

NASA Manned Launch Vehicle Lightning Protection Development

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ABSTRACT

Historically, the National Aeronautics and Space Administration (NASA) relied heavily on lightning avoidance to protect launch vehicles and crew from lightning effects. As NASA transitions from the Space Shuttle to the new Constellation family of launch vehicles and spacecraft, NASA engineers are imposing design and construction standards on the spacecraft and launch vehicles to withstand both the direct and indirect effects of lightning.

A review of current Space Shuttle lightning constraints and protection methodology will be presented, as well as a historical review of Space Shuttle lightning requirements and design. The Space Shuttle lightning requirements document, *NSTS 07636, Lightning Protection, Test and Analysis Requirements*, (originally published as document number *JSC 07636, Lightning Protection Criteria Document*) was developed in response to the Apollo 12 lightning event and other experiences with NASA and the Department of Defense launch vehicles.[1] This document defined the lightning environment, vehicle protection requirements, and design guidelines for meeting the requirements.[2]

The criteria developed in JSC 07636 were a precursor to the Society of Automotive Engineers (SAE) lightning standards. These SAE standards, along with Radio Technical Commission for Aeronautics (RTCA) DO-160, *Environmental Conditions and Test Procedures for Airborne Equipment*, are the basis for the current Constellation lightning design requirements.[3] The development and derivation of these requirements will be presented.

As budget and schedule constraints hampered lightning protection design and verification efforts, the Space Shuttle elements waived the design requirements [2] and relied on lightning avoidance in the form of launch commit criteria (LCC) constraints [4] and a catenary wire system for lightning protection at the launch pads. A better

understanding of the lightning environment has highlighted the vulnerability of the protection schemes and associated risk to the vehicle, which has resulted in lost launch opportunities and increased expenditures in manpower to assess Space Shuttle vehicle health and safety after lightning events at the launch pad.

Because of high-percentage launch availability and long-term on-pad requirements, LCC constraints are no longer considered feasible.[5] The Constellation vehicles must be designed to withstand direct and indirect effects of lightning. A review of the vehicle design and potential concerns will be presented as well as the new catenary lightning protection system for the launch pad. This system is required to protect the Constellation vehicles during launch processing when vehicle lightning effects protection might be compromised by such items as umbilical connections and open access hatches.

INTRODUCTION

On 14 November, 1969, at 11:22 am, Eastern Standard Time, the Apollo 12 mission launched from Launch Complex 39A at the Kennedy Space Center (KSC), Florida. At 36.5 seconds and again at 52 seconds into the flight, triggered lightning struck the Apollo Command and Service Module (CSM).[6] The lightning event disconnected all three CSM fuel cells from the main power bus. A decrease in main bus voltage caused the primary signal condition equipment (SCE) to quit operating. The crew was confronted with numerous caution and warning indications and fuel cell disconnect flags. At 60 seconds into the flight, flight controllers regained flight telemetry data.[7]

In order to gain some insight into the condition of the spacecraft, flight controller John Aaron, using experience with anomalous spacecraft telemetry gained during spacecraft testing at KSC, requested the crew switch the SCE to auxiliary.[8] This allowed flight controllers to see that fuel cells were not connected to the main power bus. The crew reset

circuit breakers in the spacecraft, reconnecting the fuel cells to the main bus. Throughout the launch, the Saturn launch vehicle continued to operate normally. [7]

Prior to this incident, only the lightning effects on the spacecraft for the period prior to flight were considered. The possibility of the spacecraft and launch vehicle being struck by lightning after lift-off was not a launch consideration unless natural lightning activity was present in the launch complex area. [6]

The corrective actions from the Apollo 12 event analysis included launch restrictions that would minimize the risk of triggered lightning. [6] The launch commit criteria (LCC) recommended in the Apollo 12 analysis resemble the current LCC's used by the Space Shuttle Program. [9]

REVIEW OF LAUNCH COMMIT CRITERIA

NSTS 16007, "Shuttle Launch Commit Criteria and Background Document," contains the Space Shuttle LCC's. The purpose of the LCC's is to document pre-planned decisions with a goal of reducing the amount of real-time rationalization needed to take place during off-nominal launch conditions. This is done to support Shuttle mission objectives while maintaining optimum vehicle and crew safety along with maximizing launch probability [4]

Due to the Shuttle's deficiencies in lightning protection, LCC's were developed to protect the Shuttle from the direct and indirect effects of lightning through avoidance of the phenomenon. These launch restrictions are contained in section 4 of the NSTS 16007 document and consist of eight rules to avoid natural and triggered lightning. The eight rules with a short description are as follows:

- 1) Lightning – The lightning rule prevents the Shuttle from launching within 30 minutes of the most recent natural lightning strike near the launch site.
- 2) Cumulus Clouds – The Cumulus Clouds rule prevents the Shuttle from launching if the projected flight path is through or near a cumulus cloud, depending on the size and temperature of the cloud.
- 3) Anvil Clouds – The Anvil Clouds rule prevents the Shuttle from launching through or near anvil clouds based on specialized weather models, time duration since the last electrical discharge from the cloud, and the size and temperature of the cloud.
- 4) Debris Clouds – The Debris Clouds rule prevents the Shuttle from launching through

or near debris clouds depending on the distance of the cloud from a working field mill, the field strengths reported by the field mill, and the time duration since the last electrical discharge from the cloud.

- 5) Disturbed Weather – The Disturbed Weather rule prevents the Shuttle from launching through or near non-transparent clouds that are part of a weather disturbance, depending on the amount of precipitation contained in the cloud and the cloud's radar image.
- 6) Thick Cloud Layers – The Thick Cloud Layers rule prevents the Shuttle from launching through or near thick cloud layers depending on the temperature and precipitation content of the cloud layers.
- 7) Smoke Plumes – The Smoke Plumes rule prevents the Shuttle from launching through a cumulus cloud that has developed from a smoke plume if the cloud is still attached to the plume or has recently separated from the plume.
- 8) Surface Electric Fields – The Surface Electric Fields rule prevents the Shuttle from launching within 15 minutes of a nearby field mill measurement that violates the absolute value magnitude criteria. This is dependent on the distance of the field mill from the flight path of the vehicle and the distance of nontransparent clouds from the flight path of the vehicle.

While the lightning LCC's severely impact the Shuttle's launch probability,[9] they are necessary to ensure vehicle and crew safety since a direct lightning attachment would likely cause catastrophic damage to the vehicle. Since the inception of the lightning LCCs at the dawn of the Shuttle Program, no triggered lightning events have occurred during the launch phase of the Shuttle. [10]

LAUNCH COMPLEX LIGHTNING PROTECTION AND DETECTION

In addition to the LCC's that were developed to avoid lightning during the Shuttle's launch phase, there are also features of Launch Complex 39 (LC-39) to mitigate the effects of lightning to the vehicle during ground operations. LC-39 has structures designed to protect the vehicle from the direct effects of lightning and instrumentation designed to qualify the risk to the vehicle due to the indirect effects of lightning.

The main structures that mitigate a direct lightning attachment to the Shuttle are the Fixed Service

Structure (FSS), the Rotating Service Structure (RSS), and the Catenary Wire System (CWS).

The FSS is the main structure that services the vehicle during pre-launch operations. Although lightning protection is not the primary purpose, at approximately 200 ft tall, this structure provides significant shielding to the Shuttle from a direct lightning attachment.

Attached to the top of the FSS is a 70 ft fiberglass mast which supports the CWS. This System is the primary lightning protection system at the Shuttle launch complex. The CWS is comprised of wire that run north-south from the top of the fiberglass mast to ground anchor points located 1000 ft away. It is used to direct lightning currents away from the vehicle in the event that the CWS or the FSS is struck by lightning.[10]

Also attached to the FSS is the RSS. The RSS is moved in place to cover the Shuttle when it is on the launch pad, and is used primarily for servicing the vehicle and for payload operations. The RSS, like the FSS, provides significant shielding to the vehicle while on the launch pad.

These structures, however, do not provide the Shuttle with 100% protection from the direct and indirect effects of lightning while on the launch pad. The CWS design employed a "Cone of Protection" large enough to encompass the entire volume of the vehicle; a predominant theory in 1970's lightning protection. Today's Rolling Ball theory suggests that the Shuttle is prone to being struck by lightning while on the pad once every 100 years.[10]

The main system that collects data used by engineers to qualify the risk to the vehicle from the indirect effects of lightning while on the pad is the Ground Lightning Monitoring System (GLMS). The GLMS consists of the Catenary Wire Lightning Instrumentation System (CWLIS), the Lightning Induced Voltage Instrumentation System (LIVIS), Naval Research Laboratory (NRL) Magnetic Field Sensors, Orbiter Utility Outlet Panel Measurements, current and voltage measurements within the Mobile Launch Platform (MLP), and a magnetic field sensor located on the liquid oxygen tail servicing mast.[11]

The CWLIS monitors the catenary wires attached to the FSS by passing them through current probes which transmit data to remote digitizers. The collected lightning event data conveys peak current amplitude, wave shape, and time stamping.

The LIVIS consists of eight instrumentation channels which monitor voltage and current transients on the

Shuttle and transmit data to digitizers located in the MLP. The collected data includes the wave shape, time stamping, and peak amplitude of the transient. Unlike the CWLIS, which continuously collects data, LIVIS is turned on just before the Shuttle departs the Vehicle Assembly Building (VAB) for the launch pad.

The NRL sensors consist of a three-axis search coil, an optics head, and an avionics box. The optic head converts the electrical signals from the search coil into a differential fiber-optic signal which is transmitted to the avionics box located in the pad terminal connection room. There are two coils installed in the Space Shuttle Orbiter at the pad, one on the aft flight deck and one on the mid-deck. An additional coil is installed on the FSS at the 195 ft level and one is installed in the RSS in the payload change-out room (PCR). All of these sensors are removed during a planned hold at 11 minutes remaining in the countdown.[11]

The Shuttle lightning detection systems are only able to provide qualitative data. This is due to two primary factors: 1) not all Shuttle avionics have been tested to determine their susceptibilities to lightning-induced transients and 2) the transfer function that correlates the data reported by the lightning detection systems to avionics susceptibility levels is undefined.

Though imperfect, the lightning detection systems and lightning protection systems of the Shuttle launch complex have succeeded in minimizing the effects of lightning to the vehicle. They also provide useful data to qualify the risk to the vehicle due to the indirect effects of a lightning event.[10]

DEVELOPMENT OF NSTS 07636

Early in the Space Shuttle development, NASA convened a panel of lightning phenomena and test specialist to develop standard lightning environment and design requirements for the Space Shuttle Program. This standard, NSTS 07636, released in 1973, and the activities associated with its development significantly influenced later SAE activities.

NSTS 07636 defined a lightning environment that differs from current SAE standards, but the peak amplitude, total charge transfer, and other critical aspects are similar.[1]

The early version of NSTS 07636 placed emphasis on design guidelines and less emphasis on test methods. This document, and its companion, JSC 20007, Shuttle Lightning Verification Document, emphasized protection against lightning indirect

effects and required the development of transient control levels (TCLs) and equipment transient design levels (ETDLs). This TCL/ETDL development is widely used in aircraft and avionics equipment design.[1]

SPACE SHUTTLE LIGHTNING WAIVERS

The comprehensive lightning protection program defined in NSTS 07636 which included Shuttle lightning design criteria and requirements has since been reduced to a mere historical document due to the large number of waivers.

In some cases, the Shuttle Program granted waivers because the requirements were not compatible with the vehicle's architecture. For example, the thermal protection system (TPS) on the external tank (ET) is comprised of insulating foam which must remain intact during flight. This foam is sprayed onto the exterior of the ET. It cannot be certified for lightning because a lightning direct attachment to the ET could cause foam loss. If the insulation were located on the interior of the tank, then this issue could have been avoided.

In other cases, waivers were granted when minimal additional engineering rigor would have met the lightning requirements. For example, the Space Shuttle Orbiter is exempt from the lightning indirect effects requirements. In some cases, the Orbiter structure is the avionics current return path. Alternately, the Reusable Solid Rocket Booster (RSRB) current returns are dedicated cables isolated from structure. From an architecture standpoint, this means the RSRB is much more capable of meeting the lightning indirect effects requirements contained in NSTS 07636. Unfortunately, a waiver was granted when the Program chose not to perform lightning qualification testing.

The extent of the waivers granted for NSTS 07636 lightning requirements was so widespread that upgrades to the few non-compliant subsystems could not meet the direct and indirect effects of lightning requirements. This turned the Shuttle Program's view of lightning from that of designing for immunity to avoidance.

DEVELOPMENT OF CONSTELLATION LIGHTNING REQUIREMENTS

During the 1970s, NASA participated with the United States (US) Department of Transportation Federal Aviation Administration (FAA) in the development of requirements for lightning protection for US aircraft.

The NASA Reference Publication 1008 was released in 1977,[13] and a revised version of this document was subsequently adopted by the FAA as DOT/FAA/CT-89/22, for use in developing lightning protection in the US aircraft industry.[25] The SAE carried this evolution further, first in the initial iteration of lightning requirements released in SAE AE4L-78 (June 1978) [26] and later in the Aerospace Recommended Practice (ARP) 54xx series of documents which originated, in varying degrees, from concepts developed in previous Space Shuttle lightning requirements.

Today, use of the lightning requirements documented in the SAE ARP series is referenced by the FAA for US commercial aircraft design, and in MIL-STD-464A for US military aircraft design.[16] US Federal regulation CFR 25.1309 requires that failures of systems performing critical functions (i.e., required for continued safe flight and landing) are shown to be "extremely improbable",[14] defined in the FAA System Safety Handbook as a probability of occurring less than 1×10^{-9} times per operational flight hour.[15]

The Constellation Program is a multi-year, multi-mission "system of systems" that calls for a robust, high-reliability infrastructure geared to safety and mission success as the primary design consideration. Accordingly, Constellation requirements call for a system capable of meeting operational mission requirements in 95% of all weather conditions, including operating successfully during and following the direct and indirect effects of lightning.[5] In order to establish such an operational posture against the lightning natural environment, the Constellation Program has likewise looked to the same standards as the FAA and the US military organizations, including those documents maintained by the FAA, the SAE, and the RTCA.

Constellation lightning requirements are documented in the NASA Design Specification for Natural Environments, and define the natural lightning environment as that given in SAE ARP ARP5412A, "Aircraft Lightning Environment and Related Test Waveforms." [17] Lightning zoning of Constellation vehicles is to be carried out in accordance with the definitions and provisions found in SAE ARP5414A, "Aircraft Lightning Zoning." [19]

The Constellation Program requires that SAE ARP5577, "Aircraft Lightning Direct Effects Certification," should be used as a guide in developing systems to meet lightning direct effects requirements,[24] with failure condition classifications (e.g., catastrophic, hazardous/severe-

major, major) defined in SAE ARP5413, "Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning" (obsolete, replaced by FAA AC 20-136A, December 2006).[18, 23]

Constellation also looks to SAE ARP5413 as a guide to attaining compliance with the lightning indirect effects protection and verification requirements.[18] SAE ARP5416, "Aircraft Lightning Test Methods," is referenced to provide methods for indirect effects verification testing of Constellation systems,[22] and RTCA/DO-160E, "Environmental Conditions and Test Procedures for Airborne Equipment," is given as a reference to provide methods for lightning-induced transient testing of vehicle avionics equipment.[20]

Lightning indirect effects transient levels in Constellation systems are to be determined by test and analysis using methods found in SAE ARP5415A, "User's Manual for Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning,"[21] and SAE ARP5416. Analysis may be performed in those cases where testing is impractical.[3, 22]

ARES I LIGHTNING PROTECTION DESIGN

The Ares I Crew Launch Vehicle (Ares I) will be designed to withstand the direct and indirect effects of a lightning strike to the vehicle itself, or to nearby objects, before or during launch and ascent operations. The various elements of the vehicle will also be similarly protected during transportation and storage. Ares I lightning protection will consider the lightning natural environment's interaction with the vehicle, the most likely lightning strike current entrance and exit points, and the resultant electromagnetic environment at various locations on and within the vehicle, to minimize lightning effects on the vehicle structure and to flight equipment.

At the launch pad, the natural lightning environment's direct effects will be mitigated by a surrounding structure of elevated catenary wires and supporting towers to provide a means of intercepting a large majority of higher-amplitude lightning strikes. In pre-launch operational mission modes, however, the presence of surrounding structure, connected umbilical cables, and open access hatches and doors, will compromise and degrade the vehicle's own lightning protection measures that are designed to address indirect lightning effects sustained during flight. An on-board transient monitoring will system capture and display the level of transients induced in the vehicle's avionics by a nearby lightning event, and provide a post-event basis for decisions to re-

test or replace on-board equipment that may have been damaged.

The physical effects of direct lightning arc attachment may impact the Ares I Upper Stage, First Stage, the Upper Stage Engine, and associated individual structural vehicle elements (fairings, ramps, struts, straps, etc.).

Lightning indirect effects protection designs will protect Ares I avionics subsystems and components against catastrophic, hazardous/severe-major, or major failures, as described in SAE ARP5413,[18] when subjected to direct lightning attachment environments as described in SAE ARP5412A.[17]

Elements of the Ares I vehicle will be analyzed to determine the lightning attachment zones using: (1) the attachment zone definitions, (2) the zone location process, and (3) the initial leader attachment location methods, as found in SAE ARP5414A.[19] The Ares I vehicle's outer skin will be fabricated of sufficient physical thickness and electrical conductivity to safely withstand without damage the blasting and heating effects of a lightning strike at and along paths between the strike attachment entry and exit points. Low-impedance electrical bonding at all structural joints of the conductive outer skin will provide an adequate path to carry the lightning strike current predominantly on the outside of the vehicle. Sensitive avionics equipment, propulsion subsystems, and pyrotechnic devices will be protected by being enclosed within the vehicle's conductive outer skin, to the extent possible consistent with Ares I design constraints. Apertures in the vehicle's outer skin, of sufficient size to allow the passage of electromagnetic fields into the vehicle interior, will be minimized.[12]

Protection against indirect effects will be accomplished primarily through shielding of electrical components and interconnecting wiring/cables to reduce the coupling of lightning currents or induced electromagnetic fields into electrical circuitry. Electrical wiring will be routed closely adjacent to vehicle structural components inside the protective vehicle skin wherever possible. If any cable must be routed outside the primary vehicle outer skin, it will be located inside a protective cabling tunnel with continuous, electrically bonded, conductive covers that shield the cabling conductors from lightning effects. In addition, any wiring or cable routed outside the vehicle in this manner may be enclosed by an overall shield that is grounded with a 360° shield termination to the vehicle structure at every entrance or exit point along the vehicle skin, to provide additional indirect effects protection.[12]

The environment induced by lightning in the Ares I vehicle is defined to be the Actual Transient Level (ATL) per SAE ARP5413.[18] An additional Equipment Transient Design Level (ETDL) level will be defined for Ares I avionics. The ETDL is a transient level elevated by a 6 dB performance margin above the previously-determined ATL. ETDLs will be defined using the standardized induced transient waveform parameters shown in SAE ARP-5412A.[17] ETDLs established for Ares I avionics equipment items, will be stated in equipment specifications and will constitute qualification test levels for these items. The Ares I equipment must continue to function normally, meeting all performance requirements, during and following exposure to the ETDL transient.

Ares I flight vehicle lightning protection requirements verification will be accomplished by qualification tests, analyses based on developmental test data, assessment of previously verified designs, or a combination of these methods. Verification will demonstrate that all lightning protection design requirements have been met for Ares I systems, subsystems, and/or components whose failure is designated as catastrophic, hazardous/severe-major, or major. A lightning protection verification plan (LPVP) will identify verification criteria that will be used to demonstrate that the Ares I systems, subsystems, and components have satisfied lightning protection requirements. Verification criteria will include discussion of design margins and pass/fail rationale. The LPVP will include information documented in a Lightning Protection Survey and will also include the verification test/analysis data and methods to be employed, as well as success criteria of each subsystem/component test.[12] Finally, a verification test report as described in SAE-ARP-5416 will be developed to show the results of analyses and tests used to verify the adequacy of lightning protection designs and to show compliance with requirements for protection against direct and indirect lightning effects.[22]

LIGHTNING TRANSIENT MONITORING

Lightning protection measures are designed to be most effective during flight mission modes and may be compromised by certain activities and physical attachments to the flight vehicle during ground operations.

Ground operations support facilities should be able to determine the levels of transient activity induced in vehicle avionics wiring and cables, due to a direct or nearby lightning event. Such a monitoring function must have a high-bandwidth capability and necessarily be of light weight and low physical

volume to minimize additional lift-off impacts to the flight vehicle. The monitoring system must be able to function during times when the vehicle is not powered, in order to capture transient activity, for example, during cross-country transportation or other similar ground operations when the Constellation assets are not connected at the launch pad facilities.

Even nearby lightning events can cause impacts to the flight vehicle or spacecraft when these assets are not in a flight operations mode. A nearby strike is considered to be any event within 0.5 nautical miles that is not judged to be a direct strike to the vehicle. At the launch pad, this 0.5 nmi radius includes launch pad support structures and towers. The risk of significant induced effects in the flight vehicle is high, if one of these elements (even one of the protective structures themselves) sustains a direct lightning strike attachment.

Without a method of determining a transient level in the vehicle avionics, and comparing this to previous qualification test levels that verified the vehicle's avionics as ready for flight, any lightning event (direct or nearby) may raise suspicions that the vehicle remains safe to fly. This posture may result in unneeded avionics re-test or remove-and-replace operations because they may require that the entire flight vehicle be moved back into the VAB, a costly and time-consuming process. Past experience has shown that a retest of flight vehicle avionics can take many hours, and a roll-back to vehicle assembly facilities, if needed for de-stack/retest/re-stack operations, can require days of additional time and associated launch delays. Clearly, the use of an on-board transient monitoring system to provide data that leads to an unambiguous understanding of the vehicle's avionics health will result in improved and cost-effective pre-launch operations and a more robust Constellation mission operations scenario.

In order to protect against loss of mission or loss of life, an effective lightning protection program must be implemented. Because the Constellation Program has imposed high-percentage launch availability and long-term on-pad requirements, the lightning avoidance approach employed by the Space Shuttle Program is not feasible. A Constellation Program lightning program, built on Space Shuttle Program lessons learned and adherence to industry standards, can achieve a robust vehicle design that is immune to the direct and indirect effects of lightning.

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