources within fuel tanks and systems attributable to failures either by engineering design errors or potential design changes after initial release. The lightning-related potential ignition source design features described in Section 7 of AC 25.981-1C[27] should be deleted from AC 25.981-1C[27] and brought into a revised AC 20-53. Additionally, the discussion of lightning related arcs and sparks in Section 8b of AC 25.981-1C[27] should be deleted from that AC and brought into a revised AC 20-53.

- Means to identify and assess manufacturing variability, aging, wear, corrosion or likely damage, including actions by production, maintenance, and other operational personnel which could inadvertently compromise wiring, equipment and other means used to provide fuel tank lightning protection.

- Means to identify and assess the adequacy of potential non fault tolerant designs.

- Address both conventional aluminum and composite fuel tank structures.
- Address inspection and maintenance procedures for lightning protection features.

FAA AC 20-53B - Protection of Airplane Fuel Systems Against Fuel Vapor Ignition Caused by Lightning

AC 20-53B[3] provides a reasonable format to address the above listed topics. It presently advises applicants to define requirements for maintaining and monitoring the "dedicated lightning protection devices or techniques" to ensure their integrity remains intact, and the dispatch requirements when a protective device has degraded. But it does not address other potential fault conditions in the tank structure or systems. Guidance on how to identify and treat potential fault conditions also needs to be provided in a revision of this AC. The steps to showing compliance in AC 20-53B[3] would need to be revised to address any changes that are made to the regulations.

AC 25.981-1C[27] - Fuel Tank Ignition Source Prevention Guidelines

AC25.981-1C[27] presently describes potential ignition sources due to lightning strikes. Any of this material that is specifically related to lightning should be brought into a revised AC 20-53 as noted more specifically above. The lightning protection design guidance presently contained in Section 9 of AC 25.981-1C[27] should be relocated to new documents containing additional design guidance as noted below.

Additional Guidance Material on Fault Tolerance

The ARC found that additional guidance regarding designing for fault tolerance of tank structures and systems, identifications of potential failure conditions and dealing with non-fault tolerant designs, may be helpful but beyond the scope of a revised advisory circular. It is recommended that FAA request the SAE AE-2 and EUROCAE WG31 Lightning Committees to develop this guidance. Lightning protection guidance already within Section 9 of AC 25.981-1C[27] can be included in the new guidance documents. The additional guidance should address:

- Examples of the potential failures which need to be considered, especially failures in non-fault tolerant features.
- Guidance on identifying other failure modes not listed in the examples.
- Checklist for reviewing designs and ensuring compensating features to provide fault tolerance are provided.
- Mitigation for protection features which cannot be practically designed to be fault tolerant.
- How multiple protection features can support fault tolerance with consideration of cascading types of failure modes.

Testing Guidance
Existing lightning test methods in SAE ARP5416[22] are adequate for assessing lightning protection performance, but do not describe details on how to determine fault tolerance, or ignition source thresholds. Additional guidance on test methods for fuel tank lightning protection should address:

- Details for how to select and configure tests using the present standard test methods to show that an ignition source will not occur at lightning conducted or induced current levels within the tank or system.

- Definition of test samples in order to include combinations of failure modes / tolerance limits.

Maintenance and Inspection
Specific changes have been proposed for ATA MSG-3[20] to determine maintenance tasks and intervals**.** Recommendations are presented in detail in Section 3.5.2.

3.7.2 Findings

The ARC has identified a need for revision of AC 20-53B[3] and AC 25-981-1C[27].

The ARC found that AC 20-53B[3] provides a reasonable baseline for incorporating the recommendations of the ARC, including the identification of potential ignition source threats, demonstration of fault tolerance of protection means, and the evaluation of both systems and structures under a common set of requirements.

Revisions to AC 25.981-1C[27] would be needed primarily to remove references regarding compliance for lightning protection under § 25.981.

We recommend development of Users Manuals [by SAE AE-2 & Fuel Specialists] which will provide the detailed guidance on how to identify failure modes, address fault tolerance, and on testing approaches. This Users Manual may incorporate applicable portions of the recent AE-2 guidance regarding the FAA Policy Memorandum ANM-112-08-002[10] and the current AC 20-53A Users Manual.

Additional guidance material to be used with industry documents SAE ARP5416[22] and EUROCAE ED-105 to provide details on test approaches to assess fault tolerance and to determine ignition source thresholds.

Revisions to ATA MSG-3[20] to include maintenance tasks & inspections for fuel tank lightning protection features.

4.0 DISCUSSION OF FINDINGS

This section examines the findings of the chartered tasks, how they relate to each other and how in combination they form the overall recommendations of the Lightning ARC.

In the background section of the ARC charter, FAA identified the primary problem with the current application of the rule, as the inability of the designer to meet the goal of a fail-safe design. The term fail-safe was interpreted as being the prevention of all ignition sources within the fuel tank. Industry found this to be problematic in at least three areas:

1. Providing a third layer of protection to mitigate latent failure conditions is impractical.
2. It is impractical to continuously monitor lightning protection features to identify failures.
3. There is limited capability to inspect and detect failures to minimize the time that the failures are latent.

As a result of these issues and others, FAA established the Lightning ARC with the goal of achieving a balanced approach for fuel tank lightning protection to prevent catastrophic fuel vapor ignition. Both FAA and industry understand that the elimination of all ignition sources is impossible. Therefore, the ARC was tasked to develop an acceptable level of safety that would allow manufactures to develop designs that are as free of ignition sources as practical, while using current technology in designs which are economically viable in terms of design, manufacture and operation. In addition, FAA tasked the Lightning ARC to consider fuel vapor flammability in developing a design to achieve an acceptable level of safety.

FAA assigned the Lightning ARC nine separate tasks. Though separate, each of the tasks are interrelated to the prevention of a catastrophic fuel vapor ignition resulting from the airplane being struck by lightning. The Lightning ARC studied the tasks, both individually and collectively, and developed recommendations through Lightning ARC consensus.

In § 25.981(a)(3), the applicant must prevent ignition sources, assuming that the fuel tank ullage is always flammable. The applicant must also limit fuel tank flammability, because of the concern that ignition sources could still occur. The requirements of § 25.981(a) result in a need to provide dual fault tolerant structural lightning ignition sources protection, which has proven to be impractical. The ARC found that while providing dual fault tolerant ignition source prevention is not possible, by addressing the top level event, that is, fuel vapor ignition, an acceptable level of safety can be achieved.

The Lightning ARC found that tank flammability is independent of the lightning protection. The Lightning ARC reviewed the flammability standard established by § 25.981(b), and concluded that it adequately limits this aspect of a potential fuel tank lightning-related fuel vapor ignition. These existing flammability limits can be considered when developing a practical approach for fuel tank lightning protection regulations that prevent fuel vapor ignition by focusing on potential ignition sources due to lightning.

The Lightning ARC charter stated the goal of producing a design "as free of ignition sources as possible". The ARC determined that a prescriptive fault-tolerant approach for fuel system lightning protection is practical and economically viable using current technology. The prescriptive fault-tolerant approach, when coupled with a lightning hazard assessment, as opposed to a probabilistic risk assessment approach, emphasizes effective and reliable lightning protection. At the same time, the prescriptive fault-tolerant approach uses techniques that have been proven through an outstanding history and safety record for transport airplane lightning protection. The prescriptive fault-tolerant approach using a hazard assessment allows for the most effective and economical method of addressing potential failures due to manufacturing variability, aging, wear, corrosion and likely damage.

The probabilistic risk assessment approach imposed by the current rule and the FAA Policy Memorandum ANM-112-08-002[10] was also fully examined. However, the data required to make a probabilistic risk assessment is not available for structural failures and the Lightning ARC does not see a path forward that would make reliable failure rate data available. This point was made and rejected during the comment period for the policy, though the final policy still did not provide any method or guidance on how this data would be gathered. To further the evaluation of this issue, the Lightning ARC convened a group of structural specialists who determined that a probabilistic risk assessment approach for structural failures is not practical and that there are too many variables in structural designs to make that approach practical. The Lightning ARC concurs and does not recommend the use of a probabilistic risk assessment approach.

FAA required the probabilistic risk assessment in the policy to deal with situations where fault tolerance can not be achieved, such as structural cracks and broken bolts which could also damage a fault tolerant layer of sealant. This has proven to be one of the most significant issues of the current rule and FAA Policy Memorandum ANM-112-08-002[10]. The Lightning ARC concluded, supported by the structural sub-group report, that non-fault tolerant designs associated with structural cracks and broken bolts within aluminum fuel tanks do not represent a significant risk and do not justify the economic burden and/or technical complexity required to further reduce their improbability.

Based upon the review of all available history, data and experience of both the structural and the lightning specialists, the Lightning ARC found that these threats are adequately mitigated through design, process controls and manufacturing techniques necessary to comply with existing structural regulations. The data also showed that even if a rare non-fault tolerant failure occurs, the failures are not in and of themselves a single failure leading to a catastrophic event. These failures must exist in combination with the independent factors of lightning attachment to the airplane, attachment near the non-fault tolerant condition, a lightning current of sufficient amplitude and flammable conditions

The Lightning ARC believes this is also true in regard to composite fuel tanks. However, it is generally understood that composite fuel tanks will typically require more features and result in greater variability in lightning protection performance than aluminum fuel tank designs. Currently, the maturity of the technology associated with composite tank designs have resulted in some difficultly in providing fault tolerant designs under some conditions. However, it is the opinion of the Lightning ARC that with continued technology development and maturity of industry knowledge related to variability and failures of lightning protection in composite designs, fault tolerant designs will become practical for all conditions. Therefore the Lightning ARC finds that these composite design challenges today should not influence the other safety assessment recommendations.

The Lightning ARC also studied the differences between structural lightning protection and *systems* lightning protection. The Lightning ARC found the lightning environment, means of assessment and means of protection did not support a need for different lightning requirement for *systems*. The Lightning ARC found that an acceptable level of safety can be achieved in both structures and *systems* lightning protection by a robust fault tolerant design when considering fuel tank flammability and the likelihood of lightning attachment. The Lightning ARC concluded the availability of means to implement additional layers of protection for *systems* is not justification for more stringent requirements compared to fuel tank structure. The additional design complexity that would result from additional layers of protection will have no commensurate safety benefit and may introduce unforeseen negative safety consequences. The Lightning ARC concluded the revised regulations should address both fuel tanks structure and *systems* with the same requirements.

The Lightning ARC concluded that the practical way to address the effects of manufacturing variability, aging, wear, corrosion and likely damage of lightning protection features is an approach that utilizes reliable design practices, manufacturing, quality and process controls along with instructions for continued airworthiness (ICA).

Since *likely damage* was considered a significant finding within the AFSSP[17] and usually occurs during maintenance activity, the Lightning ARC concluded that Caution information associated with critical lightning ignition source prevention features should be incorporated directly into the maintenance documentation used by maintenance personnel including the AMM, the SRM and manuals that provide maintenance personnel with standard practices such as standard wiring practices. The requirement for Caution should be used in lieu of CDCCLs as prescribed in § 25.981. The Lightning ARC determined that Caution information for critical lightning protection features should be incorporated into instructions for continued airworthiness required by § 25.1529. These Cautions should include information that will minimize likely and accidental damage to critical lightning ignition source prevention features, during performance of maintenance, alteration, or repairs.

The Lightning ARC concluded that the wording in § 25.981 (d) regarding “visible means” to identify critical features of the design is not considered practical for lightning protection features due to the multitude of protection features including fasteners, sealant as well as insulating and conducting interfaces.

The Lightning ARC determined that a more definitive approach to continued airworthiness is warranted where inspections and procedures for non-fault tolerant features should be included in the Airworthiness Limitations section of the instructions for continued airworthiness required by § 25.1529. Inspections and procedures for fault tolerant designs may utilize sampling programs or the MRB process. A modified MSG-3[20] process may be one means to derive the maintenance tasks. A more definitive approach will avoid the confusion associated with the "as necessary" terminology of § 25.981 and together with a reliable, fault tolerant design will minimize the need for fuel tank entries.

The Lightning ARC determined that the ATA MSG-3[20] process can be successful in developing instructions for continued airworthiness of fuel tank lightning protection. As outlined in the findings, changes to MSG-3[20] would be required. Revisions could be incorporated into Section 2-3, Section 2-6 or into a new Section 2-X dedicated to fuel tank lightning protection.

The ARC concluded that additional flammability reduction is not warranted. While there might be a slight numerical benefit to further reduction of flammability beyond the established criteria, there is no practical means with current technology to provide a flammability reduction of sufficient magnitude to justify a reduction in ignition source prevention requirements. The ARC found that a design as free of ignition sources as practical can be achieved with a prescriptive fault tolerant design. When combined with the current flammability requirements, a significant benefit from further flammability reduction could only be achieved if it were sufficient to justify a design which would be completely non-fault tolerant for ignition sources. Since no practical means exist for this significant of a reduction in flammability, the ARC concluded that it is inappropriate to propose adding complexity to the rule to provide for multiple levels of ignition source requirements. Proposed fault tolerant ignition source requirements combined with the existing flammability criteria will provide the desired overall level of fuel tank safety.

Finally, the ARC looked at the guidance that is currently available to the lightning specialist in regard to the current rule as well as guidance that will needed based on the ARC recommendations. As discussed in the findings, the guidance for fuel tank and system lightning protection is currently inadequate and will require update, regardless of what FAA chooses to implement from the ARC findings and recommendations.

5.0 RECOMMENDATIONS

The Lightning ARC Recommends:

1. Prevention of fuel vapor ignition due to lightning should be the objective of the regulations, achieved through both flammability control and ignition source prevention. Existing Part 25 regulations provide adequate flammability requirements. Thus, lightning-specific requirements should focus on ignition source prevention.
2. Both structure and *systems* should be addressed in the same fuel system lightning protection rule with the same requirements.
3. A prescriptive approach requiring single fault tolerant designs should be mandatory. If fault tolerance is impractical, a qualitative assessment, such as the Lightning Hazard Assessment recommended in SAE ARP5577[12], should be conducted to ensure that the combination of non-fault-tolerant failures resulting in an ignition source is remote.
4. Manufacturing variability, aging, wear, corrosion and likely damage should be addressed by design, manufacturing processes and/or by instructions for continued airworthiness (ICA).
5. Caution information for critical lightning protection features should be incorporated into instructions for continued airworthiness to minimize accidental or likely damage to these features during performance of maintenance, alteration or repairs.
6. Inspections and procedures required for non-fault-tolerant designs should be included in the Airworthiness Limitations section of the instructions for continued airworthiness, whereas fault tolerant designs should utilize tasks developed by the MRB or a sampling program where appropriate.
7. Changes should be made to Air Transport Association (ATA) Maintenance Steering Group (MSG) document MSG-3[20] to support instructions for continued airworthiness for fuel tank lightning protection. Addition of a new section specific to fuel tank lightning protection is recommended.
8. No requirement for lower flammability should be included in the lightning regulations.
9. New guidance material should be developed and existing guidance material should be revised to ensure a consistent approach to fuel system lightning protection is applied across industry.

Proposed Rulemaking:

The Lightning ARC recommends §§ 25.954, 25.981and Appendix H be revised to read as follows:

§ 25.954 Fuel system lightning protection.

(a) The fuel system must be designed and installed to prevent catastrophic fuel vapor ignition due to lightning.

(b) The fuel system lightning protection design must be fault-tolerant for failures that result in lightning-related ignition sources.

(c) Fault tolerance is not required for any specific design feature if:

(1) providing fault tolerance is shown to be impractical for that feature, and

(2) the failures that lead to lightning-related ignition sources from that feature and all other non-fault-tolerant features, when combined, are shown to be remote.

(d) Inspections or other procedures must be established as required by Sec. 25.1529 to prevent development of lightning-related ignition sources within the fuel tank system pursuant to paragraphs (b)(c) of this section. Caution information for critical lightning protection features shall be incorporated into instructions for continued airworthiness required by Sec. 25.1529 to minimize accidental or likely damage to these features during performance of maintenance, alteration or repairs. Required inspections and procedures for non-fault-tolerant features in paragraph (c) of this section must be included in the Airworthiness Limitations section of the instructions for continued airworthiness required by Sec. 25.1529.

§ 25.981 Fuel Tank Ignition Prevention

(a) No ignition source may be present at each point in the fuel tank or fuel tank system where catastrophic failure could occur due to ignition of fuel or vapors. This must be shown by:

(3) *Except for ignition sources due to lightning subject to Sec. 25.954*, demonstrating that an ignition source could not result from each single failure, from each single failure in combination with each latent failure condition not shown to be extremely remote, and from all combinations of failures not shown to be extremely improbable. The effects of manufacturing variability, aging, wear, corrosion, and likely damage must be considered.

§ H25.x Fuel System Lightning Protection Instructions for Continued Airworthiness

(a) The applicant must prepare Instructions for Continued Airworthiness (ICA) applicable to fuel system lightning protection including the following:

(1) Mandatory maintenance or inspections necessary to preclude the development of unsafe conditions due to non-fault tolerant lightning protection features shall be identified as Airworthiness Limitations and approved by the Administrator.

(2) Sampling programs, maintenance and/or inspections for fault tolerant lightning protection features, included in the manufacturer's recommended airplane maintenance program and acceptable to the Administrator.

(3) Caution information which identifies the lightning protection features of the fuel system design, to minimize the potential for inadvertent damage or disruption of lightning protection features, included in the applicable airplane maintenance documents and acceptable to the Administrator.

In addition to the above rulemaking language, the Lightning ARC also recommends that the preamble of the rulemaking should clarify that fuel system lightning protection be excluded from rules of general applicability such as §§ 25.901 and 25.1309.

Guidance that is Required to Accompany the Proposed § 25.954 Revision:
The same fuel tank lightning protection requirements apply to both fuel tanks structure and *systems*.

As defined in AC 25.1309 Arsenal version paragraph 5.B.2, *Qualitative Probability Terms*, *"remote failure conditions are those unlikely to occur to each airplane during its total life, but which may occur several times when considering the total operational life of a number of airplanes of the type."*

Structural cracks or broken fasteners that are due to overstress, fatigue or manufacturing escapes, while potentially probable for an airplane, are remote failures when considering lightning-related ignitions sources for airplanes that meet the Part 25 regulations for structural integrity, fatigue, and damage-tolerance. This is because lightning must attach in the specific vicinity of the structural crack or broken fastener and/or be of sufficient amplitude to cause sparking.

Determining the combined probability of remote non-fault tolerant conditions is intended to be supported by qualitative assessment utilizing knowledgeable engineering judgment and not intended to be a quantitative analysis. The qualitative assessment should consider the likelihood of the failures, the likelihood of other conditions necessary for the failure to result in an ignition source and any means utilized to ensure the combination of conditions will be unlikely. The assessment cannot include the likelihood of lightning attaching to the airplane or the flammability of the fuel tanks. It can include the likelihood of lightning current densities that would lead to an ignition source for that particular structural failure.

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

Evaluation of fault tolerance should include consideration failures due to aging, wear, corrosion and likely damage. Likely damage includes conditions that could be reasonably anticipated to occur in the life an individual airplane due to operation, scheduled and unscheduled maintenance. In addition, probable escapes in the production design process should be considered as probable failures. Probable failures must be assessed to show the combination of potentially related ignition sources is remote.

Effectiveness of designs to provide fault tolerance to failures should be demonstrated utilizing industry testing practices in SAE ARP5416[22] and should be evaluated in combination with expected design variability (e.g. drawing tolerances). It should not be necessary to assume that all tolerances will be at worst case concurrently (that is, stacking of tolerances is not required). Drawing and process limits are considered part of the basic design and conditions within those limits are not failure conditions.

Critical lightning protection features are those that are required to achieve a compliant design. Cautions should be developed for those critical lightning protection features that might not be obvious as lightning protection, to avoid inadvertent modification or damage during maintenance. Examples of these features will need to be described in the guidance material.

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APPENDIX A
LIGHTNING ARC MEMBERSHIP

LIGHTNING ARC MEMBERSHIP

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Massoud Sadeghi, FAA Chairman .... Federal Aviation Administration
Billy Martin, Industry Chairman .... Cessna

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Patrick Carver .... Gulfstream
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APPENDIX B
LIGHTNING ARC CHARTER

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
ARC Charter

Effective Date:
XX/XX/09

SUBJ: Large Airplane Fuel System Lightning Protection Aviation Rulemaking Committee

1. Purpose of this Charter. This charter creates the Aviation Rulemaking Committee (ARC) for Fuel System Lightning Protection according to the authority of the Administrator of the Federal Aviation Administration (FAA) under section 106(p)(5) of Title 49 of the United States Code (49 U.S.C. 106(p)(5)) . This charter also outlines the committee's organization, responsibilities, and tasks.

2. Audience. This charter applies to members of the Large Airplane Fuel System Lightning Protection ARC, including aviation industry organizations and employees within the Office of the Associate Administrator for Aviation Safety. The audience for this charter also includes employees of the Office of Chief Counsel and the Office of Aviation Policy and Plans.

3. Where to Find this Charter. You can find this charter on the FAA website at http://www.faa.gov/about/committees/rulemaking/

4. Background. Prior to Amendment 25-102 to Title 14, Code of Federal Regulations (14 CFR) 25.981, the lightning protection requirements for fuel tanks were contained in § 25.954. Section 25.954 applied to system components as well as airplane structure. That regulation required prevention of ignition of vapors in the fuel tank, but it did not take into account anticipated design failures, age, wear, or maintenance errors.

a. In May 2001 the FAA issued Amendment 25-102. This amendment added specific ignition prevention requirements and a new flammability minimization requirement to § 25.981. The amendment contained specific ignition prevention requirements in § 25.981(a)(3) that included consideration of factors such as age, wear, and maintenance errors, as well as the existence of single failures, combinations of failures, and latent failures, that might cause ignition sources in fuel tanks. These requirements applied to fuel tank systems in addition to structural components of fuel tanks.

b. Systems with potentially catastrophic failure modes would typically meet the requirements of § 25.981(a)(3) by providing at least triple-redundancy in their protective features with periodic inspections, or dual-redundancy with continuous system monitoring, to reduce the latency period. Dual-redundant designs could only comply with § 25.981(a)(3) when combined with either regular inspections at very short intervals or a monitoring device, to verify the functionality of the protective features. Inspection of the various design features might be difficult or impossible if the feature is covered by airframe structure.

c. To prevent all sources of ignition in a fuel tank, the design had to be "fail-safe," meaning that hidden (latent) component failures should not cause an ignition source when combined with another failure. An acceptable design must provide a third protective design feature. As it applies to fuel tank lightning protection for certain airframe structures (airplane skins, joints, ribs, spars, stringers, and associated fasteners, brackets, and coatings), applicants have argued that both adding a third independent protective feature and providing sufficient monitoring to detect latent failures in a dual-protective feature are impractical for certain areas of airplane wing structure. Incorporating three independent hardware protective features to control structural ignition sources might become too expensive to produce and maintain using currently available technology.

d. Confirming the continued effectiveness of these design features is difficult due to the impracticality of providing continuous monitoring of the features and the limited capability of inspecting the features. These design features are typically integral to the fuel tank structure or internal to the fuel tanks. Inspection of design features inside fuel tanks requires access to the fuel tanks, which is usually only scheduled once or twice during the life of the airplane. Increasing the frequency of internal fuel tank inspections could also increase the possibility of damaging the lightning protection features during the inspection process. Because of these issues, we issued two exemptions that were found to be in the public interest and are developing a special condition for another applicant with a composite fuel tank.

e. We now believe it is appropriate to re-examine §§ 25.954 and 25.981 to address these and other issues that have surfaced during application of the requirements of Amendment 25-102 to the design of lightning protection of fuel tanks. We wish to establish a balanced approach to ensure that airplane designs provide an acceptable level of safety, while allowing manufacturers to use designs that are economically viable in terms of design, manufacture, and operation. Regarding structural components, the new standards should require the applicant to develop a design as free of ignition sources as practical. In addition, the applicant must consider fuel vapor flammability in developing a design with an acceptable level of safety.

f. We issued policy number ANM-112-08-002, "Issuance of Special Conditions and Exemptions Related to Lightning Protection of Fuel Tank Structure," on May 26, 2009, as a temporary means to address the above issues. This policy memo will remain in effect until rulemaking to address the practicality issues with § 25.981(a)(3) is completed.

5. Organization and Administration of the Fuel System Lightning Protection ARC. We will set up a committee of members of the aviation community, including airplane lightning protection design specialists representing diverse viewpoints. FAA participation and support will come from all affected lines-of-business. Where necessary, the committee may set up specialized work groups that include at least one committee member and invited subject matter experts.

a. The committee sponsor is the Manager, Transport Airplane Directorate, who:

(1) Appoints members or organizations to the committee, at his sole discretion;

(2) Receives all committee recommendations and reports;

(3) Selects industry and FAA co-chairpersons for the committee; and

(4) Provides administrative support for the committee, through the Aircraft Certification Service .

b. The co-chairpersons will:

(1) Determine (with other committee members) when a meeting is required (a quorum is desirable at committee meetings, but not required);

(2) Arrange notification to all members of the time and place of each meeting;

(3) Draft an agenda for each meeting and conduct the meeting;

(4) Keep meeting minutes; and

(5) Provide status updates to the Manager, Transport Airplane Directorate, at 6 months and 12 months from the effective date of this charter.

6. Committee Membership. The committee will consist of about 20 members, representing airplane manufacturers, fuel tank lightning protection specialists, FAA and other aviation industry participants. Members will be selected based on their familiarity with fuel tank lightning protection, analysis and regulatory compliance. Membership will be balanced in viewpoints, interests, and knowledge of the committee's objectives and scope. Committee membership is limited to promote discussion. Active participation and commitment by members is essential for achieving the committee's objectives. Attendance is essential for continued membership on the committee. The committee may invite additional participants as subject matter experts to support specialized work groups.

7. Public Participation. Persons or organizations outside the committee who want to attend a meeting must get approval in advance of the meeting from a committee co-chairperson or designated federal representative.

8. Committee Procedures and Tasks.

a. The committee advises and provides written recommendations to the Manager, Transport Airplane Directorate, ANM-100.

b. Committee tasks include, but are not limited to, the following:

(1) Determining whether the approach to fuel tank safety related to lightning protection should be focused on fuel vapor ignition, ignition sources, or a combination of both.

(2) Determining whether the lightning protection regulation changes should apply to the complete fuel system, or just to the fuel tank structure.

(3) Determining what type of safety assessment approach should be used (e.g.; SAE Document ARP5577 or § 25.1309). Define content and procedures of the safety assessment.

(4) Determining whether a probabilistic approach, prescriptive pass/fail criteria, or a combination of both using qualitative analysis, should be applied to structure or the complete fuel system lightning protection. If a probabilistic approach is used, determine if flammability exposure should be considered. Determine how single failures should be addressed. Determine what types of single failures are impractical to preclude. Finally, determine what probabilistic distribution of lightning amplitudes would be acceptable as an industry standard.

(5) Establishing which components and installations must be addressed and which failure modes (including possibility of cascading failures) should be considered. Determine if all foreseeable, likely, or a specific set of failures should be addressed in determining adequate structural lightning protection. If a probabilistic approach is used, determine the criteria that should apply for the standard. Identify acceptable data to support the safety analysis (e.g., supporting failure rates).

(6) Determining a means to address manufacturing variability, age, wear, corrosion, and likely damage to lightning protection features.

(7) Determining criteria associated with instructions for continued airworthiness and any needed modifications to processes defined in Revision 3 to the Maintenance Steering Group (MSG-3) document.

(8) Considering the effect of reducing the flammability below the criteria of § 25.981(b), Amendment 25-125, in adjusting the other tasks listed above.

(9) Identifying compliance guidance that might be required to facilitate showing compliance with the recommendations above.

c. The committee may propose additional tasks as necessary to the Manager, Transport Airplane Directorate, for approval.

d. The ARC will submit a final report detailing recommendations within 15 months from the effective date of this charter. The Manager, Transport Airplane Directorate, may extend this deadline for up to 6 months if it is in the interest of the FAA to do so.

9. Cost and Compensation. The estimated cost to the Federal Government of the Fuel System Lightning Protection ARC is $60,000, annually. All travel costs for government employees will be the responsibility of the government employee's organization. Non-government representatives serve without government compensation and bear all costs of their committee participation.

10. Availability of Records. Under the Freedom of Information Act, 5 U.S.C. 522, records, reports, agendas, working papers, and other documents made available to, prepared for, or prepared by the committee will be available for public inspection and copying at the FAA, Transport Airplane Directorate, 1601 Lind Avenue SW., Renton, WA 98057-3356. Fees will be charged for information furnished to the public according to the fee schedule in 49 CFR part 7.

11. Committee Term. This committee becomes an entity on the effective date of this charter. The committee will remain in existence for a term of 15 months unless its term is ended sooner or extended by the Administrator.

XX/XX/09

12. Distribution. This charter is distributed to the Office of the Associate Administrator for Aviation Safety, the Office of the Chief Counsel, the Office of Aviation Policy and Plans, and the Office of Rulemaking.

J. R. Babbitt

Administrator

APPENDIX C
ACRONYMS AND ABBREVIATIONS

ACRONYMS AND ABBREVIATIONS

§..................................Section
AC..............................Advisory Circular
ACO...........................Aircraft Certification Office
AD..............................Accidental Damage
AD..............................Airworthiness Directive
AFM...........................Airplane Flight Manual
AFSSP........................Aircraft Fuel System Safety Program
AMM..........................Airplane Maintenance Manual
ARAC........................Aviation Rulemaking Advisory Committee
ARC...........................Aviation Rulemaking Committee
ATA...........................Air Transport Association
CDCCL......................Critical Design Configuration Control Limitations
CFR............................Code of Federal Regulations
CMR...........................Certification Maintenance Requirements
DER............................Designated Engineering Representative
ED..............................Environmental Damage
EUROCAE.................European Organization on Commercial Aircraft Equipment
EWIS..........................Electrical Wire Interconnect System
FAA............................Federal Aviation Administration
FD..............................Fatigue Damage
FDT............................Fatigue and Damage Tolerance
FRM...........................Flammability Reduction Means
FQIS...........................Fuel Quantity Indicating System
GVI............................General Visual Inspection
HIRF..........................High Intensity Radiated Fields
ICA.............................Instructions for Continued Airworthiness
ICOLSE......................International Conference on Lightning and Static Electricity
MRB...........................Maintenance Review Board
MSG...........................Maintenance Steering Group
MSI............................Maintenance Significant Item
NASA.........................National Aeronautics and Space Administration
OEM...........................Original Equipment Manufacturer
QA..............................Quality Assurance
SAE............................SAE International
Sec..............................Section (as used within an FAA regulation)
SFAR..........................Special Federal Aviation Regulation
SRM...........................Structural Repair Manual
SSI..............................Structural Significant Item
RTCA.........................RTCA, Inc.

APPENDIX D
STRUCTURAL WORKING GROUP
RECOMMENDATIONS FOR 14CFR 25.981

Table of Contents

1.0 INTRODUCTION

The Large Airplane Fuel Systems Lightning Protection Aviation Rulemaking Committee (ARC) commissioned a working group comprising airplane manufacturers and regulatory authority structural specialists to assist with their effort to revise 14 CFR 25.981. The members of this group have written this report in support of that effort. The members of this working group are listed in Appendix A. Current interpretation of § 25.981 has resulted in the application of statistical analysis for structural "single failure" conditions to both systems and structures. The rule in question states in part:

> *"25.981(a)(3) Demonstrating that an ignition source could not result from each single failure, from each single failure in combination with each latent failure condition not shown to be extremely remote, and from all combinations for failures not shown to be extremely improbable."*

The structural working group determined that § 25.981 should be revised or have guidance material written to state that requirements for statistical analysis of ignition sources due to lightning are not applicable to structures. Structural lightning requirements are defined according to § 25.954, *Fuel system lightning protection*. Statistical analysis is not appropriate for structural failures and potential threats because there is no reliable data to support it. Structural failures have been shown by test and service history to be minimized in existing structural designs. This is a direct result of compliance to existing structural regulations and criteria, application of standard structural analysis methods, and use of reliable manufacturing methods. The Lightning ARC has determined the most likely structural single failures that are considered to potentially cause an ignition source are cracked structure or a failed fastener, so this report will address these in more detail, but the arguments and conclusions in this report are applicable to all types of structural failures.

This report will provide detailed explanations of the structural working group position that statistical methods are not appropriate for structural failures; that threats have been minimized in current designs; that service history supports these conclusions; and how composite structure can be related to these conclusions.

FAA structural specialists Ian Won and Greg Schneider reviewed an early draft of this report and provided the comments presented in this section. In their review they agreed with the position that even though cracks, broken bolts and other failures can occur within structure, probability analysis is not an appropriate tool for the analysis of these failures, should not apply to structures and any attempt to do so is flawed due to the lack of data. The FAA structural specialists did question other aspects of the report, such as the usage of process control, testing, regulations etc. as a means to mitigate the threat from structural failures. This review led to revisions to the report that are reflected in this final version.

2.0 APPLICATION OF STATISTICAL METHODS TO STRUCTURES

The wording of § 25.981 is typical of other systems rules that use probability analysis for compliance. Structural integrity, however, is established by complying with prescribed requirements. This is due to the difficulty in assessing the variability in design, manufacturing methods, and operational environment which makes a probabilistic approach not viable.

When analyzing a structural failure, the number of failure modes and the variation in methods to predict the failure are enormous. As an example, following are some factors, for a detail such as a stringer, that affect failure predictions:

- Multiple possibilities of failure modes (tension, crippling, buckling, bondline failure, fasteners, etc.)
- Conservatism in fatigue and design loads
- Variation in airplane utilization (Fatigue Spectrum)
- Selection of design values (A-basis vs. B-basis, etc.)
- Fidelity of stress methods (coarse vs. fine grid FEM, test based data, etc.)
- Thickness tolerance variations
- Variation of stress levels within the part

Each of these items has a tolerance that is covered by things such as B-basis allowables and an ultimate factor of safety of 1.5. The variability for crack initiation is even more random than the static failure and requires testing three to five times the normal cycles in a lifetime. All airplane manufacturers develop a fatigue spectrum based on historical fleet data and the predicted operating environment for the airplane. This is used in fatigue testing and analysis to make sure the airplane will be safe over its lifetime. While there are several factors to make sure the airplane is safe even if the owner operates his airplane differently, this is another variation that makes prediction of when or where a failure would occur very difficult. The variation in each of these factors, and the interaction with each other, would require a huge test matrix to develop failure predictions. It is extremely difficult to quantitatively predict some aspects of the structural performance; therefore a statistically based approach is not viable.

The structural requirements all work to make sure analysis is done at the lowest strength values and tested to 150% of max limit load statically and with a scatter factor or three to five on fatigue test cycles. This yields a robust design that minimizes the possibility of failures that might become ignition sources if sufficient current was present. This approach has led to successful airframe designs in commercial transport airplanes, including considering prevention of fuel tank ignition. Therefore, it is the conclusion of the structural working group that not only is probability failure analysis not viable, it is also not necessary.

3.0 MITIGATION OF POSSBILE IGNITION SOURCES BY MINIMIZATION OF STRUCTURAL FAILURES

Although it is not practical to completely eliminate structural failures, potential threats due to structural failures have been minimized in existing structural designs. This section will show how minimization of failures is a result of compliance to existing structural regulations and criteria, application of standard structural analysis methods, and use of reliable manufacturing methods. Advancements in these areas will also be discussed, showing how safe designs have become even safer over time. Although most of these factors do not directly address lightning protection, they do affect the inherent robustness and minimize failures of the structure lightning protection. Service history shows that the existing approach to fuel tank structure lightning protection is safe. The difficulties in applying probabilistic analysis to structure shows that numerical analysis is not appropriate and the inherent robustness of fuel tank structure makes numerical analysis unnecessary.

3.1 STRUTURAL REGUALTIONS AND CRITERIA

Meeting prescribed structural regulations has led to airframe designs that have minimized structural failures that could pose an ignition threat. Discussion on some of the more significant regulations follows:

§ **25.303** Factor of Safety. - A 1.5 ultimate factor must be applied to limit loads. Limit load may be thought of as the highest load expected to be experienced by any one airplane or structural component in a fleet of airplanes during the fleet's life. Typical operational loads are less than 50% of limit for fuel tank type structure.

§ **25.305** Strength and Deformation – Structure must support limit loads without detrimental deformation and not interfere with a safe operation. It must also hold ultimate load for three seconds. This limit load requirement will ensure that fastener holes and other details will not yield and cause an ignition source gap.

§ **25.307** Proof of Structure – Structure must be tested, or analyzed using reliable methods. Single load path configurations have additional requirements to ensure a robust structure.

§ **25.571** Damage Tolerance and Fatigue evaluation of structure. - The structure is shown to be able to carry limit loads with failed parts or large cracks in the parts. Damage tolerance analysis and testing must be done to show that if damage does cause a crack, the crack will grow slowly and can be found during inspections. Also, widespread fatigue damage must be assessed using full scale test evidence. This paragraph also requires the wing structure (including fuel tank) be robust enough to withstand a four pound bird strike and continue safe flight and landing. The bird strike provision may drive component sizing and therefore results in a more robust structure than would otherwise be required.

§ **25.581** Lightning Protection – The airplane must be protected against catastrophic failure effects from lightning. This drives minimum gauge requirements to prevent unacceptable penetration and proper conduction paths for the lightning.

§ **25.601** General – The design must not have design features that experience has shown to be hazardous or unreliable. Field history at the airplane manufacturers shows that failed fasteners and cracks that would result in a potential ignition source have been minimized (Reference manufacturer data in Table 3.3-1 in the ARC report).

§ **25.603** Materials – Material suitability and durability properties must be established based on tests and take into account temperature and environment. This insures material used for fabrication is consistent in its properties for each unit produced for that model.

§ **25.605** Fabrication Methods – Fabrication must be done to approved processes that produce consistent structure. New methods have to be proven by test. This will ensure each structure will meet the strength/durability requirements.

§ **25.609** Protection of Structure - Structure must be protected against weathering, corrosion, and abrasion. This will ensure the structure will remain sound throughout its life and minimize failures.

§ **25.611** Accessibility – The structure must be accessible for inspections.

§ **25.613** Material Strength Properties and Material Design Values – Material strength properties must be based on test data that has a statistical basis. This will minimize the possibility of structural failures due to material variability.

The following paragraphs all describe when special factors must be used. These all help minimize the possibility of structural failures due to special materials, manufacturing or design features.
§ **25.619** Special Factors

§ **25.621** Casting Factors

§ **25.623** Bearing Factor

§ **25.625** Fitting Factors

§ **25.954** Fuel System Lightning Protection – This lightning requirement is included in the structural analysis to verify the minimum skin thickness for the structural strength requirements will not show any penetration by melting or burn through when the fuel tank skin is exposed to a lightning strike.

§ **25.963** Fuel Tanks General – The fuel tank must withstand without failure the vibration, inertial, fuel and structural loads it is subject to during operation. The structure will be robust to prevent leaks.

Many of the above regulations have been amended over time. Compliance with later amendments to the regulations will tend to increase the structural robustness. For instance, the damage tolerance aspects of § 25.571 were not introduced until 1978. Although damage tolerance requirements have been retroactively applied to older designs, the stress levels in those designs could not be modified to achieve more practical inspection programs, as has been done on newer designs as described in Section 3.2. Amendment 25-96 introduces requirements to address widespread fatigue damage, which will help further ensure that the occurrence of small cracks is minimized in the fleet.

3.2 ANALYSIS METHODS

Ongoing progress in analysis methodology has contributed to minimizing structural failures in newer designs.

Rapid progress in computing speed and analysis software such as finite element analysis has enabled the structural engineer to do an improved detailed analysis to comply with strength requirements of § 25.305. The number of load conditions that can be reasonably considered has greatly increased, improving the ability to identify which ones are critical. Detailed finite element analysis has allowed for enhanced structural optimization by identifying non-critical material for removal. This allows designers to place material where it is most beneficial, which can simultaneously lead to lighter yet more capable parts. These methods also allow analysts to better identify stress concentrations, which may not be possible with other methods.

Fatigue analysis methods are heavily dependent on test data and in some cases, in-service experience. These methods are therefore constantly being improved over time. Every new airplane development program requires fatigue tests ranging from small coupons all the way up to a full scale test of a complete airframe. The results of major airframe fatigue tests show that failures are less frequent than they were in the airplane models that preceded it, demonstrating that fatigue analysis methods have improved over time. In-service data from the fleet shows that structural failures are less common in more recent airplane designs when compared to older designs (for similar periods of operation).

Damage tolerance analysis as required by § 25.571 must show that if a crack occurs, it will not become critical before it is detected. This is done to cover random manufacturing or material flaws that could initiate a crack. Possible leaks from cracked fuel tank structure offer additional means of detection between inspections. All detected cracks in primary structure are immediately repaired so exposure time is minimized. Damage tolerance is an aspect of structural certification that has been required on newer airplane designs and which sets them apart from older generations of airplanes. In order to have a practical inspection program the design stress levels must be kept low enough to ensure the inspection frequency is not too burdensome to the operators. This in turn reduces the probability of cracks initiating. Developing a practical inspection program contributes to low stress levels in another way, since ideally critical crack lengths should be large enough to be found by visual inspections. To keep the growth of a crack slow the stress levels must be low, thus mitigating the chance of a crack initiating.

Furthermore, structural analysis methods are the only practical means of establishing a structural inspection program. The alternative would be to use ignition source criteria to determine an inspection program, which requires a crack size threshold be determined. It would likely require a large amount of testing for each possible structural configuration to do this. Assuming that it is even possible to establish the crack size threshold for which it becomes an ignition source, the results would have to be compared to the structural inspection program assumptions, such as critical crack size and probability of detection. This comparison may likely lead to more frequent and burdensome inspection requirements. Because of the complexity of testing requirements, and possible negative effects on inspection intervals and methods, implementing an inspection program for cracks based on a lightning threat is not practical, nor, as this report describes in detail, is it necessary.

These advancements in analysis methods contribute to minimizing structural failures and thus the potential for an ignition source due to lightning.

3.3 DESIGN PROCESS

The design process to produce safe and robust airplane structure that complies with current regulations also leads to a design that offers lightning protection.

In the design process, the fasteners, materials, and corrosion protection/finish schemes used to design the wing are chosen with the function, loads and design criteria in mind by the Design, Materials and Stress/Fatigue & Damage Tolerance (FDT) engineers. Material selection for fasteners and other components reflect advancements in corrosion resistant technologies to reduce potential damage occurrence in-service. Older airplanes may have used materials such as 7075-T6. This has been replaced in newer airplanes with 2324, 7050 or 7475 alloys which have higher fracture toughness and improved stress corrosion cracking properties.

All specifications and standards used for hardware, materials and processes (fasteners installation, sealing, etc.) are approved by FAA Designated Engineering Representative (DER) or FAA Aircraft Certification Office (ACO), or industry approved and used specifications. These are the documents to which the airplane is designed, manufactured, tested and inspected.

Prior to approval, the part/installation design is analyzed by the Stress/FDT Engineering Group to verify the fasteners, material selections, and design features will meet the static and fatigue load requirements. The design is approved by the Design, Material and Process, Manufacturing, Quality, Stress/FDT Engineers and the DER.

To verify the assembled wing will be able to handle the loads identified by Stress/FDT Engineering, two complete airframes are assembled, one for static testing, and the other for damage tolerance and durability testing. The static test airframe is tested to 1.5 times limit load per § 25.305. The fatigue test airframe is tested to multiple lives to satisfy the requirements of § 25.571.

Structural cracking, fractured fasteners and other defects that show up during the testing are subject to component redesign and/or having the fastener evaluated and replaced with an improved fastener. The post test inspections also include detailed teardowns of certain areas which could reveal small cracks in addition to larger, more easily detectable ones. This verification process is done in order to ensure the components and fasteners last the life of the airplane. If any airplanes have been delivered prior to completion the fatigue testing and a crack is found during the inspection, a service bulletin will be issued to rework the part(s) and fix the problem.

These aspects of the design process contribute to minimizing structural failures and thus the potential for an ignition source due to lightning.

3.4 MANUFACTURING AND QUALITY PROCESSES

Manufacturing techniques, inspection methods, and quality control processes contribute to less variation and defects in the final product. There have been many advancements in these areas which have led to enhanced product quality. These have not completely eliminated all defects but certainly reduce the likelihood of occurrence, which reduces the potential for an ignition source due to lightning.

Trends to increase automation in airplane manufacturing have resulted in more robust designs by increasing consistency and reducing defects. For example, an airplane manufacturer may implement a fully robotized process to install aluminum index head rivets. The numerically controlled machine locates and drills the hole, inserts and squeezes the rivet, and then shaves the head flush. During the squeezing of the rivet, the shank expands outward with a force great enough to not only fill the hole in the aluminum structure but also expand the hole. This ensures a tight, leak free, bonded fit.

Automated processes may not be suitable for all locations but many fasteners have inherent features which ensure proper manual installation. For Hi-Lok® type fasteners, the driving portion of the collar shears off at the required torque level, ensuring the collar is properly locked in place without being over tightened. For lock bolts, the collar swaging tool reacts against the tail of the bolt, which is designed to break when the appropriate swaging force has been applied. This ensures proper repeatable installation of the collar. Manual hole drilling is aided by drill templates (to properly locate fasteners) and drill guides (to ensure proper angularity).

Material variation has been reduced as raw material suppliers transition to computer controlled processes and more accurate sensors. Variation from unit to unit at the airplane manufacturer has also been reduced due to improvement in manufacturing processes. Computer controlled machining, forming, trimming, drilling and fastener installation have all worked to reduce variation in the process.

Quality Assurance (QA) processes ensure that both automated and manual manufacturing operations produce a final product with minimal defects.

Robotized manufacturing processes ensure the quality and repeatability of fastener installations, and are Quality Assurance verified on a scheduled basis. The machines carrying out the installations undergo a rigorous qualification process before being used to produce production parts.

Manually installed fasteners either possess inherent features (such as Hi-Lok® and lock bolt collars mentioned previously) or have robust quality measures in place to ensure proper installation. Nuts are installed by a qualified mechanic using a calibrated torque tool. Quality Assurance personnel can directly witness nut installation or verify the torque tool setting afterwards. Nuts are also inspected for gaps to verify proper installation.

After assembly, the fuel tanks are leak checked with air and/or a test fluid, which offers another opportunity to detect defects before an airplane is delivered.

3.5 SUMMARY OF MITIGATION OF IGNITION SOURCES

Compliance with existing structural regulations and standard design processes has produced designs with inherent protection against ignition due to lightning. Current manufacturing and quality assurance processes also contribute to this inherent robustness. Evolution in all these areas has helped to further minimize the occurrence of structural failures. It is therefore the conclusion of the structural work groups that probability failure analysis for structural failure conditions is not necessary. This conclusion is validated by service history, as explained in the following section.

4.0 SERVICE HISTORY

Service history has shown that existing structural lightning protection designs are inherently robust. No airplane has been lost due to a fuel tank ignition due to a lightning strike since 1976. The inherent robustness is due to the minimization of structural failures as has been described in this report. The data in Appendix Table 3.3-1 of the Lightning ARC report is based on operator reports to airplane manufacturers with regard to structural cracks found in service. The data includes the effects of manufacturing flaws and maintenance.

The data supports the general conclusion that cracks in fuel tank structure, while not completely eliminated, have been minimized. However, it is not appropriate to attempt to use this data to quantify the rate of structural cracking due to the reasons presented in this report and because newer designs are expected to perform even better due to incorporation of continuous improvements as outlined in Section 3.0.

The in-service data shows a distinction between overall reports of cracking in the fuel tank and instances of a single cracked component on multiple airplanes due to specific condition that was addressed by a Service Bulletin. In some cases the cracks are detected when they are very small, however because of the large sample size and the fact that small cracks eventually grow into larger more easily inspected cracks, the data in Table 3.3-1 of the Lightning ARC report is representative of cracking in the fleet.

5.0 COMPOSITE STRUTURE

While it is true there is less service experience with composite fuel tanks than for metal fuel tanks, in general the data shows that composites are less likely to experience cracking in service. Composites have to meet the same regulations as metallic tanks with respect to static strength, but instead of designing for a slow inspectable damage growth like metal structure, composites generally take a “no detrimental damage growth” approach to damage tolerance and in doing so, operating strains are kept below levels where cyclic damage will lead to deterioration over the life of the airplane. They are designed for no detrimental deformation at limit just like metal structure and since they do not yield like metals they usually have no detrimental deformation at ultimate also. Composites can experience delaminations under impact or direct lightning strike which is not typical in aluminum structure but again the structure is designed so these delaminations do not have detrimental growth or they are visible and repaired. In addition, composites are much less susceptible to corrosion compared to metallic structure.

A review of over 15 years worth of service data for the Boeing 777 horizontal and vertical stabilizers revealed that there have been no reports of cracks or fastener failures in any of that structure, which although it is not a fuel tank, is representative of composite wing/stabilizer fuel tank construction.

Testing of the 777 horizontal and vertical stabilizers as well as 787 wing pre-production test articles for three lifetimes was conducted as part of the airplane design effort. Results of the 777 and 787 testing showed no indication of cracking or delamination in the composite primary structure. Additionally the 777 and the 787 composite structure test programs were extensive, comprising thousands of element and hundreds of subcomponent level tests. These tests included cold, room temperature and hot/wet conditions with intentionally inflicted damage at operating stress levels in order to ensure that undetectable damage to composite structure does not grow under operational loads to the size necessary to initiate a fuel leak.

Based on the service history and design considerations discussed above, the data shows that composite designs are inherently more robust compared to metallic designs with regard to cracking or damage growth, when designed to meet the same regulatory requirements.

6.0 SUMMARY AND CONCLUSIONS

1. Structural lightning strike criteria for fuel tank ignition are covered by § 25.954 and therefore structural requirements should be removed from § 25.981. Compliance with existing structural regulations results in robust fuel tank design, where structural failures, including failures such as bolt fractures and cracking, have been minimized. This is supported by field data of structural failures from airplane operators.

2. There have been continuing improvements in the design processes and analyses, material selection and processing, manufacturing and inspection methods over the

ones used for airplanes designed in the past to support the structural rules. This results in a more robust fuel tank with respect to cracks, broken fasteners, corrosion and wear.

3. It is not appropriate to attempt to show that a structural failure that could cause an ignition source is extremely remote. Probability analysis methods are inconsistent with structural design methodology and due to the large scale of testing required, would add no significant value to the evaluation of structure.

4. The structural working group's findings of the rarity of cracks, broken bolts, etc. from the review of the airplane manufacturer data indicates the robustness of airplane manufacturers wing structure, and its ability to comply with existing regulations, and are typical of what would be expected. Additionally, given that there is no history of ignition in these airplane models, the data indicates that structural failures, including failures such as bolt fractures and cracking, are not an issue for lightning strike.

5. It is not practical or necessary to attempt to develop an inspection program to detect cracks before they become a potential ignition source.

6. The review of composite structures service and test data shows it is less likely to develop structural cracking than aluminum structure. Composite designs must meet the same structural requirements as metallic designs, which results in an equivalent robustness and is expected to result in equivalent lightning ignition service experience.

7. Maintaining the current prescriptive approach for the evaluation of structure is correct because it mitigates the chance of structural failure and allows for the incorporation of analysis and material improvements as they evolve.

APPENDIX E

EVALUATION OF SPARK OR ARC GENERATION BY LIGHTNING CURRENT AT STRUCTURAL CRACKS AND CRACKED BOLTS

TABLE OF CONTENTS

1.0 INTRODUCTION

Members of the Lightning ARC conducted some tests and analyses to learn about the possibility of cracks in fuel tank structural elements and fastener installations becoming ignition sources due to lightning currents.

The tests included conduction of simulated lightning currents through fuel tank structural materials and fastener installations with cracks introduced in them. Most of these tests were conducted at ranges of amplitudes to determine ignition source thresholds.

The analyses included finite difference time domain computations of lightning current distributions on the interior surfaces of fuel tanks and within interior tank elements such as ribs, spars and shear ties. These computations were conducted for the more common conducted currents throughout lightning Zone 3 when a wing tip is struck by lightning as well as for direct strikes to fasteners located in lightning Zones 1A and 2A on wing tank surfaces, which are less common. The Zone 3 conduction – only computations are called **CASE A**. A combination of direct strike and conduction is described in **CASE B** and the direct strike computations are called **CASE C**.

Computations were also made of current densities throughout some of the structural element test coupons so that the local current densities in the vicinity of the introduced cracks could be known. The current flow analysis results are presented in Section 2.3.

The tank structure computations showed that, for all-metal tanks, the lightning current densities at the interior surfaces of fuel tank skins and other tank boundaries are much lower than the current densities in the exterior surfaces of these same elements. This is due to the long times required for electric currents to diffuse through the thicknesses of metal conductors. This phenomenon is commonly known as *skin effect.* A general discussion of skin effect is presented in Section 2.4 of this Appendix.

Additional test data on spark thresholds of other failure conditions in fasteners and shear tie installations is contained in Section 2.5 and an assessment of the origin of "sparks" in structural elements is presented in Section 2.6.

A discussion about the likelihoods of the ignition sources actually occurring within an all-metal fuel tank, based upon the data presented in Section 2, is presented in Section 3 of this appendix.

2.0 STUDY ON LIGHTNING ENVIRONMENT REQUIRED TO CAUSE AN IGNITION AT A CRACK

To study the lightning environment to cause an ignition (item c) in Section 1, the following items are discussed in this section.

1. Test results of ignition source generation,

2. Numerical analyses of the tests and discussion on the mechanism and the threshold of the ignition generation, and

3. Examples of calculated current density distribution within a model of a typical metal fuel tank section.

In the discussions that follow, the ignition source is termed generally a *spark* which is commonly considered to result from ionization of air due to voltage, as compared with an *arc* that is commonly considered to result from current flow across conductors in contact. Sections 2.2 and 2.6 provide discussions of whether it is actually a *spark* or an *arc* that has occurred at the tested cracks.

2.1 Test Results of Ignition Source Generation Due to Conduction Current through Aluminum Plates with Cracks

2.1.1 Outline of the Test

Current conduction tests to aluminum plates with a slit or an actual crack perpendicular to the current flow are conducted. Test parameters are as follows:

- Position of a slit/crack
- Width (gap) of slit/cracks
- Current waveform and amplitude

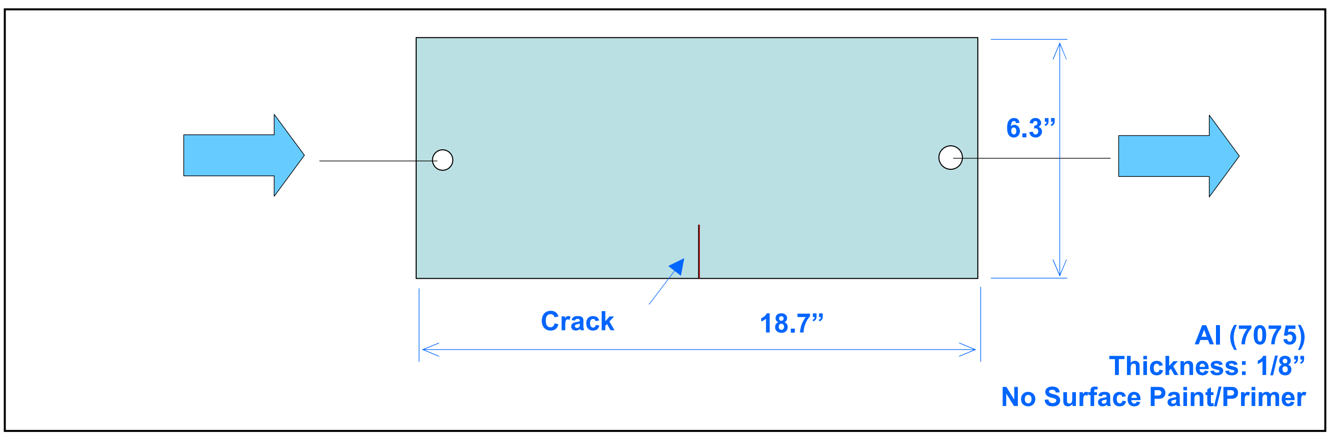


Figure 2.1 - Schematic of Current Conduction Test through Aluminum Plates with Cracks

2.1.2 Test Specimen (Case 1: Crack from Edge)

Test specimen of case 1 is as follows. They have cracks from the edges of the plates.

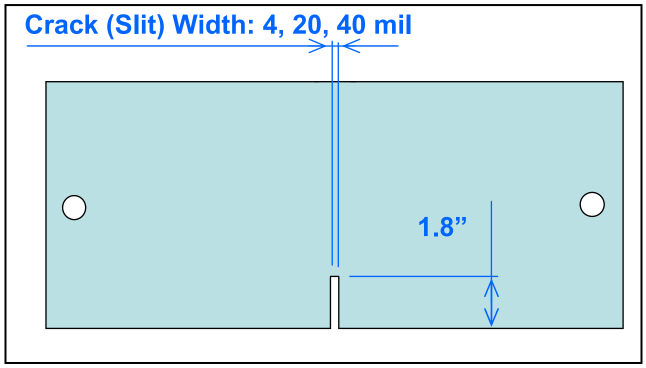


Figure 2.2 - Crack (Slits) Fabricated by Electrical Discharge Machining
-Simulating Cracks with Some Gap

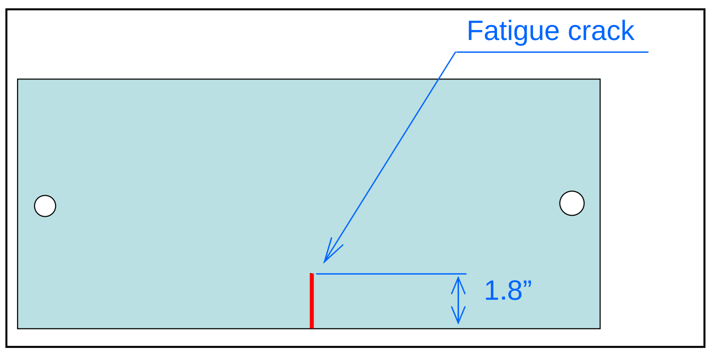


Figure 2.3 - Fatigue Crack actually Fabricated by Tension Test Apparatus
(Crack has No Width and the Surfaces may be Touching Each Other)

2.1.3 Test Specimen (Case 2: Cracks from Center Hole)

The test specimen of case 1 is shown in Figure 2.4. They have cracks at the center of the plates. This case has two types of cracks, including one with machined air gap and one with no air gap due to fatigue cracks originating from the machined crack, as shown in Figure 2.4.

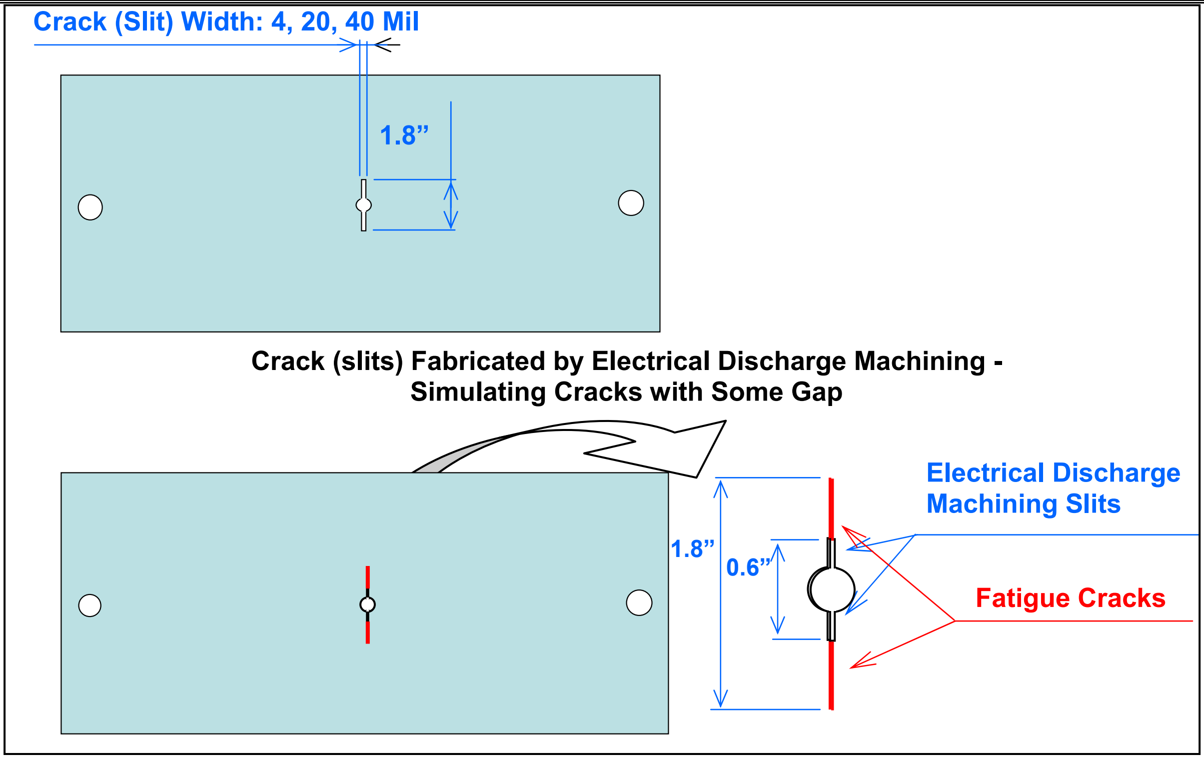


Figure 2.4 – Crack Fabricated by Machining Simulating Cracks with Some Gap and Fatigue Crack actually Fabricated by Tension Test Apparatus; Crack has No Width and Surfaces May Touch Each Other

2.1.4 Test Waveforms of Conduction Current

Test waveforms are described in Table 2.1.

Table 2.1 - Test Waveforms of Conduction Current

	Waveform	Peak Current	Notes
1	Comp. B	6 kA	A lightning intermediate current with a high DC content and therefore more likely to divide among structural elements according to element resistances and less sensitive to skin effect. Component B external environment peak amplitude is about 4 kA per SAE ARP5412A. Component B is therefore an appropriate current for representation of currents that have diffused to internal tank skin surfaces and other internal structural elements where cracks of interest as possible ignition source might be present.
2	Comp. D/2	50 kA	-Relatively high conduction current assuming proximity lightning attachment. -Comp. D/2 was tried because maximum conduction current assuming proximity lightning attachment at zone 2A of upper skin may be about a half of comp. D.
3	Comp. A	20-100 kA	

2.1.5 Test Facility and Setup

Test facility and setup used for the test is shown in Figures 2.5 and 2.6.

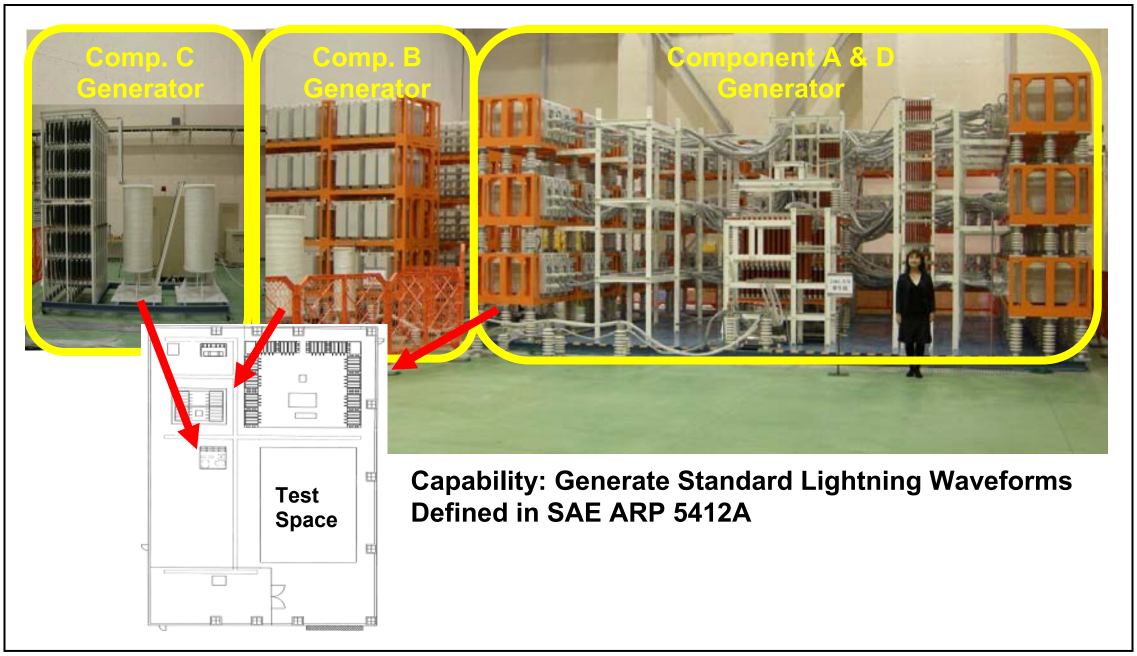


Figure 2.5 - Photo of High Current Lightning Test Lab

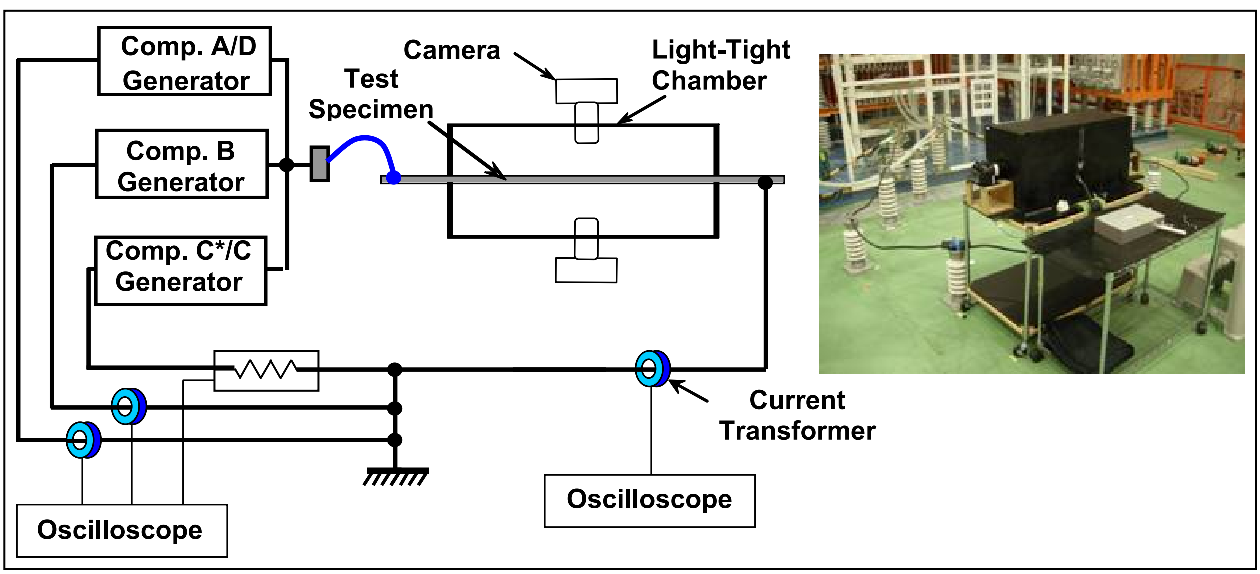
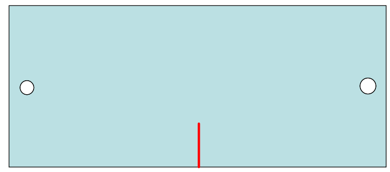


Figure 2.6 - Schematic of the Test Setup

2.1.6 Test Results

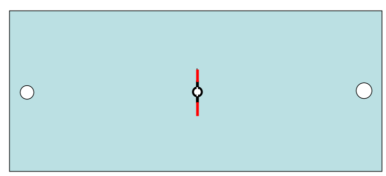
Test results are shown in Figure 2.7.

(1) Fatigue Crack from the Edge



Gap Width [mil]	Waveform (Intended Peak Current [kA])	Actual Peak Current [kA]	Culomb [C]	Action Integral x 10^4 [A^2s]	Spark	Specimen #	Note
0 (Fatigue Crack)	Comp. B (6)	6.0	10.2		No	G-531	One identical specimen (G531) was used. Test flow was as follows: Comp B 6 kA –› Comp D 50 kA –› Comp A 20
		6.0	10.1		No		
		6.0	10.1		No		
	Comp. D (50)	50.6		7.1	Spark		
	Comp. A (20)	19.7		1.9	Spark		

(2) Cracks from Center Hole

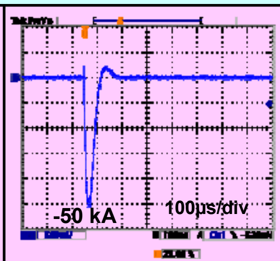
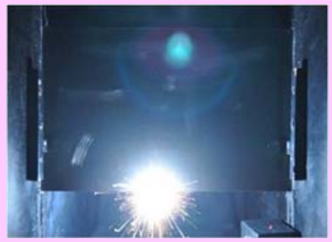
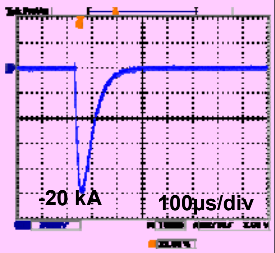
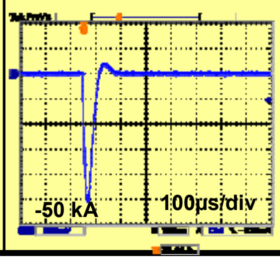
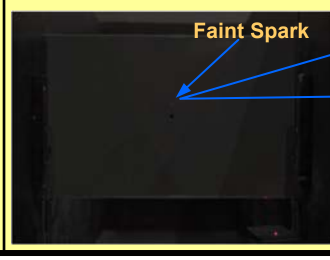


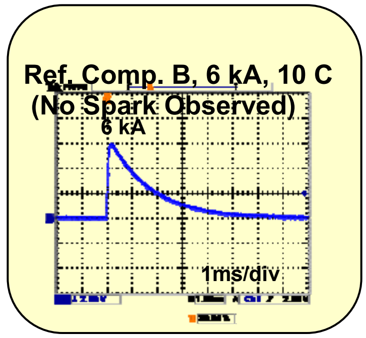
Gap Width [mil]	Waveform (Intended Peak Current [kA])	Actual Peak Current [kA]	Culomb [C]	Action Integral x 10^4 [A^2s]	Spark	Specimen #	Note
0 (Fatigue Crack)	Comp. B (6)	6.0	10.1		No	G-571	One identical specimen (G571) was used. Test flow was as follows: Comp B 6 kA –› Comp D 50 kA –› Comp A 20, 30, 40 ,50, 60, 70, 80, 90, 100 kA
	Comp. D (50)	50.6		7.1	Faint Spark		
	Comp. A (20)	19.8		1.9	No		
	Comp. A (30)	30.0		4.4	No		
	Comp. A (40)	40.1		7.9	No		
	Comp. A (50)	51.2		12.4	No		
	Comp. A (60)	61.1		17.7	No		
	Comp. A (70)	70.5		23.5	No		
	Comp. A (80)	79.6		30.6	No		
	Comp. A (90)	90.1		38.8	No		
	Comp. A (100)	100.6		48.9	No		

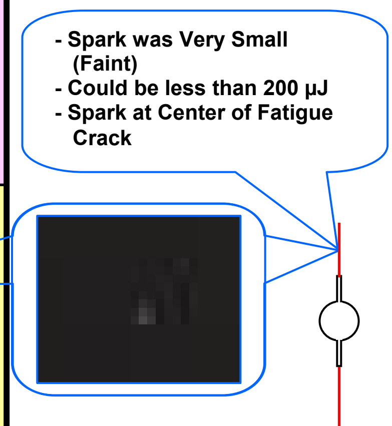
Figure 2.7 - Test Results

The specimens containing slits cut by a saw were also tested but there were no sparks observed in those specimens. No further discussion of the open slits is presented in this appendix.

Table 2.2 - Current Waveforms and Examples of Sparks

Specimen	Waveforms		Pictures
Crack from Edge (Fatigue Crack)	Comp. D/2 50 kA 7.1 x 10^4 A^2s		
	Comp. A/10 20 kA 1.9 x 10^4 A^2s		
Cracks from Center Hole (Fatigue Crack)	Comp. D/2 50 kA 7.1 x 10^4 A^2s		





2.1.7 Summary of Test Results

From the above test results, the followings can be concluded.

1. No spark was observed with cracks (slits) with some air gap.

   Sparks were observed only with actual fatigue cracks (with no gap) whose surfaces are rough and may be touching each other.

2. No spark was observed when the current density at the edge crack was 6.0e4 A/m resulting from 6 kA of Component B through the 6 inch (150 mm) wide aluminum panel.

   Sparks were observed at the edge crack with higher currents of 20 kA and 50 kA through the 6 inch wide panel. For the center crack, there was only one case of a very faint spark when 50 kA was conducted through the 6 inch wide panel.

3. Edge cracks are more likely to generate sparks then are cracks existing away from edges since the lightning current densities are highest at the edges of structural elements.

2.2 Numerical Analyses of Current Distribution of Tests and Discussion on the Mechanism and Threshold of Ignition Generation

To understand the behavior of the ignition source, electro-magnetic field analyses for the aluminum plates with slits were performed. Figures 2.8a shows the current density distribution of the Al plate and electric field within the slit for the case of slit at the edge with Component A waveform of 200 kA defined for analysis in ARP5412[16]. Slit width was 2 mm which is the size of the cells in the model. As can be seen, the current is concentrated to the edge. The overall distribution in the panel did not seem to be influenced by the existence of the slit and the intense current flow along the edge detours around the slit. Concentrations of current near the panel edges are due to the high frequency content of the Component A waveform.

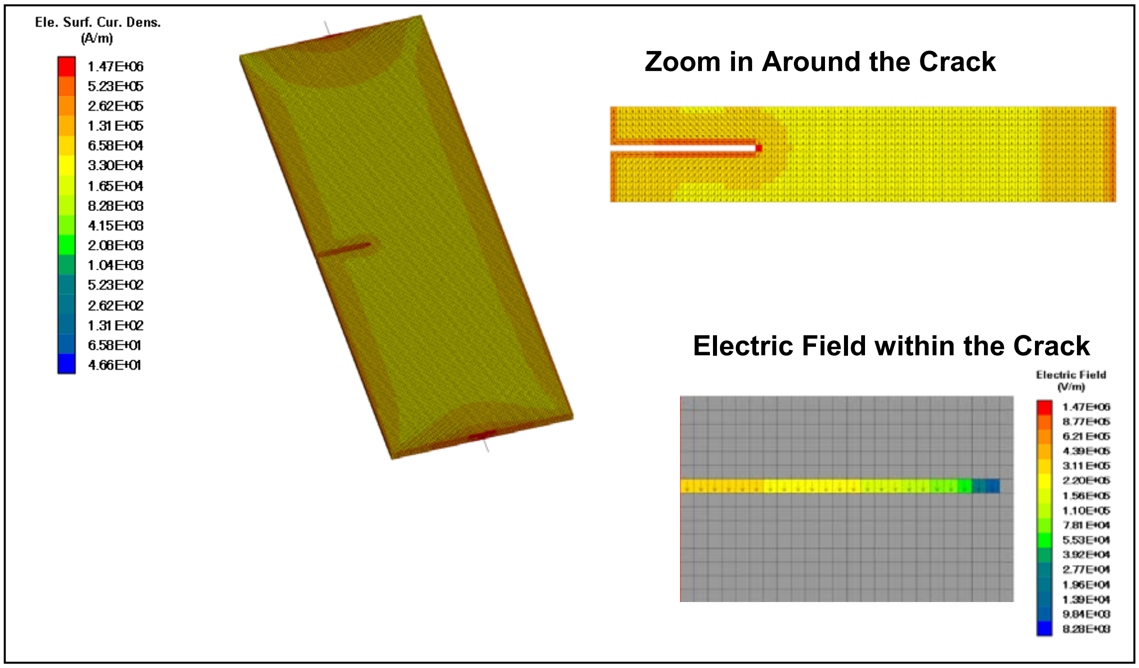


Figure 2.8a - Current Density Distribution of Al Plate and Electric Field within Slit for Case of Slit at Edge; t = 0.09 µs . At,0.09 µs the Current is Changing Most Rapidly and Voltage at Crack is Highest

Figure 2.8b shows the maximum current density around the crack at 6 microseconds when the conducted current is highest.

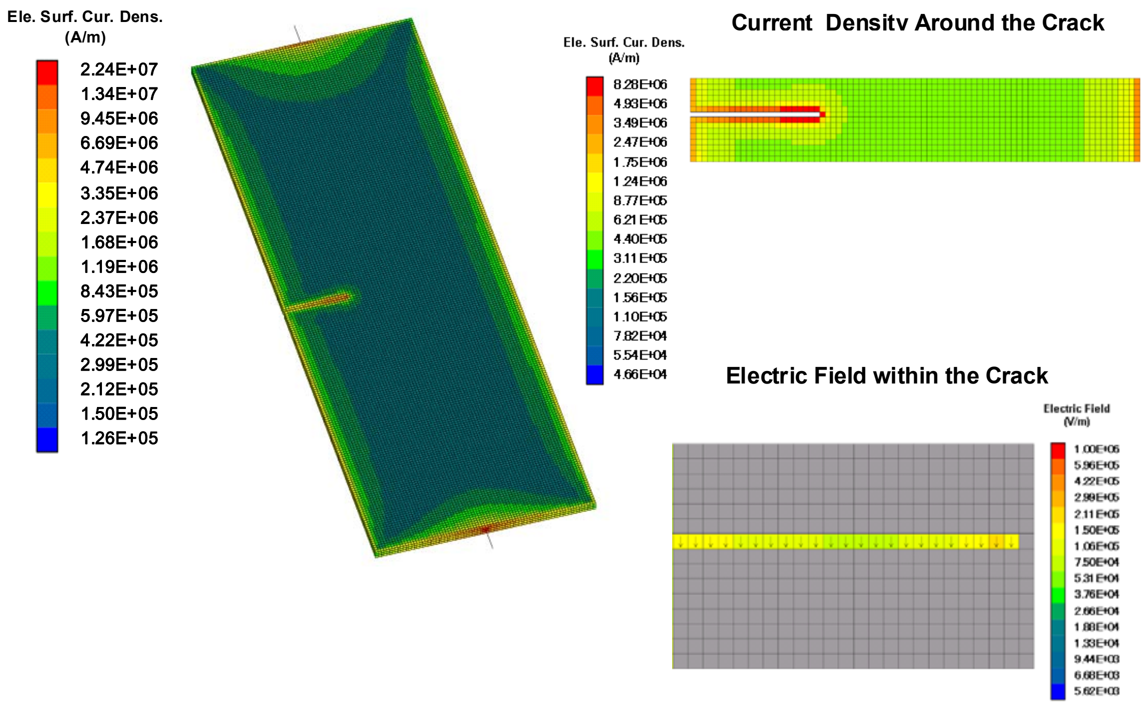


Fig 2.8b - Current Density Distribution of Al Plate and Electric Field within Slit for Case of Slit at Edge; t = 6 μs When Current Densities are Highest.
Injected current is 200 kA

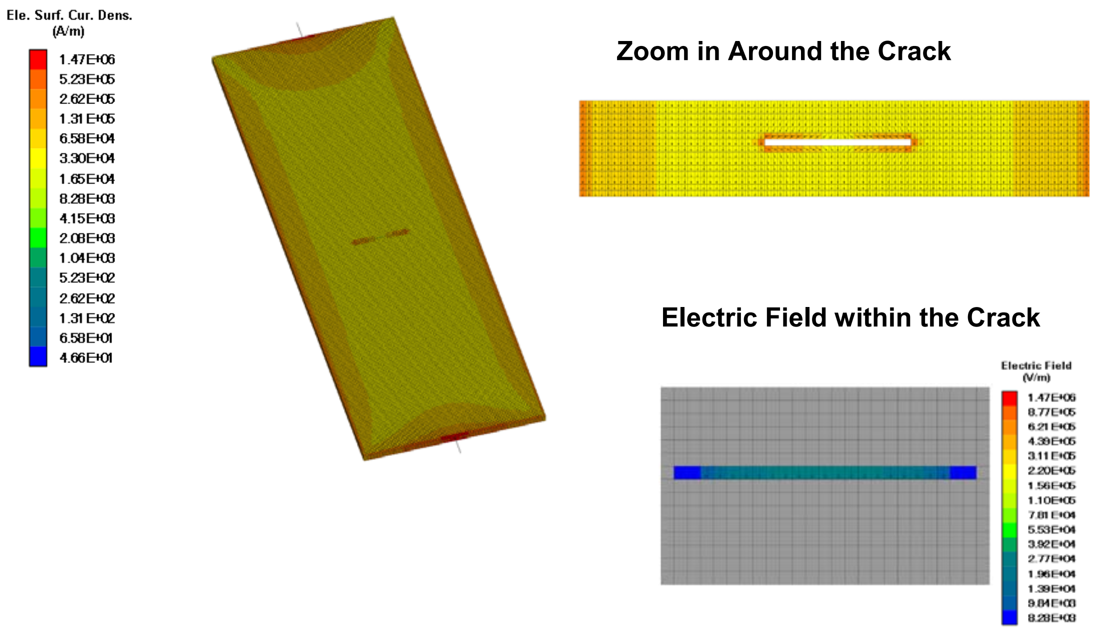
From these results, the following two possibilities for the spark generation at the fatigue cracks (with no gap) can be anticipated.

- Electric sparks (also known as voltage sparks) within small irregular gaps of fatigue cracks
- Electric arcs (also known as thermal sparks) between two rough and touching surfaces of the cracks

To estimate the possibility of the voltage sparks, the potential difference between two corners of the slit at the edge was calculated and the result was 440 V. This potential difference is constant with width variation since it is due to dϕ/dt caused by detouring current around the crack. 440 V is the maximum value for 200 kA Component A. Since this value is almost the same as the minimum value of the Paschen curve of 360 V, full threat lightning current would have to flow through an aluminum plate just several inches wide to cause a voltage spark. Therefore, the cause of the crack ignition source in the tests as well as any potential ignition source at a crack with the real lightning to the airplane situation should not be due to a voltage spark.

Figure 2.9 shows the calculated current density distribution and the electric field within the slit at the center of the panel When the Component A waveform at 200 kA (peak) was beginning to flow into the panel at 0.09 us. As can be seen, the current density around the crack is small compared to the crack at the edge. If the slit is the actual crack, there should be many contact points and therefore the current density around the crack should be much less than the density around the edge crack. Therefore, the arc or spark probability in Case 2 (center crack) should be much smaller than that in Case 1 (edge crack). If the voltage spark may occur, the potential difference is one order smaller in Case 2. Also, the spark energy in Case 2 should be quite smaller than in Case 1 because the energy should be proportional to the square of the current density.

Figure 2.9 - Current Density Distribution of Al Plate and Electric Field within Slit for Case of Slit at Center of Plate; t = 0.09 µs (Normalized Distribution at t = 6.0 µs is ~equal); At this



Time, Current is Changing Most Rapidly and Voltage at Crack is Highest.

To evaluate the current density at the crack when a spark occurred, current density distributions of the Al plate used for the crack spark tests presented above were recalculated. Previously, the waveform used to calculate the distribution was an ideal Comp. A as described in SAE ARP5412A[16]. However, the actual test current varied somewhat from the ideal definition so the actual test waveform was curve fit and used this time. This is because the current distribution is influenced by the input waveform (especially by the current rise and decay times). Figure 2.10 shows the actual injected current waveform and Figure 2.11 shows the resulting current distribution throughout the tested panel. The current density threshold not to cause an ignition source is estimated to be more than 6.0e4 A/m. Note that in the figures that follow in this appendix the notation for current density, for example, 6.0e4 and 6E4, are used interchangeably and mean the same value.

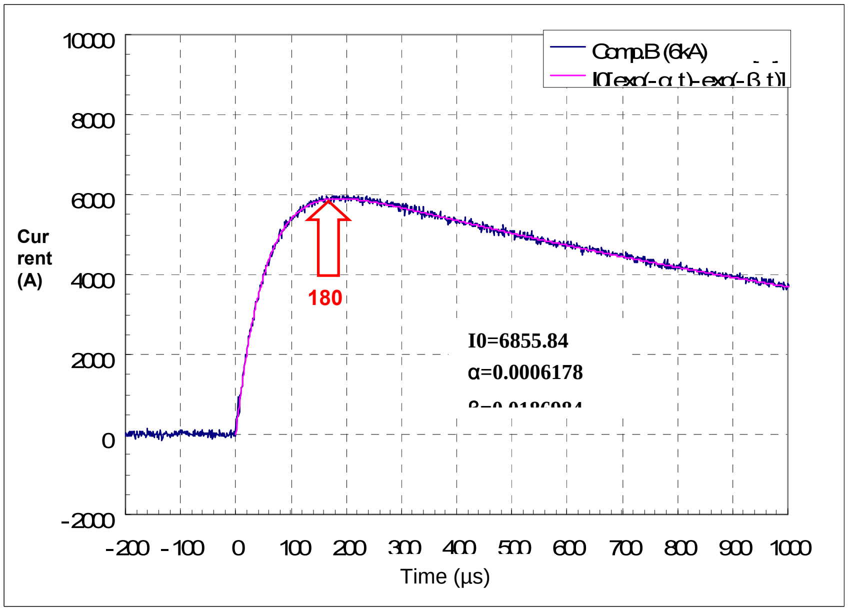


Figure 2.10 - Injection Current Fitting

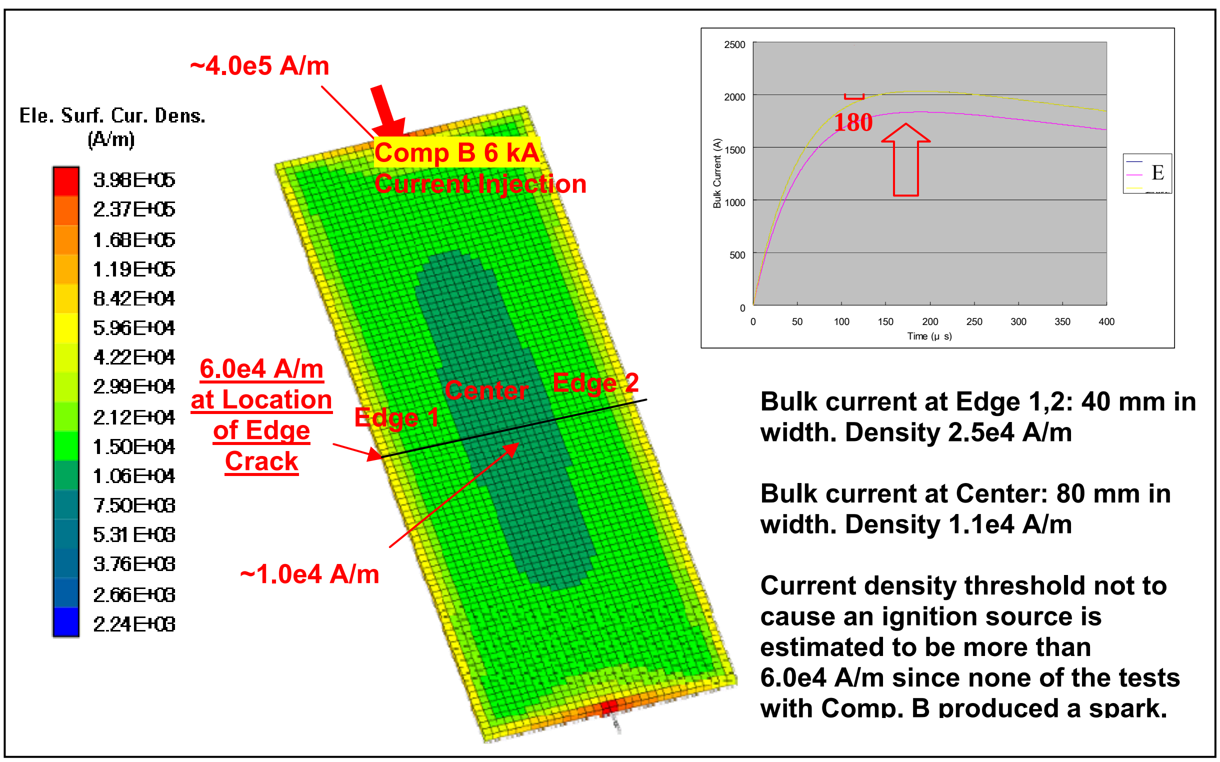


Figure 2.11 - Calculated Current Distribution of the Test Panel

Figure 2.8b shows that the current density necessary to produce an arc at the fatigue crack at the edge is 1.75e5 when 20 kA was conducted through the cracked panel.

Figure 2.11 shows that the current density that will not cause an arc at this crack is 6e4 A/m. Therefore it may be concluded that the arc threshold for this fatigue crack is somewhere between 6e4 and 1.7e5 A/m.

The current density that caused the faint spark at the center of the panel is believed to correspond to a current density similar to that at the center of the Al plate in *Fig. 2.8b* which is 6.2E5 A/m x (50 kA/200 kA) = 1.5e5 A/m (150,000 A/m) when 50 kA Component A was conducted through the panel as shown in Table 2-2. This is because the crack surfaces must be closed (and therefore touching each other at multiple locations) to cause an arc, so the current must flow through those multiple touching locations and the current density at the crack must be almost the same as the *Fig. 2.8b*. Although the current density in *Fig 2.9* around the slit is higher than that of non-slit location, with a maximum of 5.2e5 A/m x (50 kA/200 kA) = 1.3e5 A/m (130,000 A/m) for 50 kA conduction, even at the time of 0.09 μs at the ends of this slit, this is because the model assumes no conduction current flow across the slit width. This is not the case when the slit is closed. On the other hand, if the crack is open like the model of *Fig. 2.9*, there will be no touching location and no arc will be generated.

2.3 Examples of Calculated Current Density Distribution within a Typical Metal Fuel Tank Model

To assess if the current density at the crack exceeds an ignition threshold, current densities in the areas where the cracks might occur are required. Here, we present typical examples of calculated current density distributions within a conventional aluminum wing fuel tank structure model. Table 2.3 shows the summary of these calculations, which are presented in the following subparagraphs.

Table 2.3 - Calculation Conditions (Attachment Scenario, Test Current Value, etc) and Calculated Maximum Current Density

CASE	Attachment Scenario	Input Amplitude and Waveform for Calculation (kA)	Maximum Calculated Internal Current Density (A/m)	Corresponding Full Threat Amplitude (kA)	Corresponding Maximum Internal Current Density for the Full Threat Strike[2] (A/m)
CASE A	Tip Strike Zone 3 Conduction Component A at 200 kA (Most Likely Attachment Case)	200	20	200	20
CASE B	Conduction and Direct Strike in Zone 2A Component A[1] at 3 kA	3	890	100 (Comp D)	2.9e4
CASE C	Direct Strike in Zone 2A Component D at 100 kA	100	1.5e3	100	1.5e3

Note 1: Component A was applied instead of Component D in this analysis since measurements of current densities within a generic wing section for validation of the analysis had been made with Component A (See Section 2.3.1)

Note 2. Note that the corresponding maximum internal current density for the full threat strike in CASE B is extrapolated from a calculation at 3 kA since this was the amplitude of a Component A test current applied to the wing tank structure model for validation of the EMA3D numerical simulation method. The extrapolation factor was 33.

2.3.1 Calculation Model of Wing Section

EMA3D was used to calculate the current distribution of a partial cutout generic wing section (called Unit Cell) of a conventional aluminum main wing structure, including typical structure elements such as:

- Skins (with skin splices) and spars. The aluminum skins on this model are 4 mm thick.
- Ribs and stringers (one realistic rib and two fake ribs (as access doors for the Unit Cell))

- Leading and trailing edges
- A 7.5 mm air gap (slits) along a skin splice is intentionally included to obtain the worst case (strong) electromagnetic field penetration into the internal wing box through potential small apertures along the splices due to surface finishes and fay seals.

A geometric model of the Unit Cell for the calculations as well as comparison tests is shown in Figure 2.12 and Figure 2.13. The Unit Cell simulates two bays of a typical aluminum main wing section with three ribs (one realistic rib and two fake ribs act as access doors for the Unit Cell), leading/trailing edges and front/rear spars. The shape is simplified using plain surfaces instead of round shapes because such shape differences do not essentially affect the current distribution.

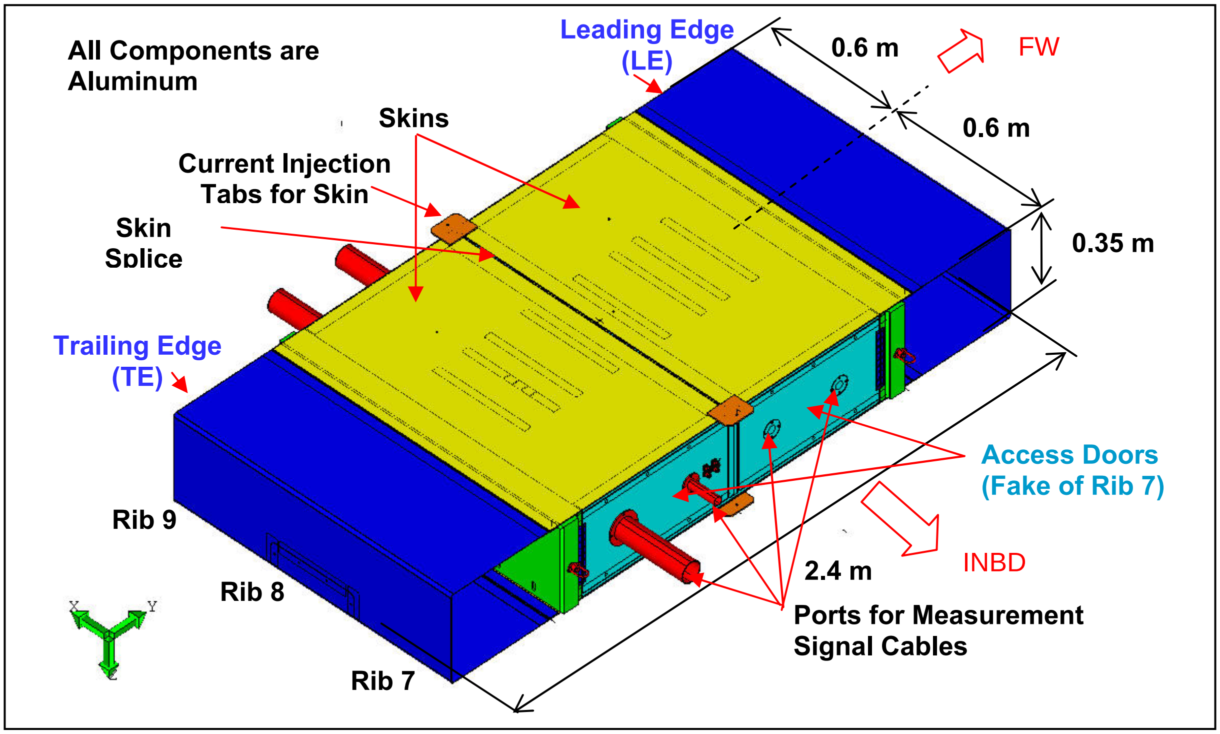


Figure 2.12 - Partial Cutout Wing Section ("Unit Cell") for Test

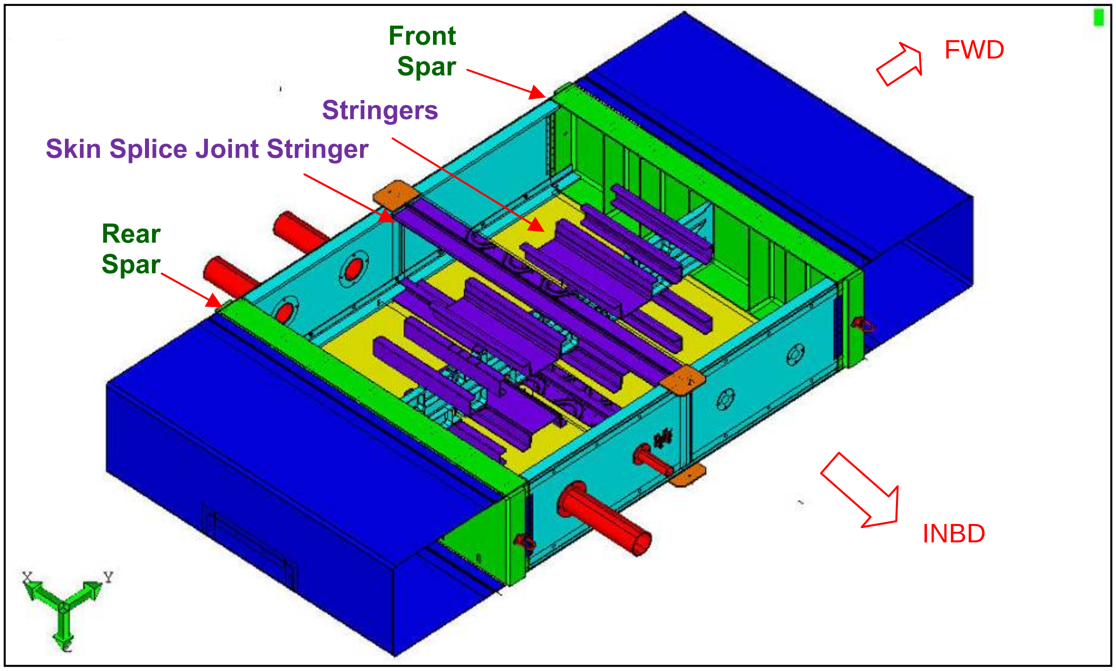


Figure 2.13 - Partial Cutout Wing Section ("Unit Cell") for Test - Top Surface Removed

2.3.2 Calculated Cases of Current Density Distributions of the Unit Cell

Details of the calculation results are summarized in Table 2.3 and are as follows.

CASE A: Tip Strike (most likely lightning attachment case) Zone 3 Conduction Component A at 200 kA

This case represents a most frequent lightning strike scenario of tip strike and Zone 3 conduction through the main wing to the wing root with a 200 kA peak current. Top view of the calculated result at 6 µs which is Component A peak is shown in Figure 2.14. In the case of the Unit Cell test, return foil was needed. Thus, the calculation model also includes the return foil. The return foil is shown in Figure 2.14 but omitted from most of the succeeding figures. The current is injected and ejected through six braided wires, respectively, as shown in the figure. The maximum current density of 2.4e6 A/m was due to the thin wire current input at return foil and therefore fictitious for anywhere on a real wing. External current tends to concentrate at edges, especially at LE/TE edges and its density is up to ~7e4 A/m. The current density on the skin surface was ~2e4 A/m.

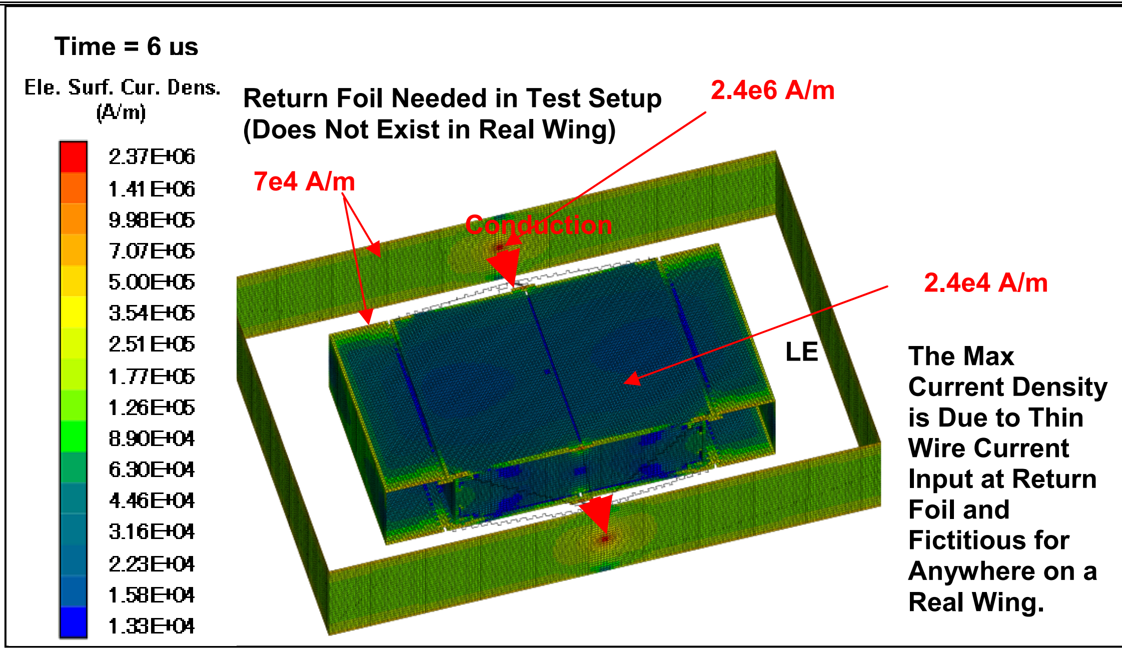


Figure 2.14 - Top View of Unit Cell Calculated Current Distribution of CASE A

Figures 2.15 to 2.20 show internal current at 6 µs. Note that the contour range is three orders smaller than Figure 2.14. Internal current is extremely small compared to the external current, several tens of A/m at the maximum. The reason that the internal currents are much smaller than the external currents is due to *skin effect* wherein a current of short time duration often does not have time to fully penetrate to the interior of a conductor. *Skin effect* is described more generally in Section 2.4.

The highest current density calculated at any surface inside the unit cell is 20 A/m at rib shear ties shown in Figure 2.16.

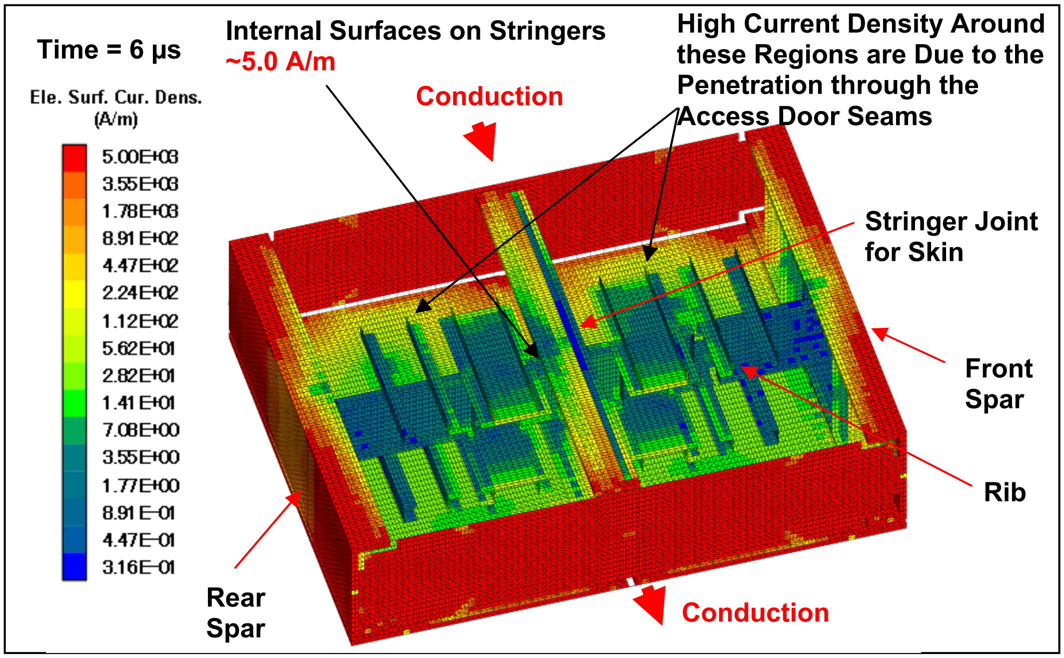


Figure 2.15 - Top View of Unit Cell Calculated Current Distribution of CASE A with Top Skin Removed to Show Internal Currents

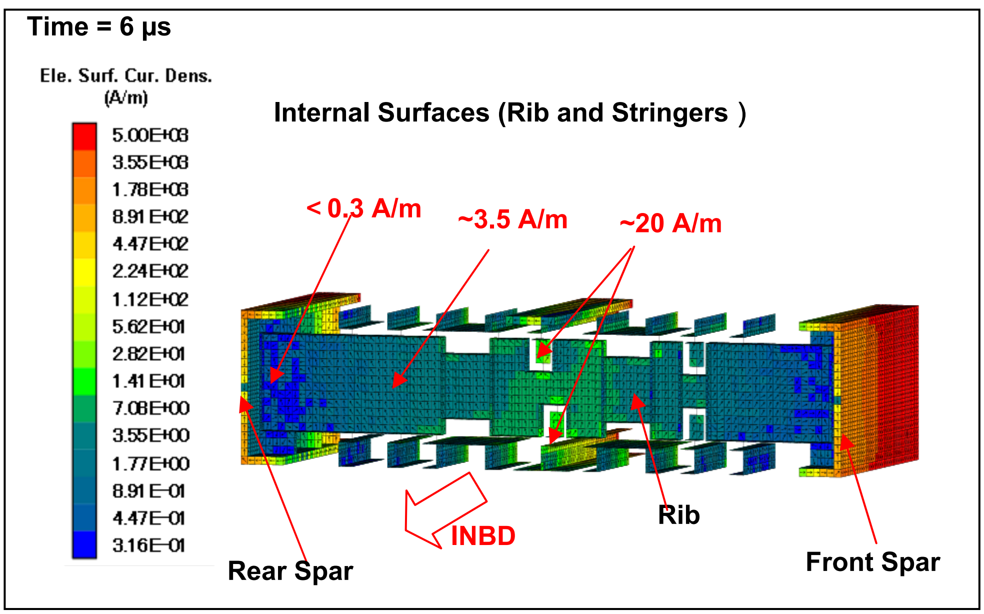


Figure 2.16 - Center Rib Section of Unit Cell Model in CASE A

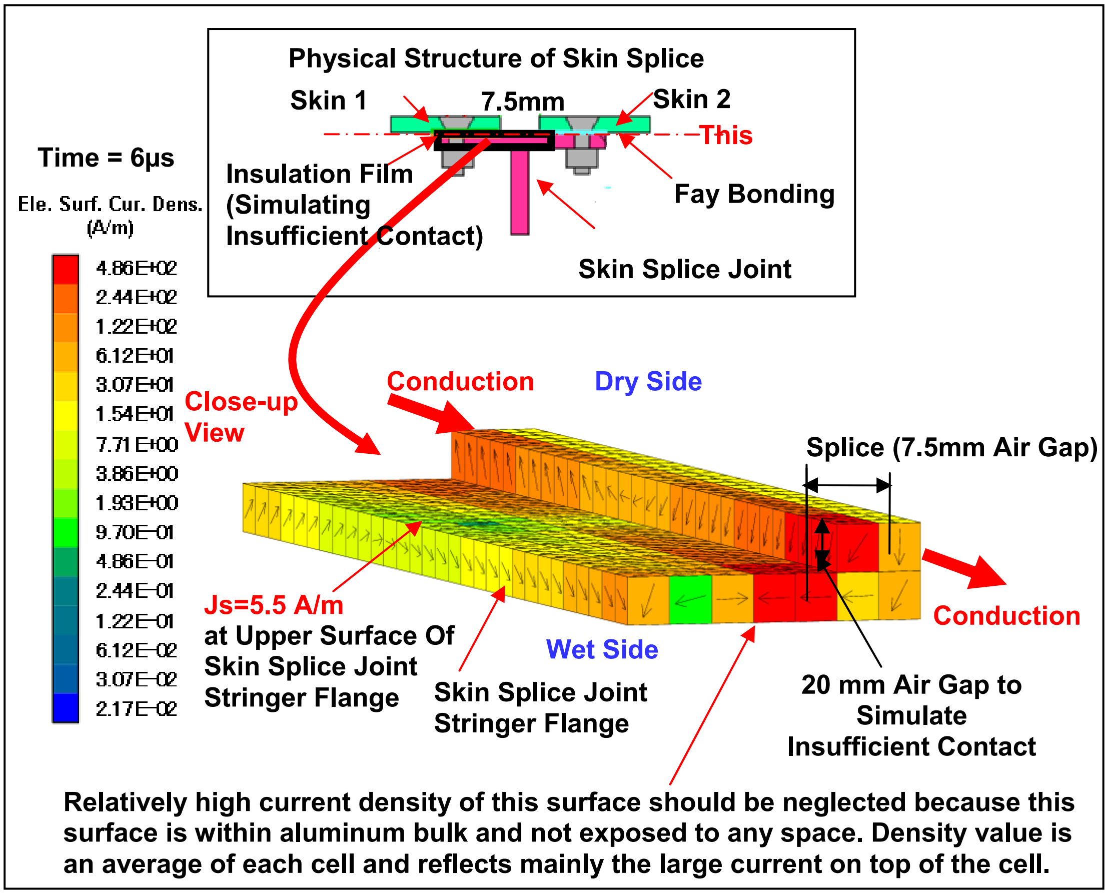


Figure 2.17 - Close-up View at the Center of the Skin Splice in CASE A

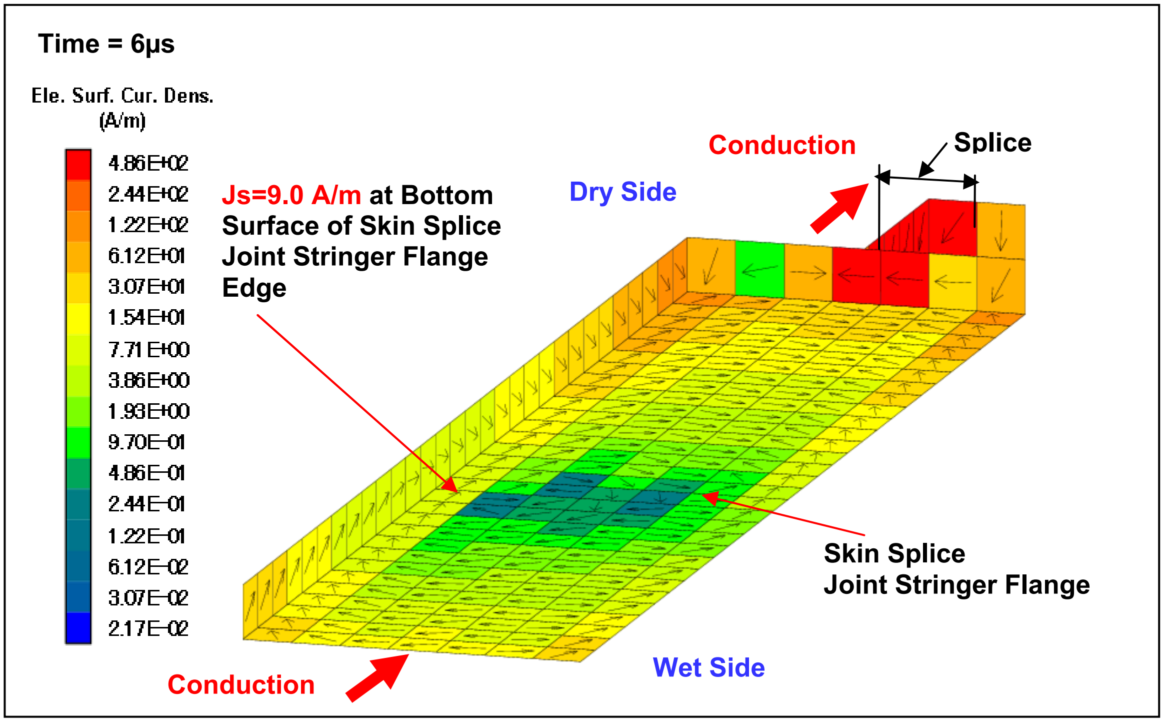


Figure 2.18 - Close-up View of the Center of the Skin Splice (Bottom View) in CASE A; Interior Surface Current Distribution at Center of Model is Due to Higher Densities at Edges near Access Doors

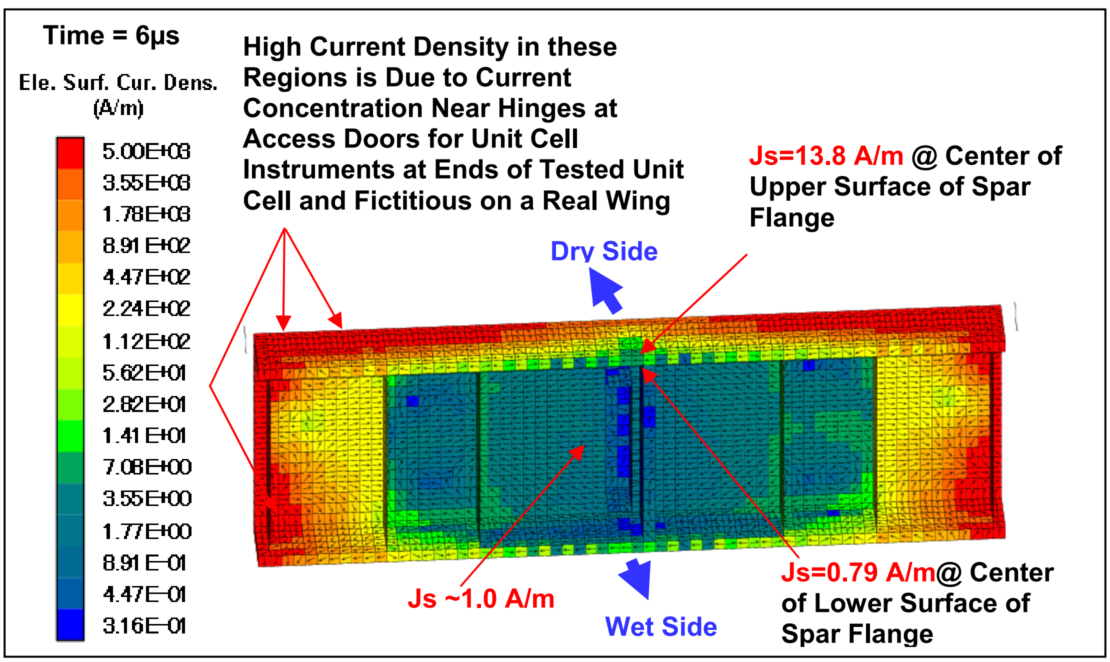


Figure 2.19 - Tank Side of the Spar in CASE A (Looking from Inside)

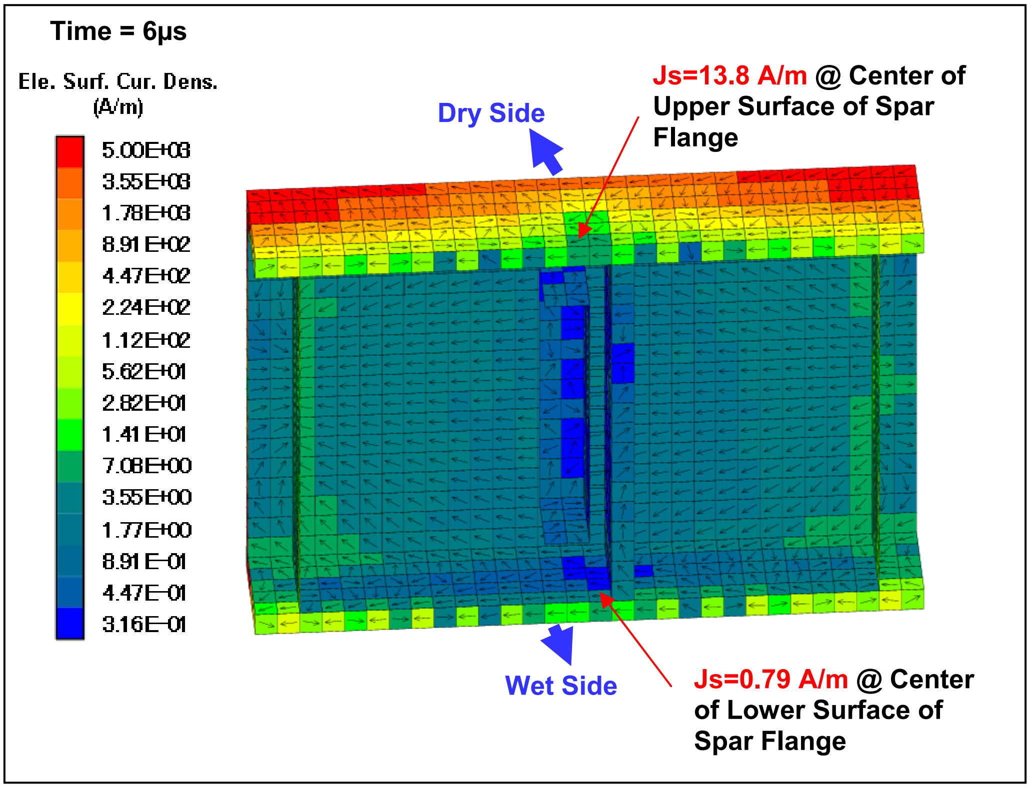


Figure 2.20 - Tank Side of the Spar in CASE A

(Close-up View)

CASE B: Conduction and Direct Strike in Zone 2A, Component A at 3 kA

3 kA, Component A was used in this case because that is the current applied in a comparison test of the same Unit Cell that was modeled. To get full scale currents at 100 kA for Zone 2A, Component D direct strike, the calculated values should be multiplied by 33. To get those at 200 kA for Zone 3 conduction Component A, the calculated values should be multiplied by 67. The results are presented this way in the summary of Table 2.3.

Figure 2.21 shows a close-up view of strike points and Figure 2.22 shows a waveform of the injection current used in the calculations. Figure 2.23 through Figure 2.30 show calculated current distributions with Component A, 3 kA peak injection. Extrapolated values to represent full threat Component D injected at a fastener are shown on Figures 2.29 and 2.30.

With the extrapolated full threat current of 100 kA injected at a fastener (Figure 2.30), the interior current value of 3e4 A/m at the maximum is quite small compared with the exterior current value on the order of 1e6 A/m at the stroke current injection location. This is due to the skin effect which forces most of the current to flow directly into the exterior surfaces of the aluminum skin and spar panels.

Also this is the highest density calculated anywhere within the aluminum Unit Cell. However this is below the arc threshold of between 6.0e4 and 1.7e5 A/m reported in Section 2.2.

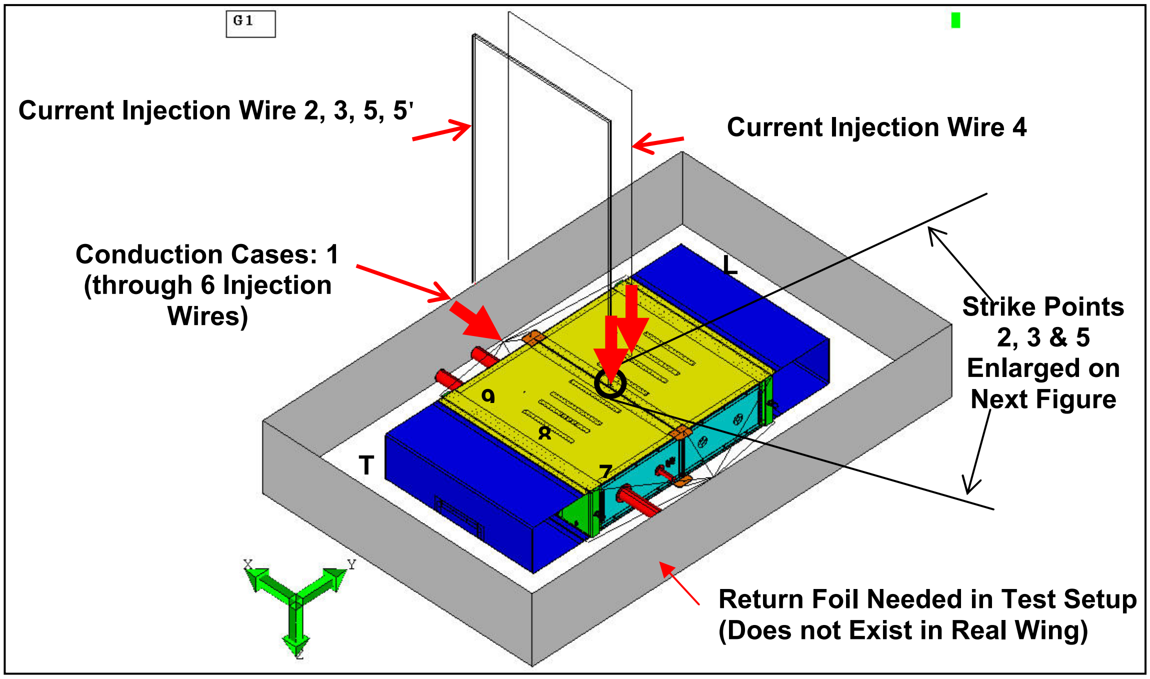


Figure 2.21 - Current Injection Configurations for CASE B, Conduction/Direct Comp A 3 kA Peak

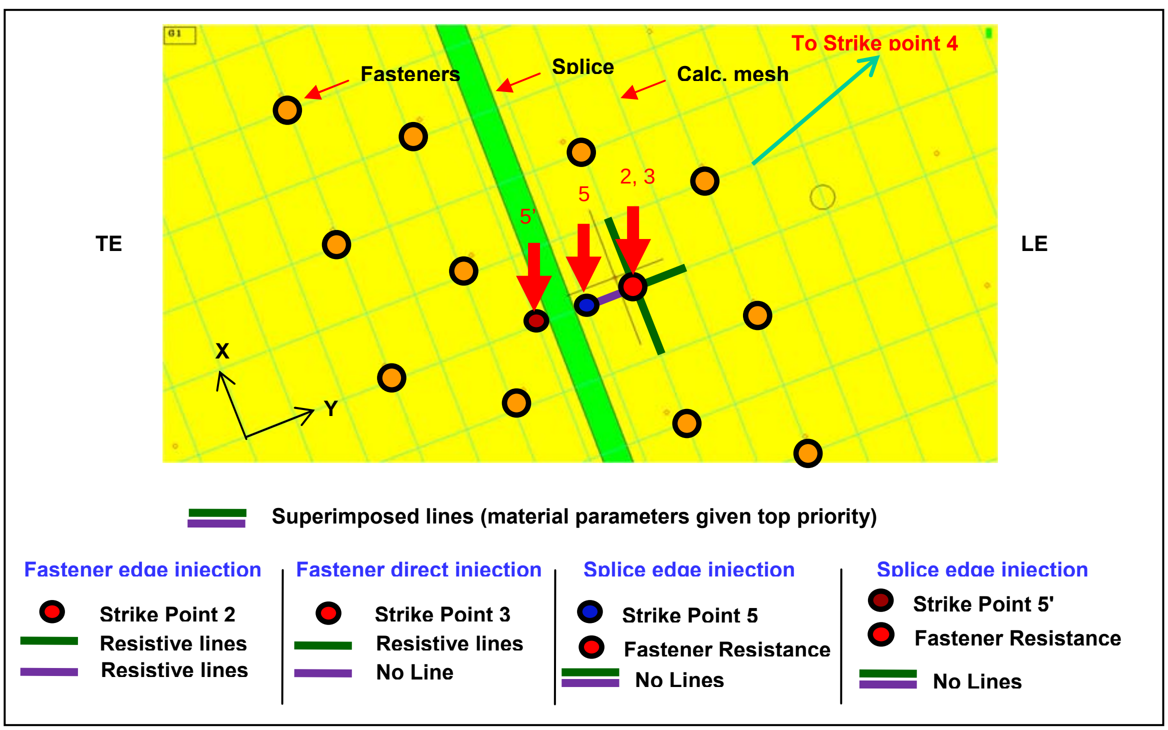


Figure 2.22 - Close-up View of Strike Point 2 to 5; Strike Point 1 is a Conduction Case of Figure 2.21

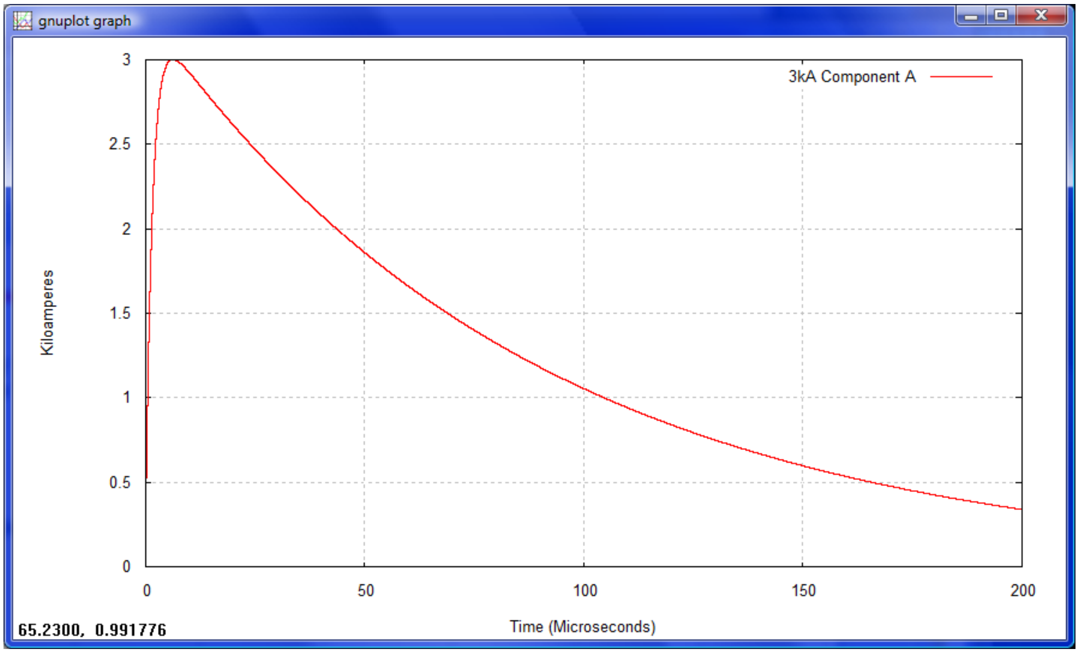


Figure 2.23 - Component A 3 kA Injection Current Time History for the Calculation

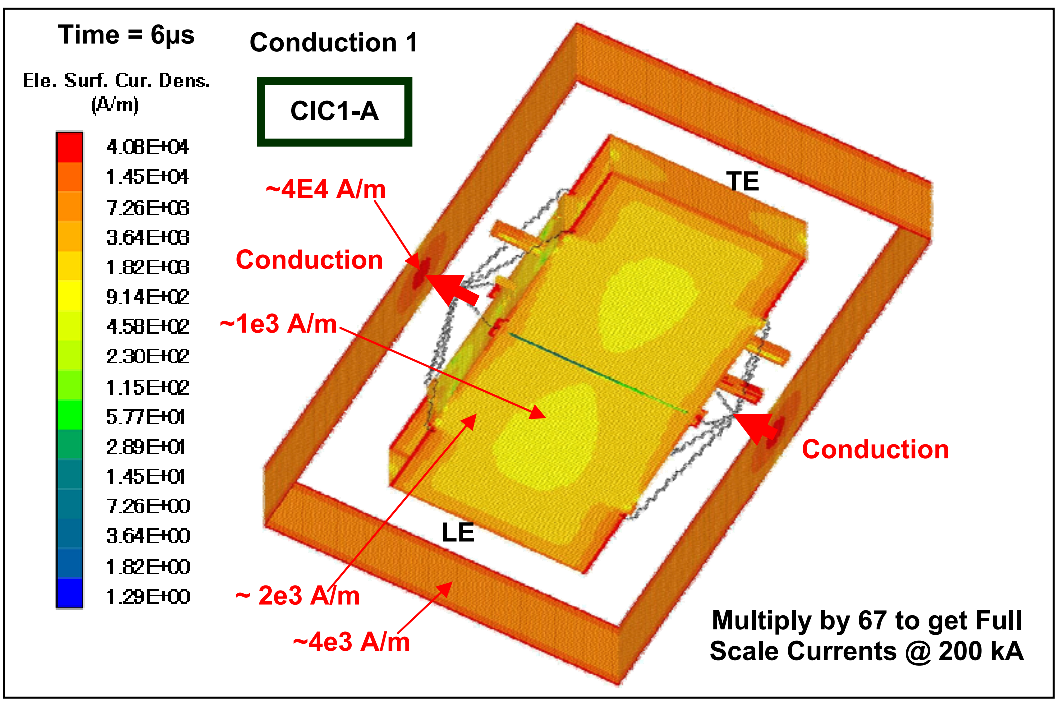


Figure 2.24 - Calculated Current Distribution at 6 μs on Exterior Surfaces for Conduction Component A, 3 kA Peak, CASE B

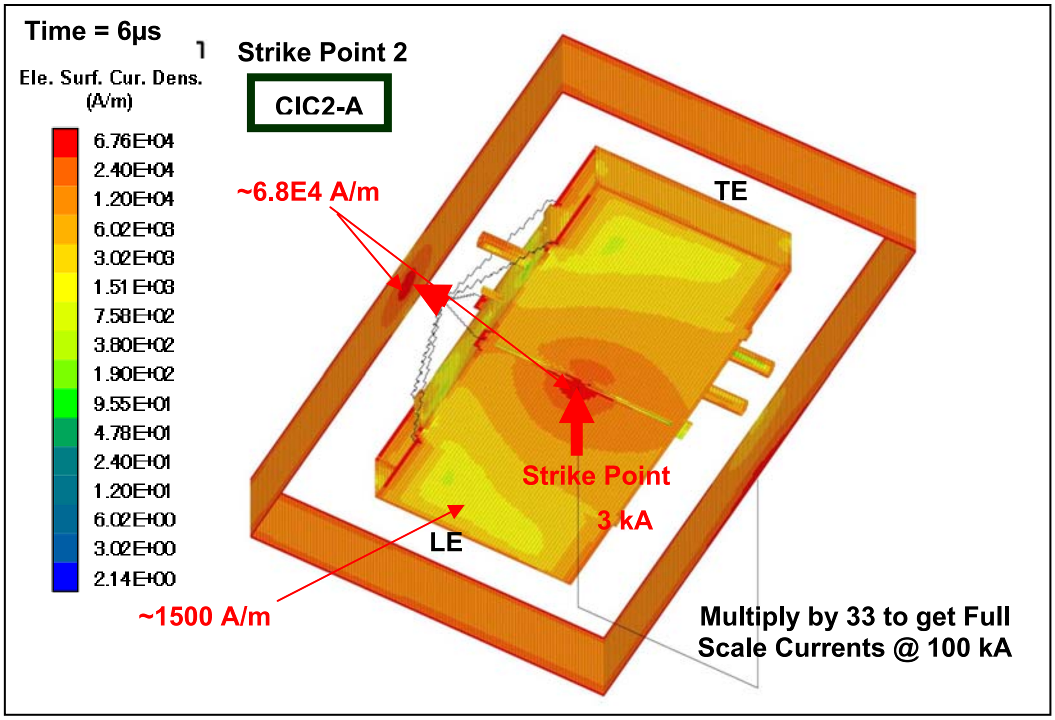


Figure 2.25 - Calculated Current Distribution at 6 µs on Exterior Surfaces for Direct Strike Component A, 3 kA Peak, CASE B

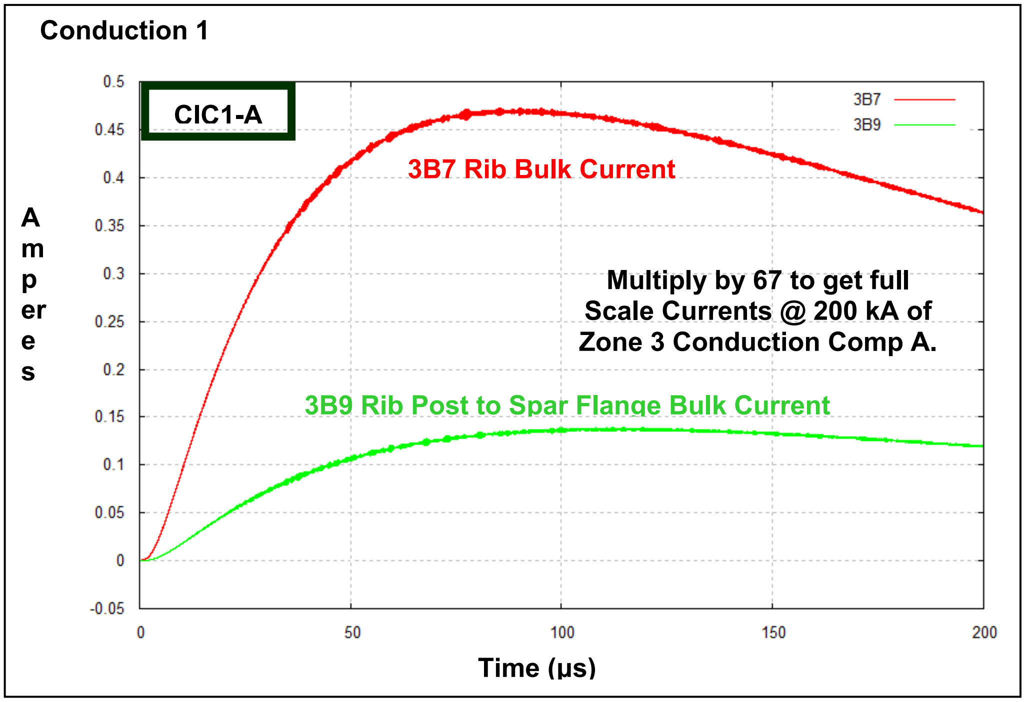


Figure 2.26 - Rib and Spar Bulk Currents of Conduction Strike Point 1 (see Figure 2.21) Comp A 3 kA Peak, CASE B

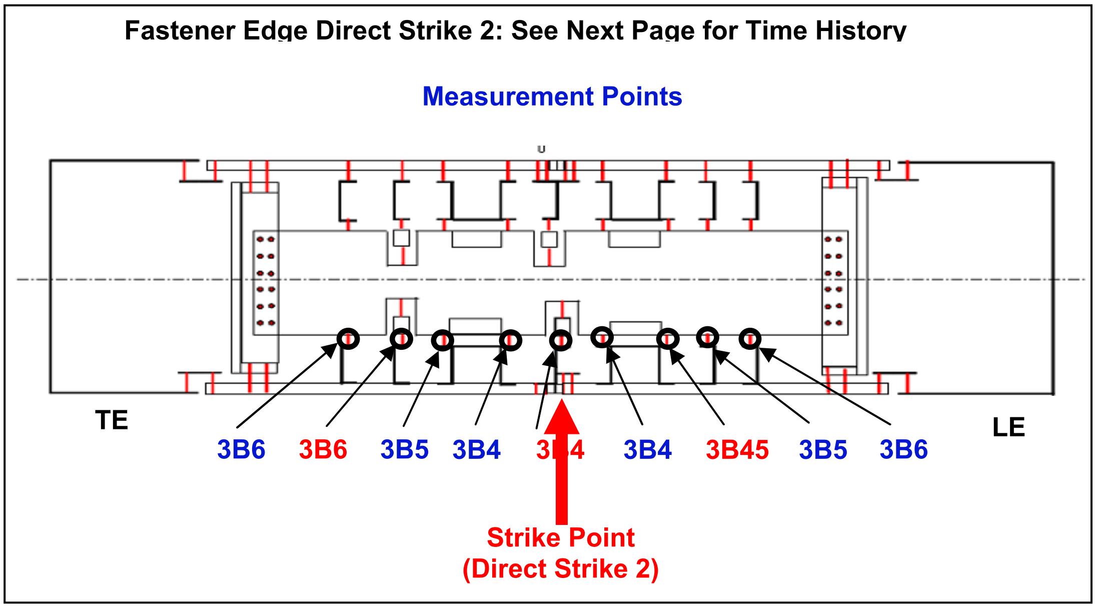


Figure 2.27 - Locations of Stringer Rib Fastener Currents for Direct Strike Point 2, Comp A 3 kA Peak, CASE B

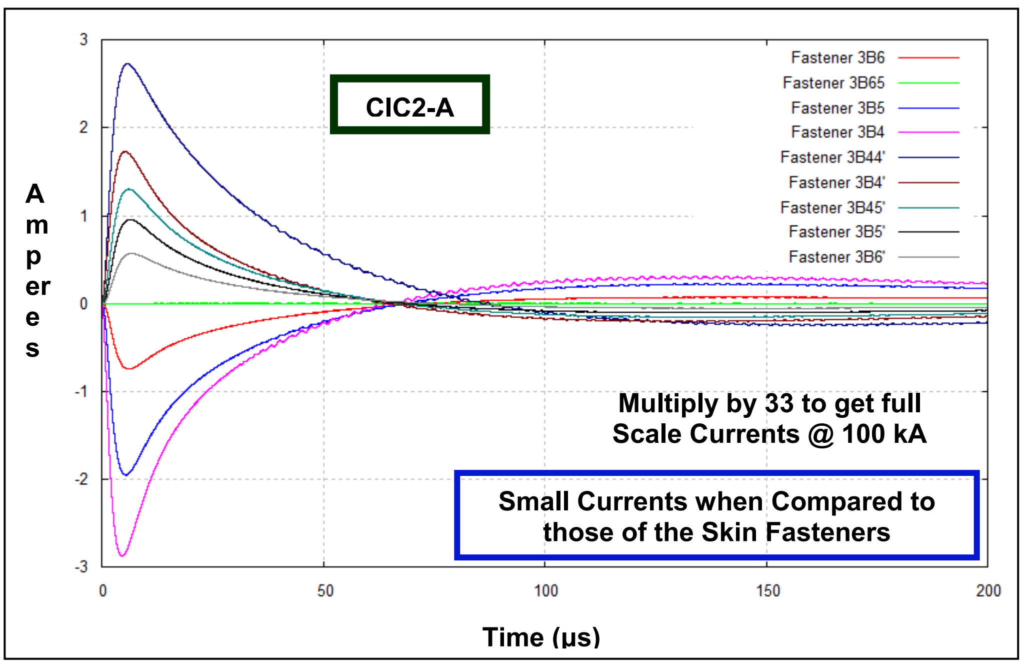


Figure 2.28 - Stringer/Rib Fastener Currents for Fastener Edge Direct Strike, Comp A 3 kA Peak, CASE B

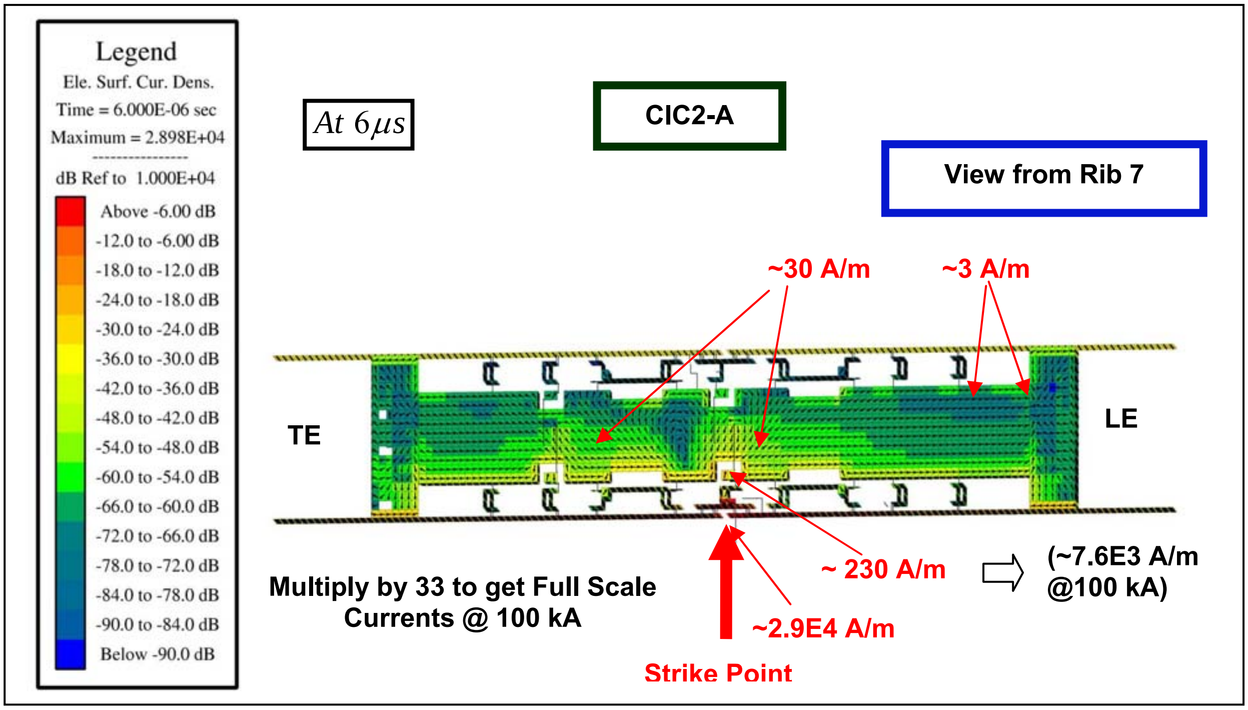


Figure 2.29 - Surface Current Densities on Rib 8, Fastener Edge Direct Strike, Comp A 3 kA Peak at 6 µs, CASE B

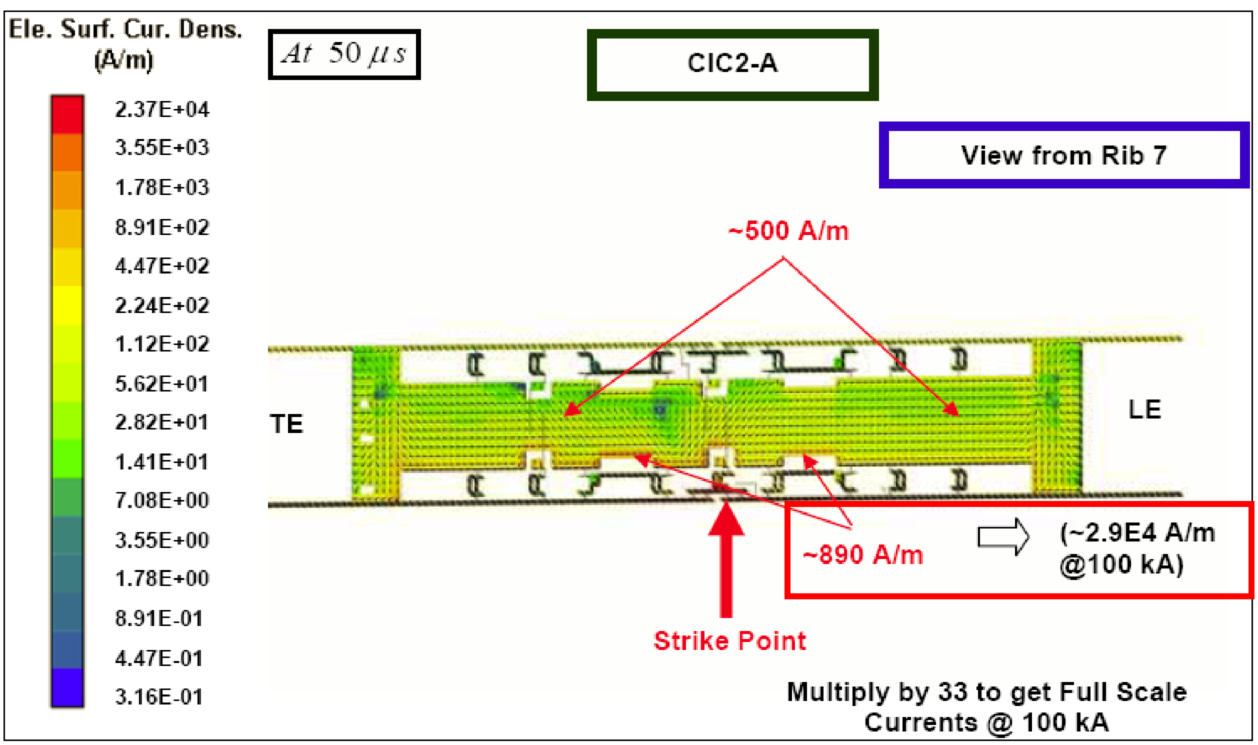
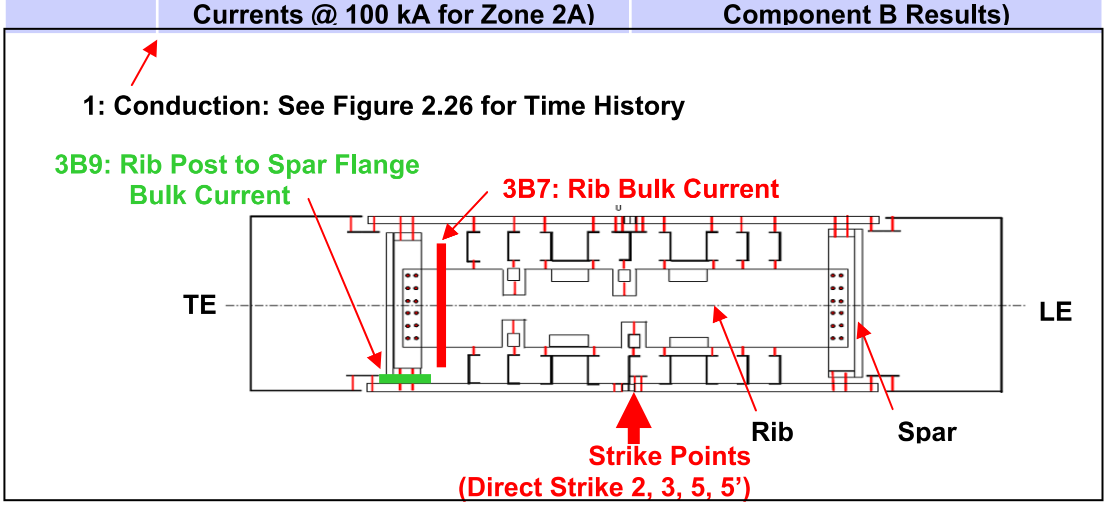


Figure 2.30 - Surface Current Densities on Rib 8, Fastener Edge Direct Strike, Comp A 3 kA Peak at 50 µs, CASE B

Table 2.4 shows total rib and spar internal surface currents due to a direct 3 kA Component A current injected to a fastener at the joint stringer below a rib. The table also shows currents due to 1 A of Component B current injected at the same location. Extrapolation factors applicable to each injected current are presented in Table 2.4.

Table 2.4 - Calculation Results of Internal Bulk Spar and Rib Currents
Conduction/Direct Comp A 3 kA Peak, DC Current

Bulk Current Probe Position	Injection Current											
	Component A (3 kA) {Peak Values}						DC Current (1A) {Final Values}					
	1	2	3	4	5	5’	1	2	3	4	5	5’
3B7	0.4	-29	-38	-20	-40	40	0.5	-12	-24	-13	-25	26
3B9	0.1	-17	-20	-10	-21	21	0.1	-8	-13	-	-13	16
Units:	Amperes (Multiply by 33 to get Full Scale Currents @ 100 kA for Zone 2A)						Milli-Amperes (Multiply by 4000 to get Full scale Component B Results)					



CASE C: Direct Strike in Zone 2A Component D at 100 kA

Figure 2.31 through Figure 2.39 show calculated current distributions of the Unit Cell on exterior and interior surfaces, with a direct strike at a fastener edge close to a skin splice in Zone 2A with Component D of 100 kA peak at 4 µs. Maximum interior current density is 1.5e3 A/m whereas exterior densities reach 1.2e6 A/m at the strike point and 7.5e4 A/m at the edges of LE/TEs. This result is also included in the summary of Table 2.3.

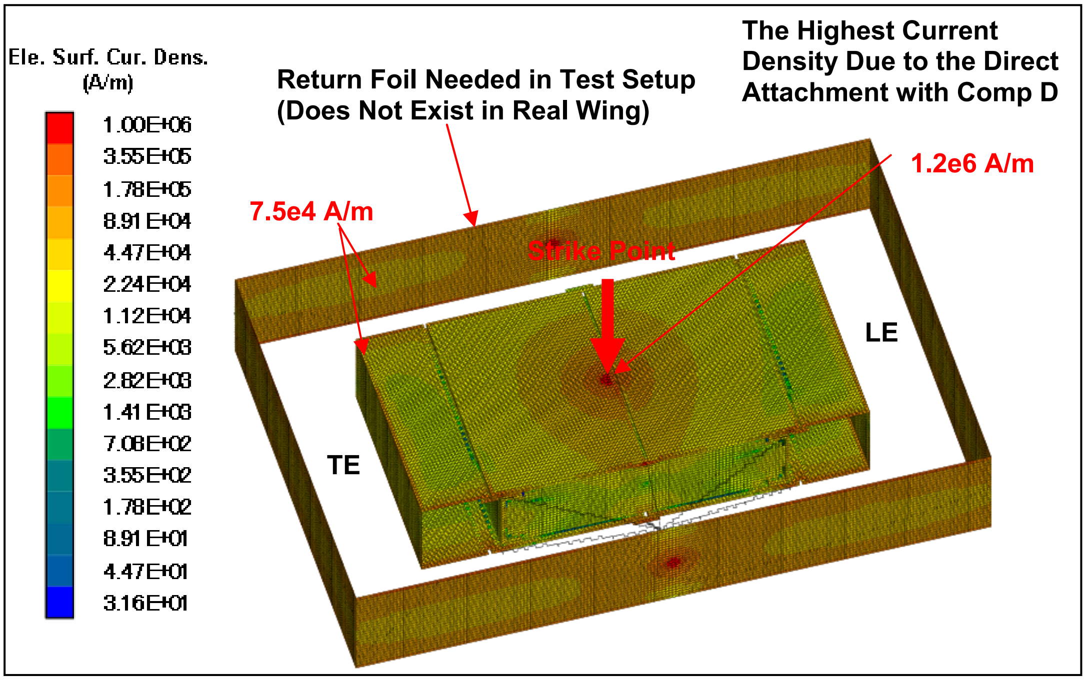


Figure 2.31 - Current Distribution at 4 μs on Exterior Surfaces, Direct Strike in Zone 2A Component D at 100 kA, CASE C; Test Current Return Conductors are Shown

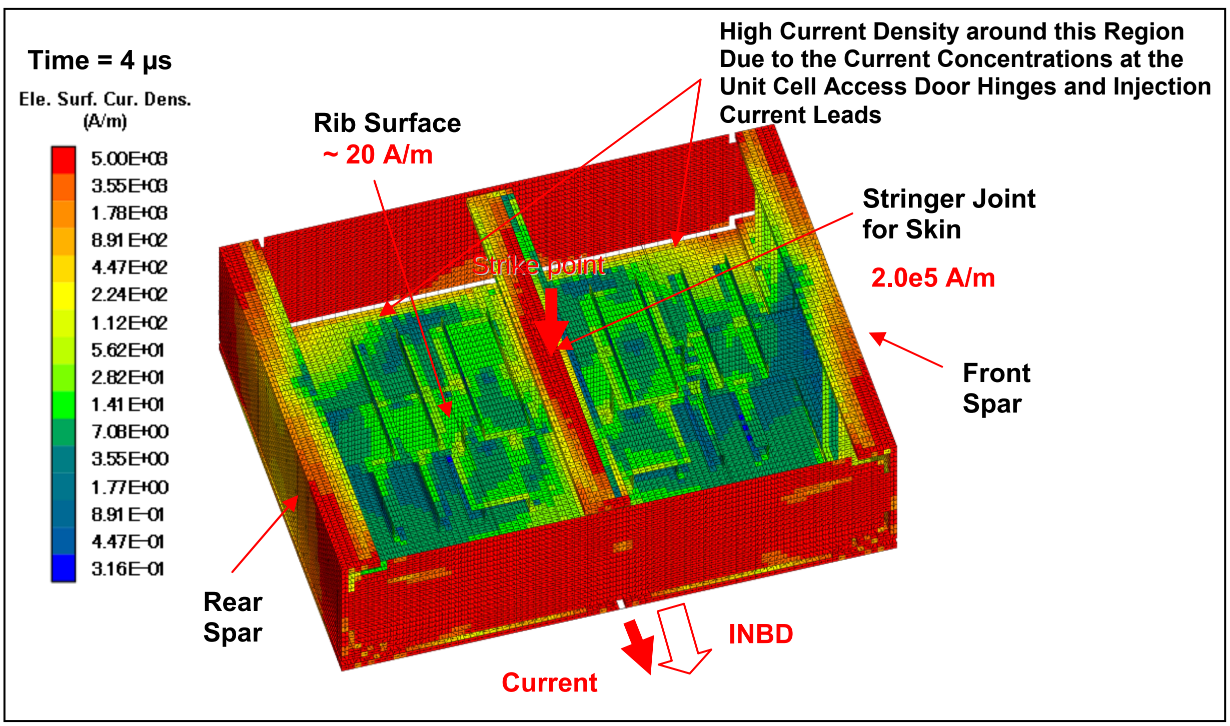


Figure 2.32 - Current Distribution on Interior Surfaces - Top Skin Removed, CASE C

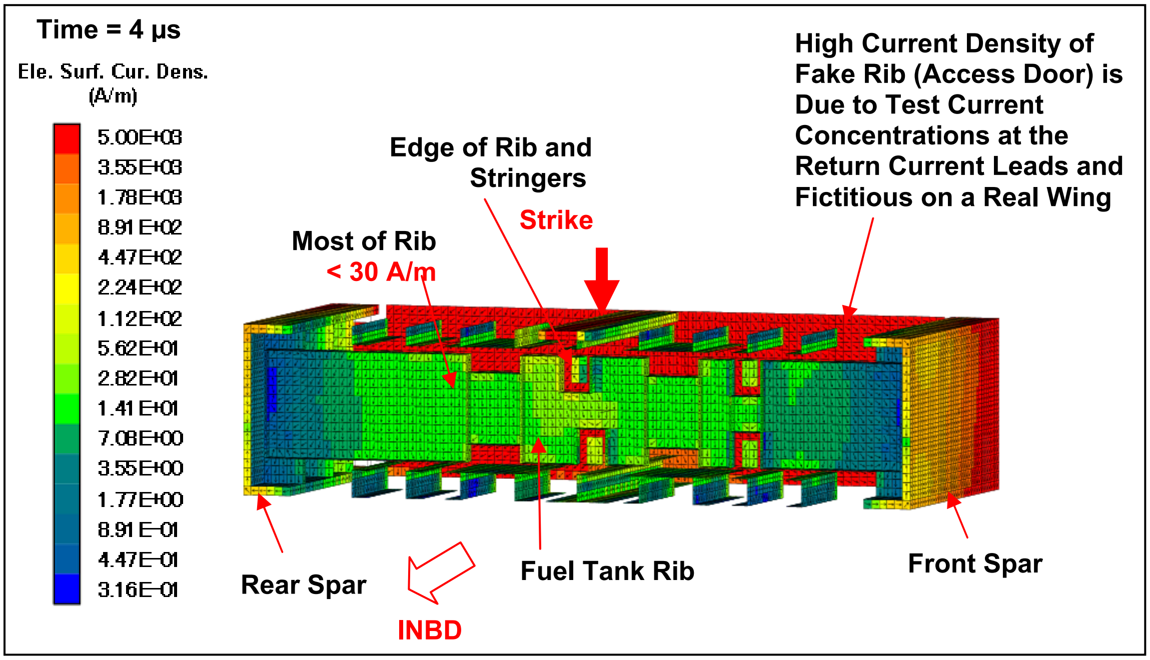


Figure 2.33 - Current Distribution on Interior Surfaces -
Close-up View of Rib and Stringers without Skins, CASE C

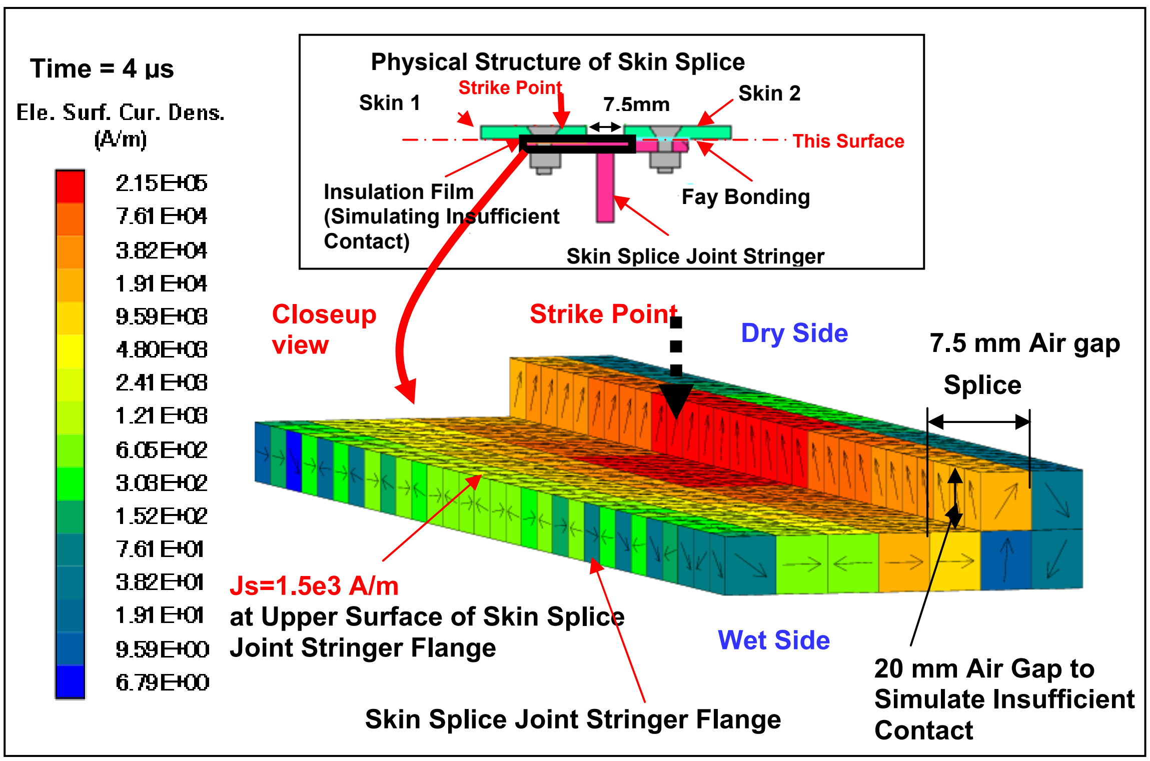


Figure 2.34 - Close-up View of the Center of the Skin Splice, CASE C.

The current density of 1.5e3 is at the upper edge of the skin splice in Figure 2.34. This is the highest current density calculated anywhere within the aluminum Unit Cell in CASE C. This is below the arc threshold of between 6e4 and 1.7e5 A/m reported in Section 2.2.

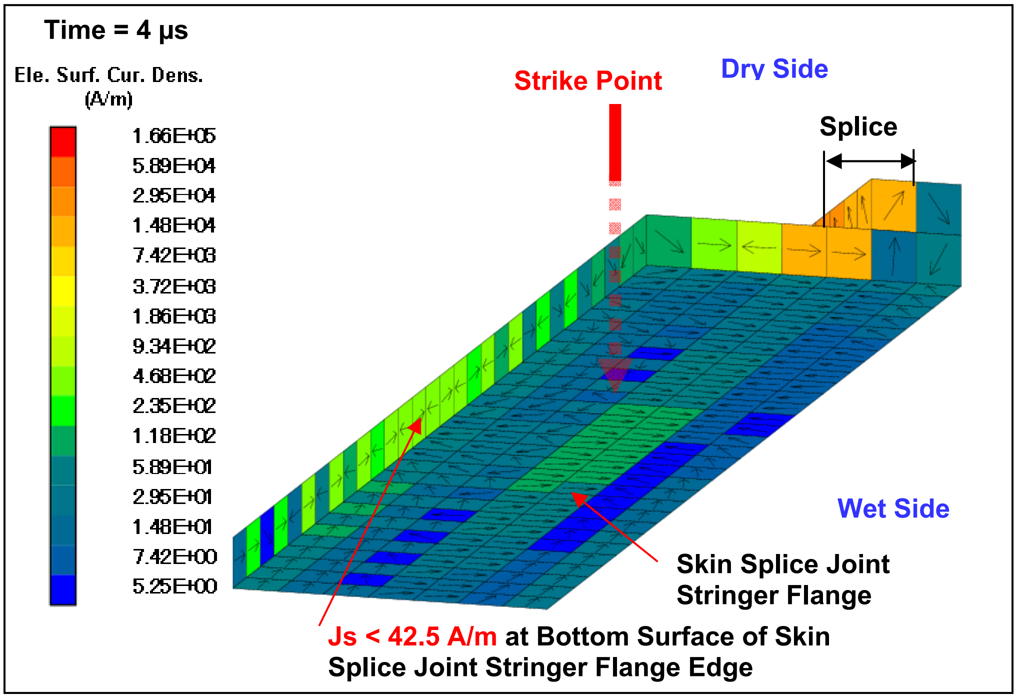


Figure 2.35 - Close-up View of the Center of the Skin Splice (Bottom View) CASE C

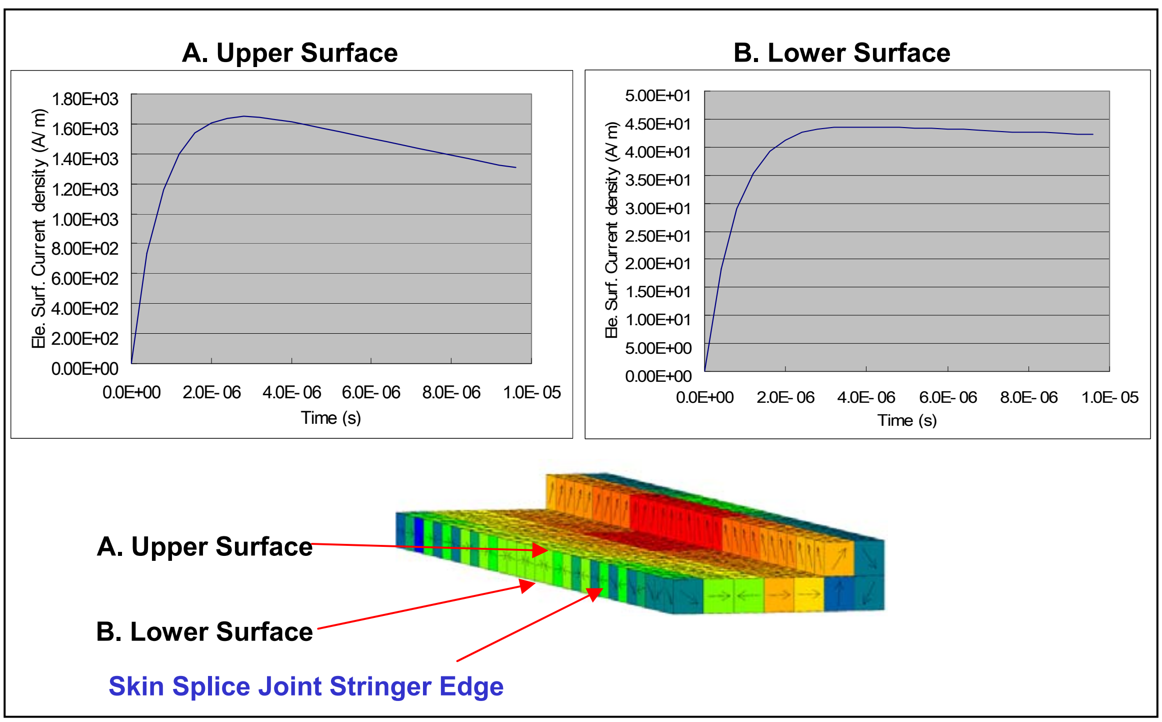


Figure 2.36 - Time Histories of Current Densities at Skin Splice Joint Stringer Flange Edges, CASE C

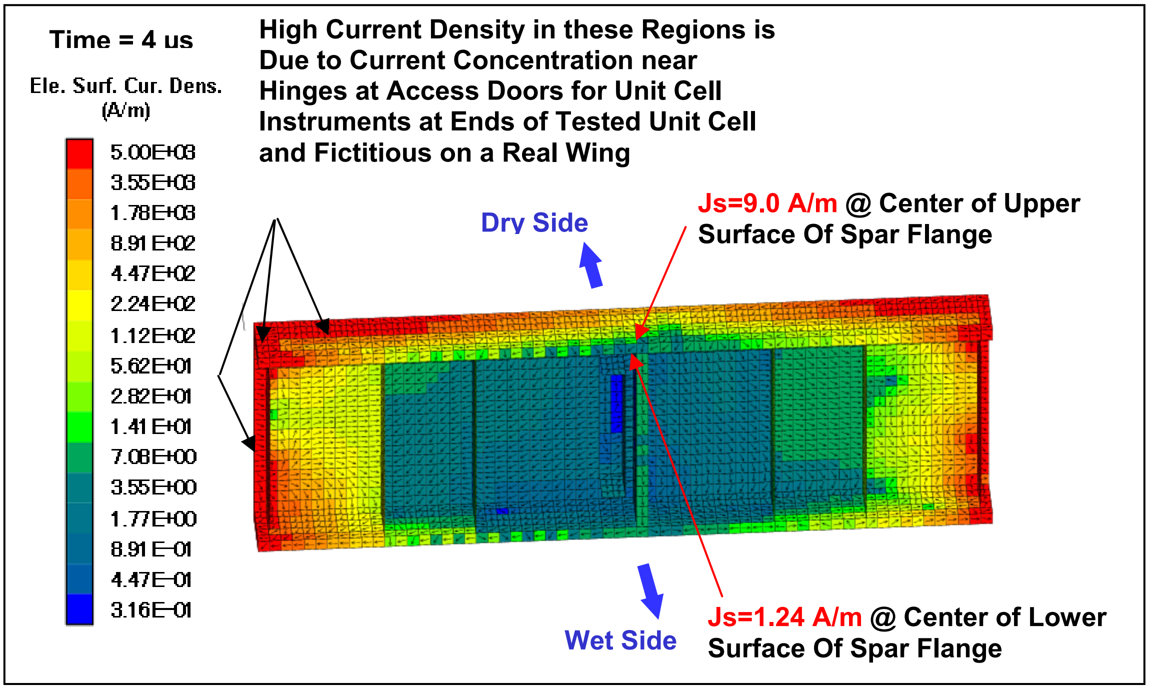


Figure 2.37 - Current Distribution of Tank Side of the Spar, CASE C

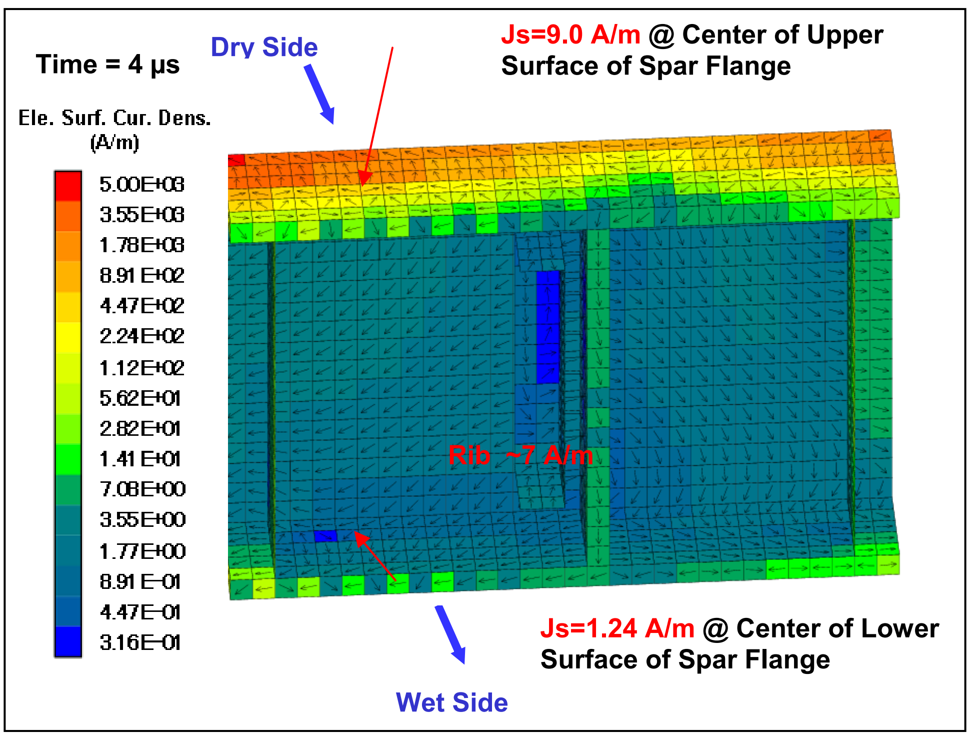


Figure 2.38 - Current Distribution of Tank Side of the Spar - Close-up View, CASE C

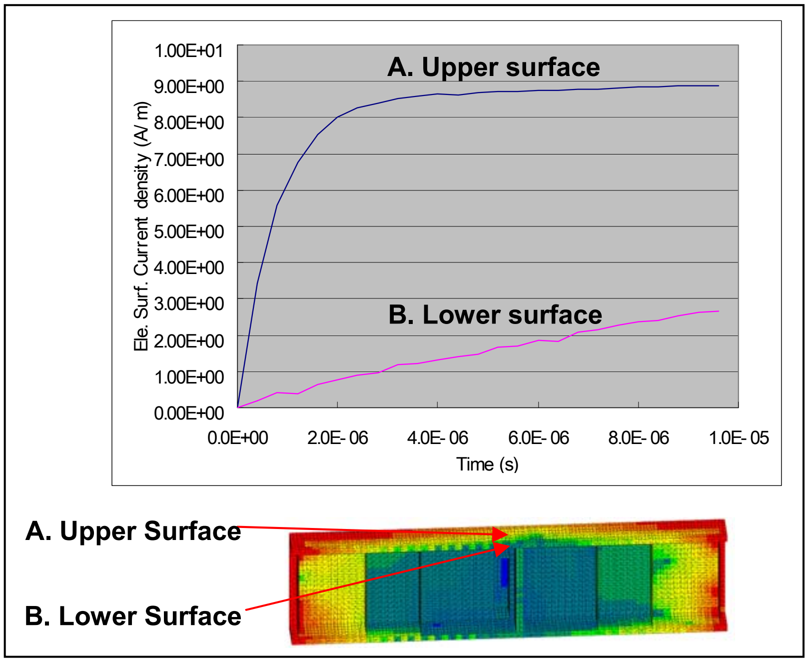


Figure 2.39 - Time Histories of Current Densities at Upper and Lower Surfaces of Spar Flange, CASE C

2.3.3 Findings of the Calculated Current Density Distributions within a Conventional Al Wing Fuel Tank Structure Model

Findings of the calculated current distribution are as follows:

- Current density of internal structure of the partial wing model (Unit Cell) was several orders of magnitude smaller than external current density due to skin effect which is very strong in an aluminum tank.

- Calculated maximum internal current densities of the Unit Cell were 2.9e4 A/m at a rib edge and 1.5e3 A/m at the edge of a skin splice when 100 kA was injected to a nearby fastener along the rib or skin splice. These maximum values exist only in the immediate vicinity of direct strike location.

- Other internal current densities were much lower, at several tens of A/m, especially for the much more likely conduction case when the strike occurs at a wing tip and current is conducted through the wing to an exit location at another place on the airplane.

2.4 The Origin of Skin Effect

When voltage is applied to a conductor, the initial current is confined to the conductor’s surface. This current is accompanied by a magnetic field. The relationship between the voltage and the magnetic field is given by Faraday’s law which states that:

The magnitude of the voltage induced in a circuit by a changing magnetic field equals the negative of the time rate of change of the magnetic flux through the area enclosed by the circuit.

Similarly, Lenz's Law states that the magnetically induced voltages drive conductor currents whose own magnetic fields tend to cancel the field initially inducing the voltage. Therefore, when an electric current begins to penetrate the volume of a conductor, it is opposed by surface eddy currents that establish magnetic fields equal and opposite to those associated with the penetrating current. These eddy currents act to cancel currents within the body of a conductor and increase the current at the surface of the conductor. In a perfect conductor (with no resistance), this process would occur with perfect efficiency, so that current could never penetrate the conductor but would always flow on the conductor's surface. In real conductors, resistive losses will diminish the eddy currents and some current will eventually penetrate further into the thickness of the conductor.

The confinement of electric currents close to the surfaces of conductors by this mechanism is known as the *skin effect*. At a given instant in time (or at a given frequency) the *skin depth*, is defined as the depth below the surface of a conductor at which the current density falls below $1/e$ of its value at the surface, where e is the natural logarithm.

The situation described above is illustrated in Figure 2.40 which shows a cylinder exposed to an initial flow of current. The current density, J, along the internal surface AB of the cylinder will be completely different from the current density along the exterior surface CD. This is because the phenomenon of skin effect delays the buildup of current on the inner surface. Only as the eddy currents decay, will the magnetic field penetrate the wall of the cylinder. This process takes 10's or hundreds of microseconds, depending on the material and thickness of the wall. The higher the conductivity of the wall material, the longer the time needed for current to appear on the inner surface. The process of current penetration into the wall of a conductive object is called *diffusion.*

The process of decay of the eddy currents and gradual penetration of current throughout the body of a conductor is known as *diffusion.* The process of diffusion is described below.

Characteristic Diffusion Response

The diffusion response is the buildup of current on the inner surface of a conductor after current has been injected into the exterior surface. A typical response to a square wave input current is shown in Figure 2.41.

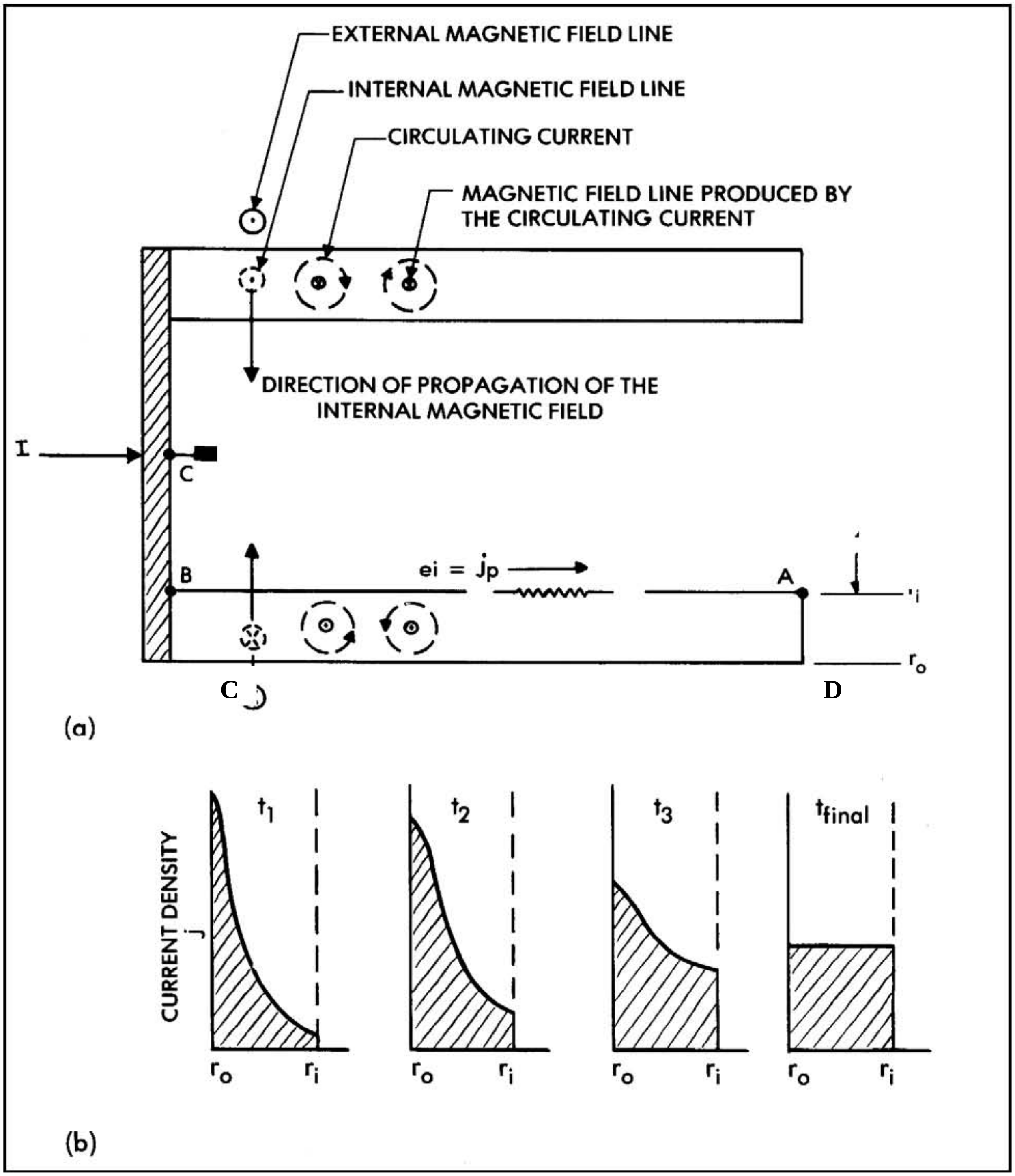


Figure 2.40 - Illustration of Skin Effect in a Metal Cylinder

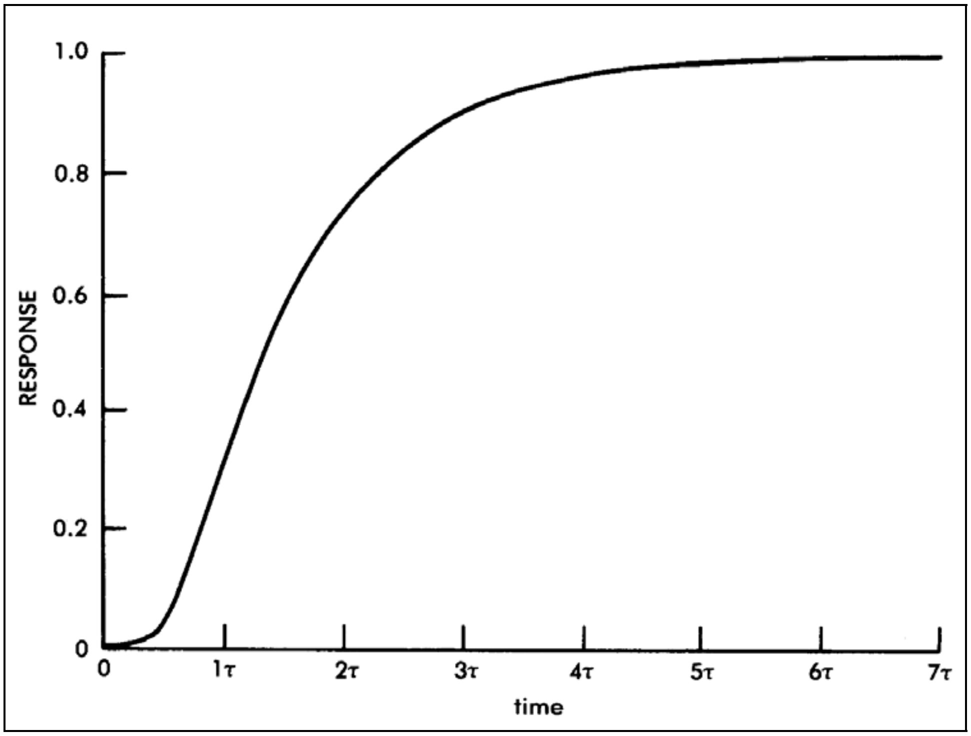


Figure 2.41 - Diffusion-Type Response of Current on Interior Surface to Square-Wave Current Injected at the Exterior Surface (Time Units are Diffusion Time Constants)

The response curve of Figure 2.41 is called a *diffusion-type response* and is characteristic of many types of situations involving the transmission of energy through a medium. An example would be the transfer of heat into a block of material if a heat flux were suddenly applied to one face of the block.

Waveshape: Two important observations might be made about the shape of the response curve shown on Figure 2.41. The first is that the response initially changes only slowly and thus has a zero first derivative, unlike a simple exponential response, which has a finite first derivative. The second is that the response approaches its final value much more slowly than does a simple exponential response. In three time constants the response has reached 90% of its final value, but the rise to the 99% point takes nearly 20 time constants.

Influence of Material: The penetration time constant is directly proportional to the permeability of the material, inversely proportional to the resistivity of the material and directly proportional to the square of the material's thickness. The relative permeability of structural materials used in airplane is always very nearly unity, but thickness and resistivity can vary over wide ranges.

Typical diffusion time constants for aluminum are about 40 μs per millimeter of skin thickness. This means that it would require 120 μs for a square wave current entering the exterior surface of an aluminum box to diffuse to the same current density throughout the aluminum skin. Thus a lightning stroke current reaching peak in 6 μs and decaying to 50 % in 69 μs can not reach equilibrium throughout the skin thickness. The current density on the interior of the skin reaches only a small percentage of that on the exterior surface, as shown by the analyses of Section 2.3.

Because of this, the skin voltage potentials available to drive currents into internal structural elements such as stringers and ribs are very small and so the currents in those elements are small.

2.5 Investigative Lightning Test of Cracked Structure and Fastener Hardware

2.5.1 Test Configuration

Tests were conducted on aluminum shear ties fastened with groups of four fasteners to aluminum panels representing fuel tank skins. Test currents were conducted from the skin panel to the shear tie, as shown in Figure 2.42. Test article variants included:

- Al panel and Al shear tie
- CFRP panel and Al shear tie
- Interference and clearance fit fastener installations

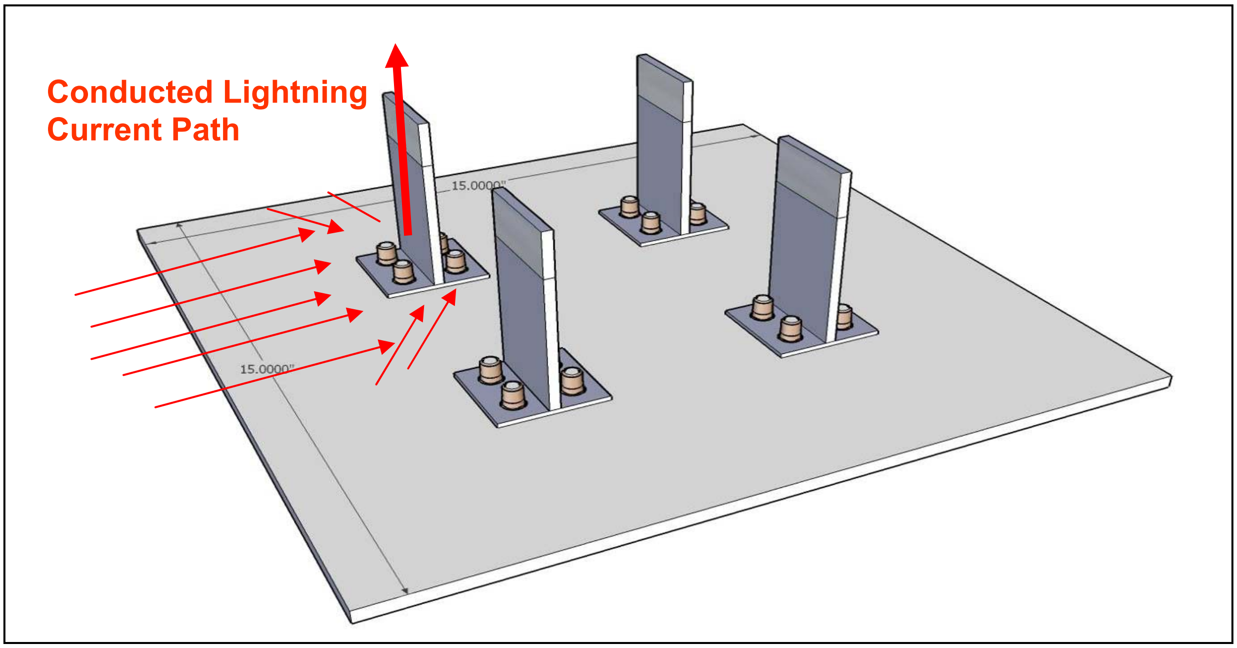
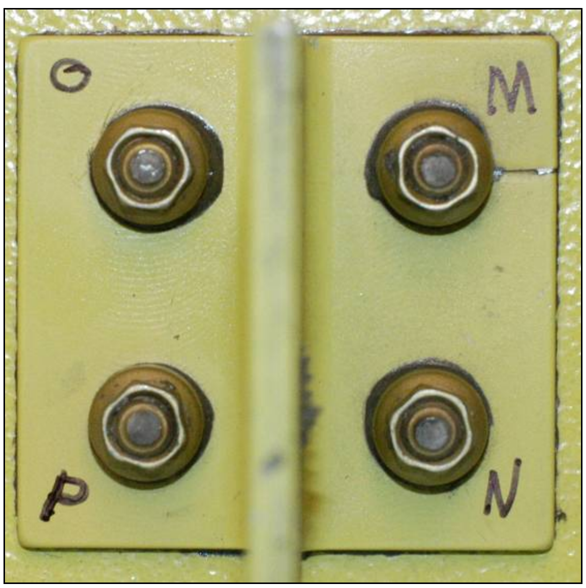


Figure 2.42 - General Test Arrangement for Fastener-Related Failure Conditions;
Test Current was Conducted from Skin Panel to Shear Tie

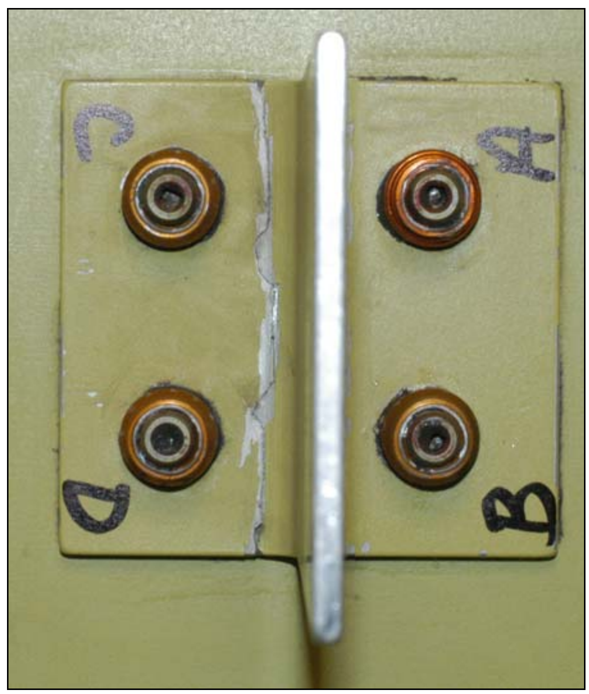
Figure 2.43 shows examples of failure conditions included on the shear tie specimens.

Cracked Collar

Missing Collar



Crack at Hole Edge in Shear Tie



Crack in Shear Tie

Figure 2.43 - Examples of Failure Conditions at Shear Tie Fasteners

The matrix of specimens tested is shown in Table 2.5. The test results are listed in Table 2.6.

Table 2.5 – Fastened Joints and Failure Conditions

Al Panel/Interference Fit	Fractured Bolt
	Cracked Collar
	Fully Cracked Shear Tie
	Crack at Hole Edge in ST
	Cracks with Fay Surface Bond
Al Panel/Clearance Fit	Fractured Bolt
	Cracked Collar
CFRP Panel/Interference Fit	Fractured Bolt
	Fully Racked Shear Tie
	Crack at Hole Edge in ST
CFRP Panel/Clearance Fit	Fractured Bolt

2.5.2 Test Results

Table 2.6 - Test Results for Shear Tie Fasteners with Failure Conditions

Test Specimen	Tested Failure Condition	Range of Conducted Test Currents that Produced Sparks
Al Panel/Interference Fit	Fractured Bolt	~20 – 40 kA
	Cracked Collar	~15 – 20 kA
	Fully Cracked Shear Tie	~70 – 80 kA
	Crack at Hole Edge in Shear Tie	~85 kA
	Cracks with Fay Surface Bond	100 kA
Al Panel/Clearance Fit	Fractured Bolt	~20 kA
	Cracked Collar	~5kA
CFRP Panel/Interference Fit	Fractured Bolt	~50 - 60 kA
	Fully Racked Shear Tie	~60 – 70 kA
	Crack at Hole Edge in Shear Tie	~25 - 30 kA
CFRP Panel/Clearance Fit	Fractured Bolt	~2 – 10 kA

Discussion about rib shear ties and fasteners with crack failure conditions:

- Cracks in aluminum fuel tank structures that comprise a complete enclosure such as a wing box are not likely to produce arcs or sparks due to lightning currents.

- Fully cracked shear ties and cracks at holes may spark under high shear tie current conditions of 50 kA – an unrealistic condition for an all-aluminum tank.

- Cracked fasteners or nuts sparked at the lowest test current applied (5 kA).

- Expect wide variability of test results for these kinds of tests. Therefore certification test levels should be set higher than expected actual shear tie currents by a margin of at least 2.1.

- The range of computed shear tie currents due to direct strikes to one of the shear tie fasteners in Section 2.3 is in the hundreds of amperes and therefore not expected to reach the lowest spark threshold of Table 2.7 for a cracked collar in aluminum structure, clearance fit (5 kA).

2.6 Investigation of Voltages across Cracks in Aluminum Panels

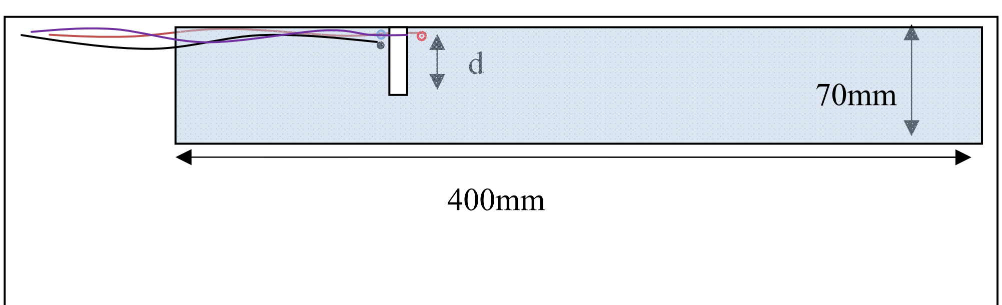
These tests were carried out in support of understanding whether the sparks observed in cracked panels described in Section 2.3 are actually sparks (also known as voltage sparks) or arcs (also known as thermal sparks). The objects of this discussion are cracks in stringers in aluminum fuel tanks.

The intent of the tests was to determine the voltage that might be expected to appear across a crack in a fuel tank stringer when the stringer carries lightning currents. This was achieved by measuring the voltage drop across a hacksaw slot cut in an aluminum strip.

The results of the tests are then related to:

1. The expected threat currents on aluminum stringers inside aluminum fuel tanks to determine expected voltages stressing the crack.
2. The consequences of the expected voltages in relation to those voltages necessary to create an arc (~300 V), and to sustain an arc on aluminum (14 V).

Test Set-up and Results: The aluminum strips were 70 mm wide, with narrow slots cut in with a hacksaw to depths of 20 mm and 40 mm. The voltage was measured within 2 mm of the slot end, an extra wire was installed as a background measurement. The strips and general test arrangement are shown in Figures 2.44 and 2.45.



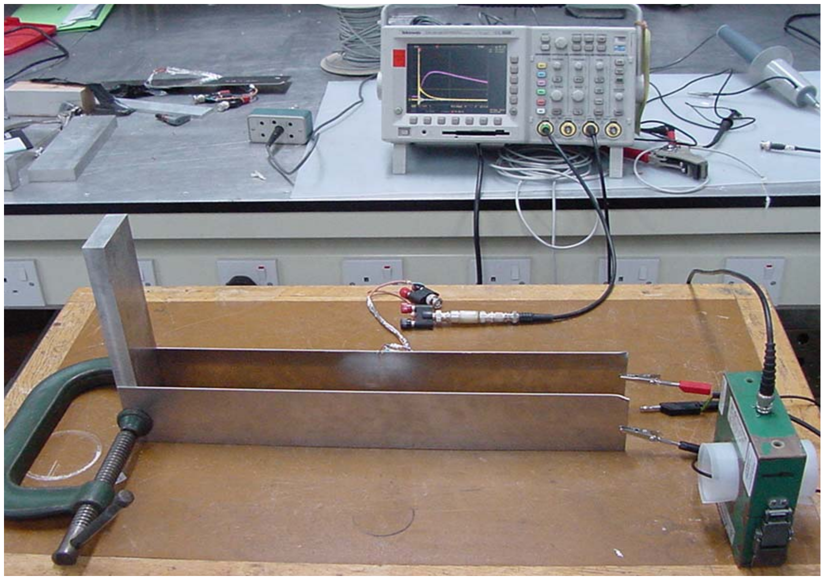


Figure 2.44 - Aluminum Strip Test Specimen and General Test Arrangement

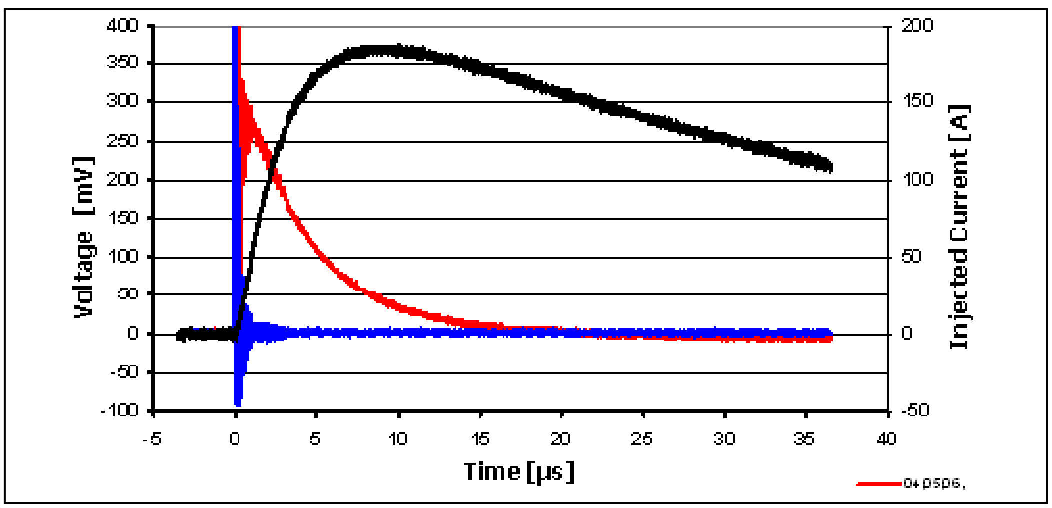


Figure 2.45 - Example Slot Voltage (Red Trace), Background Voltage (Blue Trace) and Injected Current (Black Trace)

Test Set-up: Injected current was typically 170 A with a time to peak of 10 μs and a peak rate of rise of approximately 50 A/μs. For each slot depth sample, two configurations of return path were tested; one with a 2 mm separation of the strip from the return plate to simulate a crack in that part of a stringer parallel and close to the wing skin; one with the return strip 70 mm away to simulate a crack away from the skin. Results of the four test configurations are summarized in Figure 2.46. In all cases, the voltage given is the peak waveform 2 (WF2) voltage value.

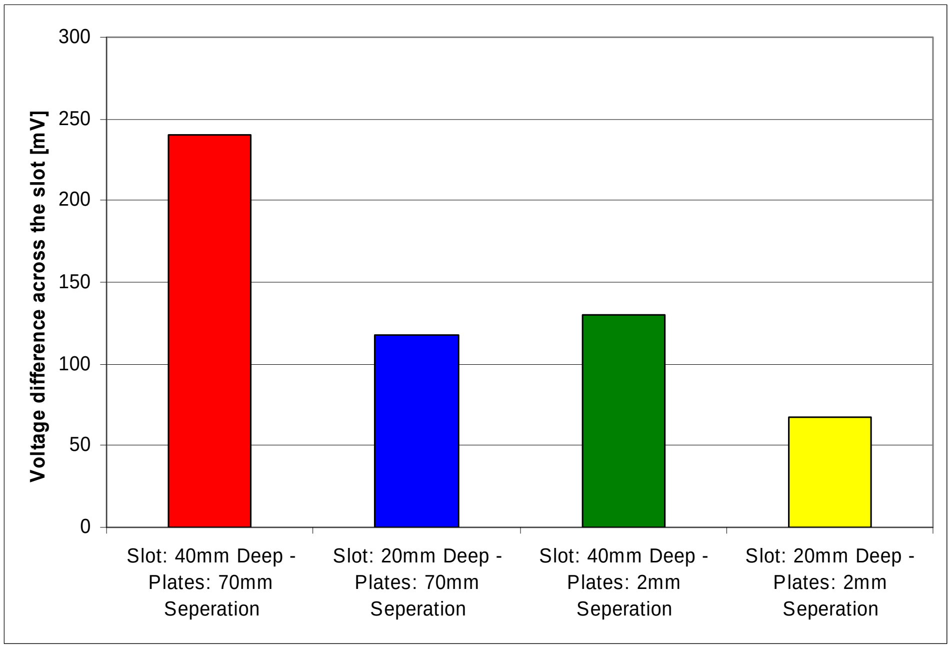


Figure 2.46 - Summary of Results (Peak Waveform 2 Voltage) for the 4 Different Test Configurations

Discussion of Crack Voltage Test Results: Tests reported in 2003 recorded measured currents on components inside aluminum fuel tanks. [[28]] In these tests the waveshapes inside the aluminum tanks were very slow, typically 100 us to peak. The highest measured value was 920 A, for the case of a Component A attachment over a stringer, in which stringer to fuel pipe current (via a bond strap) was measured at 920 A. Other currents were similarly slow, but much lower. It is possible to imagine stringer currents locally of greater than this, but having a similar slow waveshape that would not produce higher voltages at cracks.

If there were to be a 5 kA current of 100 μs peak, this would result in a di/dt of only ~150 A/μs. Extrapolating from our test results on the slots, this would generate a voltage of ~750 mV across a 40 mm crack in a 70 mm wide stringer.

Bearing in mind that >300 V is needed to form a spark or >14 V to maintain an arc once formed, there appears to be no risk of an arc initiated by a voltage spark at a crack.

Other tests have shown that metallic stringers in composite would be subject to much higher currents, with relatively fast rise times, and the so cracks would present a significant hazard. Whether cracked metallic stringers are a potential structural fault in composite skinned tanks is being addressed separately in the Lightning ARC report.

3.0 Conclusions

<u>The tests reported in Section 2.1</u> of this Appendix have shown that no sparks occurred when the local current density where a fatigue crack exists at the edge of a panel was 6.0e4 A/m (60,000 A/m) *(Fig. 2.11)*. This current density at the edge of a panel is available when 6,000 A of lightning current are conducted through a single structural panel that is 6 inches wide *(Fig. 2.7)*

The local current density necessary to produce an arc at the fatigue crack is 1.75e5 (175,000 A/M) when 20 kA was conducted through the 6 inch wide structural element with a fatigue crack that has grown from an edge of this panel *(Fig 2.7).*

From these crack test results it is concluded that the ignition source threshold of fatigue cracks originating at the edge of a fuel tank structural element exposed to fuel vapor is somewhere between 60,000 A/m and 175,000 A/m (this is equivalent to between 6,000 A and 20,000 A through a 6 inch wide structural panel). No currents of this large magnitude have been measured on structural elements within an aluminum fuel tank.

For cracks originating at a hole away from the edge of a structural element, there was only one case of a very faint spark. This spark is believed to correspond to a current density similar to that at the center of the Al plate in *Fig. 2.8b* which is 6.2E5 A/m x (50 kA/200 kA) = 1.5e5 A/m (150,000 A/m) when 50 kA Component A was conducted through the 6 inch wide panel. The current density to cause an arc at a fatigue crack at the edge or at the center of a panel is therefore about the same. With identical total currents in a panel, it is more likely that an arc would appear at an edge crack than at a crack away from an edge because the local current density is higher at an edge than at the center of a panel.

<u>Current Density Analysis reported in Section 2.3</u> of this Appendix showed that, for all-metal tanks, the lightning current densities at the interior surfaces of fuel tank skins and other tank boundaries are much lower than the current densities in the exterior surfaces of these same elements. This is due to the long times required for electric currents to diffuse through the thicknesses of metal conductors. This phenomenon is commonly known as *skin effect.*

Calculated maximum internal current densities of a wing section “Unit Cell” were 2.9e4 A/m (29,000 A/m) *(Figure 2.30)* and 1.5e3 (1,500 A/m) *(Fig. 2.34)* at 100 kA peak. These maximum values appeared at the edge of a rib and the upper surface of the skin splice joint stringer flange, respectively. These current densities exist only in the immediate vicinity (i.e. within one fastener spacing or at a rib directly beneath and fastened to the struck fastener) of a fastener that has been directly struck in Zone 2A. They are significantly lower than the currents that produced arcs at the crack tests of Section 2.1.

Other internal current densities within the tank were much lower, such as several tens of A/m, especially for the much more likely ‘wing tip strike’ cases, where the lightning current is conducted through a wing, between a struck wing tip and an exit location elsewhere on the airplane.

The aluminum wing section whose internal current density computations are reported in this Appendix is typical in size of an average wing box chord and depth, and of the wing tip area of a large transport airplane.

Lightning Tests of Cracked Structure and Fastener Hardware Reported in Section 2.5 of this appendix showed that in most situations 10's of kiloamperes of lightning currents were required to produce ignition sources at failure conditions in broken bolts, collars and shear ties. The data is summarized in the table below. These currents are higher than the currents computed for these elements within the wing

Test Results for Shear Tie Fasteners with Failure Conditions (Table 2.6)

Test Specimen	Tested Failure Condition	Range of Conducted Test Currents that Produced Sparks
Al Panel/Interference Fit	Fractured Bolt	~20 – 40 kA
	Cracked Collar	~15 – 20 kA
	Fully Cracked Shear Tie	~70 – 80 kA
	Crack at Hole Edge in Shear Tie	~85 kA
	Cracks with Fay Surface Bond	100 kA
Al Panel/Clearance Fit	Fractured Bolt	~20 kA
	Cracked Collar	~5kA
CFRP Panel/Interference Fit	Fractured Bolt	~50 - 60 kA
	Fully Racked Shear Tie	~60 – 70 kA
	Crack at Hole Edge in Shear Tie	~25 - 30 kA
CFRP Panel/Clearance Fit	Fractured Bolt	~2 – 10 kA

The large difference between ignition source thresholds determined by test and the computed actual current densities in a typical aluminum tank structure indicates that lightning is not likely to produce ignition sources at fatigue cracks, broken bolts, or collars within a metal fuel tank. The tests of fastener installations in CFRP panels indicate that lower currents may produce ignition sources. This is because a higher percentage of currents entering external fasteners flow through these fasteners to the interior structural elements.