P9.1

THE IMPACT OF TRIBOELECTRIFICATION ON THE ARES I-X LAUNCH AND CONSIDERATIONS FOR OTHER LAUNCH VEHICLES

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1. INTRODUCTION

The scrub of the Ares I-X launch attempt on October 27, 2009 was very unusual. It was the first weather scrub due to the triboelectrification rule in the lightning launch commit criteria (LCC) at the Florida Spaceport in over a decade. The triboelectrification rule is, itself, unusual in the lightning LCC since it is one of the few rules where the dangerous electric fields are not generated by the mixed phase of water at key temperatures. Triboelectrification is caused by the collision of the in-flight space launch vehicle with ice particles below a critical speed. The Ares I-X was one of the very few launches at the Florida Spaceport in many years that did not satisfy the conductivity or engineering analysis caveats within the Launch Commit Criteria Triboelectrification rule. This paper will review the Ares I-X unusual scrub due to triboelectrification, lessons learned during the weather support planning and execution of Ares I-X, and recommendations to new launch vehicle programs.

2. BACKGROUND

In the right atmospheric conditions, a launch vehicle can trigger lightning. The lightning LCC are a complex set of weather rules to avoid natural and rocket-triggered lightning strikes to in-flight rockets. These rules were developed by the Lightning Advisory Panel, a team of top American scientists in the field of atmospheric electricity, and are described in more detail in Merceret and Willet (2010), Krider et al. (2006), McNamara et al. (2009), and Roeder and McNamara (2006), Willet and Merceret (2010).

On the Eastern Range, the lightning LCC are evaluated and reported by the 45th Weather Squadron (45 WS) throughout a launch countdown. The criteria generally describe cloud conditions and weather within 10 nautical miles of the vehicle and its flight path. The lightning LCC apply to all space launches from within the U.S. including the Eastern Range, and the Federal Aviation Administration (FAA) applies these rules to the commercial launch ranges they regulate.

The triboelectrification rule within the lightning LCC is somewhat unique because rather than preventing triggered lightning, the rule is designed to prevent launch from generating a ‘spark’ within the vehicle which could affect sensitive electronics, interfere with command and control radio signals used to destroy the vehicle if it goes too far off course, and even lead to the destruction of the vehicle in extreme cases (NASA, 1974). Many customers are not as familiar with the triboelectrification rule compared to the other lightning LCC because other vehicles on the Eastern Range are treated or tested for triboelectrification; therefore, these vehicles never have weather violations related to the triboelectrification rule.

3. TRIBOELECTRIFICATION

Aircraft electrostatic build up was studied extensively after World War II because radio communications on aircraft were disrupted when flying through precipitation. The studies determined the impact with precipitation caused a charge buildup and subsequent discharge. The discharge caused static problems during radio communications, and this interference was often called precipitation static, or p-static (Heritage, 1988). The same phenomenon may occur when rockets fly through clouds with ice crystals. When a rocket impacts ice crystals, charges are deposited onto the rocket. This process is known as triboelectrification. If the skin of the rocket is not a conductive material and the vehicle is not properly treated and bonded, a charge buildup may occur around the surface of the vehicle potentially causing a static discharge. Static discharges can be hazardous to launch vehicles, potentially damaging sensitive electronic equipment, possibly disrupting the signal for the flight termination system (NASA, 1974). In extreme cases, discharges can lead to the destruction of the vehicle itself. Shielding against triboelectrification adds weight to the vehicle, a costly trade-off; therefore, knowing how much to protect the vehicle without adding unnecessary weight is critical to launch vehicle designers (Heritage, 1988).

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Electrostatic charging can be hazardous to in-flight rockets. Three main sources of electrostatic charging exist: 1) engine-exhaust charging, 2) induction charging, and 3) triboelectric charging. Electrostatic hazards are the suspected cause of failures of several launches in the late 1960s and early 1970s including a Europa II failure in which electrostatic charging of an ungrounded screen affected the guidance system, two minuteman failures caused by sparks due to bonding deficiencies, two Titan II guidance anomalies caused by an internal electrostatic charge, and two Scout failures possibly caused by electrostatic discharges initiating the destruct system (Andrus and Walkup, 1969; Taillet, 1975; Merceret and Willet, 2010).

The electrostatic hazard relating to weather is triboelectric charging. Because of this potential hazard, the lightning LCC include a triboelectrification rule, and if a launch vehicle is not properly grounded, bonded, and treated, the rule restricts flight through clouds above the -10°C level. The primary concern is triboelectrification due to impact with ice crystals in high clouds. The triboelectrification rule in the Lightning LCC reads as follows:

"A launch operator must not initiate flight if the Flight Path will carry the launch vehicle through any part of a cloud, specifically including all transparent parts, at any altitude where both section (a) and section (b) are satisfied:

(a) The temperature is colder than or equal to -10 degrees Celsius; and

(b) The launch vehicle's velocity is less than or equal to 3000 feet/second; unless Section (1) or Section (2) is satisfied:

(1) The launch vehicle is treated for surface electrification; or

(2) A launch operator has previously demonstrated by test or analysis that electrostatic discharges on the surface of the launch vehicle caused by triboelectrification will not be hazardous to the launch vehicle or the spacecraft.

A launch vehicle is treated for surface electrification if

(1) All surfaces of the launch vehicle susceptible to ice particle impact are such that the surface resistivity is less than 10^9 ohms/square; and

(2) *All conductors on surfaces (including dielectric surfaces that have been treated with conductive coatings) are bonded to the launch vehicle by a resistance that is less than 10^5 ohms."* (Willett and Merceret, 2010)

Note: The 10^9 ohms/square in the second set of clauses of the triboelectrification rule is a frequent source of confusion, with some people expecting a unit of area, e.g. 'square meters'. However, in this context, the unit of 'square' refers to a geometric square and is correct as is (Heritage, 1988).

High clouds contain ice crystals. When a launch vehicle impacts these ice crystals, the collision can produce dangerous static electrification, potentially affecting sensitive electronic equipment within the vehicle. When the launch vehicle reaches speeds above 3000 ft/sec or faster, there is enough energy in a collision with an ice crystal to completely melt the ice; therefore, triboelectrification no longer occurs (Willett and Merceret, 2010).

The following are the rationale for the triboelectrification rule listed in the Lightning Flight Commit Criteria Rationales document by Willet and Merceret (2010):

"Proper grounding, bonding, and treatment of insulating surfaces are essential for flight safety

- *Charging of dielectrics can produce surface discharges on both the exterior and interior surfaces of those dielectrics and allow penetration of disruptive electric fields into the interior of the vehicle.*

- *Differential charging of inadequately bonded metallic surfaces can cause sparking between those surfaces or to the airframe, resulting in the penetration of disruptive electrical noise in into the interior.*

- *<u>Bonding</u>: Lowering the electrical resistance between isolated metallic surfaces and the airframe to prevent sparking* (electrical bonding prevents sparking due to static voltage discharges)

- *<u>Surface treatment</u>: altering (if necessary) the surface resistivity of dielectrics so that surface discharges do not occur."*

4. ARES I-X

The Ares I-X was the first new space launch vehicle from Launch Complex 39 at Kennedy Space Center since the first Space Shuttle in 1981. This launch was a flight demonstration model for the Ares I vehicle being developed by NASA under the Constellation program, the follow-on program for the Space Shuttle program (subsequently canceled for reasons unrelated to this test launch). The Ares I-X was a suborbital vehicle that had an outer mold line, or outer-shell, very similar to the Ares I, and it consisted of a modified Space Shuttle solid rocket booster and a dummy upper stage, capsule, and launch abort system.

4.1. ARES I-X LAUNCH COMMIT CRITERIA

The entire Ares I-X launch was designed and executed in approximately three years, a very short amount of time for a launch program. In January of 2009, the team developing the weather LCC for the Ares I-X began by modifying the weather LCC used for the Space Shuttle. The team included the Marshall Space Flight Center (MSFC) Natural Environments Branch lead, the 45 WS Launch Weather Officer at

Cape Canaveral Air Force Station, and the Kennedy Space Center Weather Office. The Space Shuttle's Lightning LCC mirrored the Range's except for one rule, the triboelectrification rule. Although this rule was well documented in the range weather lightning LCC, the Space Shuttle program removed the rule from their weather lightning LCC in 1988 because the vehicle met the specified coating and bonding criteria and was cleared from the cloud restriction within the rule. Since the triboelectrification rule was not in the Shuttle lightning LCC, there was no requirement for the Ares I-X vehicle design to mitigate triboelectrification during the design phase a couple of years prior to the development of the LCC document.

The MSFC Natural Environments Branch conducted a brief analysis to determine the impact of triboelectrification on a launch attempt in April 2009, the originally scheduled launch date, and carried the analysis through May and June to allow for launch delays (Figure 1). The analysis showed minimal impact on launch availability from the triboelectrification rule when added to the other weather LCC. Upon completion and a review of the analysis by the MSFC team, the triboelectrification LCC rule was added to the Ares I-X LCC. Over the following few months, the launch date moved to October of 2009, beyond the time-period covered by the MSFC Natural Environments Branch's triboelectrification rule analysis.

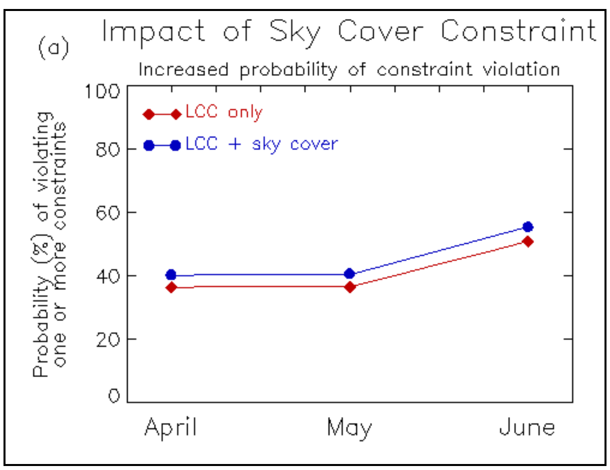

Figure 1. Analysis of Impact to Launch Availability. Probabilities of violating LCC constraints with and without sky cover constraint, April - June. The maximum increase in the probability of a constraint violation is 4.5% in June.

4.2. ARES I-X LAUNCH

During the week before scheduled launch on 27 October 2009, the weather forecast began indicating the potential of violating the triboelectrification rule on launch day. Given the high-impact on launch availability, the Electromagnetic Effects Team at MSFC began an analysis on the vehicle to determine if the vehicle met the 'bonded' and 'treated' portions of the triboelectrification LCC. Although the Ares I-X vehicle was sufficiently electrically bonded to withstand even a direct lightning strike at the launch pad, the challenge was to address the use of materials on the outside of the vehicle that did not conform to the range requirement of $<10^9$ ohms per square. (As discussed previously, the unit of 'square' refers to a geometric shape and is not a unit of area so no additional units like 'square meters' is needed.)

On 27 October 2009, the Ares I-X rocket was poised and ready to launch at Launch Complex 39B. With the triboelectrification rule in the Lightning LCC and the analysis on the vehicle still in-work, high thin clouds caused weather to be RED for the triboelectrification rule and RED for launch (Figure 2). Subsequently, the Eastern Range was NO-GO for launch, protecting the launch from the risk of damage due to a corona buildup and subsequent spark across the surface of the vehicle.

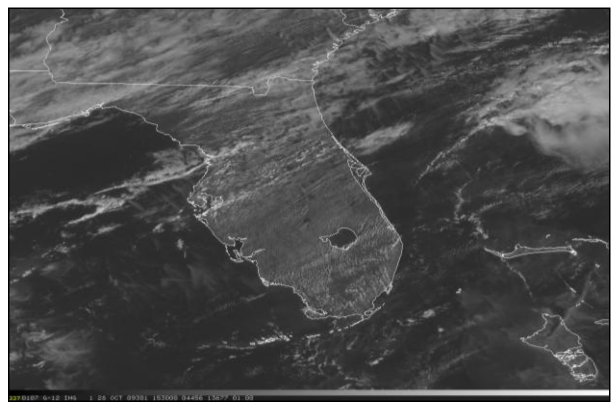

Figure 2. Satellite picture of the first Ares I-X launch attempt; high, thin clouds caused a violation of the triboelectrification rule within the Lightning Launch Commit Criteria, and the launch was scrubbed the first launch attempt.

On October 28, 2009, the analysis was nearly complete, but work was held off to allow personnel to push forward with the launch countdown. Similar conditions during the 4-hour launch window, again, caused a violation of the triboelectrification lightning LCC. Finally, due to aircraft reports from the T-38 aircraft with two astronauts on board evaluating cloud locations, a hole in the clouds moved over the launch pad, and the launch proceeded. Cameras and the aircraft verified the vehicle did not fly through clouds and was protected from impacting ice crystals resulting in vehicle charging. The launch and flight were successful (Figure 3).

Figure 3. Launch of the Ares I-X Rocket. A flight demonstration model for the Ares I launched from Kennedy Space Center (Kennedy Space Center Public Affairs).

4.3. LESSONS LEARNED

There were many lessons learned during this Ares I-X case:

- The Ares I-X launch availability was significantly reduced due to the triboelectrification lightning LCC (Price, 2010).

- Since the triboelectrification rule was not in the Shuttle LCC, Ares I-X decision makers did not have experience with the rule.

- Even though triboelectrification was discussed at a technical interchange meeting on lightning over a year prior to launch and was included in the Ares I-X LCC document eight months before launch, the impact the triboelectrification LCC on launch availability was realized very late in the launch process (Price, 2010).

- The weather reconnaissance aircraft is critical to the evaluation of the triboelectrification rule if high clouds are in the area, but caution must be taken as to not create contrails in or upwind of the rocket's flight path since contrails contain ice crystals, violating the triboelectrification rule (EPA, 2000).

- When only a short break in the weather is possible during a long launch window, if a quick T-0 cannot be established, missed opportunities for launch may occur.

5. RECOMMENDATIONS

Given the Ares I-X experience, the following are recommended to launch programs and ranges:

- Since electrostatic hazards can be significant even in the absence of clouds (NASA, 1974), all vehicles should be treated, tested, or bonded to mitigate the hazard. This should be addressed during the requirements and design development phase (Price, 2010).

- Launch ranges and vehicles should include the triboelectrification rule in the lightning LCC even if the vehicle is bonded, treated, or tested preventing the need to evaluate the weather portion of the rule. This will ensure the triboelectrification risk is considered during vehicle modifications and follow-on programs.

- If high-clouds must be avoided to prevent triboelectrification, a weather reconnaissance aircraft is critical to gain launch availability.

- Not having climatology for LCC makes it difficult for launch managers to determine the risk of a lightning LCC to launch availability. Knowing the impact of a Lightning LCC to the customer is extremely useful. Unfortunately this type of data is difficult to gather and maintain since it is not possible to simply use a database of ground observations to determine lightning LCC violations. Developing and maintaining a process for a lightning LCC database for a particular location could provide several critical pieces of information to help a launch program develop a cost risk analysis and determine whether to spend or not spend dollars to mitigate a lightning LCC. Examples include the need of weather reconnaissance aircraft during countdown; the cost of bonding, treating, and/or testing a vehicle for triboelectrification; how extensive of meteorological instrumentation is needed for launch; etc. The 45 WS is attempting to develop a lightning LCC climatology from preexisting weather databases with the Naval Postgraduate School. One M.S. thesis has been completed (Muller, 2010) and another is in-progress.

6. SUMMARY

Electrostatic hazards have caused launch vehicle failures, and launch programs should mitigate electrostatic hazards during the requirements and design phases of vehicle development. Triboelectrification is a weather-related electrostatic hazard captured in the Lightning LCC developed by the Lightning Advisory Panel. During the Ares I-X launch attempts, the triboelectrification rule significantly impacted launch availability. Launch ranges should educate customers on the lightning LCC and consider providing information on the impact of the triboelectrification rule to launch availability.

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