

# Lightning Protection for the Orion Space Vehicle

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**The Orion space vehicle is designed to requirements for both direct attachment and indirect effects of lightning. Both sets of requirements are based on a full threat 200kA strike, in accordance with constraints and guidelines contained in SAE ARP documents applicable to both commercial and military aircraft and space vehicles. This paper describes the requirements as levied against the vehicle, as well as the means whereby the design shows full compliance.**

## I. Introduction

The Orion space vehicle is designed to requirements for both direct attachment and indirect effects of lightning. Both sets of requirements are based on a full threat 200kA strike in accordance with constraints and guidelines contained in SAE ARP documents applicable to both commercial and military aircraft and space vehicles. These requirements were levied upon the vehicle to provide for full protection during ground processing, pad stay, ascent, descent, and recovery. Additional benefit from this approach results in a very robust electromagnetic compatibility design, providing assurance the vehicle will perform its intended missions when subjected to environmental threats from external continuous wave or impulsive radio frequency sources, triboelectricification during ascent, or electrostatic discharge threats associated with spacecraft charging.

The goal of the design for direct attachment was to ensure the vehicle would survive such an event without loss of integrity, protecting the crew from harm and enabling continuance of flight to orbit or descent to safe landing under abort or normal descent operations. The goal of the design for indirect effects was to ensure continued and safe operation of all systems, with emphasis on precluding damage to critical systems. Critical system upset during or resulting from a strike event, with recovery both with and without operator intervention following the event was allowed.

Basic requirements were taken from the SAE ARP 54XX series of lightning standards and then tailored as appropriate to the vehicle. The vehicle was zoned, and with this accomplished, the various levels expected to appear on internal surfaces and cables, and ultimately pins of electrical and avionic equipment, were determined through analysis using detailed knowledge of the vehicle structural design including the composite materials employed, the manner of electrical bonding of both external and internal components, and the shielding characteristics of the various structural materials, cable shields, and electrical equipment enclosures.

Testing using a low level swept continuous wave injection to the vehicle will be performed during certification of the vehicle to demonstrate the design satisfies all indirect effects requirements. Cables and pins will be selected for instrumentation during the testing to monitor the cable responses to the presence of the swept signals, allowing for extrapolation of the results to a full threat event, regardless of wave-shape. Data from this testing will also be available for future analysis, should minor design changes occur, allowing for determination of compliance without the need for additional testing. Testing of representative coupons is planned to demonstrate that structural elements satisfy the direct effects requirements. Such testing would need to be re-performed if structural elements are altered, or different materials are employed in the construction of the vehicle.

A lightning monitoring system will be installed temporarily in the Crew Module (CM) during roll-out and pad stay, until immediately prior to hatch closure. The monitoring system will provide near real-time data on the strength of the magnetic field inside the CM and any transients on the primary power bus induced by lightning activity. Data from this system will facilitate rapid assessment of the impact to the vehicle's systems and enable engineering to quickly report back to the Mission Management Team (MMT) with vehicle status.

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Pad 39B from which Orion will launch was stripped of the old Space Shuttle Program fixed and rotating service structures, removing the old single wire catenary system. A new catenary system consisting of three 594 foot tall steel and fiberglass towers creates a net over the pad, and is constructed such that the vehicle will fly through a pentagram-shaped opening. The new system provides a very good protection level from direct attachment for the vehicle on the pad.

Finally, the Lightning Launch Commit Criteria (LLCC) that were developed after the loss of the AC-67 launch in March of 1987 and that have been refined and used on the eastern and western ranges since remain in place and will serve to protect the vehicle during launch.

## **II. Requirements and Certification**

The Orion space vehicle shall meet its operational performance requirements in the event of a lightning direct attachment, nearby lightning events, and other atmospheric electrical environments, as described in Multi-Purpose Crew Vehicle 70080 (MPCV 70080), the Cross Program Electromagnetic Environmental Effects (E3) Requirements document<sup>1</sup>. These requirements shall apply to the launch pad roll out, launch pad, launch, reentry, abort, landing, and recovery and everywhere else the Orion is exposed to lightning including transport. The lightning environments for different phases of operation are contained in Space Launch System Specification 159 (SLS-SPEC-159), the Cross Program Specification for Natural Environments<sup>2</sup>. SLS-SPEC-159 specifies the range of natural environments that must be accounted for by the Exploration Systems Development (ESD) Enterprise, consisting of the Orion space vehicle, the Space Launch System Program (SLSP) launch vehicle, and Ground Systems Development and Operations (GSDO).

SLS-SPEC-159 references, and the Orion space vehicle lightning requirements are tailored from, the Society of Automotive Engineers (SAE) series of Aerospace Recommended Practices (ARPs) that provide information concerning lightning interactions with aircraft, design and certification guidance for direct and indirect effects, and test methods. These documents are SAE ARP5412B, Aircraft Lightning Environment and Related Test Waveforms<sup>3</sup>, SAE ARP5414B, Aircraft Lightning Zoning<sup>4</sup>, SAE ARP5415B, User's Manual for Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning<sup>5</sup>, SAE ARP5416A, Aircraft Lightning Test Methods<sup>6</sup>, and SAE ARP5577, Aircraft Lightning Direct Effects Certification<sup>7</sup>. FAA AC 20-136B, Aircraft Electrical and Electronic System Lightning Protection<sup>8</sup>, is also applied as a source of requirements, design methodologies, and expectations for testing results.

The lightning protection requirements in MPCV 70080 are designed to (1) enable the crew to land safely following a lightning event during ascent or descent, (2) protect the Launch Abort System (LAS) performance such that it shall not be impaired after a lightning strike even with minimal damage to the strike areas, and (3) ensure that minimum essential Orion systems shall survive in order to ensure #1 & 2. Examples of specific requirements include LAS functionality after a lightning strike under the aerodynamic, thermal, and mechanical loads of Boost and Launch Abort to 300,000', and Composite Graphite Epoxy (C/Ep) panels shall survive direct attachment lightning.

Lightning protection design and certification programs that achieve a compliant protection design with minimum weight and cost impact result when the lightning protection efforts proceed in a logical, stepwise manner. With the fundamental lightning requirements in place, the Orion space vehicle design was enabled to employ such a logical and stepwise approach.

The basic steps can be expressed as:

- 1) Locate lightning strike zones on the system
- 2) Establish the lightning environment
- 3) Establish internal lightning threats
- 4) Design lightning protection measures
- 5) Verify protection adequacy

### **A. Vehicle Zoning**

Zoning definitions are for in-flight aircraft which experience lightning attachment moving along the surface because the aircraft is moving. For the Orion space vehicle, these definitions will be tailored to include mission phases. The SAE definitions are as follows with comments relevant to the Orion space vehicle:

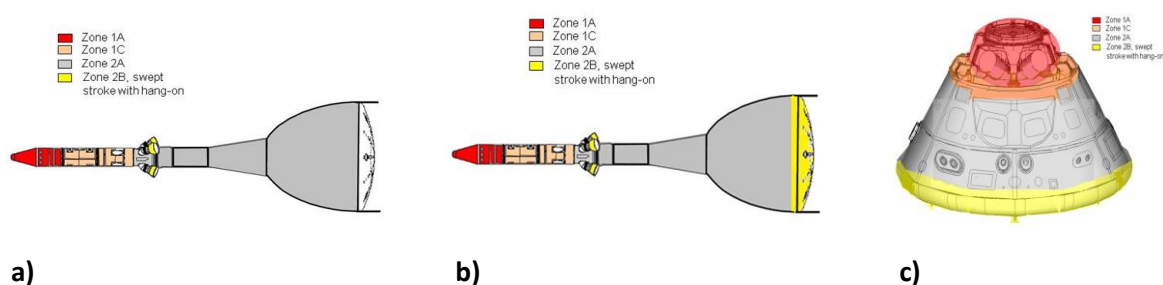
- 1) Zone 1A-First Return Stroke Return Zone: This zone is where a first strike attachment is likely but not expected to hang onto that spot. This applies to in-flight.

- 2) Zone 1B-First Return Stroke Zone with Long Hang On: This zone is where a first strike attachment is likely and is likely to 'hang on' to that spot. This applies to stationary on the launch pad and in-flight. On the ground, this zone is most likely the top of the LAS and the bottom of the SLS. In-flight it is at the tail of the SLS.
- 3) Zone 1C-Transition Zone for First Return Stroke: This zone is where a first return stroke of reduced amplitude attaches but not likely to 'hang on'. This applies to in-flight.
- 4) Zone 2A-Swept Stroke Zone: This zone is all areas where the return stroke is likely to sweep by with no 'hang on'. This applies to in-flight.
- 5) Zone 3-Transition Zone: This zone has little likelihood of experiencing a direct attachment but will carry substantial current between the other zones. This applies to ground and in-flight. On the ground, this applies to everything between the top of the LAS and the bottom of the SLS.

Analysis performed to date for the Orion space vehicle has employed three methods for determining attachment points:

- 1) ARP 5414 recipe - Guidance from historical experience with vehicle features
- 2) 2D rolling sphere analysis - Vehicle geometry and strike distance of final lightning step (as a function of 1st return stroke current)
- 3) 3D Electric field modeling - Electric field enhancement values at surface of vehicle for an approaching lightning channel

To define the extents of Zones 1 and 2 all Orion space vehicle flight profiles (speed vs. altitude) for all configurations that may occur below the lightning ceiling of ~40,000 ft were identified and appropriately considered. The resulting Orion space vehicle zone definitions are shown in the Fig. 1 for a) a normal launch with the Orion space vehicle attached to the SLS, b) an aborted launch with detachment of the Orion from the SLS, and c) an Orion space vehicle in its descent configuration.



**Figure 1. Lightning zones of the Orion space vehicle corresponding to normal launch, abort, and descent phases of flight.**

## B. External Lightning Environment

Historical climatological lightning data provides an average over an extended time period, and is indicative of general trends in activity. Only accurate, local weather forecasting can provide data that can be used to make operational decisions with respect to the potential for lightning activity on a given day at a given time. According to the KSC Weather Office, with all lightning constraints in place there is between a  $10^{-3}$  and  $10^{-4}$  chance of a lightning strike during ascent. Risk calculations for lightning are not perfect, nor is it reasonable to expect perfection. Such calculations are based on the best estimates available for the impacts of climatology, the viability of weather prediction, the efficacy of ground movement controls, and the effects of hardware and facility design and protection measures. Lightning is capricious and does not follow rules or risk calculation predictions.

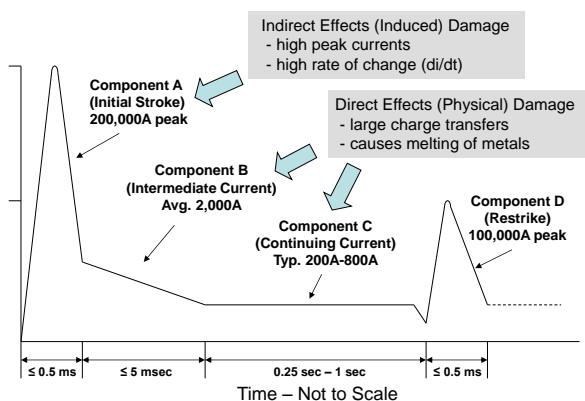
Lightning climatology at Kennedy Space Center (KSC) in Florida has been thoroughly researched and documented over many years. Such studies have shown that lightning behavior tends to follow a pattern. Fig. 2 illustrates a ten-year record of lightning strikes within 5 nmi of pads 39A and 39B; the data are shown in 6 hour blocks to match the length of roll-out time for the Space Shuttle.

Lightning activity is inevitable; having a design standard, and a means of quantifying effects on hardware prior to launch, is necessary for success. SLS-SPEC-159 details lightning environments as a function of operational phase:

- 1) Transportation Environments to the Launch Site (KSC)
- 2) Lightning During On-pad Operations
- 3) Natural and Triggered Lightning During Launch and Ascent
- 4) Lightning During Normal Landing Operations
- 5) Lightning During Abort Landing Operations
- 6) Lightning During Post-Flight and Recovery Operations in the Normal Landing Area

These environments reflect the climatology at KSC, and establish the source of electromagnetic effects on flight hardware caused by nearby or direct attachment lightning strikes during all phases of flight, including ground processing and On-Pad operations. These environments do not account for effects of positive stroke lightning.

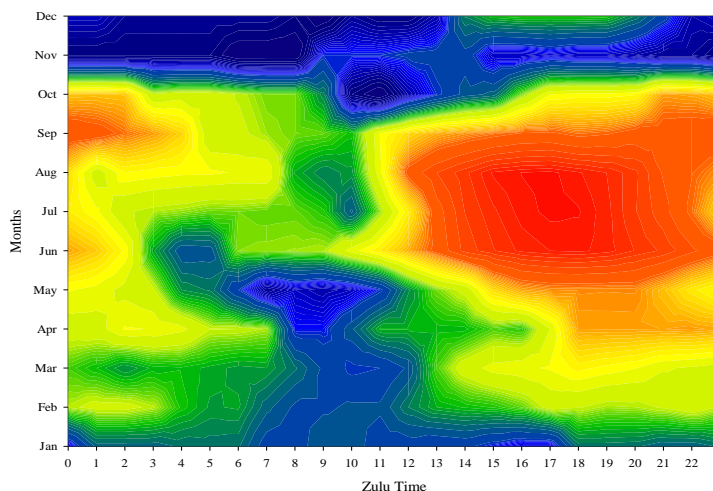
For any given lightning strike, research has found there may be several different components involved. These components are shown in Fig. 3. Each of these components has different effects on space vehicles, depending on a number of factors, including how far away from the vehicle was the strike and any associated current flows, the amplitude of the strike, the rise and fall time of the electromagnetic pulse transients associated with the strike, the immunity to damage presented by the exterior structure and any externally mounted components, the transfer function/relationship between the internal portions of the vehicle and the external electromagnetic effects, and finally the immunity to damage presented by the design of the internal structure and the electrical/electronic systems contained therein.



**Figure 3. Diagrammatic representation of a lightning strike.**

associated with such a strike is very high. Indirect effects damages are caused by Component A, “Initial Stroke” currents, Component D “Restrike” currents, and by Component H, “Transition Zone Restrike” currents, not shown in Fig. 3. Component H, also not shown in Fig. 3, is part of the multi-burst waveform set, used for test and analysis.

Recorded Number of Lightning Strikes w/in 5 nmi of KSC Midway Between VAB and Pad 39 Complex as a Function of Time of Year & Day (Source: 1997-2007 NLDN 6 Hour Data Block)



**Figure 2. Diagram of recorded lightning strikes w/in 5 nmi of KSC midway between the VAB and launch complex 39.**

It is very important to realize and understand what is meant by a nearby strike versus a direct strike. A direct strike is one that physically contacts the vehicle at any time in its processing or pre-launch activities. A strike is also considered as direct if it physically contacts the mobile launcher platform while the vehicle is mounted to it. Direct effects damages are caused by Component B, “Intermediate Current” and Component C, “Continuing Current”.

Direct effects are characterized by melting and vaporization of materials and substructures, injection of large surface and structural currents, burning, blasting, scorching, and the generation of large touch and step voltages.

A nearby strike is any lightning strike within approximately 0.5 nautical miles of the vehicle that doesn’t qualify as a direct strike. That means a strike to the catenary system is considered to be a nearby strike. The threat to the vehicle of the indirect effects

Indirect effects are characterized by damage resulting from the presence of transient voltages and currents coupled to electrical and electronic systems through apertures, diffusion through outer mold line materials, or via cabling and wiring to external antennas, lights or other external features. Very high peak currents with fast current risetime/falltime will increase induced voltages and currents.

Note that there is a modified Component C known as C\*, not shown in Fig. 3. Component C and C\* can be the most damaging in terms of energy deposited and temperature rise. From SAE ARP5412A, the following guidance is quoted:

- 1) Current Component C – Continuing Current: For direct effects testing, the Component C should have a current amplitude between 200A and 800A, a time duration between 0.25 and 1.0s, and a charge transfer of 200 coulombs ( $\pm 20\%$ ). For analysis purposes, a square waveform of 400A for a period of 0.5s should be used.
- 2) Current Component C\* - Modified Component C: This component represents the portion of Component C which flows into an attachment point in Zone 1A or 2A if the dwell time at that point exceeds 5 ms. Component C\* is a current averaging not less than 400A for a period equal to the dwell time minus the 5 ms duration of the Component B.

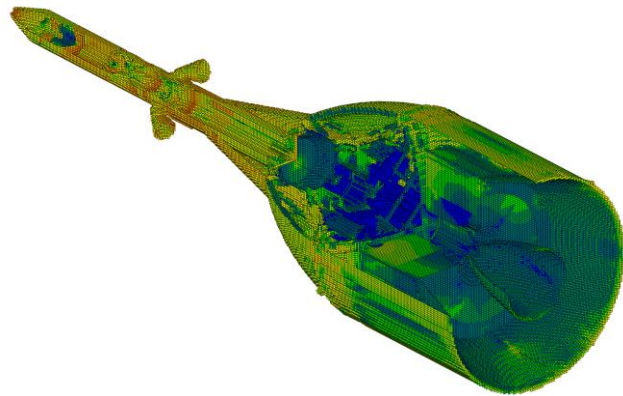
The combination of Components A or D, B, and C\*, represents the dwell time of a given lightning strike, which may range from 1 to 50 ms. Unpainted surfaces may have dwell times of 1 to 5 ms. Surfaces with ‘conventional’ primers and paints may have dwell times of 20 ms. Surfaces covered with thick or high dielectric coatings (like the Orion space vehicle cork thermal protection) will have dwell times of 20 to 50 ms.

With the zones of the vehicle identified, the next step is to assign the various components to the zones in accordance with the SAE ARP process. This process essentially amounts to looking up the appropriate components in SAE ARP 5412A. The assignment of these components essentially completes establishment of the external lightning environment. For the Orion space vehicle, the assignments are:

- 1) Zone 1A – Components A, B, C\*, H
- 2) Zone 1C – Components Ah, B, C\*, D, H
- 3) Zone 2A – Components B, C\*, D, H
- 4) Zone 2B – Components B, C, D, H

### C. Design for External and Internal Lightning Threats

With the external lightning environment established, it then becomes necessary to examine the various external features of the vehicle with an eye towards satisfying the requirements, and any design elements that require modification to survive the environment. All surfaces exposed during roll-out, on-pad, and launch/ascent need to be protected by establishing sufficient conductive paths for lightning current to flow. Lightning current does not travel in a single narrow path, but rather spreads out across the surfaces of the vehicle, penetrating the vehicle through seams and apertures, and via diffusion, tending to reduce the amplitude at any one location aside from an entry attachment point or an exit attachment point. A diagram illustrating this is shown in Fig. 4. The challenge then becomes identifying the various materials used in the outer mold line surfaces, determining their inherent immunity, and modifying them accordingly to achieve the necessary level of protection. The Orion space vehicle is designed with a lot of composite material in its structure, as well as various dielectric materials used for thermal protection. One very effective technique to provide protection for such materials that has been widely used in the aerospace community is to embed a conductive mesh as the first layer in the composite layup prior to autoclaving. Another method is to overlay a conductive material, either a physical layer or an applied coating, to the surface of dielectric materials. Both methods have been used for the Orion space vehicle. Based on the structural design of the

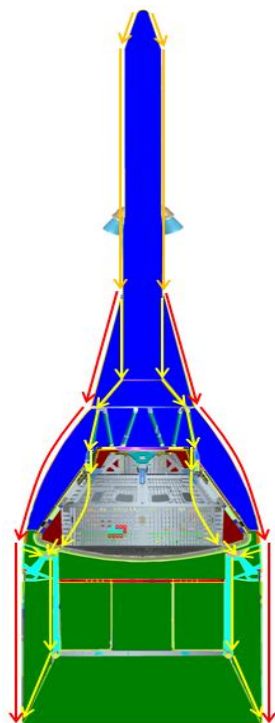


**Figure 4. False Color Plot of Current Density for the EMA3D Model of the Launch Configuration.**

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Orion space vehicle and the various materials and their treatments, the expected paths for lightning current can be traced out through the vehicle, as shown in Fig. 5.

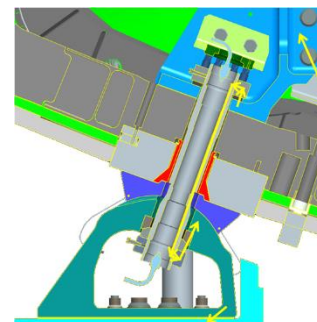


**Figure 5. Lightning current paths through the Orion space vehicle**

Clearly some current will penetrate the vehicle, and control of this current is accomplished again in review and assessment of the materials in the paths, and ensuring that sufficient conductivity is provided via proper electrical bonding throughout the vehicle to allow passage of the current without damage to the vehicle structure. An example of this is shown in Fig. 6, in which the bonding for a Retention and Release (R&R) fitting is illustrated.

Only those areas, surfaces, and fittings that are deemed to be critical for safe flight operations are normally given the highest attention. Protection efforts have focused on the LAS structure and the abort motors in particular, exposed composites and dielectrics, the LAS to Orion mechanical interface, the CM to SM mechanical interface, including the CM/SM R&R mechanisms, the CM to SM umbilical, the Orion to SLS mechanical interface, and the Orion to GSDO mechanical interfaces.

As the lightning currents penetrate and flow through the vehicle, internal systems are exposed to voltage and current transients on internal surfaces and structural elements, any and all wire harness and cabling shielded or not shielded, and ultimately to the pins of the individual electrical and electronic components, referred to as “black boxes”. Not every “black box” in the vehicle needs protection. Systems that have garnered the highest attention inside the Orion vehicle include the pyrotechnic subsystem, the propulsion subsystem, exposed components on the LAS and SM including windows and hatch, the landing battery, the Power Distribution Units (PDUs), the parachute subsystem, and the backup Flight Control System (FCS) computer module. As indicated above, the threats to these systems are ultimately cable currents and pin voltages. Table 1 illustrates some notional threat levels for some of Orion’s systems.



**Figure 6. R&R Mechanism**

#### **D. Protection Measures and Certification**

Classic protective measures have been employed in the Orion space vehicle and its systems to protect against the effects of lightning. The process can be described as follows. After zoning and environment assignment are completed, the next step is to identify all flight critical components or systems, as well as any components or systems that may propagate lightning direct or indirect effects into flight critical components or systems. At this stage, a hazard assessment should be performed by Systems Engineering, and coordinated with Safety, Reliability and Quality Assurance (SR&QA) to assess the impact of both direct and indirect effects on subsystems and components. Hazard assessments for direct and indirect effects will determine the possible safety consequences of any lightning attachment to, or lightning event nearby, the Orion space vehicle, by identifying structure, subsystems, and components whose failure or malfunction could result in a catastrophic, hazardous/severe-major, or major failure, either immediately or after some delay. A catastrophic failure is one which would prevent continued safe flight operations, including landing. A hazardous/severe-major failure would reduce the capability of the system or the ability of the crew to cope with adverse operating conditions, resulting in a large reduction in safety margins or functionality, an undue amount of crew workload that would prevent the performance of tasks accurately or completely, or significant adverse effects on the crew including serious or potentially fatal injury. A major failure would reduce the capability of the system or the ability of the crew to cope with adverse operating conditions, resulting in a moderate reduction in safety margins or functionality, a moderate increase in crew workload or impairment of crew efficiency, or discomfort to occupants, possibly including injuries.

Table 1. Notional Pin Voltage and Cable Current Threat Levels for Orion Systems

	Cable Description	DO-160 Test Category Designation	Pin Voltage (V) *	Cable Bundle Current (A) *
LAS	Connected to OML	B4K55	750	5000
	All other LAS Cables	Z2Z33	125	1000
CM	int. cables, unshielded	A2XXX	125	-
	int. cables, shielded	AZJ11	4	100
	int. cables, shielded external penetration	BZJ11	500	100
	int. cables, shielded external penetration and surge protection	BZJ11	25	100
	ext. cables, shielded	BZK55	500	5000
	ext. cables, shielded, surge protection	BZKZZ	25	1000
	Unit on OML, shielded cable	BZK55	400	5000
	Connections to the SAJ	B4KZZ	750	3000
SM	Spacecraft Adapter/MSA	B2K33	125	1000
	ESM to SLS	Z3ZZZ	300	600
	ESM, unshielded	B2K33	125	1000
	ESM, shielded	B1K33	50	1000
* Pin Voltage is given for test waveform with largest action integral, in most cases 5A and cable bundle current is also given for the waveform with the largest action integral. Please reference full DO-160 requirements in the category designation for a complete test set with test levels.				

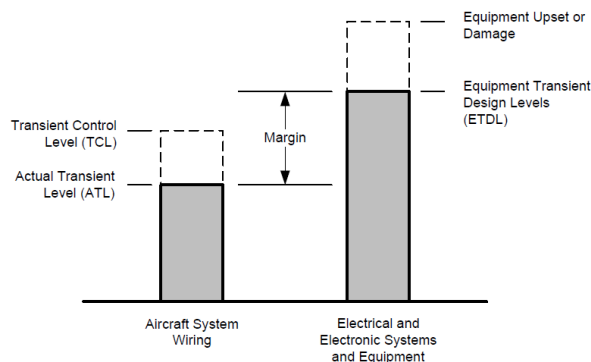
Once the hazard assessments are complete, the next step is to identify the maximum allowable damage to the system or its subsystems and equipment, or interference with the system operation, or operation of its subsystems and equipment, that will not result in a catastrophic, hazardous/severe-major, or major failure, either immediately or after some delay. Determination of maximum allowable effects, or acceptance criteria, taken together with the results of the hazard assessments, establishes the level of protective measures that must be employed to successfully survive and operate during and after exposure to the lightning environments associated with the identified zones. For determination of allowable external damage related to direct effects, testing of representative structures, coupons, sub-scale models, or waveform scaling may be used. In this testing, direct attachments are simulated by the use of high voltage sources such as Marx generators, and large current sources such as capacitor banks. Analysis of such test results are then used to verify that the observed maximum damage is, or is not, less than that defined in the acceptance criteria. If the observed damage is not less than the acceptance criteria, design changes must be incorporated to improve the observed performance of the article or articles under test to the point the acceptance criteria are met.

Internal allowable effects are bounded by Actual Transient Levels (ATLs) associated with the defined lightning environment for a given zone. Test or analysis may be used to determine the ATLs for a given subsystem, equipment, or component. If test is used, ATLs may be induced onto interconnecting wiring with appropriate waveform generators and current clamps such that they appear at electrical or electronic equipment interfaces. Direct injection into suitably terminated connector pins may also be used for potential damage assessment caused by ATLs. ATLs are defined in terms of Open Circuit Voltage (Voc) and Short Circuit Current (Isc), and the Voc and Isc for a given configuration are related by the source or loop impedances of the interconnecting wire. There may be different ATLs for different circuit functions, locations, amount of shielding, or operating voltages. Once the ATLs are determined, Equipment Transient Design Levels (ETDLs) can be determined.

EDTLs represent the voltage and/or current transient levels that Orion space vehicle subsystems or equipment are required to withstand and remain operational without damage or system functional upset. EDTLs are generally higher than ATLs by a predefined margin. An even higher level, known as the Equipment Transient Susceptibility Level (ETSL), may be defined as well in some cases, and is a level at which some damage or upset is likely to occur in equipment or subsystems. ATLs, TCLs, and EDTLs are shown graphically in Fig. 7.

In line with the described process various techniques have been used to protect Orion space vehicle composites and dielectric materials. Proper electrical bonding has been engineered throughout the vehicle's structural elements to provide adequate conductivity via identified current paths. As for the internal systems, based on the identified internal threat levels, cable and enclosure shielding has been improved where necessary, and for those systems for which such measures are not sufficient, internal electrical circuitry design has been employed, such as the use of transzorbs in power and signal lines. All "black boxes" will undergo electromagnetic interference testing, and critical items will also undergo specific pin and cable bundle testing to ensure the adequacy of the design.

At the vehicle level, certification will involve three separate tests. The vehicle will first go through intra-system testing designed to exercise the various critical systems one against another, switching each system individually through all possible operational modes, to identify any interference issues with the integrated system. Next, the vehicle will undergo inter-system testing designed to expose the vehicle to the defined radio frequency environment. During this testing, the critical systems will again be exercised one against another, switching each system individually through all possible operational modes, to identify any interference issues with the integrated system attributable to external influence. Finally, the vehicle will go through a low level swept continuous wave current injection test. The results of this test will be used to establish a transfer function between the external environment and the internal systems of the vehicle. Continuous wave currents ranging in frequency from essentially dc to 100 MHz or so will be injected into the vehicle's external skin. Current clamps will be used to monitor cable and harness currents, and breakout boxes will be used to monitor pin voltages at the inputs of various critical "black boxes".



**Figure 7. ATLs, TCLs, and EDTLs**

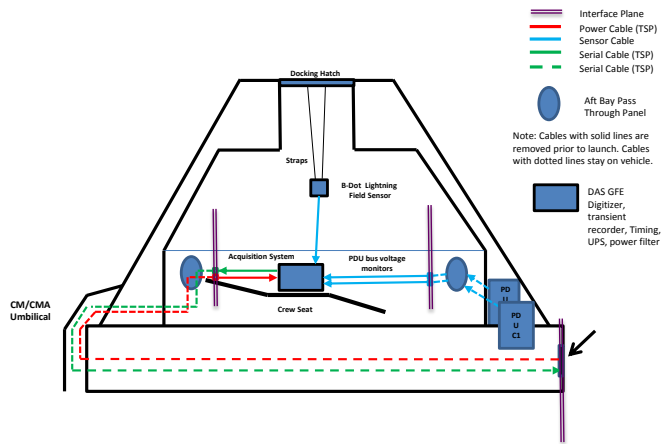
### **III. Monitoring, Pad Infrastructure, and LLCC**

Protecting spacecraft from lightning is a difficult undertaking, requiring many, many engineering tradeoffs and decisions regarding risk levels associated with impacting vehicle structure and systems design. Inherent in this is the fact that no matter how well the vehicle is designed, it will still have vulnerability to lightning. So other means of providing protection need to be devised and put into place to afford a more nearly complete protective scheme. The Orion space vehicle is no exception to this, and will benefit greatly from the legacy of the Space Shuttle Program. That program employed a completely revised lightning monitoring system during the last few years of flight operations that was instrumental on multiple occasions to facilitate rapid assessment of flight safety following lightning activity at the pad. The pad itself was designed with a single catenary system designed to intercept lightning channels and prevent direct attachment to the Space Shuttle stack on the pad. Finally, the range has had detailed LLCC in force since the 1987 catastrophic loss of flight AC-67.

#### **A. Monitoring**

Orion's lightning monitoring system, shown diagrammatically in Fig. 8, will locate a magnetic field sensor inside the CM that will capture any magnetic field components that penetrate the vehicle associated with lightning activity during roll-out and at the pad. The system will also have connections to the internal electrical power bus, allowing the system to capture any high-speed transients induced by lightning activity that appear on the bus. This data will be sent out of the vehicle and routed to the flight control center from where it can be rapidly distributed to engineering for assessment and reporting back to the MMT.





**Figure 8. Conceptual diagram of the Orion lightning monitoring system**

### C. Lightning Launch Commit Criteria

Launch safety rules employed at the eastern and western ranges include flight-commit criteria that identify each condition that must be met in order to initiate flight. Embedded in these criteria are 11 LLCC that govern the decision to launch given any weather conditions that might be conducive to natural or triggered lightning. All launch activity of the Orion Program must abide by the flight-commit criteria, including the LLCC. The conditions detailed in and imposed by the LLCC are monitored by trained weather personnel who report directly to the launch director during the countdown process. Clear and convincing evidence that none of these criteria are violated at the time of launch must be present and reported by the weather personnel. Whenever there is ambiguity about which of several LLCC applies to a particular situation, all potentially applicable LLCC must be applied. If any other hazardous conditions exist in addition to the LLCC, the launch weather team will report these hazardous conditions as well to the launch director. The launch director makes the final determination whether initiating flight would expose the launch vehicle to a lightning hazard and will not initiate flight in the presence of an identified hazard.

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### IV. Conclusion

This paper has attempted to capture at a summary level the sum total of the efforts made to protect the Orion vehicle from the direct and indirect effects of lightning during all phases of flight. As has been intimated by this paper, the process of protection is long and complex, involving many different aspects of planning, design, infrastructure, and programmatic and meteorological support to make up a cohesive and effective whole. The end result of all of this effort is a safe and reliable Orion space vehicle with respect to the threat of lightning.

### B. Pad Infrastructure

Orion will be launching from Pad 39B at KSC in Florida. After the Space Shuttle Program ended, and plans for the Constellation Program, now replaced by the combined Orion, SLS, and GSDO Enterprise, included a revisitation of the catenary design at the pad. Several other pads at KSC have multiple catenary support towers rather than the single tower concept that was employed for Shuttle. Multiple towers allow for a much larger catenary wire system to be suspended above the pad, affording a far greater and more reliable level of protection from direct attachment to any vehicles sitting on the pad awaiting launch. A view of the older style single catenary wire and the newer pad 39B multiple tower system is shown in Fig. 9.



**Figure 9. Space Shuttles Atlantis and Endeavour on the pad in preparation for the STS-125 Hubble repair mission**

### **Acknowledgments**

The author would like to express his gratitude for the inputs and support of his colleagues in the electromagnetic environmental effects (E3) group at Lockheed Martin, and his E3 staff at Johnson Space Center.

### **References**

- <sup>1</sup>MPCV 70080, Cross Program Electromagnetic Environmental Effects (E3) Requirements, NASA Orion Program
- <sup>2</sup>SLS-SPEC-159, Cross Program Specification for Natural Environments, NASA Space Launch System Program
- <sup>3</sup>SAE ARP5412B, Aircraft Lightning Environment and Related Test Waveforms, SAE International, Warrendale, PA, USA
- <sup>4</sup>SAE ARP5414B, Aircraft Lightning Zoning, SAE International, Warrendale, PA, USA
- <sup>5</sup>SAE ARP5415B, User's Manual for Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning, SAE International, Warrendale, PA, USA
- <sup>6</sup>SAE ARP5416A, Aircraft Lightning Test Methods, SAE International, Warrendale, PA, USA
- <sup>7</sup>SAE ARP5577, Aircraft Lightning Direct Effects Certification, SAE International, Warrendale, PA, USA
- <sup>8</sup>FAA AC 20-136B, Aircraft Electrical and Electronic System Lightning Protection, Federal Aviation Administration