8.3 NATURAL AND TRIGGERED LIGHTNING LAUNCH COMMIT CRITERIA

E. P. Krider,[1*] H. J. Christian,[2] J. E. Dye,[3] H. C. Koons,[4] J. Madura,[5]
F. Merceret,[5] W. D. Rust,[6] R. L. Walterscheid,[4] and J. C. Willett[7]

[1]University of Arizona, Tucson, Arizona
[2]NASA GHCC, Huntsville, Alabama
[3]NCAR MMM, Boulder Colorado
[4]Aerospace Corporation, Los Angeles, California
[5]NASA Kennedy Space Center, Florida
[6]NOAA NSSL, Norman, Oklahoma
[7]Garrett Park, Maryland

1. INTRODUCTION

After lightning struck the Atlas-Centaur vehicle in March, 1987 [Christian et al., 1989], the Air Force (AF) and NASA asked a number of experts to re-examine the mission launch rules that were designed to minimize the hazards to spaceflight operations from natural and triggered lightning [Titan Program, 1988]. After considerable thought and consultation with other scientists and operations personnel, the AF/NASA Lightning Advisory Panel has recently proposed an improved set of lightning flight commit criteria (LFCC) that are summarized in the following section. At the time these rules were being formulated [Krider et al., 1999] and later improved using airborne and radar measurements (see Dye et al. [2006], this conference), it was recognized that there are still many unknowns about both natural and triggered lightning and the magnitude and spatial extent of the cloud electric fields that produce a threat (see Willett et al. [2006], this conference). Because of this, the LFCC have deliberately been made conservative.

2. PROPOSED LIGHTNING FLIGHT COMMIT CRITERIA (LFCC)

Each of the proposed Natural and Triggered Lightning Flight Commit Criteria (LFCC) are paraphrased below (in italics) and are followed by a short rationale. It should be noted that each of the LFCC requires ***clear and convincing evidence*** to trained weather personnel that its constraints are ***not violated***. Under some conditions, trained weather personnel can make a clear and convincing determination that the LFCC are not violated based on visual observations alone. However, if the weather personnel have access to additional information such as measurements from weather radar, lightning sensors, electric field mills, and/or aircraft, and this information is within the criteria outlined in the LFCC, it will allow a launch to take place where a visual observation alone would not.

2.1 Lightning

Do not fly within 10 nm of any type of lightning, or any cloud that has produced it, within the past 30 min. An exception is allowed if the cloud has moved beyond 10 nm ***and*** *if an electric field mill within 5 nm of the* ***lightning*** *(and any other mills within 5 nm of the flight path) have shown benign readings for at least 15 minutes.*

Any cloud that is producing natural lightning (either intracloud, cloud-to-air, or cloud-to-ground) will contain electric fields that are large enough to trigger lightning to any airborne vehicle. Further, natural lightning itself can be a hazard both by attaching directly to a vehicle in flight (approximately 10% of the strikes to aircraft are the interception of an on-going flash) and by the indirect effects induced on the vehicle. 30 minutes is an interval beyond which the chances of an additional lightning discharge in a given thunderstorm cell is very low [Holle et al., 1999; Holle et al., 2003]. Also, the chance that any lightning discharge will propagate beyond a distance of 10 nautical miles from the parent thunderstorm is low, and the chance that it would propagate in a direction that affects the vehicle is even lower.

* E. Philip Krider, Inst. of Atmospheric Physics, University of Arizona, Tucson, AZ 85721-0081 <krider@atmo.arizona.edu

2.2 Cumulus Clouds

For purposes of this criterion, "cumulus clouds" do not include altocumulus, cirrocumulus or stratocumulus clouds.

Do not fly within 10 nm of any cumulus cloud that has a top above the -20 °C temperature level and within 5 nm of any cumulus cloud that is above – 10 °C. Do not fly through a cumulus cloud that is above the + 5°C level. An exception is allowed for any cumulus cloud top between ± 5 °C if that cloud is not precipitating ***and*** *if a field mill within 2 nm of that top (and any other mills within 5 nm of the flight path) have shown benign readings for at least 15 minutes.*

Cumulus clouds contain convection that can grow and strengthen very rapidly, and if the cloud top exceeds the -20 °C level there is a good chance that an electrification mechanism involving ice-ice collisions (see section 3.2.1) has already created, or soon will be creating, high electric fields. Therefore, these clouds should be treated as if they are already producing natural lightning.

Cumulus clouds that reach the -10 °C level but have not exceeded the -20 degrees Celsius level are not as likely to be highly electrified, but since the latent heat released by the freezing of liquid drops can rapidly enhance convection and the growth of precipitation [Szymanski et al., 1980], potentially leading to rapid electrification, the region within 5 nautical miles of any cumulus cloud that reaches the – 10 °C level should be avoided.

Cumulus clouds that reach the – 5 °C level but do not exceed the -10 °C are not likely to be highly electrified, but such clouds should not be penetrated because clouds with tops in this height range often grow rapidly and could become electrified by the time the vehicle would penetrate the cloud.

Cumulus clouds with tops between the +5 °C and the -5 °C levels have the potential to grow rapidly and become electrified by the time the vehicle flies through the cloud, especially if the cloud is precipitating. However, if the cloud is not precipitating and if all electric field measurements made close to the cloud and near the flight path have been low for 15 minutes or longer, then such rapid growth and electrification are unlikely. Small cumulus clouds are not likely to contain significant screening layers (unlike stratiform clouds and anvils) because of the mixing and entrainment that takes place at their boundaries, so a nearby field mill can be relied upon to indicate the electrical state of such clouds.

2.3 Attached Anvil Clouds

Do not fly within 10 nm of any non-transparent, attached anvil for at least 30 minutes after the last lightning discharge occurs in the parent cloud or anvil, and do not fly within 5 nm of an attached anvil for 3 hours after the last lightning discharge in the parent cloud or anvil. Never penetrate an attached anvil cloud. If the anvil cloud is everywhere colder than 0 °C ***and*** *if its volume-averaged, height-integrated, radar reflectivity (VAHIRR) is less than 10 dBZ-km, exceptions are allowed to both the 5 nm stand-off distance and the no-penetration requirement after 30 minutes.*

Airborne measurements show that the electric fields inside attached anvil clouds are frequently very large for long periods of time. If the parent thunderstorm has stopped producing lightning for at least 30 minutes, the observed fields at distances between 5 and 10 nautical miles from the anvil are low and flight can occur in that region. If lightning has not occurred for 3 hours, the observed fields are low everywhere outside the cloud, so under those conditions, flight can occur within 5 nautical miles of an attached anvil. If weather radar measurements are available, a radar-based exception can be applied to attached anvil clouds.

2.4 Detached Anvil Clouds

For purposes of this section, detached anvil clouds are never considered debris clouds.

Do not fly within 10 nm of a non-transparent, detached anvil for 30 minutes after detachment, or within 5 nm for 3 hours after it or its parent cloud before detachment produces lightning. Do not penetrate a non-transparent, detached anvil for 3 hours after it is observed to detach, or for 4 hours after it has produced lightning. The duration of the 5 nm stand-off requirement is reduced to 30 minutes after lightning if a field mill within 5 nm of the cloud (and any other mills within 5 nm of the flight path) have shown benign readings, ***and*** *if the cloud radar reflectivity has been less than 10 dBZ, for at least 15 minutes. The 5 nm stand-off requirement can also be reduced to 30 minutes, and the no-penetration requirement reduced to 30 minutes after lightning, if all parts of the cloud are colder than 0 °C* ***and*** *if its volume-averaged, height-integrated, radar reflectivity (VAHIRR) is less than 10 dBZ-km.*

Airborne measurements show that, after anvil clouds become detached from the parent thunderstorm, the electric field can persist for a long period of time in the absence of internal cells of convection. If the detached anvil, or its parent cloud before detachment, has not produced lightning for at least 30 minutes, the observed fields between 5 and 10 nautical miles outside the cloud are well below the threshold for triggering lightning. If lightning has not occurred for 3 hours, the fields within 5 nautical miles of a detached anvil are below the threshold for triggering lightning. Note that a field mill exception permits flight within 5 nautical miles, but not penetration, of certain detached anvil clouds because screening layers can build up on detached anvils and prevent the detection of high fields within them from the ground. If weather radar measurements are available, the LFCC for detached anvil clouds can incorporate those measurements to further insure the absence of high electric fields inside detached anvils.

2.5 Debris Clouds

*Do not fly within 5 nm of a non-transparent debris cloud for 3 hours after it detaches or decays from its parent cloud **and** for 3 hours after it produces lightning. An exception to the 5 nm stand-off requirement is allowed if a field mill within 5 nm of the debris cloud (and any other mills within 5 nm of the flight path) have shown benign readings, **and** if the cloud radar reflectivity has been less than 10 dBZ, for 15 minutes.*

Airborne measurements show that thunderstorm debris clouds can contain high electric fields for long periods of time. In the absence of any convective development that generates further charge, as indicated by lightning, the electrification should decay away after a 3-hour interval. Note that the field mill exception permits flight within 5 nm, but not through, certain debris clouds because screening layers might build up on these non-convective clouds and prevent the detection of high fields within them from the ground.

2.6 Disturbed Weather

Do not fly through a non-transparent cloud associated with disturbed weather that produces cloud tops colder than 0 °C and either moderate to greater precipitation or evidence of melting precipitation within 5 nm of the flight path.

Measurements show that disturbed weather often produces high electric fields, especially when there is evidence of melting precipitation or a radar bright band in the clouds aloft. The mechanism(s) for producing this electrification may be different from non-inductive ice-ice collisions, so vehicles should not fly through such clouds.

2.7 Thick Cloud Layer

*Do not fly through a non-transparent cloud layer that is thicker than 4500 feet and contains temperatures between 0 °C and -20 °C (nor any non-transparent cloud layer that is connected to such a thick cloud layer within 5 nm of the flight path). An exception is allowed if the thick cloud layer contains no liquid water **and** has never been associated with a convective cloud.*

A non-inductive charging mechanism involving ice-ice collisions requires the presence of supercooled water drops in a region of the cloud that has appreciable numbers of ice-ice collisions. A thick cloud that encompasses the 0° to -20 °C temperature levels will usually contain supercooled water, and can also include imbedded cells of convection. Imyanitov et al. [1972, Chapter 1] have reported maximum electric fields of 20 kV/m in altostratus clouds with an average thickness of 1300 meters, and the ABFM I campaign also found fields of the order of 10 kV/m in thick Florida clouds.

2.8 Smoke Plumes

Do not fly through any cumulus cloud that develops from a smoke plume for 60 minutes after it has detached form that plume.

Latham [1991] has documented that convective clouds initiated by large, wildland fires can produce lightning, and Vonnegut et al. [1995] have suggested that the dominant mechanism for creating this electrification may not be ice-ice collisions but one or more influence mechanisms involving electrostatic induction. Since the mechanism(s) for producing cloud electricity when the cloud is connected to a smoke plume are still not understood, a delay of at least 60 minutes is required after detachment to insure flight safety.

2.9 Surface Electric Fields

Do not launch if any electric field mills within 5 nm of the flight path have exhibited readings in excess of 1 kV/m in the past 15 minutes. The field threshold can be raised to 1.5 kV/m if all clouds within 10 nm of the flight path are transparent or both have tops warmer than +5 °C and have not been part of convective clouds with tops colder than – 10 °C for at least 3 hours.

Two key facts support this rule. First, extended volumes of space charge that contain elevated electric fields can constitute a potential energy source for triggering lightning. Therefore, any indication of elevated fields aloft must be regarded as a threat, whether or not any particular cloud type is present. Second, when the charge overhead increases, the electric field at the ground tends to be "clamped" or limited to a steady value between 3 and 5 kV/m, depending on the site, because of corona emissions from the surface. Thus, when any surface electric field measurement approaches 2 kV/m (a value appropriate for the Kennedy Space Center), it may not provide a true indication of the electric field aloft.

A cloud-based exception can be granted if the surface field is below a threshold for producing appreciable corona space charge so that this field can be regarded as indicative of conditions aloft. In particular, it has been observed that splashing waves and bubbling in the surf zone, power line corona, and other sources of electricity in fair weather produce elevated fields near the ground but do not pose a threat for triggering lightning. These processes rarely produce fields in excess of 1500 V/m at the Kennedy Space Center.

2.10 Triboelectrification

Do not fly through any cloud that is colder than – 10 °C at vehicle velocities less than 3000 ft/s unless the vehicle has been treated or hardened against surface discharges.

Any collisions of the space vehicle with ice particles have the potential for separating charge and causing discharges on insulating surfaces. In order to avoid this possibility, the launch vehicle must either be treated for surface electrification or it must be shown that surface discharges will not be hazardous to the vehicle or its payload.

3. DISCUSSION

Cloud electric fields have been measured routinely for research for more than 50 years, but as yet, there is still no aircraft that has the performance characteristics required to support launch operations and that has the capability of measuring the 3D vector electric field (at the relevant altitudes) inside clouds. Thus, there is a possible hazard due to cloud electricity that we do not understand quantitatively and cannot measure directly but which we absolutely must avoid.

The solution to this dilemma has been to draft a set of launch rules that maintain a safe distance (10 nm) from any natural lightning, avoid clouds that have a high potential for being electrified on the basis of previous research, and avoid clouds that produce significant electric fields on the ground.

We believe these criteria are safe, but we also recognize that the primary threat is a high electric field aloft, and the present LFCC do not even specify this parameter. Because, of the above uncertainties, we clearly have two types of possible errors: false alarms and failures to warn.

3.1 False Alarms

The present LFCC are conservative; therefore there will be times when a launch is held or aborted when there is not a hazard aloft. A large fraction of the convective clouds that produce rainfall are not electrified, and the same is true for stratus clouds. Large storms that are distant from a network of ground-based sensors can produce elevated electric field readings when the fields aloft are not likely to be dangerous.

3.2 Failures to warn

It is very important to avoid any cloud that is producing natural lightning, either intracloud or cloud-to-ground, because all such clouds are capable of triggering a discharge to an airborne vehicle. Sometimes, however, instrumentation fails to detect lightning events with a small amplitude or other characteristics that prevent detection, or events occur at times when the lightning sensors are not responding for other reasons. Electrical screenings layers near the cloud boundary and corona layers near the ground can mask hazardous fields aloft or make it is difficult to detect such fields in a complex weather environment. Also, the present LFCC are based largely on research in warm-season thunderstorms at mid-latitudes. The electrical properties of thunderstorms (and many other types of clouds) in other geographic regions and seasons has received relatively little attention by the research community.

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