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LIGHTNING STRIKE PEAK CURRENT PROBABILITIES AS RELATED TO SPACE SHUTTLE OPERATIONS

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ABSTRACT

A summary is presented of basic lightning characteristics/criteria applicable to current and future aerospace vehicles. The paper provides estimates on the probability of occurrence of a 200 kA peak lightning return current, should lightning strike an aerospace vehicle in various operational phases, i.e., roll-out, on-pad, launch, reenter/land, and return-to-launch site. A literature search was conducted for previous work concerning occurrence and measurement of peak lightning currents, modeling, and estimating the probabilities of launch vehicles/objects being struck by lightning. This paper presents a summary of these results.

INTRODUCTION

Lightning continues to be a topic of concern for the launch of aerospace vehicles, especially those launched from the USAF's Eastern Range and NASA's Kennedy Space Center in Florida. The significance of this concern developed with the lightning incident associated with the launch of Apollo 12 in 1969 (Durrett 1976). In 1987 the Atlas/Centaur 67 accident drew additional attention to the subject (Busse 1987). Launch Commit Criteria relative to lightning conditions have undergone several stages of review and enhancement with the latest version being implemented in 1998 (Roeder, et al. 1999).

This paper addresses a recent study of lightning characteristics and strike peak current probability estimates based on measurement information documented in the literature over the past couple decades. The motivation for this study was the concern about potential lightning risks relative to the incorporation of a new avionics unit on the Space Shuttle. The study addresses questions concerning lightning risks, and provides a summary of the information available on the subject. The results may have broader applications for other aerospace vehicles being designed for launch from the USAF and NASA sites at Cape Canaveral, FL.

LIGHTNING CHARACTERISTICS

On a cloudless day, the potential electrical gradient in the atmosphere near the surface of the Earth is relatively low (less than 300 V/m). When clouds develop, the potential gradient near the surface of the Earth increases as water droplets of sufficient

size develop. The potential gradient may then result in a lightning discharge, i.e., gradients greater than 10,000 v/m at the surface.

A variety of charge separation processes occur at microphysical and cloud-size scales and vary in importance depending on the developmental stage of convective clouds (Beard and Ochs, 1983). It has been suggested that both induction and interface charging are the primary electrification mechanisms in convective clouds (Leteinturier, 1990). Inductive charging involves bouncing collisions between particles in the external field. The amount of charge transferred between the polarized drops at the moment of collision depends on the time of contact, contact angle, charge realization time, and net charge on the particles. Interface charging involves the transfer of charge due to contact or freezing potentials that develop during the collisions between riming precipitation particles and ice crystals. The sign and magnitude of the charge transfer depends on the temperature, liquid water content, and ice crystal size and impact velocity.

Gradients may be considerably higher with altitude than just above the surface. The Earth-ionospheric system is considered a large capacitor with the Earth's surface the negatively charged plate, the ionosphere the positive plate, and the atmosphere the dielectric.

When a cloud develops into the cumulonimbus state, lightning discharges result. For a discharge to occur, the potential gradient at a location reaches a value equal to the critical breakdown value of air at that location. Laboratory data indicate this value is as high as one million v/m at standard sea-level atmospheric pressure. Electrical fields measured at the surface of the Earth are much lower than one million v/m during lightning discharges. The measured electrical field at the Earth's surface is limited by discharge currents arising from grounded points, such as grass, trees and structures, which ionize the air around the points thus producing screen space charges.

Lightning is a secondary effect of electrification within a thunderstorm cloud system. It is a giant electrical spark that can have a peak current flow greater than 200,000 amperes during a period of a few microseconds. Thunder results from the sudden heating of the air to about 20,000 K by the flow of current along a narrow channel. This flow can be from cloud to ground with several individual strokes separated by a tenth of a second. Or it can be from cloud to cloud strokes that diffusely illuminate the cloud. Strokes can also be from cloud to an aircraft or aerospace vehicle operating in the vicinity.

When lightning strikes a protected or unprotected object, such as an aerospace vehicle on the launch pad, the current flows through a path to true Earth ground. The voltage drop along this path may be great enough over a short distance to be dangerous to people and equipment.

A static charge may accumulate on an aerospace vehicle from its motion through an atmosphere containing raindrops, ice particles, or dust. A stationary object, if not grounded, can also accumulate a charge from small windborne particles, or rain, or snow particles striking the object. This charge can build up until the local electric field at the point of sharpest curvature exceeds the breakdown field and triggers a lightning discharge. The quantity of maximum charge depends on the size and shape of the object.

If a charge builds up on a non-grounded structure, any discharge could ignite explosive gases or fuels, interfere with radio communications or telemetry, or cause severe shocks to people. Static electrical charges occur more frequently during periods of low humidity and may occur at any geographical area.

Lightning protection assessment and design consideration are critical functions in the design and development of an aerospace vehicle. The project's engineer responsible for lightning must be involved in preliminary design and remain an integral member of the design and development team throughout vehicle construction and verification tests. For an overview of the guidelines to be considered for an adequate lightning protection design see Goodloe (1999).

STATEMENT OF PROBLEM

The NASA Johnson Space Center (JSC) Shuttle Systems Integration Office requested probabilities for three peak lightning strike currents (i.e., 200 kA, 100 kA and 50 kA) if the Space Transportation System (STS) was hit by a lightning cloud-to-ground (CG) return stroke during roll-out, on-pad, and for triggering lightning on ascent. This is Question A. The Shuttle Program needed this STS lightning design criteria guidelines for a new STS avionics box. Question B asked, was if all lightning launch commit criteria (LCC) rules are followed, what is the probability of a 200 kA, 100 kA, and 50 kA peak current lightning strike if the STS is hit while in the launch/ascent phase? This paper responds to these questions. Annual probabilities are expressed in percent and in terms of a mean return period (RP) in years. Currents are expressed in kiloamps (kA).

RESPONSE

Table 1 is the response to these questions.

Table 1. KSC Maximum Current Probabilities

Question A:

For Roll-Out To Pad (during evening hours, with no forecasting considered):

| Lightning Peak Current: | >200kA | | >100kA | | >50kA | |
|-------------------------|----------------|--------------|----------------|--------------|----------------|--------------|
| Point Probability: | <u>Prob. %</u> | <u>RP_yr</u> | <u>Prob. %</u> | <u>RP_yr</u> | <u>Prob. %</u> | <u>RP_yr</u> |
| Worst Case | 0.00218 | 45,963 | 0.00590 | 16,934 | 0.01150 | 8,696 |
| KSC SLC40 | 0.000037 | 2,681,000 | 0.00031 | 322,000 | 0.00404 | 24,749 |

For On-Pad (STS protected by Pad Lightning System):

| Lightning Peak Current: | >200kA | | >100kA | | >50kA | |
|-------------------------|----------------|--------------|----------------|--------------|----------------|--------------|
| On-pad Point Probab: | <u>Prob. %</u> | <u>RP_yr</u> | <u>Prob. %</u> | <u>RP_yr</u> | <u>Prob. %</u> | <u>RP_yr</u> |
| Worst Case | 0.00226 | 44,220 | 0.06138 | 1,629 | 0.11953 | 837 |
| KSC SLC40 | 0.00039 | 258,000 | 0.00323 | 30,954 | 0.04200 | 2,381 |

For Launch (Lightning triggered by vehicle): (See Section 4.5 - Vehicle Triggered Lightning)

| Lightning Peak Current: | >200kA | | >100kA | | >50kA | |
|-------------------------|----------------|--------------|----------------|--------------|----------------|--------------|
| Point Probability: | <u>Prob. %</u> | <u>RP_yr</u> | <u>Prob. %</u> | <u>RP_yr</u> | <u>Prob. %</u> | <u>RP_yr</u> |
| Worst Case | | TBD | | TBD | | TBD |
| KSC SLC40 | | TBD | | TBD | | TBD |

Question B:

For Launch (STS protected by LCC storm distance rule only):

| Lightning Peak Current: | >200kA | | >100kA | | >50kA | |
|-------------------------|----------------|--------------|----------------|--------------|----------------|--------------|
| Point Probability: | <u>Prob. %</u> | <u>RP_yr</u> | <u>Prob. %</u> | <u>RP_yr</u> | <u>Prob. %</u> | <u>RP_yr</u> |
| Worst Case | 0.000304 | 329,000 | 0.000825 | 121,000 | 0.00161 | 62,274 |

RATIONALE FOR RESPONSE**BACKGROUND**

NASA documents that reference natural lightning criteria and current lightning models used in the STS program have been published (Bankson 1991, Johnson 1993, NSTS 1998, Roeder, et.al., 1999). However, no document completely answers the questions concerning the probability of peak return stroke current magnitudes possible. Hence, a literature search for lightning statistics and procedures produced five reports dealing with lightning probabilities that can be applied to the Florida/KSC/Pad area. These were used for this study. They are (Stahmann 1991), (Mach 1989), (Chai 1997), (Santis 1998), and (Gabrielson 1988). The following three key general references were consulted regarding extreme lightning peak current cumulative percentage frequencies (CPF). (Uman 1987), (Volland 1995), and (Fisher 1990). A technical summary of the KSC references (Stahmann, Mach, & Chai) follows. An in-depth analysis of this literature search is in an upcoming NASA research publication (Johnson and Vaughan 1999).

KSC AREA/PAD LIGHTNING

The lightning protection system (LPS) at KSC's Pad 39A has been struck by lightning an average of 3 times per year since 1979 (Stahmann 1991). Stahmann's theoretical probability calculations for lightning striking the 122 m (400 ft) tower is 2.0 strokes/yr.,

producing an average peak current amplitude of 122 kA with all calculations based on a pad stroke density of 20 strokes/km²/yr.

Six years (1990-1995) of CG Lightning Surveillance System (CGLSS) measurements for Cape Canaveral Space Launch Complex 40 (SLC 40) were analyzed and published (Chai 1997). Chai's paper presents a summary of ~6200 CG events occurring within 5 nmi of SLC 40. The absolute maximum peak current measured was -284 kA (negative), the positive current peak was +144 kA. The 5-year total mean current peak was ~30.5 kA (with a SD value of ~14.5 kA). The associated negative mean peak current was -30.9 kA and the positive was +23.3 kA. Of the 6186 flashes; 94.5% of the flashes measured were negative, and 5.5% positive. Also, 91% of flashes occurred from June through September and 9% from October through May. Only three SLC 40 flashes carried current > 200 kA (i.e., -284 kA, -281 kA, and -203 kA; all negative). These strikes ranged from 1.9 to 4.9 nmi from SLC 40. The probability for natural lightning current >200 kA to occur within 5 nmi of SLC 40 per year is estimated to be 0.0513% (or 1 event in ~1,950 yrs.) (Chai 1997). This is an "area" probability, not a "point" probability. A plot of the lightning peak current cpf for SLC 40 is shown in figure 1 (200 kA peak current ~99.9 percentile), along with peak current global estimates by other investigators.

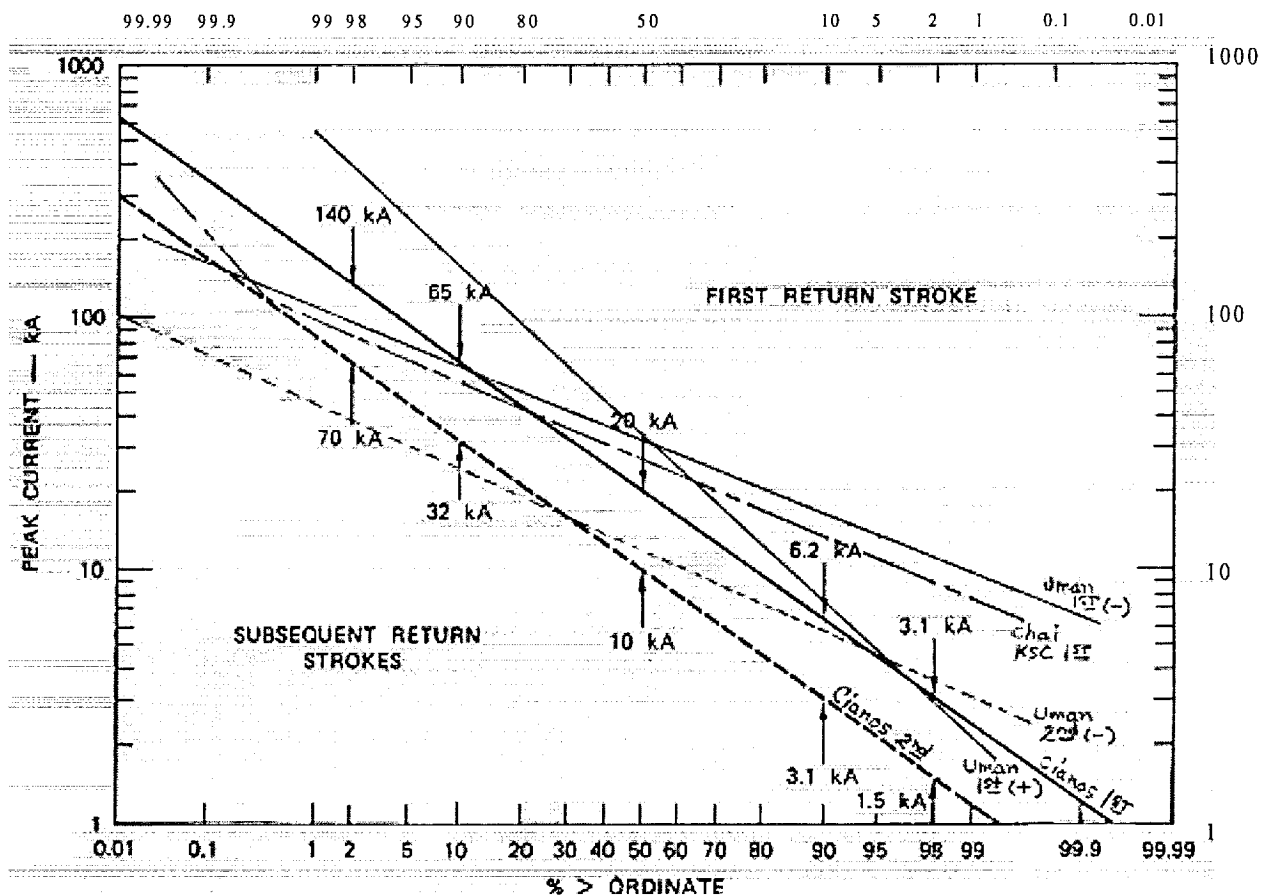


Figure 1. Distribution of peak currents for first return stroke and subsequent strokes (Cianos 1972, Uman 1987 and Chai 1997)

Mach's paper entitled: "Shuttle Lightning Threat Analysis" (Mach 1989), gave lightning probability estimates for various Shuttle operational phases. Mach emphasized all his probabilities are estimates and can be in error by more than an order of magnitude. In addition, his estimates do not take into account all possible pathways for lightning to damage STS systems. The three operational phases analyzed in his paper are roll-out, on-pad, and launch.

For roll-out, high current damage (~200 kA) to the Solid Rocket Booster (SRB) and continuing-current to the External Tank (ET) provide the greatest possibilities for major Shuttle damage (Mach 1989). The estimated probability for lightning damage to an SRB is 1 in 3,200,000 years (or 3.1×10^{-7}). For ET damage is 1 in 55,000 years (or 1.9×10^{-5}).

On-pad it is estimated the lightning protection system's (LPS) catenary wire will shield the STS from ~97.2% of all pad area strikes (i.e., ~2.8% not diverted), (Mach 1989). If there are ~1.8 pad strikes/yr, and each STS spends ~2 weeks on the pad, Mach calculated the probability for potential SRB damage from lightning as 9.5×10^{-5} (RP=11,000 yrs). The probability for potential ET damage is 5.6×10^{-3} (RP=178 yrs). Therefore, the maximum estimated probability of a lightning strike of "any" current magnitude hitting the STS directly while protected on the pad is 0.028 (2.8%). Mike Maier of Patrick AFB/CSR stated, "Since 1990, the NASA OTV (operational television) has documented two direct strikes to the pad structure which have bypassed the catenary wire LPS. Neither event resulted in a strike to the vehicle; one struck the GOX (gaseous oxygen) vent arm, and the other the far corner of the partially retracted RSS (rotating service structure)." (Maier, 1998 personal communication.).

On the boost-phase of launch the estimated probability of the STS vehicle and exhaust intercepting a "natural" (not triggered) lightning flash from a nearby storm was calculated assuming the following conditions: a low flash rate (1/min) to a high flash rate (60/min), distance from the storm edge of 2 nmi, 5 nmi and 10 nmi standoffs, ascent time of ~50 s, and 8 launches per year. Mach's probability estimates are presented in table 2.

Table 2. Probability Estimates for Natural CG Lightning to Strike STS on Launch:*

| Exposure Time t(sec.) | Standoff From Storm Edge(nmi) | Storm Severity Flash Rate(min-1) | Probability per yr.(%) | Probability RP(yrs) |
|--------------------------|----------------------------------|-------------------------------------|---------------------------|------------------------|
| 50 | 2 | high = 60 | 0.625 | 160 |
| 50 | 5 (LCC) | avg . = 6 | 0.00434 | 23,000 |
| 50 | 10 (LCC) | low = 1 | 0.00007 | 1,300,000 |
| 50 | 10 (LCC) | high = 60 | 0.00434 | 23,000 |

* assuming 8 STS launches per year (Mach, 1989)

RP = mean return period (yrs.) LCC = launch commit criteria.

If Shuttle lightning launch commit criteria (LCC) are followed during countdown/launch, the estimated probability of the STS being struck by any magnitude

lightning is 1 in 23,000 (or 0.0043%). The only LCC rule applied herein is the 5- and 10- nautical mile limit to thunderstorms (NSTS-16007). Not included are triggered lightning from anvils, cloud thickness, ceiling, and other LCC rules.

PROBABILITY FOR A >200 kA ETC. CURRENT STRIKE

Question A:

The three references (Stahmann 1991, Chai 1997, Mach 1989) provided the main statistics to develop the conclusions arrived at in this section. To estimate the probability for “any” peak current strike to the STS, the highest probability of lightning intercepting the STS (either on-pad (2.8%) or in-flight (0.0043%)) was applied. Multiplying the average strikes to pad per year (3.0) x probability of lightning striking the STS (0.028) x 2-week pad exposure (0.03846 yr) gives:

$$3.0 \times 0.028 \times 0.03846 = 0.00323 \text{ strikes/yr} \quad (1)$$

or (0.323% or RP=310 yr)

This estimated probability includes “all” possible strike currents. To estimate the probability of >200 kA, >100 kA, or >50 kA strike, the most representative peak current cpf was used. The probability of strong CG negative and stronger CG positive lightning currents was applied (not the lower current triggered lightning current probabilities). The “Lightning Protection of Aircraft” (Fisher 1990) used the older 1972 Cianos peak current plot (figure 1), which gives <140 kA current at the 98th percentile; Lightning peak currents fit a log-normal probability distribution well (Fisher 1990). Uman’s peak current summary curves of first return stroke peak current cpf for both negative and positive flashes (Uman 1987) and Chai’s KSC Pad 40 peak current cpf (Chai 1997) are shown in figure 1. There is still some disagreement about these exact peak current statistics (Uman 1987). Figure 1 indicates these differences.

Uman’s first return stroke peak current has a median value in the range 20 to 40 kA (median ~30 kA for negative flashes and ~35 kA for positive strokes) with <200 kA occurring at about the 99% level. The Uman 95th percentile negative first stroke peak current is <80 kA, while for positive first strokes is <250 kA. With exception of Uman’s positive stroke curve, the more recent cpf current plots seem to parallel each other, and slope differently from the standard, 1972 Cianos plots. Table 3 presents the various extreme probabilities for a <200, <100, and <50 kA peak return stroke CG lightning current given by Uman, Cianos, and Chai.

Table 3. Estimated Cumulative Percentage Frequencies (CPF) of <200kA <100kA and <50kA Peak Lightning Current Occurrences (Extracted from Figure 1)

| <u>Peak Current</u> | <u>Uman87 Positive</u> | <u>Cianos72 1st Return</u> | <u>Uman87 1st Negative</u> | <u>Chai97 1st Return</u> |
|---------------------|----------------------------|---|---|---|
| <200kA | 93.0% | 99.35% | 99.98% | 99.88% |
| <100kA | 81.0% | 95.6% | 98.2% | 99.0% |
| <50kA | 63.0% | 84.0% | 80.0% | 87.0% |
| | (Worst Case) | (Standard Case) | | (KSC Case) |

One could use any of the first return stroke peak current estimated cpf curves of figure 1 for negative or positive strokes, and apply them for the KSC area. This answers Question A. However, the Chai KSC CGLSS Pad 40 lightning current estimated cpf values may be more applicable/realistic for the SLC 39 area, and were used in this study.

Maier provided insight to the lightning climatology at SLC 40 compared to Pad 39. He stated: "The situation around 39A and 39B is almost the same. We have found the two Shuttle pads are exposed to slightly higher flash densities than the Titan pads, since they are a bit farther north and closer to the mean "storm track" which extends ENE from the local lightning frequency maximum west of KSC. However, the peak current distributions don't seem to have any significant (at least within our area) spatial variations so the Cape area distribution would apply." (Maier 1998 personal communication).

Therefore, using the Chai lightning current statistics at SLC 40 to represent the Pad 39 area, we can assume a <200 kA return stroke peak current at the 99.88% level (table 3). Multiplying the equation 1 value by 0.0012 (0.12% is the probability of >200 kA), we calculate a probability of 0.000388% (or RP=258,000 yr). This provides a response to Question A. However, the worst-case situation might arise if a rare, strong, positive current lightning strike occurs at KSC generating much higher currents. If the Uman positive stroke curve applies to KSC, the table 3 worst-case probability of 93.0% for a <200 kA peak current would be used with equation 1. We then would arrive at a resulting worst-case probability of 0.00226% (or RP=44,220 yr) for a >200 kA current event. This is a more conservative answer to Question A (a greater factor of safety). Probabilities for occurrence of peak lightning stroke currents >100 kA and >50 kA are similarly computed (table 1).

Question B:

To answer Question B the Mach report (Mach 1989) probabilities (table 2) were applied directly to the worst-case cpf values. The main assumptions are that the lightning 5- and 10- n mi storm distance LCC rules used, and then only CG (not triggered) lightning is assumed.

Therefore, in calculating the point probability that the STS would get struck "naturally" on ascent by a >200 kA lightning induced peak current, multiply the table 2 probability

(0.00434) for “any” current, by the worst-case probability (0.07), to compute a resultant vehicle-hit probability of 0.0003038% (or RP= 1 in 329,164 yr).

STS ROLL OUT RISK

To calculate the probability of a ≥ 200 kA current lightning strike to the STS during roll-out, the following assumptions were used. The height of the Shuttle atop the mobile launching platform (MLP) and crawler is ~235 feet (72 m agl). The horizontal dimensions of the MLP are 135 ft x160 ft giving an ~21,600 ft² (~2007 m²) striking area. The ground/terrain is assumed flat for the ~6-hour trip over the 4.2-mile distance from VAB to Pad 39B.

The first item to determine is what is the probability of “any” magnitude lightning strike (str) to hit “any” square area (A) on the ground (between the VAB and Pad 39) of 2007 m², using the KSC annual flash density (f) of 20 strikes/km²/yr? Assuming a poisson distribution (Santis 1998), the probability that any flat surface area will be hit by any magnitude lightning in a certain number of years is:

$$Y(\text{yrs}) = 1/(A \times f), \quad (\text{Santis 1998}). \quad (2)$$

Therefore: $Y = 24.91$ yr/str, or $P_{\text{yr}} = 0.04014$ str/yr, (or 4.01%). However, to calculate the resultant probability of a ≥ 200 kA current strike at KSC, apply the table 3 worst case probability (0.070) with other key parameters (i.e., elevated vehicle, worst month, a 6-hr exposure period, and best diurnal time to roll out).

For an elevated object of height 235 ft, Viemeister presents a strike/height chart (Fig. 50 Viemeister, 1972) for an isolated tower or object to 600 feet tall (on level terrain), located in a moderate (30 thunderstorm days/yr) lightning environment. The probability of a lightning strike given in the chart is directly related to height. An object 235 ft. tall will be hit twice as often as an object 117 ft. tall. Viemeister’s strike value for 235-ft height is 1.0 lightning strikes/yr. Since the KSC area has more thunderstorm days (76) than Viemeister’s 30, this strike value of 1.0 is multiplied by 2.533 (76/30) resulting in 2.533 strikes per year. This figure is close to reality because elevated Pad 39 gets hit directly by lightning ~ 2 to 3 times per year as indicated earlier (Stahmann 1991). Therefore:

$$P_{(\text{yr.elev})} = (0.04014 \text{ str/yr}) \times (2.533) = 0.10167 \text{ str/yr}, \\ (\text{or } P_{(\text{yr.elev})} = 10.17\%). \quad (3)$$

This yearly probability should be converted to a monthly probability. Dividing by 12 gives

$$P_{(\text{mo.elev})} = 0.008473, \quad (\text{or } P_{(\text{mo.elev})} = 0.847\%). \quad (4)$$

Now the remaining parameters can be applied to this probability value:

- (1) To obtain a ≥ 200 kA current for the worst case (table 3), use 0.070.
- (2) For “any” 6-hr exposure period during a month, an exposure period of 6/720 = 0.008333 month is used.

- (3) Since the roll-out vehicle should be exposed during the peak lightning season, July KSC data is used. The average monthly KSC thunderstorm days is ~6.333 (KSC July averages ~16.0), giving a factor of $16/6.33 = 2.53$ applying to July (Mailander 1990).
- (4) Finally, assume that the STS will be rolled out during the 6-hour time frame when thunderstorm activity is minimal, i.e., between 0200 and 0900 LST when the probability of July KSC thunderstorm occurrence is ~1.0% (Golde 1977). The July KSC probability peaks at ~23% at 1600 LST. Since The average KSC July hourly thunderstorm probability is ~6.9%, a factor of $1.0/6.9 = 0.145$ is applied during the early morning hours for conservative roll-out purposes.

The “final” resultant probability combines all four above mentioned procedures.

$$P_{(mo.elev)} = 0.008473 \times 0.07 \times 0.008333 \times 2.53 \times 0.145 = 0.000001813 \text{ str/mo.} \quad (5)$$

Converting this probability back to an annual value results in a yearly probability and return period.

$$P_{(yr.elev)} = 0.002176\%, \text{ and } (45,963 \text{ yrs/str}). \quad (6)$$

Computed lightning current estimated probability values associated with STS roll-out for ≥ 200 kA, ≥ 100 kA, and ≥ 50 kA, using table 3 worst-case and KSC/SLC40 conditions, are presented in table 2.

Note: If the Shuttle roll-out did not occur during the evening hours, but during the peak July afternoon hours, the resultant nominal probabilities for a ≥ 200 kA and ≥ 50 kA lightning strike are 0.04% (RP = 2,508 yr), and 0.21% (RP = 475 yr), respectively. Thus it does matter “when” the Shuttle is rolled out.

VEHICLE TRIGGERED LIGHTNING

If the STS vehicle is launched under LCC storm distance rules, Mach has given a “non-triggered”, natural CG lightning hit probability estimate of 0.00434 (23,000 yrs).

Since the peak stroke current measurements from the KSC rocket-triggered program is 99 kA (Jafferis 1995), this seems to follow the subsequent peak current curve for return strokes (of half the value of an initial return stroke current). Using the Cianos subsequent-stroke curve (figure 1) for estimating the < 200 kA, < 100 kA and < 50 kA triggered current cpf’s, one derives ~99.94%, ~99.35%, and ~96.2%, respectively. This implies a 0.06% risk would have to be applied (multiplied) to the probability of a rising vehicle triggering a > 200 kA stroke at KSC. But this ascent-triggered probability has not yet been determined. See next paragraph for more insight concerning ascent vehicle triggered lightning.

An ascent vehicle-triggered lightning probability can be “implied” (Gabrielson, 1988). Gabrielson calculated a probability for any lightning strike to directly hit a standing 10-m tall vehicle on the ground during moderate storm/lightning conditions, to be

$$P_d = 2.9 \times 10^{-9}, \text{ and } (RP = 3.45 \times 10^{+8} \text{ yrs}) \quad (7)$$

He based his probability estimate of either a direct strike (P_d) or a nearby strike (P_n) on thunderstorm day data only. The probability is estimated using three independent parameters - flash density (fD), vulnerability area (A_v), and exposure time (t), i.e., $P_d = fD \times A_v \times t$. Gabrielson neglected exposure time in calculating P_d .

Gabrielson also calculated the probability of any nearby (within 10 km of the vehicle) vehicle-triggered lightning strike during flight, resulting in either a cloud-to-cloud or cloud-to-ground discharge. In this second case, Gabrielson kept all inputs the same except he assumed the presence of exhaust gases after launch extends the vehicle's effective height 10 times, thereby affecting the vulnerability area. Also, he included an additional 5% to the calculated flash density to account for discharges (inter-cloud) triggered on non-stormy days. Vehicle exposure time during ascent was assumed to be 50 seconds. The nearby strike threat estimate (probability) for this vehicle ascent case is:

$$P_n = 4.06 \times 10^{-4}, \quad (\text{RP} = 2,463. \text{ yrs}) \quad (8)$$

Note that this resultant probability value is still a very conservative, small probability of occurrence, compared to the reality at KSC of two major vehicle triggered strikes (Apollo 12 and the Atlas-Centaur) within ~20 years. However, from these two estimated probabilities one can see that a "nearby" triggered lightning estimate (P_n) for "any" magnitude current strike is approximately 140,000 times greater than the direct hit to a vehicle on the ground estimate (P_d). This is a factor to be considered when launching. Another factor to consider is that KSC test-rocket triggered lightning discharges generally indicate that large currents (>100 kA) are extremely rare compared to natural CG lightning discharge currents.

SUMMARY

KSC "worst case" lightning maximum current probability estimates have been summarized, based on an analysis of published information on subject. Table 1 presents the "KSC SLC40" results.

Answer to Question A is the estimated probability of 0.00226% (or a RP of 1 in 44,220 yr) for a ≥ 200 kA peak lightning strike current occurring to the STS vehicle, while protected on the pad.

Answer to Question B is the estimated probability of 0.0003038% (or a RP of 1 in 329,000 yr) for a ≥ 200 kA peak natural lightning current occurring on or near the launched STS while following (only) the lightning LCC distance to storm rule. Other lightning LCC rules such as anvil, thick cloud, ceiling, etc. are not applied here.

Answer to the question regarding Roll-Out is the estimated probability of 0.00218% (or a RP of 1 in 45,963 yr) for a ≥ 200 kA peak lightning strike current occurring during roll out, and exposed for 6 hours during the worst KSC lightning month (July), during the most lightning inactive time of day (night hours). Weather forecasting is not considered here. In reality a weather forecast always precedes an STS roll-out at KSC. The best-condition real-time forecast still allows for a ~10% chance of lightning strike.

Answer to the question regarding Launch-Triggered Lightning is that the estimated probability for a ≥ 200 kA lightning strike current occurring has not yet been determined. However, a "triggering" factor (a factor of 140,000 increase in probability and RP) was determined from one case found in the literature, and will be looked into further to see how it might apply.

Lightning strike possibilities to the STS vehicle exist during Shuttle exposure at locations other than KSC. While on the Edwards AFB runway for up to a week and while flying atop the Boeing 747 aircraft on the trip back to KSC (must fly with no clouds or adverse weather present). These two operational categories were not dealt with in this paper.

The probabilities given in this paper are only estimates and may be greatly in error (author's and Mach 1989). This paper is based on an oral presentation given at the Eighth American Meteorological Society Conference on Aviation, Range, and Aerospace Meteorology, held January 1999 in Dallas, TX.

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