NASA/TM—2000–210131

Analysis and Assessment of Peak Lightning Current Probabilities at the NASA Kennedy Space Center

D.L. Johnson
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

W.W. Vaughan
University of Alabama in Huntsville, Huntsville, Alabama

May 1999

The NASA STI Program Office…in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results…even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at (301) 621–0134

- Telephone the NASA Access Help Desk at (301) 621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2000–210131

Analysis and Assessment of Peak Lightning Current Probabilities at the NASA Kennedy Space Center

D.L. Johnson
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

W.W. Vaughan
University of Alabama in Huntsville, Huntsville, Alabama

National Aeronautics and
Space Administration

Marshall Space Flight Center • MSFC, Alabama 35812

May 1999

Acknowledgments

We acknowledge Hugh Christian, Douglas Mach, William Koshak, Dennis Boccippio, and their MSFC Global Hydrology and Climate Center colleagues for advice, references, inputs, and reviews of the lightning probability section of this report. Also appreciated are inputs and comments by Dawn Trout, Carolyn Goodloe, Tony Clark, Steve Pearson, O.E. Smith, and Stanley Adelfang of the MSFC Electromagnetics and Aerospace Environments Branch (EL23). Thanks go to our NASA Kennedy Space Center (KSC) colleague, John Madura at the KSC Weather Office, Michael Maier of Computer Sciences Raytheon at Patrick Air Force Base, Wayne Ordway at NASA Johnson Space Center, and Mark Stanley at New Mexico Institute of Technology, Socorro, NM, for their comments, encouragement, and help. Special thanks to Margaret Alexander/EL23 for editing the draft and to Belinda Hardin, Member of Technical Staff (Associate, CSC) for processing the manuscript.

Credit

Page ix: National Aeronautics and Space Administration photograph: Powerful electrical storm near NASA Kennedy Space Center launch complex 39A prior to launch of STS–8, August 30, 1983.

Available from:

NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076–1320
(301) 621–0390

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
(703) 487–4650

PREFACE

This report presents a summary of lightning characteristics and lightning criteria for the protection of aerospace vehicles and probability estimates for certain lightning strikes (peak currents of 200, 100, and 50 kA) applicable to three operational phases of the Space Transportation System (STS) vehicle at the NASA Kennedy Space Center, Florida. Presented are results of an extensive literature search to compile information others developed for this area in order to answer key lightning current questions posed by the Space Shuttle Program Office at the Johnson Space Center. Vehicle-triggered lightning probability estimates for the various lightning current categories are still being worked. Section 4.5, however, provides some insight on this subject.

TABLE OF CONTENTS

1. INTRODUCTION 1

2. LIGHTNING STRIKE PROBABILITY QUESTIONS 3

3. RESPONSE 4

4. RATIONALE 5

   4.1 Background 5
   4.2 KSC Area and Pad Lightning 5
   4.3 Probability for A >200, >100, and >50 kA Current Strike 7
   4.4 STS Vehicle Rollout Risk 9
   4.5 STS Vehicle-Triggered Lightning 10

5. CONCLUSIONS 12

APPENDIX A—Literature Search 13

   A.1 Lightning and Current Statistics 13
   A.2 Positive Lightning 13
   A.3 Positive Superstrokes 14
   A.4 NLDN Statistics 14
   A.5 Sprites From Positive Flashes 14
   A.6 Sprites Observed Over KSC 16

APPENDIX B—Space Shuttle Lightning Launch Commit Criteria 18

REFERENCES 25

BIBLIOGRAPHY 29

LIST OF FIGURES

1. Distribution of peak currents for first return stroke and subsequent strokes 6

LIST OF TABLES

1. Probability estimates for natural CG lightning to strike STS vehicle during launch 7

2. Estimated CPF's from figure 1 of <200, <100, and <50 kA peak lightning current occurrences 8

ACRONYMS

AFB	Air Force Base
CC	continuing current; cloud to cloud
CG	cloud to ground
CGLSS	cloud-to-ground lightning surveillance system
CPF	cumulative percentage frequency
CSC	Computer Sciences Corporation
EDT	eastern daylight time
EL23	Electromagnetics and Aerospace Environments Branch
ENE	East Northeast
ET	external tank
GBFM	ground-based field mills
IC	in-cloud
JSC	Johnson Space Center
KSC	Kennedy Space Center
LCC	launch commit criteria
LPC	large peak currents
LPS	Lightning Protection System
LST	local standard time
MCS	mesoscale convective systems
MLP	mobile launch platform
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NLDN	National Lightning Detection Network
NSTS	National Space Transportation System
OTV	operational television
RP	return period (mean)
RSS	rotating service structure
SAE	Society of Automotive Engineers
SD	standard deviation
SLC	space launch complex
SRB	solid rocket booster
STS	Space Transportation System
TBD	to be determined
TBP	to be published
TL	triggered lightning
TM	technical memorandum
U.S.	United States
UTC	coordinated universal time
VAB	vehicle assembly building

SYMBOLS AND ABBREVIATIONS

≈	approximately
A	Area
A_v	vulnerability area
av	average
elev	elevation
f or fD	flash density
ft	feet
h	hour
K	Kelvin
kA	kilo amp
km	kilometer
m	meter
M	mega
min	minute
nm	nautical mile
P, PROB	probability
P_d	direct strike
P_n	nearby strike
s	second
str	lightning strike
t	exposure time
V/m	volts per meter
wk	week
Y, yr	year

Powerful electrical storm near NASA Kennedy Space Center launch complex 39A prior to launch of STS–8, August 30, 1983.

TECHNICAL MEMORANDUM

ANALYSIS AND ASSESSMENT OF PEAK LIGHTNING CURRENT PROBABILITIES AT THE NASA KENNEDY SPACE CENTER

1. INTRODUCTION

On a cloudless day the electrical potential gradient in the atmosphere near the surface of the Earth is relatively low (<300 V/m); but when clouds develop, this gradient increases. If the clouds become large enough to have water droplets of sufficient size to produce rain, the atmospheric potential gradient may result in a lightning discharge.

A variety of charge separation processes occurs at microphysical and cloud-size scales.[1] These processes vary in importance depending on the developmental stage of convective clouds. It has been suggested, however, that both induction and interface charging are the primary electrification mechanisms in convective clouds.[2] 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 (no charge transferred at grazing collisions), charge relaxation time, and net charge on particles. Interface charging involves the transfer of charge due to contact or freezing potentials during collisions between rimming precipitation particles and ice crystals. Sign and magnitude of the charge transfer depend on the temperature, liquid water content, and ice crystal size and impact velocity.

The Earth-ionospheric system can be considered a large capacitor with the surface of the Earth the negatively charged plate, the ionosphere the positively charged 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 a value as high as 1M V/m at standard sea level atmospheric pressure. Electrical fields measured at the surface of the Earth during lightning discharges are much lower than 1M V/m. Reasons include the following:

1. Most clouds have centers of both polarities that tend to neutralize values measured at the surface.

2. Each charge in the atmosphere and its image within the Earth resembles an electrical dipole. The intensity of the electrical field decreases with the cube of the distance from the dipole.

3. The atmospheric electric field measured over land at the surface of the Earth is limited by discharge currents which arise from grounded points such as grass, trees, and other structures that ionize the air around the points and produce screen space charges.

Lightning, a secondary effect of electrification within a thunderstorm cloud system, is a giant electrical spark that can have a peak current flow >200 000 A during a few microseconds.

Thunder results from sudden heating of the air to ≈20 000 K by the flow of current along a narrow channel. This flow of current can be from cloud to ground (CG) as several individual strokes separated by a tenth of a second. It can be from cloud to cloud (CC) in strokes not readily visible from the ground but which diffusely illuminate the cloud. The flow can also be from cloud through an aircraft or aerospace vehicle operating in the vicinity. About 1 800 thunderstorms are active over the surface of the Earth at any given time. Lightning strikes the Earth ≈100 times per second.

When lightning strikes a protected or unprotected object such as an aerospace vehicle on a launch pad, the current flows through a path to true ground. The voltage drop along this path may be great enough over a short distance to be dangerous to people and equipment. While standing under a tree struck by lightning, cattle and humans have been electrocuted by the current flow through the ground and the voltage potential between their feet.

A static charge may accumulate on an object such as an aerospace vehicle from its motion through an atmosphere containing raindrops, ice particles, or dust. A stationary object, if not grounded, can accumulate a charge from windborne particles (often invisible nuclei), rain, or snow particles striking the object. This charge can build 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 (especially sharp points on the structure).

If a charge builds on a structure not grounded, discharges could ignite explosive gases or fuels, interfere with radio communications or telemetry, or cause severe shocks to people. Static electrical charges occur most frequently during periods of low humidity in any geographical area.

Lightning protection assessment and design considerations are critical and important functions in the development and design of an aerospace vehicle. The project lighting protection engineer must be involved in preliminary design and remain an integral member of the design and development team until construction of the vehicle is completed and all verification tests are accomplished. A National Aeronautics and Space Administration (NASA) technical memorandum (TM) provides guidelines and an overview of considerations for an adequate lightning protection design.[3]

This TM presents a summary of the probability of peak lightning strike currents to the NASA Space Shuttle during rollout, on-pad, and boost/launch phases at the Kennedy Space Center (KSC).

2. LIGHTNING STRIKE PROBABILITY QUESTIONS

The NASA Johnson Space Center (JSC) Shuttle Systems Integration Office requested the Electromagnetics and Aerospace Environments Branch (EL23) of the Marshall Space Flight Center (MSFC) to provide probabilities for three peak lightning strike currents (i.e., 200, 100, and 50 kA) which could occur if the Space Transportation System (STS) vehicle is hit by a lightning CG return stroke during rollout, while on-pad, and for triggered lightning on ascent. This is referred to as question A. The answer to this question is needed in order to provide lightning criteria applicable to a new STS avionics box. Question B asked if all lightning launch commit criteria (LCC) rules are followed, what is the probability of a 200, 100, and 50 kA peak current lightning strike while the STS vehicle is in the boost/launch phase. The response given in this technical memorandum provides estimates for these questions. Annual probabilities are expressed in percent and mean return period (RP) in years. Currents are expressed in kiloamps (kA). The launch site is KSC space launch complex 39 (SLC 39).

3. RESPONSE

Question A:

Rollout to pad (evening hours, no forecasting considered)

Lightning Peak Current	>200 kA		>100 kA		>50 kA	
Point Probability	Prob %	RP yr	Prob %	RP yr	Prob %	RP yr
Worst Case	0.002 180	45 963	0.005 90	16 934	0.011 500	8 696
KSC SLC 40	0.000 037	2 681 000	0.000 31	322 000	0.004 040	24 749

On-pad (STS vehicle protected by pad Lightning Protection System (LPS)

Lightning Peak Current	>200 kA		>100 kA		>50 kA	
Point Probability	Prob %	RP yr	Prob %	RP yr	Prob %	RP yr
Worst Case	0.002 260	44 220	0.061 38	1 629	0.119 53	837
KSC SLC 40	0.000 390	258 000	0.003 23	30 954	0.042 00	2 381

Launch (lightning triggered by vehicle) (see sec. 4.5 STS Vehicle-Triggered Lightning)

Lightning Peak Current	>200 kA		>100 kA		>50 kA	
Point Probability	Prob %	RP yr	Prob %	RP yr	Prob %	RP yr
Worst Case	TBD		TBD		TBD	
KSC SLC 40	TBD		TBD		TBD	

Question B:

Launch (STS protected by LCC storm distance rule only)

Lightning Peak Current	>200 kA		>100 kA		>50 kA	
Point Probability	Prob %	RP yr	Prob %	RP yr	Prob %	RP yr
KSC SLC 40	0.000 304	329 000	0.008 250	121 000	0.001 610	62 274

4. RATIONAL

4.1 Background

Lightning statistics and procedures from five published reports dealing with lightning probabilities and the Florida/KSC/pad area are presented in this report.[4–8] Two key general references were consulted regarding extreme lightning peak current cumulative percentage frequencies (CPF).[9,10] A technical summary using three key KSC references (Stahman, Mach, and Chai) is given in section 4.2.[5–7] Appendix A presents additional information from the literature on CG lightning stroke peak current characteristics and statistics.

4.2 KSC Area and Pad Lightning

Since 1979 the Lightning Protection System (LPS) on SLC 39A at KSC was struck by lightning an average of three times per year.[5] Stahmann's theoretical probability calculations for lightning striking the 122-m (400-ft) tower are two strokes per year and produce an average peak current amplitude of 122 kA.[5] All calculations were based on a pad stroke density of 20 strokes/km^2/yr.

Six years (1990 to 1995) of CG lightning surveillance system (CGLSS) measurements for Cape Canaveral SLC 40 were analyzed and published by Chai.[7] His paper presents a summary of ≈ 6 200 CG events at or near (within 5 nmi) 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 (standard deviation (SD) value ≈14.5 kA). The associated negative mean peak current was –30.9 kA; the positive was 23.3 kA. A plot of the lightning peak current CPF for SLC 40 is shown in figure 1 (200 kA peak current ≈ 99.9 percentile). Of the 6 186 flashes, 94.5 percent were negative and 5.5 percent positive. Also, 91 percent of the flashes occurred from June through September and 9 percent from October through May. Only three SLC 40 the flashes carried current >200 kA (i.e., –284, –281, and –203 kA). 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 0.051 30 percent (1 event in ≈1 950 yr).[7] This is an "area" probability and not a "point" probability.

A paper entitled "Shuttle Lightning Threat Analysis" by Mach gave lightning probability estimates for various Space Shuttle operational phases.[6] Mach emphasized all his probabilities are estimates and could be in error by more than an order of magnitude. In addition, his estimates do not account for all possible pathways for lightning to damage the STS systems.[6] The three operational phases in his paper of main interest in this report are rollout, on-pad, and launch.

During rollout, high current (200 kA) damage to the solid rocket booster (SRB) and continuing current (CC) to the external tank (ET) are the greatest possibilities for major Space Shuttle damage.[6] The probability for lightning damage to the SRB is 1 in 3 200 00 yr (or 3.1×10^{-7}) and to the ET, 1 in 55 000 yr (or 1.9×10^{-5}).

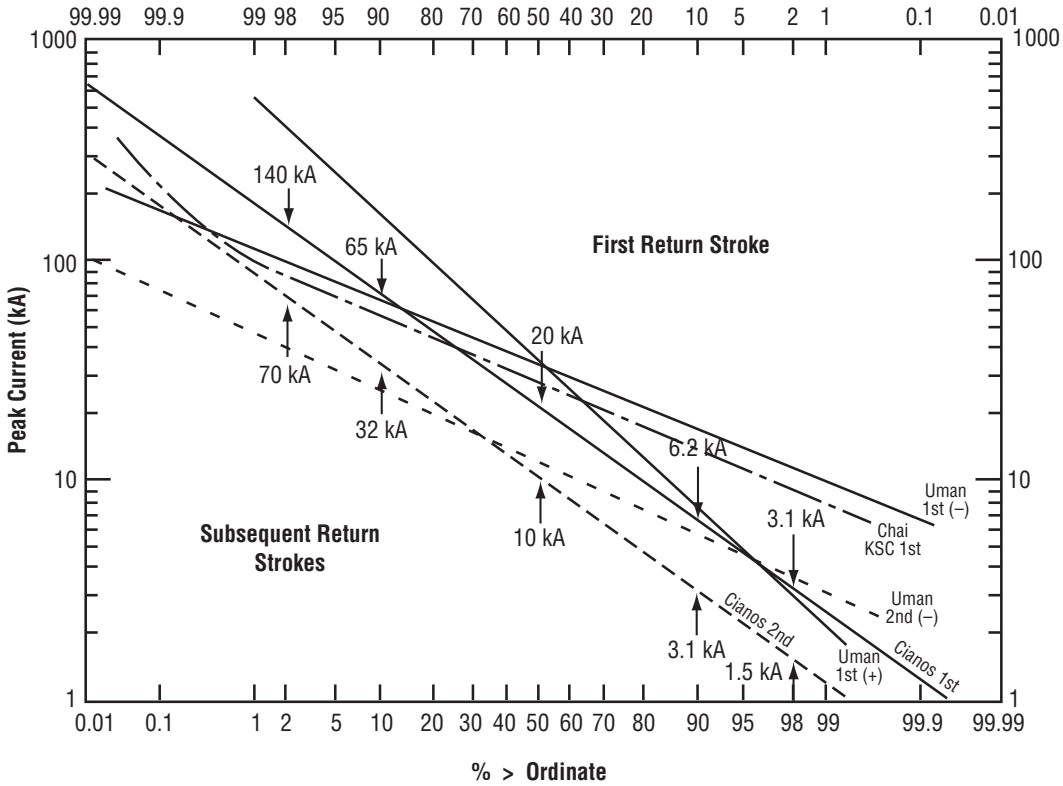

Figure 1. Distribution of peak currents for first return stroke and subsequent strokes.[7,9,12]

While on-pad, it is estimated the LPS catenary wire shields the STS from ≈97.2 percent of all pad area strikes, with ≈2.8 percent not diverted.[6] Mach calculated if there are ≈1.8 pad str/year and each STS spends ≈2 weeks on-pad, the probability for SRB damage from lightning is 9.5×10^{-5} (RP=11 000 yr) and for ET damage is 5.6×10^{-3} (RP=178 yr). Therefore, the maximum probability of a lightning strike of "any" current magnitude hitting the STS directly, while protected on the pad, is 0.028 (2.8 percent) per year. Mike Maier of Patrick Air Force Base (AFB)/Computer Sciences Raytheon stated: "Since 1990, the NASA operational television (OTV) has two documented direct strikes to the pad structure which bypassed the catenary wire LPS. Neither event resulted in a strike to the vehicle; one struck the gaseous oxygen vent arm and the other the far corner of the partially retracted rotating service structure (RSS)."

In the boost phase of launch the probability of the STS vehicle and exhaust intercepting a "natural" (not triggered) lightning flash from a nearby storm was calculated assuming a low flash rate (1/min) to a high flash rate (60/min), distance from the storm edge of 2, 5, and 10 nmi standoffs, ascent time ≈50 s, and eight launches per year. Mach's resulting probability estimates are presented in table 1.[6]

If Space Shuttle LCC regarding natural lightning are followed during countdown and launch, the estimated probability of the STS being struck by "any" magnitude lightning is 1 in 23 000 (0.004 30 percent). The only LCC rule applied here is the 5- and 10-nmi limit to thunderstorms.[11] Not included here are triggered lightning from anvils, cloud thickness and ceiling, and other LCC rules. See appendix B for lightning LCC rules.

Table 1. Probability estimates for natural CG lightning to strike STS vehicle during launch*

Exposure Time t (sec)	Standoff From Storm Edge (nmi)	Storm Severity Flash Rate (min^{-1})	Probability Per Year (%)	Probability RP (yr)
50	2	High = 60	0.625 00	160
50	5 (LCC)	Avg = 6	0.004 34	23 000
50	10 (LCC)	Low = 1	0.000 07	1 300 000
50	10 (LCC)	High = 60	0.004 34	23 000

*Assuming eight STS launches per year (Mach)[6]

4.3 Probability for A >200, >100, and >50 kA Current Strike

Question A:

The three references mentioned in section 4.1 provided the main statistics to develop the conclusions in this section.[5–7] To estimate the probability for "any" peak current strike to the STS, use the higher probability of lightning intercepting the STS (either on-pad 2.8 percent or in-flight 0.004 30 percent). Since the on-pad STS strike probability is higher, multiply the average strikes to pad per year (3) by the probability of lightning striking the STS (0.028) by the 2-week pad exposure (0.038 46 yr). Results are

$$3\times0.028\times0.03846 = 0.00323 \text{ str/yr} \quad \text{or} \quad (0.323 \text{ percent and RP=310 yr}) \tag{1}$$

This estimated probability includes "all" possible strike magnitude currents. To estimate the probability of a >200, >100, or >50 kA strike, the proper (most representative) peak current CPF is used. The probability of strong CG negative lightning and stronger CG positive lightning currents was applied (but not the lower current-triggered lightning current probabilities). In the 1990 "Lightning Protection of Aircraft," Fisher used the old 1972 Cianos peak current plot (fig. 1) and gave 140 kA current at the 98 percentile.[10,12] Lightning peak currents fit a log-normal probability distribution well.[10,13] Uman's peak current summary curves of first return stroke peak current CPF for both negative and positive flashes and Chai's SLC 40 peak current CPF are also shown in figure 1.[7,9] Much disagreement exists as to which lightning peak current probability curve to use.[9]

Uman's first return stroke peak current has a range of 20 to 40 kA with median value of ≈30 kA for negative flashes and ≈35 kA for positive flashes and <200 kA occurring at the ≈99 percentile level. The Uman 95 percentile negative first stroke peak current is <80 kA and the positive first stroke is <250 kA.[9] 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.[12] Table 2 presents the various extreme probabilities for a <200, <100, and <50 kA peak return stroke CG lightning current by the various investigators.

For the KSC area, use any of the first return stroke peak current CPF curves in figure 1 for negative (and the higher magnitude positive) strokes. This partially answers question A. The Chai CGLSS/SLC pad 40 lightning current statistics, however, may be more applicable and realistic for the SLC 39 area.

Table 2. Estimated CPF's from figure 1 of <200, <100, and <50 kA peak lightning current occurrences

Peak Current	Uman87[9] 1st Positive	Cianos72[12] 1st Return	Uman87[9] 1st Negative	Chai97[7] 1st Return
<200 kA	93.0%	99.35%	99.98%	99.88%
<100 kA	81.0%	95.6%	98.2%	99.0%
<50 kA	63.0% (Worst Case)	84.0% (Standard)	80.0%	87.0% (KSC)

Mike Maier made these statements regarding this unique database: "The CGLSS has been very carefully calibrated using both rocket-triggered lightning (from the former NASA experiment) and direct strikes to SLC 39A and SLC 39B. NASA has both shuttle pads instrumented to measure the peak currents, and these data (once its calibration was fixed) have helped corroborate the triggered lightning calibration. This is an absolute unique data set which can be used to provide the most accurate frequency distributions of peak currents for KSC. This data set is also more accurate than the National Lightning Detection Network (NLDN) data since NLDN has performance problems in this area and has undergone major changes over the years, resulting in changes to the distributions. The CGLSS distributions are probably more accurate and the sample sizes are big. Our median values are below the NLDN, but this is because of the historic NLDN detection efficiency biases against the smaller weak flashes."

Maier also compared the lightning climatology at SLC 40 to SLC 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."

In using the Chai lightning current statistics at SLC 40 to represent the SLC 39 area, we assume a <200 kA return stroke peak current at the 99.88 percent level (table 2). Multiply the equation (1) value by 0.001 20 (0.12 percent is the probability of >200 kA) to calculate a probability of 0.000 388 percent (or RP=258 000 yr). This probability of the STS being hit by a lightning strike of >200 kA current also responds to question A. However, the worst-case situation could arise if a strong, positive current lightning strike (associated with a sprite) occurs at KSC (a rare event) and generates much higher currents. If the Uman positive stroke curve applies to the KSC area, the table 2 worst-case probability of 93 percent for a <200 kA peak current is used with equation (1). Then the result is a worst-case probability of 0.002 26 percent (or RP=44 220 yr) for a >200 kA current event. This is the more conservative answer to question A (with a greater built-in safety factor). Probabilities for occurrence of peak lightning stroke currents >100 and >50 kA are similarly computed (sec. 3).

Question B:

To answer question B, the Mach report probabilities (table 1) were applied directly to the worst-case CPF values.[6] Lightning LCC rules applicable to the 5- and 10-nmi storm distances are used and

only natural CG (not triggered) lightning is assumed. Observing LCC storm distance rules to calculate the point probability that the STS would be struck "naturally" on ascent by a >200 kA lightning-induced peak current, multiply the table 1 probability (0.004 34) for "any" current by the worst-case probability (0.07) to compute a resultant vehicle-hit probability of 0.000 303 8 percent (or RP=1 in 329 164 yr).

4.4 STS Vehicle Rollout Risk

To calculate the probability of a 200-kA current lightning strike to the STS during rollout, the following assumptions were used. The height of the Space Shuttle atop the mobile launch platform (MLP) and crawler is ≈235 feet (72 m) above ground level. The horizontal dimensions of the MLP are 135 feet by 160 feet for an ≈21 600 feet^2 (2 007 m^2) strike area. The terrain is assumed flat and level for the ≈6-hr trip over the 4.2-mi distance from the vehicle assembly building (VAB) to pad 39B.

To determine the probability of "any" magnitude lightning strike (str) to "any" square area (A) on the ground (between the VAB and pad 39) of 2 007 m^2, use the KSC annual flash density (f) of 20 strikes/km^2/yr. Assuming a Poisson distribution as indicated by Santis,[8] the probability any flat surface will be hit by any magnitude lightning in a certain number of years is

$$Y\ (\text{yr}) = 1/(A \times f) \tag{2}$$

Hence,

$$Y = 24.91\ \text{yr/str} \quad \text{or} \quad P_{yr} = 0.04014\ \text{str/yr}\ (4.01\%) \tag{3}$$

To calculate the probability of a 200-kA current strike at KSC, apply the table 2 worst-case probability (0.070) with other key parameters (elevated vehicle, worst month, 6-hour exposure period, and best diurnal time to roll out).

For an object 235 feet tall, Viemeister[14] presents a chart (fig. 50) indicating an isolated tower or object up to 600 feet (on level terrain) located in a moderate (30 thunderstorm days/yr) lightning environment has the probability of lightning strikes directly related to height (i.e., an object 235 ft tall will be hit twice as often as a 117-feet object). Viemeister's strike value for 235-ft height is 1 lightning strike per year. Since the KSC area has more thunderstorm days (76) than Viemeister (30), this strike value of 1 is multiplied by 2.533 (76/30) for 2.533 strikes per year. This figure is close to reality because elevated pad 39 is hit directly by lightning approximately two or three times per year.[5] Therefore,

$$P_{(\text{yr elev})} = (0.04014\ \text{str/yr}) \times (2.533) = 0.10167\ \text{str/yr}\ (\text{or}\ P_{(\text{yr elev})} = 10.17\%) \tag{4}$$

Since monthly analysis is needed, this yearly probability is converted to a monthly (any month) probability by dividing by 12 to obtain

$$P_{(\text{mo elev})} = 0.008473 \quad (\text{or}\ P_{(\text{mo elev})} = 0.847\%) \tag{5}$$

Remaining terms are applied to this probability value as follows:

1. To obtain a 200 kA current for the worst case (table 2), use 0.070.

2. Apply this resultant to "any" 6-hour exposure period during a month for an exposure period of 6/720 or 0.008 333 month.

3. The rollout vehicle could be exposed during the peak lightning season (July for KSC). Since the average monthly KSC thunderstorm days is ≈6.333 and KSC July averages ≈16, apply the factor 16/6.33 or 2.53 for July.[15]

4. Assume the Space Shuttle is rolled out during the 6-hr timeframe when thunderstorm activity is minimal; i.e., between 0200 and 0900 LST when the probability of July KSC thunderstorm occurrence is ≈1 percent.[16] The July KSC probability peaks at ≈23 percent at 1600 LST. The average KSC July hourly thunderstorm probability is ≈6.9 percent. Therefore, the factor, 1/6.9 or 0.145, is applied during early morning hours for conservative rollout purposes.

The "final" resultant probability which combines all four of the above procedures is

$$P_{(\text{mo elev})} = 0.008473 \times 0.07 \times 0.008333 \times 2.53 \times 0.145 \text{ or } 0.000001813 \text{ str/mo} \tag{6}$$

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

$$P_{(\text{yr elev})} = 0.002176\% \text{ and RP} = 45\,963 \text{ yr/str} \tag{7}$$

Computed lightning current probability values associated with STS rollout for 200, 100, and 50 kA using table 2 worst-case and SLC 40 conditions are presented in table 1.

If Space Shuttle rollout is not during evening hours but is during peak July afternoon hours, the resultant nominal probabilities for 200 and 50 kA lightning strikes are respectively 0.04 percent (RP=2 508 yr) and 0.21 percent (RP=475 yr); i.e., it does matter "when" the Shuttle is rolled out.

4.5 STS Vehicle-Triggered Lightning

If the STS vehicle is launched under LCC storm distance rules, Mach gives a "nontriggered," natural CG lightning hit probability of 0.004 34 (RP=23 000 yr).[6] The peak stroke current measurement from the KSC rocket-triggered program is 99 kA, which follows the subsequent peak current curve for return strokes (i.e., half the value of an initial return stroke current).[17] Therefore, using the Cianos subsequent stroke curve in figure 1 to estimate the <200, <100, and <50 kA triggered current CPF, the respective probabilities are approximately 99.94, 99.35, and 96.2 percent. This implies a 0.06-percent risk must be applied (multiplied by) to the probability of a rising vehicle triggering a >200 kA stroke at KSC. This ascent-triggered probability is undetermined. However, some information concerning ascent vehicle-triggered lightning follows.

Gabrielson determined that an ascent vehicle-triggered lightning probability can be implied.[4] He calculated a probability for any lightning strike to directly hit a standing 10-m tall vehicle on the ground under moderate storm and lightning conditions by

$$P_d = 2.9\times10^{-9} \text{ and } \mathrm{RP} = 3.45\times10^{8} \text{ yr} \tag{8}$$

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. Hence, $P_d = fD \times A_v \times t$. Gabrielson neglected exposure time in calculating P_d.

Gabrielson then calculated the probability of any nearby (within 10 km of the spacecraft) 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, extending the effective height of the vehicle 10 times and, thereby, affecting the vulnerability area. Gabrielson stated, "As the vehicle rises, the surface area increases significantly causing a large change in the probability prediction."[4] Gabrielson also included an additional five percent to the calculated flash density to account for discharges (intercloud) triggered on nonstormy days. Vehicle exposure time during ascent is assumed to be 50 seconds. The nearby strike threat estimate (probability) for this vehicle ascent case is

$$P_n = 4.06\times10^{-4} \text{ and } \mathrm{RP}=2\,463 \text{ yr} \tag{9}$$

This resultant probability value is still a very conservative, small probability of occurrence when compared to reality at KSC with two major vehicle-triggered strikes (Apollo 12 and Atlas-Centaur) within ≈20 yr. From these two calculated probabilities, a nearby triggered lightning estimate, P_n, for "any" magnitude current strike is ≈140 000 times greater than the direct hit to a vehicle on the ground estimate, P_d, indicating that vehicle-triggered lightning is indeed a launch consideration. Another consideration is that test rocket-triggered lightning discharges measured during summer campaigns generally indicate large currents (>100 kA) at discharge are extremely rare compared to natural CG lightning discharge currents.

5. CONCLUSIONS

Estimates for the JSC questions concerning KSC SLC 39 "worst-case" lightning probabilities for the STS vehicle are determined. Section 3 also presents KSC SLC 40 results.

The answer to JSC question A is the probability of a >200 kA peak lightning current strike to the STS vehicle while protected on-pad is 0.002 26 percent with an RP of 1 in 44 220 yr.

The answer to JSC question B is the probability of a >200 kA peak natural lightning current occurring on or near the launched STS while following the lightning LCC distance to storm rule only is 0.000 303 8 percent with an RP of 1 in 329 000 yr. Other lightning LCC rules such as anvil, thick cloud, ceiling, etc. were not applied.

The answer to the JSC question regarding rollout is the probability of a >200 kA peak lightning current strike to the STS during the 6-hour rollout in the worst KSC lightning month (July) and most lightning inactive time of day (night hours) is 0.002 18 percent with an RP of 1 in 45 963 yr. Man forecasting is not considered here; but at KSC a weather forecast always precedes STS rollout. However, the best condition, real-time forecast still allows for an ≈10 percent chance of any lightning strike.

The answer to the JSC question regarding launch-triggered lightning is that the probability of a >200 kA lightning strike current occurring is undetermined. However, a "triggering" factor of ≈140 000 increase in probability and RP has been determined from one special case in the literature and will be investigated to see if it applies to this question.

Lightning strike possibilities to the STS also exist during space shuttle exposure at locations other than KSC, i.e., on the Edwards AFB runway for up to a week atop the Boeing 747 aircraft during the return trip (no clouds or adverse weather present) to KSC. These operations are not included in this report.

A reminder by the authors and Mach is the concluding probabilities in this report are estimates only and can be greatly in error.[6] To quote Gabrielson, "It is difficult, if not impossible, to establish a probability for lightning strikes with a high level of confidence."[4]

APPENDIX A Literature Search

This appendix presents a summary of key information from the literature on recent CG lightning stroke peak current statistics and its application to this analysis for the STS vehicle at KSC.

A.1 Lightning and Current Statistics

Most lightning discharges produced by summer thunderstorms at KSC originate in the cloud and lower (carry) negative charge to Earth in CG flashes. In-cloud (IC) lightning generally accounts for ≈60 percent of all lightning occurrences with ≈40 percent as CG.[18] However, Boccippio believes that this IC:CG ratio of 3:2 should be lowered. He states, "3:1 to 5:1 ratios are more in line with what the lightning community tends to quote and have been confirmed by recent results from the NASA OTV sensor." Peak currents generated in the first return CG stroke typically are 30 kA and range to a maximum of 250 kA.[9,12,19] Subsequent return strokes are typically one-half (≈15 kA) the initial return stroke. Negative flashes to ground account for ≈90 percent of the total CG's with positive flashes accounting for ≈10 percent. Orville gives values <10 percent positive in summer storms compared to >50 percent positive in winter for an entire year of data over the eastern U.S.[20,21] Fuquay reported only ≈3 percent positive flashes (summertime, Rocky Mountains) and Reap ≈4 percent positive flashes (summer season, entire U.S.).[21] However, a fraction of the positive lightning flashes can involve the highest measured peak currents, more than generated from negative flashes.[10,19,22,23]

A.2 Positive Lightning

Natural CG positive lightning occurrences are responsible for the largest recorded lightning peak currents in the 200 to 300 kA range.[9] Positive lightning can be initiated from tall buildings and towers by an upward-moving leader with no first return stroke of the type associated with downward (CG) initiated flashes.[9,19] Winter thunderstorms, dissipating storms, and rocket-initiated triggered lightning generally bring a higher percentage occurrence of positive charge to ground.[19,21] The occurrence frequency of the positive flashes apparently increases with increasing latitude and elevation or from a low-level cloud base.[19] From available measurements, there is no difference between the currents to towers and those to ground.[9] An interesting conclusion from the 1983 to 1986 Florida triggered lightning studies was all flashes triggered were of the classic type which lowered negative charge.[9] The Florida triggered lightning study in 1990 and in Alabama in 1991 lowered negative charge also and reported a 38 kA peak current measurement.[24] The fact that positive flashes are less common at KSC latitudes is evidenced by Mach's analysis of 130 KSC strokes in 1986. Of these, 86 were negative CG natural, 41 negative triggered, 1 positive triggered, and 2 positive CG natural strokes (97.7 percent negative and 2.3 percent positive). The 86 negative CG strokes had a peak current of 84 kA while the two positive CG strokes had peak current values of 125 kA and 150 kA.[25] Hence, peak positive currents should still be considered. Rocket-triggered flash currents peaked at 60 kA (mean 15 kA) from 1985 to 1987.[26] The entire 1984 to 1991 summer rocket-triggered lightning program at KSC produced only one peak return stroke current of magnitude 99 kA.[17] Artificially triggered lightning strokes are very similar to the subsequent strokes of natural lightning.[24,27] Triggered lightning current strikes to instrumented aircraft have generally been of lower amplitude than natural CG lightning measured at ground level.[9,10]

A.3 Positive Superstrokes

Rare superstrokes do occur.[28] They were measured mainly in winter thunderstorms in Japan with flashes approximately 56 to 94 percent negative.[10,22,23,29,30] Peak current values >250 kA in positive flashes are documented (>270 kA[23]; and 280, 320, and 340 kA[29]; 322 kA with three other observations >300 kA and four observations between 250 and 300 kA[30]). The NLDN data indicated <5 percent of all observations were positive in summer and >50 percent in winter with peak values of positive flash current between 300 and 400 kA from the 1984 to 1985 Northeast U.S. network.[20] The 150-meter meteorological tower at KSC was hit July 19, 1976 by a three-return stroke lightning flash that produced large peak currents. The first stroke of the flash yielded a current between 150 and 640 kA (210 kA calculated). The peak current of the second return stroke was between 200 and 870 kA and the third between 66 and 280 kA.[31]

A.4 NLDN Statistics

Examination of summarized continental U.S. NLDN total (and positive) CG lightning events by Orville, et al. from 1989 through 1995 revealed that the maximum flash density occurs in central Florida and the Midwest.[32,33] Also, the positive CG flash density yearly maximum can occur in central Florida but tends to peak in the Midwest. The annual continental mean percentage of positive CG flashes range from 3.1 to 9.5 percent (average ≈5.1 percent). The summer months exhibit low continental percentages (3 percent in August); winter months show monthly positive CG percentages (to 25 percent in December). The climatology of peak current CG flashes of both polarities was prepared from 14 summer months of NLDN data. The positives were strongly clustered in the High Plains and Upper Midwest. The large negative CG flashes were concentrated in southeast U.S., especially over the waters of the Gulf/Atlantic, including the KSC area.[34] The annual percentage of positive flashes is also <2 percent at the latitude of Florida but near or greater than 25 percent at latitudes of the Upper Midwest, Maine, and along the West Coast. Orville indicated from the NLDN 1988 eastern database that the first stroke mean peak current is a function of latitude. The peak current varies by almost a factor of 2, from 25 kA in New England to 40 to 45 kA in northern Florida.[35] Since the NLDN upgrade in 1994, the mean peak currents of CG flashes decreased (from a preupgrade mean of 37.5 kA over 1989 to 1993 to a 1995 value of 30.2 kA) and the percentage of positive flashes increased. The positive peak current decreased from 54.4 to 31.6 kA.[36] Recently some controversy exists over the NLDN upgrade and resulting statistics. The NLDN database for the entire U.S. and Florida now extends from 1986 through 1995.[33,37] It is interesting that the location of maximum positive CG flash density in the Midwest is geographically in agreement with the reported locations of sprite discharges between cloud tops and the ionosphere.[33]

Large positive CG peak current values measured by the NLDN arise from extrapolated calibration curves (network initially calibrated to ≈80 kA). Therefore, numerical values of these peak currents associated with large positive CG flashes should be treated with extreme caution.

A.5 Sprites From Positive Flashes

In 1995, red sprites were studied in detail.[38,39] Sprites are infrequent, illuminosity features that shoot upward from the top of mature or dissipating midlatitude mesoscale convective systems (MCS). Many times they appeared from anvil up to the ionosphere and were observed from an altitude of ≈40 to

95 km.[40] The MCS regions produced negative CG strokes and positives (with large peak return stroke currents) from the stratiform precipitation regions. In 1994 Boccippio compared the NLDN observations with two days of sprite occurrences in the Midwest. For these storm systems, ≈85 percent of all sprite events coincided with positive CG events and exhibited higher peak (>400 kA) CG current. This is two times greater than the subset of positive CG strokes with no sprites.[41] The sprite peak currents were as much as three times larger than the median negative CG peak current observed during this same period.

Sprites occur in thunderstorm area complexes where the ratio of positive to negative CG lightning is higher than usual.[42] Other ground-based (1993 to 1997) and aircraft research was done in Colorado and over Kansas, Nebraska, Minnesota, the Southeast, etc.[34,40,41] The relationship between sprites, Q-bursts, and positive CG strokes was confirmed and preference established to occur in decaying portions of thunderstorms.[40,42–44] Lyons says the possibility exists that sprite flashes may be hazardous to spacecraft and aircraft.[45] Sprites, however, appear weak compared to the CG strikes, despite being directly related.

The best places in the U.S. to observe sprites are above the northern High Plains and Upper Midwest in a broad belt from Colorado to North Dakota, to Minnesota, and down to Texas. Sprites can occur above strong storms worldwide.[41] Using the CG NLDN climatology, an estimate was made of the chance of the Space Shuttle encountering a sprite (or elve) during descent to KSC. The probability is ≈1 in 100 (higher than the chance of a direct strike by conventional lightning during conditions conducive to thunderstorm activity).[34] All lightning does not produce sprites. Approximately 40 percent of lightning is CG. Only 5 to 10 percent of CG flashes are positives. Of the positive strokes only ≈10 percent create sprites.[18] Sprites are mentioned in this paper because the strongest currents generated from CG lightning strikes appear to be associated with sprite occurrences to the ionosphere. As state-of-the-art sprite research continues, peak CG lightning current extremes and probability of occurrence will be understood better.

Lyons recently presented some interesting U.S. NLDN CG statistics derived from ≈60M CG flashes over 14 summer months (June through September) from 1991 through 1995.[46] CG polarity, diurnal features, multiplicity, and LPC ≥75, ≥200, and ≥400 kA are presented for the entire U.S. and for the central U.S. which coincides with the heart of the sprite belt from 30 to 50 ^{o}N latitude and 88 to 110 ^{o}W longitude.

Lyons concluded the following: The average positive (+) CG peak current for the entire U.S. is 35.5 kA (with a peak occurrence of 580 kA); the average negative (–) CG peak current is 30.4 kA (with a peak occurrence of 957 kA). For the entire U.S. ≈95 percent of all CG flashes are negative in polarity with ≈87 percent LPC –CG's, i.e., CG's ≥75kA. This indicates that the vast majority of "LPC" strokes nationally are negative in polarity. However, for the central U.S. ≈70 percent of all LPC CG's are negative (about 30 percent positive). These positive CG's in the central U.S. constitute ≈67 percent of all national NLDN LPC +CG's. This makes the region one of high positive CG count where sprites occur most frequently. In the central U.S. the occurrence of positive and negative LPC CG's, as a percent of all LPC CG's, is ≈9 and 22 percent, respectively.

In contrast, negative LPC CG's preferentially occur over the coastal waters of the Gulf of Mexico and throughout the southern U.S. Of the ≈1.46M LPC CG's occurring over the southern U.S., including the Atlantic and the Gulf, ≈86 percent are negative with ≈14 percent positive. This national peak region for maximum negative LPC CG activity includes the KSC area.

The large peak current statistics of Lyons still offer a small probability of occurrence. On a national basis, the LPC –CG's (≥75 kA) constitute 2.23 percent of all negatives. However, the LPC +CG's (≥75 kA) represent 7.37 percent of all positives. For LPC CG's ≥200 kA and ≥400 kA, the percentages fall, but LPC +CG's still represent a greater percentage than LPC –CG's. Positive CG's ≥200 kA represent ≈0.08 percent of all LPC +CG's; while negative CG's ≥200 kA represent ≈0.02 percent of all LPC –CG's. For LPC CG's ≥400 kA the probabilities fall to 0.000 44 percent and 0.000 09 percent for positive and negative. The overall U.S. probability of occurrence of CG's (+ or –) ≥75, ≥200, and ≥400 kA is respectively ≈2.46, 0.018, and 0.000 1 percent. Keep in mind these overall probabilities involve only the statistics of lightning strike occurrences, i.e., not the true probability of a lightning stroke with a certain peak current hitting an object. In order to calculate that true probability, additional derivations are necessary.

A.6 Sprites Observed Over KSC

Sprites have been observed over the KSC area. During the 1997 summer field season at KSC, Dr. Mark Stanley of the New Mexico Institute of Technology captured at least four days of sprite data. Dr. Stanley remarked about his measurements: "I was surprised by how many positive CG's I detected during my KSC field program last summer (mid-May to mid-July). However, the ratio of negative CG's to positive CG's was probably still quite high due to the very large numbers of the former." Even Maier indicated: "In the KSC area our data show the largest peak currents are from negative flashes, not positive. However, the frequency distributions for positive flashes show a higher percentage of positives having big currents relative to negatives." According to Maier, positive flashes account for only two to four percent of CG strokes at KSC. A conclusion from this is if the sprite occurrence and positive CG correlation do exist, sprite occurrence should be less in Florida than in the Midwest.

Dr. Stanley also stated: "Most of the sprites that I detected while at KSC were associated with positive CG's, though there may have been at least one which was caused by just an IC. In two years of research I have never detected a sprite which could clearly be associated with a negative CG. As for the magnitude of the positive CG's, I do not have the NLDN data yet. The static electric field change data that I obtained at KSC indicate that positive CG's associated with sprites on June 22 had range-normalized step field changes significantly larger than those of average negative CG's from the same storm. However, the differences were not spectacular, which seems to indicate that these positives were probably all <100 kA. However, I can say something about the continuing currents (CC's) which often follow positive CG's and sometimes negative CG's. My electrostatic field change measurements of CG's clearly indicate that positive CG's are considerably more violent (by at least an order of magnitude) on average than negatives in regard to CC current magnitude. This is, in my opinion, the reason why positive CG's cause sprites and negatives don't. The peak current does not seem to be relevant to whether a particular positive CG will initiate a sprite."

Boccippio used all May through October 1995 NLDN CG data within 1 000 km of KSC to compute diurnal cycles for "positive" CG currents >50, >100, and >200 kA. Data counts were tallied for each hour. For positive flashes >50 and >100 kA, the peak count (>2 000 and >400, respectively) occurs at 0000 UTC (2000 EDT). The minimum count (about 940 and 165, respectively) occurs at 0600 UTC (0200 EDT). This indicates diurnal amplitude modulation is a factor of ≈two for positive strokes near KSC. The diurnal cycle for peak positive CG currents >200 kA was less discernible due to the small sample size (count between 7 and 32 over 24 hours).

Diurnal positive CG KSC results by Boccippio differ with the diurnal results of Santis.[8] However, Santis used the total NLDN database (positives and negatives) for the entire U.S. between June 12, 1996, and October 9, 1996. Uniform diurnal cycle of CG strikes by Santis peaked at 1700 EDT (≈13 percent) with a minimum at 1000 EDT (<2 percent).

APPENDIX B Space Shuttle Lightning Launch Commit Criteria

Figure 9.8 in NASA TM 4511 depicts the SAE 1987 current test waveforms for severe direct lightning strikes to the NASA Space Shuttle.[47]

NSTS 16007 LAUNCH COMMIT CRITERIA AND BACKGROUND SSID: WEA–01

4.5 Natural and Triggered Lightning Constraints

NOTICE: ANY CHANGES TO THIS SECTION WILL REQUIRE COORDINATION WITH THE 3OTH AND 45TH SPACE WING RANGE SAFETY OFFICES.

Even when constraints are not violated, if any other hazardous conditions exist, the Launch Weather Officer will report the threat to the Launch Director. The Launch Director may HOLD at any time based on the instability of the weather.

The Launch Weather Officer must have clear and convincing evidence the following constraints are not violated:

A. Do not launch if any type of lightning is detected within 10 nautical miles (nmi) of the flight path within 30 minutes prior to launch, unless the meteorological condition that produced the lightning has moved more than 10 nmi away from the flight path.

NATURAL LIGHTNING IS AN OBVIOUS HAZARD (COMPARED TO VEHICLE TRIGGERED LIGHTNING) AND IS ALSO THE MOST DIRECT EVIDENCE ELECTRIC FIELDS ARE PRESENT WITH SUFFICIENT INTENSITY TO CAUSE TRIGGERED LIGHTNING. THE MEASURED FREQUENCY DISTRIBUTION OF THE DISTANCE BETWEEN SUCCESSIVE FLASHES TO GROUND APPROACHES ZERO NEAR 6 NMI; THUS 10 NMI PROVIDES A SAFETY FACTOR. THE 30-MINUTE TIME PERIOD WITHOUT LIGHTNING INDICATES THE STORM HAS DISSIPATED OR MOVED AWAY. HOWEVER, FORECASTERS MUST STILL REMAIN ALERT FOR REDEVELOPMENT OR FORMATION OF A NEW CELL.

B. Do not launch if the flight path will carry the vehicle:

(1) Through a cumulus cloud with its top between the +5.0 °C and –5.0 °C levels unless:

(a) The cloud is not producing precipitation;

AND

(b) The horizontal distance from the furthest edge of the cloud top to at least one working field mill is less than the altitude of the –5.0 °C level or 3 nmi, whichever is smaller.

AND

(c) All field mill readings within 5 nmi of the flight path are between –100 V/m and +1,000 V/m for the preceding 15 minutes.

(2) Through cumulus clouds with tops higher than the –5.0 °C level.

(3) Through or within 5 nmi (horizontal or vertical) of the nearest edge of cumulus clouds with tops higher than the –10.0 °C level.

(4) Through or within 10 nmi (horizontal or vertical) of the nearest edge of any cumulonimbus or thunderstorm cloud, including nontransparent parts of its anvil.

(5) Through or within 10 nmi (horizontal or vertical) of the nearest edge of a nontransparent detached anvil for the first hour after detachment from the parent thunderstorm or cumulonimbus cloud.

NOTE: Cumulus does not include altocumulus or stratocumulus.

B(l) CUMULUS (CONVECTIVE) CLOUDS CAN DEVELOP AND PRODUCE ELECTRIC CHARGE VERY RAPIDLY. NORMALLY THIS OCCURS WELL ABOVE THE FREEZING LEVEL. HOWEVER, THE +5.0 °C LEVEL WAS SPECIFIED BECAUSE ELECTRIC CHARGE HAS BEEN SPECULATED TO OCCUR IN SOME "WARM" CLOUDS IN THE TROPICS AND BECAUSE CUMULUS CLOUDS CAN BUILD VERY RAPIDLY. CHARGE SUFFICIENT TO TRIGGER LICHTNING IS NORMALLY NOT DETECTED UNTIL THE CLOUD REACHES WELL ABOVE THE –10.0 °C LEVEL. THUS, IF THE CLOUD IS NOT PRODUCING PRECIPITATION (PRECIPITATION IS BELIEVED TO BE A NECESSARY CONDITION FOR CLOUD ELECTRIFICATION) AND THE GROUND-BASED FIELD MILLS ARE NOT MEASURING ELEVATED ELECTRIC FIELDS ASSOCIATED WITH THE ONSET OF CUMULUS CLOUD ELECTRIFICATION, THEN LAUNCH MAY BE PERMITTED THROUGH CLOUDS BELOW THE –5.0 °C LEVEL.

B(2) AS CLOUD TOPS APPROACH –10.0 °C, CHARGE MAY DEVELOP VERY RAPIDLY. THUS, NO LAUNCH IS PERMITTED THROUGH CLOUDS WITH TOPS AT OR ABOVE –5.0 °C.

B(3) CLOUDS WITH TOPS ABOVE –10.0 °C CAN CREATE ELECTRIC FIELDS OUTSIDE THE CLOUD WITH SUFFICIENT STRENGTH TO TRIGGER LIGHTNING. THUS, NO FLIGHT PATH IS PERMITTED WITHIN 5 NMI, HORIZONTALLY OR VERTICALLY, OF CLOUDS FROM –10.0 °C TO –20.0 °C.

B(4) THE MOST DANGEROUS CLOUD IS THE CUMULONIMBUS WHICH TYPICALLY PRODUCES NATURAL LIGHTNING. THUS, THE DISTANCE CRITERION (10 NMI) IS THE SAME AS FOR NATURAL LIGHTNING IN RULE A. DANGEROUS ELECTRIC CHARGE CAN ALSO BE ADVECTED INTO THE HIGH LEVEL ANVIL PRODUCED BY A CUMULONIMBUS CLOUD, THUS THE FLIGHT PATH MUST REMAIN 10 NMI HORIZONTALLY AND VERTICALLY, FROM THE ANVIL.

B(5) SIGNIFICANT CHARGE CAN REMAIN IN AN ANVIL FOR UP TO 1 HOUR AFTER IT DETACHES FROM ITS PARENT SOURCE CLOUD. THUS, THE SAME 10 NMI DISTANCE CRITERION APPLIES AS IN RULE B(4). AFTER 1 HOUR THE DETACHED CLOUD IS TREATED PER RULE F.

C. Do not launch if, for Ranges equipped with a working surface electric field mill network, at any time during the 15 minutes prior to launch time the absolute value of any electric field intensity measurement at the ground is >1,000 V/m within 5 nmi of the flight path unless:

(1) There are no clouds within 10 nmi of the flight path except

(a) Transparent clouds

OR

(b) Clouds with tops below the +5.0 °C level that have not been associated with convective clouds with tops above the –10.0 °C level within the last 3 hours;

AND

(2) A known source of electric field (such as ground fog) that is occurring near the sensor, and that has been previously determined and documented to be benign, is clearly causing the elevated readings. (Documents dated April 3, 1997, defining benign ground fog, smoke, and sunrise effect, and the criteria to evaluate their presence, are located in the 45th Space Wing's Range Weather Operation Instruction 15–3, entitled "Launch Weather Constraint Monitoring, Evaluation, and Reporting Procedures.")

NOTE: For confirmed failure of the surface field mill system, the countdown and launch may continue, since the other lightning LCC completely describe unsafe meteorological conditions.

GROUND-BASED FIELD MILLS (GBFM) JUST MEASURE THE ELECTRIC POTENTIAL AT THE EARTH'S SURFACE. THEY CAN ONLY INFER THE ELECTRIC FIELD IN AND NEAR CLOUDS ALOFT (WHICH PERHAPS DECREASE WITH THE HORIZONTAL DISTANCE CUBED AND THE CHARGE HEIGHT SQUARED); AND THEIR READINGS CAN BE MASKED BY INTERVENING LAYERS OF SPACE CHARGE BETWEEN THE MILLS AND THE CLOUD.

MEASUREMENTS OF CHARGE ALOFT USING AIRCRAFT EQUIPPED WITH FIELD MILLS, AND EXPERIMENTS WITH ROCKETS FIRED INTO CLOUDS TO TRIGGER LIGHTNING, INDICATE GBFM MEASUREMENTS >1,000 V/M CAN BE INDICATIVE OF ELECTRIC FIELDS ALOFT SUFFICIENTLY HIGH TO TRIGGER LIGHTNING.

THERE ARE OTHER NEAR-SURFACE SOURCES OF ELECTRIC CHARGE NOT RELATED TO CHARGE ALOFT; FOR INSTANCE GROUND FOG, SMOKE, POWER LINES, SEA SPRAY, ETC. IF THERE IS NO POSSIBLE SOURCE OF CHARGE ALOFT AND THERE IS A CONFIRMED, DOCUMENTED SOURCE OF NEAR-SURFACE CHARGE, THEN THIS RULE IS NOT VIOLATED.

NOTE: DOCUMENTED MEANS SUFFICIENT DATA HAS BEEN GATHERED ON THE PHENOMENA TO PROPERLY STUDY IT, AND CIRCUMSTANCES CAUSING IT TO BE PRESENT ARE UNDERSTOOD AND WRITTEN IN A TECHNICAL REPORT.

D. Do not launch if the flight path is through a vertically continuous layer of clouds with an overall depth of 4,500 feet or greater where any part of the clouds is located between the 0.0 °C and the –20.0 °C levels.

THIS RULE COVERS STRATIFORM CLOUDS. ELECTRIFICATION PROCESSES PRIMARILY OCCUR WITHIN CLOUDS BETWEEN –0.0 AND –20.0 °C, AND INCREASE WITH INCREASING CLOUD THICKNESS. IF CLOUD LAYERS ARE CONNECTED BY TURRETS, THE CLOUD LAYER DEPTH IS DETERMINED BY MEASURING FROM THE BASE OF THE LOWER CLOUD LAYER TO THE TOP OF THE HIGHER CLOUD LAYER. THE TURRETS INDICATE POSSIBLE CHARGE-PRODUCING CONVECTION, AND THE CHARGE MAY BE ADVECTED INTO THE INDIVIDUAL LAYERS. THUS, AN INDIVIDUAL CLOUD LAYER MAY NOT BE 4,500 FEET THICK BUT THE RULE MAY BE VIOLATED IF TWO LAYERS ARE CONNECTED AND THEIR LAYERS SUM TO 4,500 FEET OR GREATER.

E. Do not launch if the flight path is through any clouds that

(1) Extend to altitudes at or above the 0.0 °C level

AND

(2) Are associated with disturbed weather that is producing moderate (29 dBz) or greater precipitation within 5 nmi of the flight path.

CLOUDS EXTENDING ABOVE THE FREEZING LEVEL AND SUFFICIENTLY ACTIVE TO PRODUCE MODERATE OR GREATER PRECIPITATION CAN ALSO CREATE ELECTRIC CHARGE. THIS CHARGE CAN BE ADVECTED INTO ASSOCIATED CLOUDS AND CAN CREATE ELECTRIC FIELDS AT A DISTANCE. THUS, IF THE PRECIPITATION IS WITHIN 5 NMI, THIS RULE IS VIOLATED.

F. Do not launch if the flight path will carry the vehicle:

(1) Through any nontransparent thunderstorm or cumulonimbus debris cloud during the first 3 hours after the debris cloud formed from the parent cloud.

(2) Within 5 nmi (horizontal or vertical) of the nearest edge of a nontransparent thunderstorm or cumulonimbus debris cloud during the first 3 hours after the debris cloud formed from a parent cloud, UNLESS

(a) There is at least one working field mill within 5 nmi of the debris cloud;

AND

(b) All electric field intensity measurements at the ground are between +1,000 V/m and –1,000 V/m within 5 nmi of the flight path during the 15 minutes preceding the launch time;

AND

(c) The maximum radar return from the entire debris cloud is <10 dBz during the 15 minutes preceeding launch time.

(3) The start of the 3-hour period is reckoned as follows:

(a) Detachment—if the cloud detaches from the parent cloud: The 3-hour period begins at the time when cloud detachment is observed or at the time of the last detected lightning discharge (if any) from the detached debris cloud, whichever is later.

(b) Decay or detachment uncertain—if it is not known whether the cloud is detached or the debris cloud forms from the decay of the parent cloud: The 3-hour period begins at the time when the parent cloud top decays to below the altitude of the –10.0 °C level, or at the time of the last detected lightning discharge (if any) from the parent cloud or debris cloud, whichever is later.

CLOUDS PRODUCED BY CUMULONIMBUS AND THUNDERSTORMS CAN RETAIN THEIR CHARGE EVEN AFTER THE PARENT STORM HAS DECAYED AND STOPPED PRODUCING CHARGE, OR AFTER THE CLOUD HAS BROKEN AWAY FROM THE CHARGE SOURCE. AIRBORNE FIELD MILL MEASUREMENTS SUGGEST MOST OF THE CHARGE HAS DECAYED WITHIN 90 MINUTES. HOWEVER, THE CRITERION WAS SET AT 3 HOURS DUE TO THE UNCERTAINTY REGARDING THE START OF THE CLOUD DECAY OR CLOUD BREAKOFF TIME, AND THE POSSIBILITY OF BRIEF INTERNAL CHARGE GENERATION WITHIN THE CLOUD EVEN AFTER BREAKING OFF FROM THE PARENT CLOUD.

SINCE NEGLIGIBLE RADAR RETURNS AND BENIGN GBFM READINGS INDICATE THE CLOUD IS NOT PRODUCING CHARGE, AND ANY RESIDUAL CHARGE HAS DECAYED SUBSTANTIALLY, THEN THE 5 NMI STANDOFF CAN BE REDUCED TO JUST A "FLIGHT THROUGH" PROHIBITION. NOTE BENIGN GBFM VALUES CANNOT BE USED BY THEMSELVES TO CONCLUDE THE CLOUD CAN BE SAFELY PENETRATED, SINCE SHIELDING LAYERS CAN MASK SIGNIFICANT FIELDS (AND CHARGE) INSIDE THE CLOUDS FROM THE GBFM NETWORK.

TRANSPARENT DEBRIS CLOUDS ARE NOT CONSIDERED CAPABLE OF CARRYING SUFFICIENT CHARGE TO BE DANGEROUS.

G. Definitions/Explanations

(1) Anvil stratiform or fibrous cloud produced by the upper level outflow or blow-off from thunderstorms or convective clouds.

(2) Cloud edge—The visible cloud edge is preferred. If this is not possible, then the 10 dBz radar cloud edge is acceptable.

(3) Cloud layer—An array of clouds, not necessarily all of the same type, whose bases are approximately at the same level. Also, multiple arrays of clouds at different altitudes that are connected vertically by cloud elements; e.g., turrets from one cloud array to another. Convective clouds (e.g., clouds falling under Rule B) are excluded from this definition unless they are imbedded with other cloud types.

(4) Cloud top—The visible cloud top is preferred. If this is not possible, then the 13 dBz radar cloud top is acceptable.

(5) Cumulonimbus cloud—Any convective cloud with any part above the –20.0 °C temperature level.

(6) Debris cloud—Any nontransparent cloud that has become detached from a parent cumulonimbus cloud or thunderstorm, or results from the decay of a parent cumulonimbus cloud or thunderstorm.

(7) Documented with respect to rule C(2), "documented" means sufficient data has been gathered on the benign phenomena to both understand it and to develop procedures to evaluate it, and the supporting data and evaluation have been reported ina technical report, journal article, or equivalent publication. For launches at the Eastern Range, copies of the documentation shall be maintained by the 45th Weather Squadron and the KSC Weather Projects Office. The procedures used to assess the phenomena during launch countdowns shall be documented and implemented by the 45th Weather Squadron.

(8) Electric field (for surface-based electric field mill measurements)—The 1-minute arithmetic average of the vertical electric field (Ez) at the ground, such as measured by a ground-based field mill. The polarity of the electric field is the same as that of the potential gradient; that is, the polarity of the field at the ground is the same as that of the charge overhead.

(9) Flight path—The planned flight trajectory including its uncertainties ("error bounds").

(10) Precipitating cloud—Any cloud containing precipitation, producing virga, or having radar reflectivity greater than 13 dBz.

(11) Thunderstorm—Any cloud that produces lightning.

(12) Transparent synonymous with visually transparent—Sky cover through which higher clouds, blue sky, stars, etc., may be clearly observed from below. Also, sky cover through which terrain, buildings, etc., may be clearly observed from above. Sky cover through which forms are blurred, indistinct, or obscured is not transparent.

REFERENCES

1. Beard, K.; and Ochs, H.: "Cloud Electrification," *Rev. in Geophys. Space Phys.*, Vol. 21, pp. 984–992, 1983.

2. Leteinturier, C.; et al.: "Current and Electric Field Derivatives in Triggered Lightning Return Strokes," *J. Geophys. Res.*, Vol. 95, pp. 818–828, 1990.

3. Goodloe, C.: "Lightning Protection Guidelines For Aerospace Vehicles," *NASA/TM—1999–*209734, May 1999.

4. Gabrielson, B.: *The Aerospace Engineer's Handbook of Lightning Protection*, Interference Control Technologies, Inc., 1988.

5. Stahmann, J.: "Launch Pad Lightning Protection Effectiveness," 1991 International Aerospace and Ground Conference on Lightning and Static Electricity, Cocoa Beach, FL, pp. 31–1 through 31–12, April 16–19, 1991.

6. Mach, D.: "Shuttle Lightning Threat Analysis," AMS Third International Conference On Aviation Weather Systems, Anaheim, CA, pp. 92–95, January 30–February 3, 1989.

7. Chai, J.; et al.: "Survey of CGLSS/SLC40 Lightning Data and Retest Criteria," IEEE 1997 International Symposium on Electromagnetic Compatibility, Austin, TX, pp. 391–396, August 18–22, 1997.

8. Santis, L.: "The Calculated Risk of Experiencing a Lightning Caused Unplanned Detonation," *ISEE Proceedings of the 14th Annual Symposium on Explosives and Blasting Research*, New Orleans, LA, pp. 107–119, February 8–11, 1998.

9. Uman, M.: "The Lightning Discharge," *Int. Geophys. Ser.*, Vol. 39, Academic Press, Inc., 1987.

10. Fisher, F.; et al.: "Lightning Protection of Aircraft," Chapter 2, Lightning Technologies, Inc., Pittsfield, MA, 1990.

11. "Launch Commit Criteria and Background," NSTS 16007, Revision F, Change No. 99, Section 4.5, "Natural and Triggered Lightning Constraints."

12. Cianos, N.; and Pierce, E.T.: "A Ground-Lightning Environment For Engineering Usage," Stanford Research Institute, Technical Report 1, SRI Project 1834, August 1972.

13. Galeja, J.: *Terrestrial Propagation of Long Electromagnetic Waves*, Pergamon Press, 1972.

14. Viemeister, P.: *The Lightning Book*," MIT Press, 1972.

15. Mailander, J.: "Climate of the Kennedy Space Center and Vicinity," *NASA TM–103498*, June 1990.

16. Golde, R.: *Lightning—Volume 2—Lightning Protection*, Academic Press, Inc., 1977.

17. Jafferis, W.: "Rocket Triggered Lightning—Kennedy Space Center and Beyond," 1995 International Aerospace and Ground Conference On Lightning and Static Electricity, p. 57–1, September 26–28, 1995.

18. Marshall, L.: "Capturing Sprites and Elves From Afar," Penn. State and AGU Release, December 16, 1996.

19. Volland, H. (Editor): *Handbook of Atmospheric Electrodynamics*, CRC Press, Chapter 4, "Lightning Currents," T. Ogawa, pp. 93–136, 1995.

20. Orville, R.; et al.: "Cloud-to-Ground Lightning Flash Characteristics from June 1984 Through May 1985," *J. Geophys. Res.*, Vol. 92, pp. 5640–5644, May 20, 1987.

21. Stolzenburg, M.: "Observations of High Ground Flash Densities of Positive Lightning in Summertime Thunderstorms," *Monthly Weather Rev.*, Vol. 122, p. 1740, August 1994.

22. Ishif, M.; and Hojo, J.: "On The Statistics of Field Waveforms Associated With Lightning Return Strokes," 1988 International Aerospace and Ground Conference On Lightning and Static Electricity, Oklahoma City, OK, April 19–22, 1988.

23. Narita, K.; et al.: "Bipolar Lightning in Winter at Maki, Japan," *J. Geophys. Res.*, Vol. 94, No. D11, pp. 13191–13195, September 30, 1989.

24. Fisher, R.; et al.: "Parameters of Triggered-Lightning Flashes in Florida and Alabama," *J. Geophys. Res.,* Vol. 98, No. D12, pp. 22887–2902, December 20, 1993.

25. Mach, D.; and Rust, D.: "Photoelectric Return-Stroke Velocity and Peak Current Estimates in Natural and Triggered Lightning," *J. Geophys. Res.*, Vol. 94, No. D11, pp. 13237–13247, September 20, 1989.

26. Bankson, N.: "Lightning Current Rate of Rise in the New Lightning Flash Model for the Space Shuttle Program," 1991 International Aerospace & Ground Conference on Lightning and Static Electricity, Cocoa Beach, FL, Vol. 1, pp. 5–1 through 5–14, April 16–19, 1991.

27. Depasse, P.: "Statistics on Artificially Triggered Lightning," *J. Geophys. Res.*, Vol. 99, No. D9, pp. 18515–18522, September 20, 1994.

28. Turman, B.: "Detection of Lightning Superbolts," *J. Geophys. Res.,* Vol. 83, p. 2566, 1977.

29. Goto, Y.; and Narita, K.: "Electrical Characteristics of Winter Lightning," *J. Atmospheric and Terrest. Phys.*, Vol. 57, No. 5, pp. 449–458, April 1, 1995.

30. Sawada, S.; et al.: "Current Measurement of Lightning Superbolt at the Japan Sea Coast," *NOAA International Aerospace and Ground Conference on Lightning and Static Electricity*, pp. 103–111, April 1, 1988.

31. Uman, M.; et al.: "An Unusual Lightning Flash at Kennedy Space Center," *Science,* Vol. 201, No. 4350, July 7, 1978.

32. Orville, R.; et al.: "Cloud-to-Ground Lightning Flash Characteristics in the Contiguous United States: 1989–1991," *J. Geophys. Res.*, Vol. 99, pp. 10833–10841, May 20, 1994.

33. Orville, R.; and Silver, A.C.: "Annual Summary-Lightning Ground Flash Density in the Contiguous United States: 1992–95," *Monthly Weather Rev.*, Vol. 125, pp. 631–638, April 1997.

34. Lyons, W.: "Final Report—Sensor System to Monitor Cloud-to-Stratosphere Electrical Discharges," submitted to NASA/KSC under NASA SBIR Phase II, Contract NAS10–12113, April 25, 1996.

35. Orville, R.: "Peak-Current Variations of Lightning Return Strokes as a Function of Latitude," *Nature*, Vol. 343, pp. 149–151, January 11, 1990.

36. Wacker, R.: "Changes in Measured Lightning Return Stroke Peak Current After the 1994 National Detection Network Upgrade," *M.S. thesis*, Texas A&M University, May 1997.

37. Hodanish, S.; and Sharp, D.: "A 10-Yr. Monthly Lightning Climatology of Florida: 1986-1995," *Weather & Forecasting*, Vol. 12, pp. 439–448, September 1997.

38. Boccippio, D.; et al.: "Sprites, ELF Transients, and Positive Ground Strokes," *Science*, Vol. 269, pp. 1088–1091, August 25, 1995.

39. Winckler, J.: "Further Observations of Cloud-Ionosphere Electrical Discharge Above Thunderstorms," *J. Geophys. Res.*, Vol. 100, pp. 14335–14345, 1995.

40. Sentman, D.; et al.: "Preliminary Results From the Sprites 94 Aircraft Campaign: Red Sprites," *Geophys. Res. Letters*, Vol. 22, No.10, pp. 1205–1208, May 15, 1995.

41. Lyons, W.: "Sprites, Elves, and Blue Jets," *Weatherwise*, August–September 1997.

42. Fullekrug, M.; et al.: "On the Accuracy of Arrival Azimuth Determination of Sprite-Associated Lightning Flashes by Earth-Ionosphere Cavity Resonances," *Geophys. Res. Letters*, Vol. 23, No. 25, pp. 3691–3694, December 15, 1996.

43. Inan, U.; et al.: "VLF Signatures of Ionospheric Disturbances Associated with Sprites," *Geophys. Res. Letters*, Vol. 22, No. 24, pp. 3461–3464, December 15, 1995.

44. Staff: Geography Institute, University of Alaska, “Red Sprites and Blue Jets,” internet home page, http://elf.gi.alaska.edu/sprites.html, 1997.

45. Wakefield, J.: “High-Altitude Flashes Mystify Scientists,” *Eos AGU*, Vol. 75, No. 51, pp. 601–602, December 20, 1994.

46. Lyons, W.; et.al.: “Large Peak Current Cloud-to-Ground Lightning Flashes during the Summer Months in the Contiguous United States,” *Monthly Weather Rev.*, Vol. 126, pp. 2217–2233, August 1998.

47. Johnson, D.L.: “Terrestrial Environment (Climatic) Criteria Guidelines for Use in Aerospace Vehicle Development, 1993 Revision, Section IX Atmospheric Electricity,” *NASA TM–4511*, August 1993.

BIBLIOGRAPHY

Boccippio, D.: Marshall Space Flight Center, Hydrology Research Office, personal communications, January 1998.

Maier, M.: Patrick AFB, Computer Sciences Raytheon, personal communications, February 1998.

Stanley, M.: New Mexico Institute of Technology, personal communications, February 1998.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operation and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

1. AGENCY USE ONLY *(Leave Blank)*

2. REPORT DATE
May 1999

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Analysis and Assessment of Peak Lightning Current Probabilities at the NASA Kennedy Space Center

5. FUNDING NUMBERS

6. AUTHORS
D.L. Johnson and W.W. Vaughan*

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

8. PERFORMING ORGANIZATION REPORT NUMBER
M–977

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TM—2000–210131

11. SUPPLEMENTARY NOTES
Prepared by Electromagnetics and Aerospace Environments Branch, Systems Engineering Division, Systems Analysis and Integration Laboratory, Science and Engineering Directorate
*University of Alabama in Huntsville

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 18
Nonstandard Distribution

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
This technical memorandum presents a summary by the Electromagnetics and Aerospace Environments Branch at the Marshall Space Flight Center of lightning characteristics and lightning criteria for the protection of aerospace vehicles. Probability estimates are included for certain lightning strikes (peak currents of 200, 100, and 50 kA) applicable to the National Aeronautics and Space Administration Space Shuttle at the Kennedy Space Center, Florida, during rollout, on-pad, and boost/launch phases. Results of an extensive literature search to compile information on this subject are presented in order to answer key questions posed by the Space Shuttle Program Office at the Johnson Space Center concerning peak lightning current probabilities if a vehicle is hit by a lightning cloud-to-ground stroke. Vehicle-triggered lightning probability estimates for the aforementioned peak currents are still being worked. Section 4.5, however, does provide some insight on estimating these same peaks.

14. SUBJECT TERMS
lighting characteristics and criteria, aerospace vehicle lightning protection, peak current probabilities, vehicle-triggered lightning

15. NUMBER OF PAGES
40

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited