8.9 TRIGGERED LIGHTNING RISK ASSESSMENT FOR REUSABLE LAUNCH VEHICLES AT THE SOUTHWEST REGIONAL AND OKLAHOMA SPACEPORTS

John C. Willett*
Garrett Park, Maryland

E. Philip Krider
Institute of Atmospheric Physics, University of Arizona, Tucson, Arizona

Grace S. Peng, Frederick S. Simmons, Glenn W. Law, Robert W. Seibold
The Aerospace Corporation, El Segundo, California

Karen Shelton-Mur
FAA Office of Commercial Space Transportation, Washington, DC

1. INTRODUCTION

Oklahoma and New Mexico are actively seeking to obtain a license to operate a launch site from the Federal Aviation Administration, Office of Commercial Space Transportation (FAA/AST). Because commercial space activities are expected at both launch sites, The Aerospace Corporation was tasked by the Volpe National Transportation Systems Center to provide technical support to FAA/AST in assessing the risks involved with triggered lightning during suborbital launches and reentries of reusable launch vehicles (RLVs) from the proposed Southwest Regional Spaceport in New Mexico and from the proposed Oklahoma Spaceport, Burns Flat, Oklahoma.

Risk of triggered lightning was studied for five conceptual RLVs originating and/or landing at these proposed spaceports. Three areas were addressed: (1) observed frequencies of cloud-to-ground lightning at the proposed spaceports, including estimates of violation frequencies of the existing lightning launch commit criteria (LLCC), (2) estimates of the ambient fields required for triggering by each of the concept vehicles, including consideration of potential methods for estimating the probability of encountering these field magnitudes from the measured radar returns of thunderstorm anvil clouds, and (3) review of the current LLCC to determine if the criteria are relevant to each suborbital RLV concept, including an evaluation of local geographical effects pertaining to each spaceport to determine whether additional LLCC are necessary to conduct safe launch operations there.

The results and findings from this research are presented herein and in companion briefings at this Range and Aerospace Session of the 12th ARAM Conference. The present paper focuses on the triggering conditions, whereas Peng [2005] addresses the meteorology of the proposed spaceports, and Krider *et al*. [2005] discusses the existing LLCC and their rationales.

2. TRIGGERED LIGHTNING

At least 80 - 90% of all lightning strikes to flying aircraft and spacecraft are “triggered,” in the sense that they are locally initiated by the penetration of a large conductor into a sufficiently large region of high-intensity ambient electrostatic field. This fact was first conclusively demonstrated by Mazur *et al*. [1984], who used a UHF radar to document the initial spatial development of lightning discharges *away from* an instrumented F-106 aircraft when it was struck. Recordings of currents and electric-field changes on board other aircraft have been interpreted to indicate that such triggered strikes invariably begin with a positive “leader” propagating away from an extremity on which positive charge had been induced by the ambient field, followed after a few milliseconds by the development of a negative leader from a negatively charged extremity, propagating in the opposite direction [e.g., Boulay *et al*., 1988; Mazur, 1989]. Here the term, “leader,” denotes a highly ionized, conducting, filamentary channel extending into virgin air. The term, “positive streamer,” in contrast, will always refer to the poorly conducting “corona” space-charge waves [*e.g.*; Dawson and Winn, 1965; Phelps and Griffiths, 1976] that are an important component of the advancing “head” of a positive leader.

Detailed study of the triggering phenomenon (as well as other important aspects of lightning) has been facilitated by rocket-triggering techniques.

*John C. Willett, Ph.D., P.O. Box 41, Garrett Park, MD 20896, willettj@compuserve.com

"Classical" rocket-triggered lightning [St. Privat D'Allier Group, 1985] is initiated by a small rocket lifting a grounded wire aloft under a thunderstorm. This technique was pioneered by Newman *et al*. [1958, 1967]. The key to its success is likely a hypothesis by Brook *et al*. [1961] that the sufficiently rapid introduction of a grounded conductor into a high-field region might actually initiate the discharge.

It is now well established that classical rocket-triggered lightning normally begins with an upward-propagating, positive leader that moves from the tip of the triggering wire toward a negatively charged cloud. Most "upward-initiated" discharges to towers [Uman, 1987, Chapter 12] are also initiated by positive leaders. The onset conditions for the latter discharges are somewhat different from those for rocket-, aircraft-, and spacecraft-triggered lightning, however, because a fixed tower tends to be surrounded by considerable corona space charge, which inhibits leader formation, whereas this space charge is blown away by the rapid motion of flying vehicles.

Very similar positive leaders have been shown to initiate "altitude" triggered lightning [*e.g.*, Laroche *et al*., 1989], which is produced when a small rocket lifts an ungrounded wire aloft. Altitude triggered discharges are believed to be a good analog for lightning strikes to flying aircraft and spacecraft. For all of the above reasons, we focus here on the extended development of a positive leader as the proximate cause of triggered strikes to spacecraft, and we use triggering conditions derived from experiments with classical rocket-triggered lightning to estimate the conditions for such strikes.

The initiation and continued propagation of positive leaders from conducting objects has been studied in detail in the laboratory, using sparks up to tens of meters in length, but to a much lesser extent on the scale of lightning discharges in the free atmosphere [*e.g.*; Bazelyan and Raizer, 1998, 2000; Willett *et al.*, 1999]. Material from these references that is relevant to the triggering conditions will be summarized here.

Basically, there are three conditions that must be satisfied in order to initiate and propagate a positive leader.

First, "breakdown" must occur in a small volume of air near the surface of the object in question, in order to produce free electrons in sufficient quantities to carry an electric current. This means that at normal temperatures and pressures the local electric field must reach a value near 3.0 MV/m, and when this occurs, a phenomenon called "glow corona" is produced.

Second, the current in the corona region must be amplified to the point where positive streamers occur. These streamers propagate outward from the breakdown region, further heating a small volume that is called the "stem," and the stem is where the positive-leader channel begins.

Third, the *ambient* field must be large enough over a sufficiently large volume of space that the positive leader, once it has been initiated, will continue to grow and propagate (*i.e.*, the potential at its tip will remain large enough relative to the local ambient potential to sustain propagation). This last condition is what we will refer to as "leader viability."

We identify leader viability with the triggering conditions for several reasons. First, long, thin conductors like classical rocket-triggering wires are known to create air breakdown near their tips, initiate positive streamers, and even produce short, non-viable positive leaders long before -- at much shorter wire lengths or in much weaker ambient fields than -- they trigger lightning. Second, even shorter and stubbier conductors, such as large aircraft, are known to be in corona much of the time, due to charging by their engines and/or by particle impaction inside clouds, without triggering lightning. Thus it appears that the ambient field, rather than the locally enhanced field at the extremities of a flying vehicle, is the key determinant of triggering. Third, the net charge on such a vehicle is usually unknown, making it difficult or impossible to calculate the conditions for localized breakdown by the familiar enhancement-factor approach. Finally, the enhancement factor estimated from the nose radius of curvature and the effective length (including the exhaust plume) of any of the RLVs of interest here (assuming it to be uncharged) predicts the onset of breakdown at a higher ambient field than that required to produce leader viability (as determined from the data and model described in Section 4). Thus the leader-viability approach affords a margin of safety in these cases.

3. POSSIBLE SOLUTIONS

There are two ways to reduce the risk of triggered lightning -- hardening the vehicle, or avoiding the hazard. The former was not considered in any detail here because the weight (and testing) requirements are generally prohibitive and expensive for all but military rockets. Therefore, avoidance was the main focus of the present study.

3.1 *In Situ E* Measurements

In situ measurement of the ambient electrostatic field is undoubtedly the best way to determine whether any particular cloud along or near the planned flight path poses a triggered-lightning hazard to any particular RLV. This is because most clouds do not give a clear indication to any known remote-sensing technique (*e.g.*, morphology or radar reflectivity) of whether or not they are electrified and capable of triggering lightning. The obvious exceptions are cumulonimbus clouds and any clouds that are producing natural lightning; clearly, any such clouds should always be avoided. Developing cumuli should also be avoided because they are capable of becoming electrified very rapidly.

Some types of clouds, such as “thick clouds” and “thunderstorm debris clouds” (as defined in the current LLCC), are statistically known to constitute a hazard in a relatively small percentage of cases. Thus, in the absence of direct measurements, they should be avoided, even though avoidance may produce unnecessary launch delays and scrubs. In such cases, an *in situ* measurement capability could virtually eliminate false alarms and maximize launch availability, without compromising safety. Unfortunately, the only appropriate method of obtaining *in situ* electric field measurements -- a high-performance aircraft instrumented with five or more field mills (an Airborne Field Mill, or ABFM, system) -- is expensive and both technically and operationally difficult.

The use of an *in situ* measurement capability, such as outlined above, to reduce the false alarms that would otherwise be inherent in any cloud-based avoidance criteria (like the current LLCC) requires a knowledge of the electric-field conditions that are necessary to trigger lightning with the vehicle in question. To this end, the electric-field magnitudes that constitute a threat to five concept RLVs are estimated below. The electric-field “threshold” for triggering lightning is vehicle-, engine-, altitude- and velocity-dependent. More theoretical and experimental work is needed on all of these dependencies, although some estimates can be made with reasonable confidence.

3.2 Cloud Based Rules

The existing LLCC are examples of cloud-based avoidance criteria. Although they are believed to be very safe, these rules were developed for large orbital boosters like the Titan and the Space Shuttle, and they do produce false alarms and reduce launch availability. Nevertheless, they should be applied to flight operations of the RLVs of interest here until and unless an operational ABFM and/or further statistical analysis of existing ABFM experiments enable some of the rules to be tailored to smaller launch vehicles.

Note that the most important of these rules, *whether an operational ABFM is used or not*, are (A) to avoid all clouds that are producing any type of natural lightning and (B) to avoid cumulus clouds that may become electrified in just a few minutes and could produce natural (or triggered) lightning. Note also that measurements of surface electric fields using a Ground-Based Field-Mill system (GBFM, as opposed to an ABFM) are incorporated into certain of these LLCC, where they are important for both adding safety (detection of additional hazards) and providing some relief from the otherwise very conservative cloud-based rules. It should be emphasized that a GBFM is not a substitute for an ABFM because of the electrical charges on screening layers that can accumulate at cloud boundaries, even if the GBFM system has the necessary areal extent for sensitivity to the clouds of interest.

4. TRIGGERING MODELS

We now briefly review four possible models for predicting the viability of a positive leader, hence a lower bound on the triggering conditions, in classical rocket-triggered lightning. [In this section, we will only consider triggering at altitudes near the surface, *i.e.*, at standard temperature and pressure (STP)]. Two simple models are the following: A) A leader might become viable when the magnitude of the ambient field is larger than the potential gradient found in a DC arc that carries the same current -- only a few kilovolts per meter at typical leader currents of a few Amperes. This is probably a necessary condition, but fortunately for us, it is not sufficient. B) It has also been suggested that triggering can occur when the potential “spanned” by the triggering wire exceeds about 3.5 MV. This might be called the “constant-potential-spanned” criterion. It turns out to be overly simplistic, however, when compared to two more

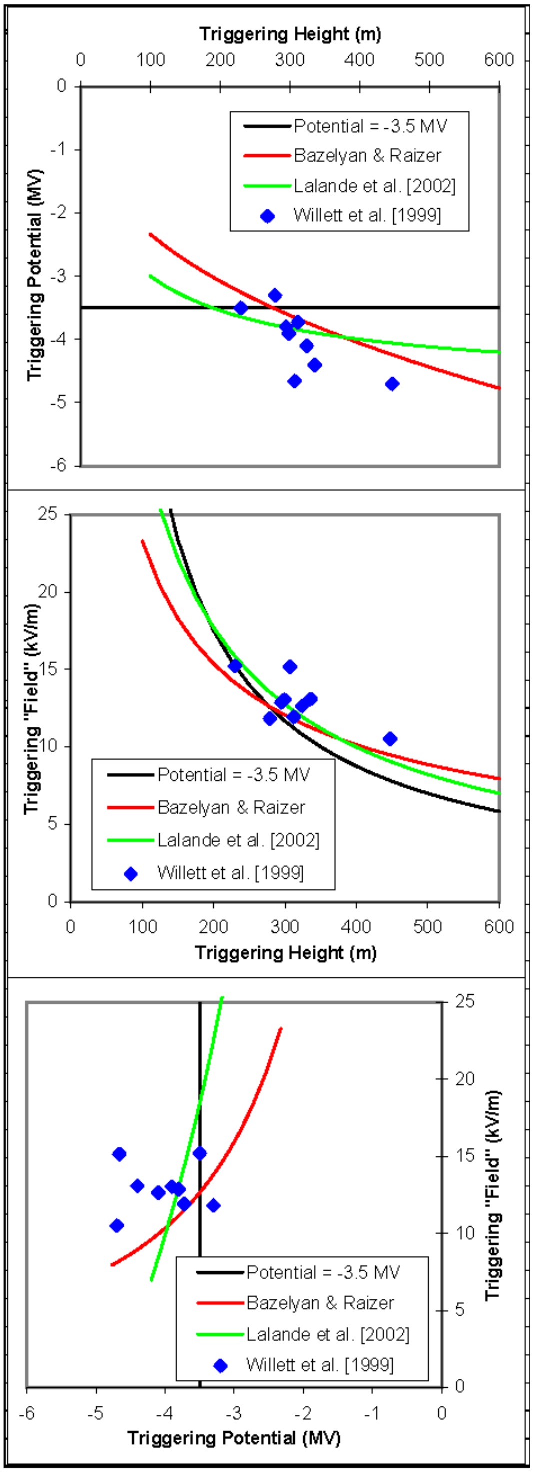

Figure 1. Comparison of the "Constant-Potential-Spanned," Bazelyan and Raizer [2000], and Lalande *et al*. [2002] Positive-Leader Models with the Data of Willett *et al*. [1999].

sophisticated models of leader propagation that cannot be discussed in any detail here.

These two models of the physical development of positive leaders have led to predictions of the ambient field (assumed uniform) *vs*. wire length that is required for a viable upward positive leader in classical, rocket-triggered lightning: C) Aleksandrov *et al*. [2005] have presented a formula corresponding to a model that was developed previously by Bazelyan and Raizer [2000]. D) Lalande *et al*. [2002] gave a comparable formula corresponding to their very different physical model.

In Figure 1 we show the predictions of models B, C, and D, plotted together with the direct measurements of Willett *et al*. [1999]. (Note that we are plotting the average measured electric field between the surface and the triggering height, as opposed to the field *at* the triggering height, because models C and D both assume a uniform ambient field.) The black curves in Figure 1 represent the assumption that a viable positive leader will be initiated whenever the potential spanned by the triggering wire exceeds a constant threshold of 3.5 MV -- model B above. The red curves are for model C of Bazelyan and Raizer, and the green curves are for model D of Lalande *et al*. The data of Willett *et al*. can be seen to agree reasonably well with all three of these models, giving little to recommend one over any of the others. Nevertheless, the relatively limited data available from lightning strikes to instrumented aircraft (not shown) appears to conclusively rule out model B and to favor model C over model D. For this reason, and because the Bazelyan and Raizer model is safer -- it predicts a smaller triggering field for a conductor of any given length in the size range relevant to our RLVs -- we adopt model C for present purposes. Clearly, however, more work needs to be done on the models of triggering and their validation.

5. ALTITUDE AND VELOCITY DEPENDENCE OF TRIGGERING

The altitude dependence of electrical breakdown in long sparks is essentially unknown. The triggering field threshold for any given vehicle might range anywhere from the $p^{3/2}$ dependence on ambient pressure at constant temperature that was found for the positive-streamer "stability field" by Phelps and Griffiths [1976] down to the $p^{1/3}$ dependence that has been measured for DC arc drops [see Raizer, 1991, Fig. 10.15], or even lower. Here we compromise on the p^1 dependence that is implied by Paschen's Law at constant temperature, with the understanding that this behavior is quite uncertain at present.

The vehicle-velocity dependence of triggering is believed to be a threshold that is based on the ion-drift velocity in the geometrically enhanced electric field at the altitude of interest, as originally suggested by Brook *et al*. [1961]. Most estimates of this velocity threshold at STP are lower than the flight speeds of any of the RLVs of interest, except during balloon ascents or the late stages of parachute descents. Given that the small-ion mobility increases with altitude approximately in inverse proportion to air density, our assumption that the triggering field increases in proportion to density suggests that the threshold speed may be approximately altitude-independent.

6. FIVE VEHICLE TYPES AND TWO SPACEPORTS

6.1 Representative Suborbital Vehicle Concepts

In order to determine the electric fields that could trigger lightning to suborbital vehicles, the types of vehicles and their trajectories must be known. Because this information is difficult to obtain or unavailable for the five suborbital vehicle concepts being considered, representative vehicle configurations were developed that closely resemble the currently proposed suborbital vehicle concepts. The five vehicle configurations are described below.

1) Horizontal takeoff and landing (HTHL) vehicle with jet engines and rocket engines. This vehicle takes off using jet engines and proceeds to an airborne launch point, where it then climbs to apogee using rocket power and glides to a landing on a runway. It is similar to the Rocketplane “XP” concept.
2) Ferried and horizontal landing vehicle with rocket engines (referred to as “Air Launch vehicle”). The vehicle is carried aloft to the drop point by a carrier aircraft where it is released and climbs to apogee using rocket power, and glides to a landing on a runway. It is similar to the Scaled Composites “SpaceShipOne” concept.
3) HTHL vehicle with rocket engines. This vehicle takes off using rocket engines, climbs to apogee using rocket power, and glides to a landing on a runway. It is similar to the XCOR Aerospace “Xerus” concept.
4) Vertical takeoff and landing (VTVL) vehicle with rocket engines. This vehicle takes off vertically using rocket engines, coasts to apogee, and lands by rocket-powered descent, similar to the Armadillo Aerospace “Black Armadillo” concept.
5) Balloon takeoff-carrying launch vehicle to altitude. At altitude, the vehicle will climb to apogee using rocket power and lands using a parachute landing system. It is similar to the DaVinci Project’s “Wild Fire” concept.

Table 1 presents information on each of the five vehicles that was used to perform triggered lightning analyses.

6.2 Spaceports

New Mexico has proposed to establish the Southwest Regional Spaceport near Upham, New Mexico, approximately 45 miles north of Las Cruces and 30 miles east of Truth or Consequences. This location is along the western boundary of the White Sands Missile Range, and will benefit from the controlled airspace around the Missile Range. The proposed Spaceport will encompass a 27 square mile site consisting of open, generally level, range land with an average elevation of 4700 ft. The plans for the Spaceport facility call for a launch complex, a landing strip and aviation complex, a payload assembly complex, a support facilities complex, and a system development complex.

The Oklahoma Spaceport is being developed at the Clinton-Sherman Industrial Airpark at Burns Flat, Oklahoma, approximately 100 miles west of Oklahoma City. The Clinton-Sherman Airpark encompasses approximately 3,000 acres and has two runways of 13,500 ft and 5,200 ft. The Spaceport has an operational control tower and an instrument landing system (ILS) capability that can support a full range of aircraft operations. The Spaceport has multiple commercial-size hangars that can accommodate multiple suborbital vehicle companies, and has adequate access to air, ground, and rail transportation modes. The spaceport also has access to manufacturing facilities and the facilities of Oklahoma’s Western Technology Center, and will coordinate all suborbital flights from its spaceport operations center, which is under development. Current plans are for the Oklahoma Spaceport to be operational in 2006.

Table 1. Representative Vehicle Design Information

Vehicle Number	1	2	3	4	5
Vehicle Type	HTHL w/ Jet Engines	Air Launch	HTHL w/ Rocket Engines	VTVL	Balloon Launch
Vehicle Length	40.0 ft	21.2 ft	24.3 ft	23.2 ft	18.0 ft
Vehicle Wingspan	25.0 ft	14.4 ft	17.0 ft	N/A	N/A
Vehicle Diameter	5.0 ft	5.0 ft	5.0 ft	5.0 ft	5.0 ft
Nose Radius of Curvature	1.7 ft	4.2 ft	4.2 ft	2.0 ft	3.0 ft
Vehicle Gross Weight	18,000 lb	9,103 lb	13,276 lb	10,724 lb	8,500 lb
Fuel Type	JP-1 and RP-1	Rubber	RP-1	Ethanol	RP-1
Oxidizer Type	Liquid Oxygen	Nitrous Oxide	Liquid Oxygen	Liquid Oxygen	Liquid Oxygen
Rocket Sea Level Thrust (total)	23,800 lb	10,500 lb	13,300 lb	14,500 lb	10,000 lb
Engine Firing Altitude	24,000 ft	50,000 ft	0 ft	0 ft	"80,000 ft"
Engine Burnout Altitude	150,000 ft	173,000 ft	144,000 ft	114,000 ft	"206,000 ft"
Rocket Burn Time	74.4 sec	96.7 sec	145.1 sec	85.0 sec	"100 sec"
Total Flight Time	1537.4 sec (25.6 min)	973.8 sec (16.2 min)	914.7 sec (15.2 min)	869.7 sec (14.5 min)	"90 - 110 min"
Furthest Distance from Takeoff Site	36 nmi	28 nmi	12 nmi	14 nmi	"10 - 100 km, depending on winds"

7. ESTIMATION OF VEHICLE PLUME LENGTHS

The electrical conductivity of a plume is primarily a function of the electron density; the particle content might also be a secondary factor. The electron density is strongly dependent on the temperature and the presence of easily ionized trace species, mainly sodium and potassium compounds in the fuel. Soot particles are produced by the combustion of hydrocarbon fuels such as JP-1 and RP-1 with liquid oxygen or nitrogen/ oxygen compounds used as oxidizers. One possible effect of these particles might be the thermionic production of electrons consequent to their reaction with entrained air. (Temperatures in the mixing layer of O_2/RP-1 plumes generally reach about 2400 K at low altitudes, hundreds of degrees hotter than the exhaust at the nozzle exit.) The governing plume parameter in triggering lightning is assumed to be an effective length, to be combined with a vehicle body length. The question is how to define an effective plume length with respect to the electrical conductivity.

There are a number of ways in which an effective plume length might be estimated. One method might be to use the distance along the axis where the temperature drops to a specified value. A more casual definition might be simply to use the visible length of the plume, but this would be highly subjective because, in photography, the visible length will depend on both the exposure and the degree of halation of the film. Visible plume lengths are also functions of the concentrations of soot that produce most of the visible radiation. (An O_2/ethanol plume is virtually invisible in daylight.) However the plume lengths are defined, they also vary strongly with the engine size, *i.e.*, with thrust or mass flow of propellants, and with the nozzle configuration. The nozzle expansion ratio governs the exit pressure, and the maximum propulsive efficiency occurs with the pressure matched to the ambient conditions. In practice, the expansion ratio is optimized for some intermediate altitude in the missile flight.

Here we base our estimates of the conducting lengths of RLV plumes on (A) the visible plume length scaled from two video images of SpaceShipOne during a test flight and (B) scaling to the other vehicles in proportion to the square root of engine thrust, on the assumption of single nozzles with the same expansion ratios and fuel-oxidizer mixtures in all cases. (The value for the Titan IV was scaled in a similar way from video images of that vehicle.) We further assume that (C) these plumes are all under-expanded throughout the altitude range of interest for triggered lightning (roughly 0 - 10 km), so that their lengths do not change much with altitude. Obviously the results, given in the third column of Table 2, are quite uncertain in terms of the actual conductive lengths of these plumes.

The overall electrical effective length of each vehicle during the boost phase has been estimated in the last column of Table 2 as one half of the sum of vehicle length plus conducting plume length. For a long, thin, uncharged conductor of actual length equal to that sum, this value of electrical effective length, when multiplied by the ambient-field magnitude (assumed uniform and parallel to the conductor's long dimension), would give the correct potential difference between each tip of the conductor and the nearby ambient atmosphere. Nevertheless, the proper value of electrical effective length to use in the Bazelyan and Raizer model might range from something less than half the vehicle length (if the plume actually has no effect at all) to as much as the sum of vehicle plus plume length (if the tip of the conducting plume acts as a potential equalizer), so this value is also quite uncertain.

Table 2. Estimated Plume Lengths

System	Vehicle length, m	Conducting plume length, m	Electrical effective length, m
Concept 1	12.2	29	21
Concept 2	6.5	13	10
Concept 3	7.4	16	12
Concept 4	7.1	18	13
Concept 5	5.5	12	9
Titan IV	60	300	180

8. TRIGGERING CONDITIONS

The ambient electric-field thresholds that are required for triggering have been estimated for each of the concept RLVs (except the concept 5 spacecraft, for reasons that are discussed briefly below) at two altitudes, 0 and 10 km, both during boost phase (with the exhaust plume) and during landing (without the plume). These thresholds are summarized and compared with similar estimates for the Titan IV in Table 3. Triggering conditions during the glide phase have not been given for the concept 4 vehicle because this vehicle is designed to land vertically, breaking first with a parachute and then with its rocket motor. Thus, the exhaust plume may play a role during landing as well as during launch.

Table 3. Estimated Electric Fields for Triggering

System	Boost Phase		Glide Phase	
	Surface, kV/m	10 km, kV/m	Surface, kV/m	10 km, kV/m
Concept 1	60	20	125	42
Concept 2	93	31	182	61
Concept 3	83	28	169	56
Concept 4	79	26	--	--
Concept 5	--	--	--	--
Titan IV	16	5	--	--

Although these field thresholds are quite uncertain in absolute terms, they should be reasonably comparable between vehicles at the same altitude. Thus, they do provide a quantitative basis for the following three conclusions:

A) For vehicles that are designed for unpowered horizontal landings (concept vehicles 1, 2, and 3), there is a significant increase in triggering threshold (or, qualitatively, a reduction in the likelihood of lightning strikes) during the glide phase of the flight.

B) During the glide phase, these three concept RLVs have higher triggering thresholds than those of medium-sized aircraft (which have been measured to be on the order of 45 kV/m at 4 - 5 km altitudes).

C) Not surprisingly, each concept RLV has much higher triggering fields than the Titan IV. This is typical for large, orbital boosters that the current LLCC have been designed to address.

The following additional conclusion is less certain because conventional aircraft do not have electrically significant exhaust plumes and, consequently, are not strictly comparable to space vehicles during the boost phase:

D) Although concept 1, the largest vehicle, has an appreciably lower triggering threshold as compared to the other concepts; during boost phase they are all comparable to the triggered-lightning threshold of medium-sized aircraft.

Our last conclusion is not based on quantitative triggering conditions, but rather on the balloon-launched nature of the 5th concept RLV:

E) Launch conditions for the concept 5 vehicle will have to be even more rigorous than specified by the current LLCC because of the large balloon that is required to lift the vehicle to 80,000 ft. altitude before ignition. Wind shear, turbulence, and icing must all be avoided, in addition to lightning. Therefore, we do not believe that triggered-lightning conditions, nor even the LLCC, are relevant in this case.

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