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|  | NASA Engineering and Safety Center Technical Consultation Report | Document #: RP-06-39 | Version: 1.0 |
| Title: Kennedy Space Center (KSC) Pad B Catenary Capability Analysis and Technical Exchange Meeting (TEM) Support | | Page #: 1 of 116 | |

**Kennedy Space Center (KSC) Pad 39B
Catenary Capability Analysis Consultation Report**

July 13, 2006

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Volume I: Report

1.0 Authorization and Notification

Mr. Billy Stover, Ground Support Equipment Project Engineer at KSC, initiated a request to conduct a technical consultation on May 18, 2005.

The authority to conduct a technical consultation was approved in an out-of-board action of the NASA Engineering and Safety Center (NESC) Review Board (NRB) on May 18, 2005.

The technical consultation was conducted by Mr. Tim Wilson.

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2.0 Signature Page

Signatures on file

Tim Wilson, Team Lead

Robert Kichak

Dr. Vladimir Rakov

Richard Kithil, Jr.

Noel Sargent

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3.0 List of Team Members

Team Members

| Name | Position/Affiliation | Center/Contractor |
|---------------------|--|-------------------------------------|
| Tim Wilson | NESC Deputy Director | Langley Research Center (LaRC) |
| Robert Kichak | Power and Avionics Discipline Expert | Goddard Space Flight Center (GSFC) |
| Dr. Vladimir Rakov | Professor – Department of Electrical and Computer Engineering/Co-Director, Int’l Center for Lightning Research and Testing | University of Florida |
| Richard Kithil, Jr. | Founder/Chief Executive Officer | National Lightning Safety Institute |
| Noel B. Sargent | Senior Electromagnetic Compatibility Engineer | Glenn Research Center (GRC) |
| Support | | |
| Elizabeth Holthofer | Technical Writer | ViGYAN, Inc./LaRC |

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4.0 Executive Summary

The NESC was asked to support a review of a lightning analysis done at KSC. Systems Engineering and Integration (SE&I) was working on this issue as one of the integrated hazards they were trying to document. The existing catenary wire system appeared to provide protection against lightning strikes above a given current level but did not protect against lower intensity strikes. The strike current level that is “acceptable” was not determined, so upgrades to the catenary system might be required to adequately protect the vehicle when the rotating support structure (RSS) is rolled back for loading and launch. The NESC role was to assist in a review of the analysis to determine lightning risk and recommend upgrades to reduce that risk.

The review of lightning analysis was accomplished at two Technical Exchange Meeting (TEMs) – one in July and one in October of 2005. The stated primary objective of the TEMs was to understand the existing lightning protection at Pad 39B and then determine, based on present-day methodologies, what is the capability of this design. KSC could then work in a logical and technically sound manner to address and resolve any lightning risks and concerns.

The scope of the two-day discussion only addressed air terminal (catenary) issues. Subjects such as bonding, grounding, personal safety, secondary effects, and surge protection were beyond the scope of the analysis. The main discussion was the safety of the vehicle while at Pad 39B and in particular vulnerability while:

- Vehicle is fueled,
- RSS is rolled from the vehicle, and
- Gaseous Oxygen (GOx) Vent Arm is not positioned over the External Tank (ET), as this would represent the worst case condition for the vehicle.

The NESC and Space Shuttle Program (SSP) lightning experts concluded the existing system has vulnerabilities at lower current lightning strikes. Several schemes for additional catenary wires to provide enhanced protection were discussed and appeared to have technical merit. Temporary means of protection enhancement such as location of mobile cranes or balloons were also discussed. Future work to study personnel safety and enhancement of the lightning protection system was recommended. Specifically, Monte Carlo simulations of various lightning strikes were to be provided to the NESC team for additional assessment.

Immediately following the conclusion of the TEMs, preliminary results of the meetings were presented to the SSP by Billy Stover. Additional planned near-term work included the generation of Monte Carlo results based on a probabilistic analysis quantifying the possibility of a direct lightning strike attaching to the flight hardware while at Pad 39B in launch configuration

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(RSS rotated back with GOx Vent Arm extended and withdrawn) during July 13 - 31, 2005. July historically is the highest month of the year for lightning strikes. The NESC and SSP lightning experts were to review and comment on these results and reconvene in July to discuss the results, Monte Carlo methodology, configurations, and assumptions used in the simulations.

The NESC and SSP lightning experts concluded the Space Shuttle could be at risk of lightning strikes in various configurations, particularly for strikes with relatively small current amplitudes. Safety for personnel and secondary effects to equipment were not discussed in detail in this forum.

The stated objectives of the two-day lightning TEM at KSC were met. The technical assessments of the NESC experts were conveyed in real-time to minimize delays, and are also included verbatim in this report. Following the TEM, the NESC experts continued to support a technical review of the Monte Carlo analysis. These results were also conveyed in real-time. This report contains a summary of those major inputs.

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5.0 Plan

To provide specific expertise, Robert Kichak, NESC Discipline Expert for Power and Avionics, contacted his Super Problem Resolution Team (SPRT) and located external experts. This followed a recommendation of potential candidates from Dr. Robert Scully, who is an SPRT member but was supporting the assessment for the SSP. The independent lightning experts contracted for the consultation by the NESC included Dr. Vladimir Rakov of the University of Florida, Mr. Richard Kithil of the National Lightning Safety Institute, and Mr. Noel Sargent Senior Electromagnetic Compatibility (EMC) Engineer at GRC and former member of National Interagency Coordination Group for Lightning Research. The SSP also provided several external experts including personnel from The Aerospace Corporation who had expert knowledge of the Cape Canaveral Air Force Station (CCAFS) Launch Complex lightning protection. In addition, Dr. Frank Fisher of Lightning Technologies, who was a key participant in the design of the Apollo and Pad 39B catenary systems and the Mobile Launch Platform (MLP) lightning provisions, was included as an SSP expert.

The effectiveness of the existing lightning catenary wire and single tower system at Pad 39B (Space Shuttle), which as an outgrowth of the system that had initially been employed for the Apollo Program, was analyzed by Drs. Pedro Medelius and Carlos Mata at KSC. Two approaches were employed - the "classical" rolling sphere method (RSM), as described in Section 7.1, and RSM in conjunction with Mont Carlo simulations. As revealed by both approaches, the existing system showed effectiveness for high current lightning strikes (100 kiloamperes [kA] or greater), but showed varying degrees of vulnerability for lower current lightning strikes depending on the specific configuration. Based on historical data, the current lightning strike was demonstrated to be on the order of 31 kA. Also, based on both historical and analytical techniques, it was estimated Pads 39 A and 39B will see approximately three lightning strikes per year, with July and August being the peak months for electrical storm activity. A particularly severe electrical storm occurred near the launch facility prior to the launch of STS-8 on August 30, 1983, and is shown in Figure 5.0-1.



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Figure 5.0-1. Powerful Electrical Storm near KSC Launch Complex Prior to Launch of STS-8, August 30, 1983 (NASA Photo)

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6.0 Description of the Problem, Proposed Solutions, and Risk Assessment

The existing lightning protection system at Pad 39B for the Space Shuttle is an outgrowth of a system that was put in place for the Apollo Program. Dr. Frank Fisher of Lightning Technologies was a key participant in the design and implementation of that system. He conveyed to the NESC team that the catenary wire provision was put in place quickly (as assurance against possible vehicle damage causing critical launch delays) rather than being implemented as a comprehensive system designed to provide a high degree of guaranteed protection. Also, the technology of lightning protection has evolved over time with considerable work being conducted by groups such as the electric utilities companies, aircraft manufacturers, universities, and others. Several accepted present-day methods for analysis of lightning protection were used by Drs. Medelius and Mata to study the expected lightning environment for the Pad 39B facility and to analyze the degree of protection against direct lightning attachment to the Space Shuttle. The specific physical configuration directly affects the vulnerability, so cases that were considered included the RSS next to and rolled back from the Space Shuttle, and the GOx Vent Arm both extended and withdrawn from the ET. Elements of the lightning protection system at Pad 39B are shown in Figure 6.0-1 and consist of an 80 foot insulating mast on top of the Fixed Support Structure (FSS), a catenary wire system that runs from the mast in a North/South direction to grounds 1000 feet away on each side of the mast, the RSS which can either be next to or away from the Space Shuttle, and a GOx vent that can either be extended or retracted from the top of the ET.

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Figure 6.0-1. Pad 39B Lightning Protection

The NESC team investigated the KSC Pad 39B catenary lightning protection, consisting of the two shielding wires, their terminations to earth, and the cabling interface between the Pad, MLP, and Orbiter. The team was also shown elements of the launch pad detection systems, including the Catenary Wire Lightning Instrumentation System and the Induced Voltage Instrumentation System. These are described in Appendix I. Random and cursory bonding and grounding measurements were performed to investigate equi-potential connections and conductive soil conditions. During the walkthrough it was observed that personal lightning safety information messages were absent, including near key areas such as the catenary ground points.

The existing analysis approach using today's standards, techniques, and methodology was presented to the TEM after seeing all the hardware. Lightning Technologies presented historical background information and KSC presented the lightning protection systems and capabilities. Dr. Medilius also presented several possible techniques to improve the performance of the existing system by the incorporation of additional wires. The technical teams provided feedback, concerns, issues, and in general, a consensus that the analysis presented by Dr. Medilius correctly identified deficiencies of existing system capabilities. Based on this, the NESC team feels that there is a technical basis for concluding there is an overall lightning risk with respect to flight hardware. The NESC team also identified the need to better qualify and quantify personnel and hardware risk exposure.

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7.0 Data Analysis

7.1 Electrogeometrical Model (EGM)

The attachment of the leader to the strike object is often described using the EGM, the core of which is the concept of a “striking distance.” This concept obscures some of the significant physics, but allows the development of relatively simple and useful techniques for designing lightning protection systems for various structures. The striking distance can be defined as the distance from the tip of the descending leader to the object to be struck at the instant when an upward connecting leader is initiated from this object. It is assumed that the lightning termination point is uniquely determined. For a given striking distance, an imaginary surface can be defined above the ground and objects on the ground (see Figure 7.1-1) such that, when the descending leader passes through that surface at a specific location, the leader is “captured” by a specific point on the ground or on a grounded object. The geometrical construction of this surface can be accomplished simply by rolling an imaginary sphere of radius equal to the assumed striking distance across the ground and across objects on the ground, i.e., the RSM.¹ The locus of all points traversed by the center of the rolling sphere forms the imaginary capture surface. Those points the rolling sphere touches can be struck, according to this approach and accordingly points where the sphere does not touch cannot. Figure 7.1-2 illustrates the rolling sphere method. The shaded area in Figure 7.1-2 is that area into which lightning cannot enter.

¹ Lee, R.H. “Protection zone for buildings against lightning strokes using transmission line protection practice.” *IEEE Trans. Ind. Appl.* 14 (1978): 465-70. and *NFPA 780 (National Fire Protection Association) Standard for the Installation of Lightning Protection Systems*. Available from NFPA, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101 (1997).



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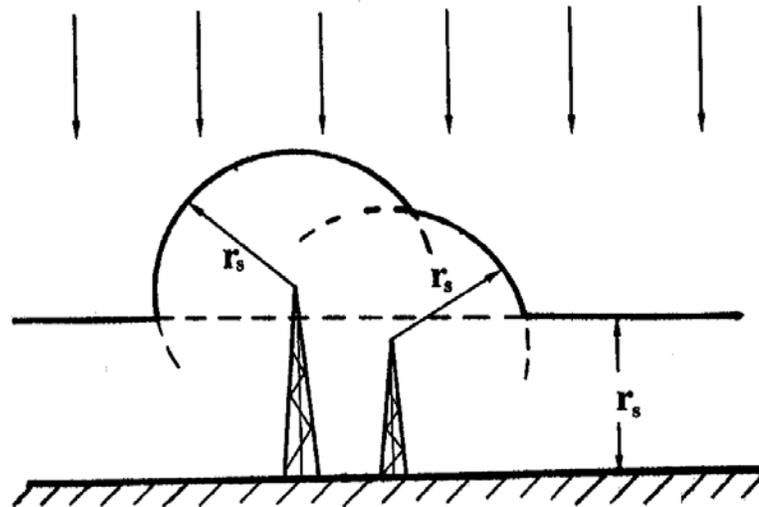


Figure 7.1-1. Illustration of Capture Surfaces of Two Towers and Earth's Surface in the EGM Model - r_s is the Striking Distance - Vertical Arrows Represent Descending Leaders Assumed to be Uniformly Distributed Above the Capture Surfaces (Adapted from Bazelyan and Raizer)²

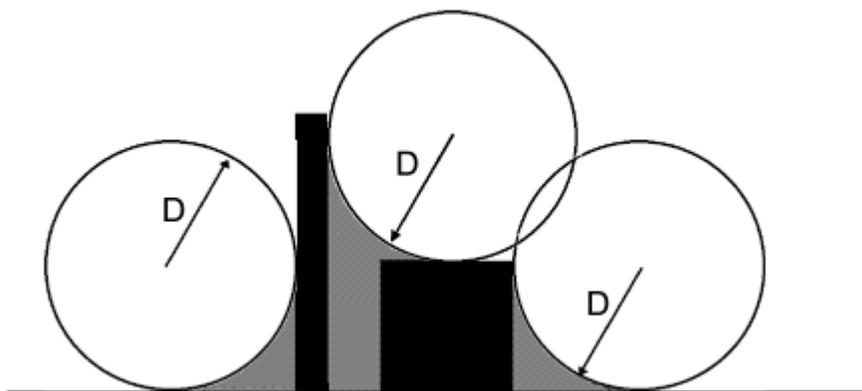


Figure 7.1-2. Illustration of The Rolling Sphere Method for Two Objects Shown in Black - D is The Striking Distance (Same As r_s In Figure 7.1-1) - Shaded Area is that Area into which Lightning Cannot Enter (Adapted from Szczerbinski)³

² Bazelyan, E.M., and Yu Raizer. *Lightning Physics and Lightning Protection*. Bristol: IOP, 2000, p. 325.

³ Szczerbinski, M. "A discussion of 'Faraday cage' lightning protection and application to real building structures." *J. Electrostatics* 48 (2000): 145-54.

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In the RSM, the striking distance is assumed to be the same for any object projecting above the earth's surface and for the earth itself. There are variations of the EGM in which the assumption of different striking distances for objects of different geometry are used.⁴ The main application of the RSM is positioning air terminals on an ordinary structure. The positioning is such that one of the terminals, rather than a roof edge or other part of the structure, initiates the upward leader that intercepts the descending leader and hence, becomes the lightning attachment point.

The striking distance is usually expressed as a function of prospective return-stroke peak current. The procedure to obtain such an expression typically involves assumptions of leader geometry, total leader charge, distribution of charge along the leader channel, and critical average electric field between the leader tip and the stroke object at the time of the initiation of upward connecting leader from this object. This critical electric field is assumed to be equal to the average breakdown field from long laboratory spark experiments with rod-rod and rod-plane gaps. This varies with the waveshape of applied voltage as well as with other factors such as the high-voltage generator circuitry. The typical assumed values range from 200 to 600 kV/m. As a result, an expression can be obtained relating the striking distance to the total leader charge. In the next step, the observed correlation (see Figure 7.1-3) between the charge and resultant return-stroke peak current is used to express the striking distance, r_s , in terms of the peak current, I .⁵ The most frequently used striking-distance expression, included in many lightning protection standards, is:

$$r_s = 10 I^{0.65} \quad (1)$$

where I is in kA and r_s is in meters. This and other expressions for the striking distance found in literature are illustrated in Figure 7.1-4. Given the assumptions involved and large scatter seen in Figure 7.1-3, each of these relationships is necessarily simplistic, and the range of variation among the individual expressions (see Figure 7.1-4) is a factor of three or more. Therefore, there are considerable uncertainties in estimating the striking distance. However, there is satisfactory long-term experience with the RSM (Hungarian Standard on Lightning Protection since 1962⁶) as applied to placement of lightning rods on ordinary structures and with the EGM in general as applied to power lines. This experience is the primary justification for the continuing use of this method in lightning protection studies. As of today, the EGM is the best engineering tool for estimating lightning incidence to structures that is endorsed by the Institute of Electrical and Electronics Engineers (IEEE) and the International Electrotechnical Commission (IEC). The

⁴ Eriksson, A.J. "The incidence of lightning strikes to power lines." IEEE Trans. PWRD-2 (1987): 859-70.

⁵ Berger, K., and E. Garabagnati. "Lightning current parameters." URSI Conference, Florence, Italy (1984).

⁶ Horvath, T. Rolling Sphere – Theory and Application." Proceedings of the 25th Int'l Conference. on Lightning Protection, Rhodes, Greece (2000): 301-305.



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RSM is also endorsed by the recently released (January 2006) IEC lightning protection document (No. 62305).⁷

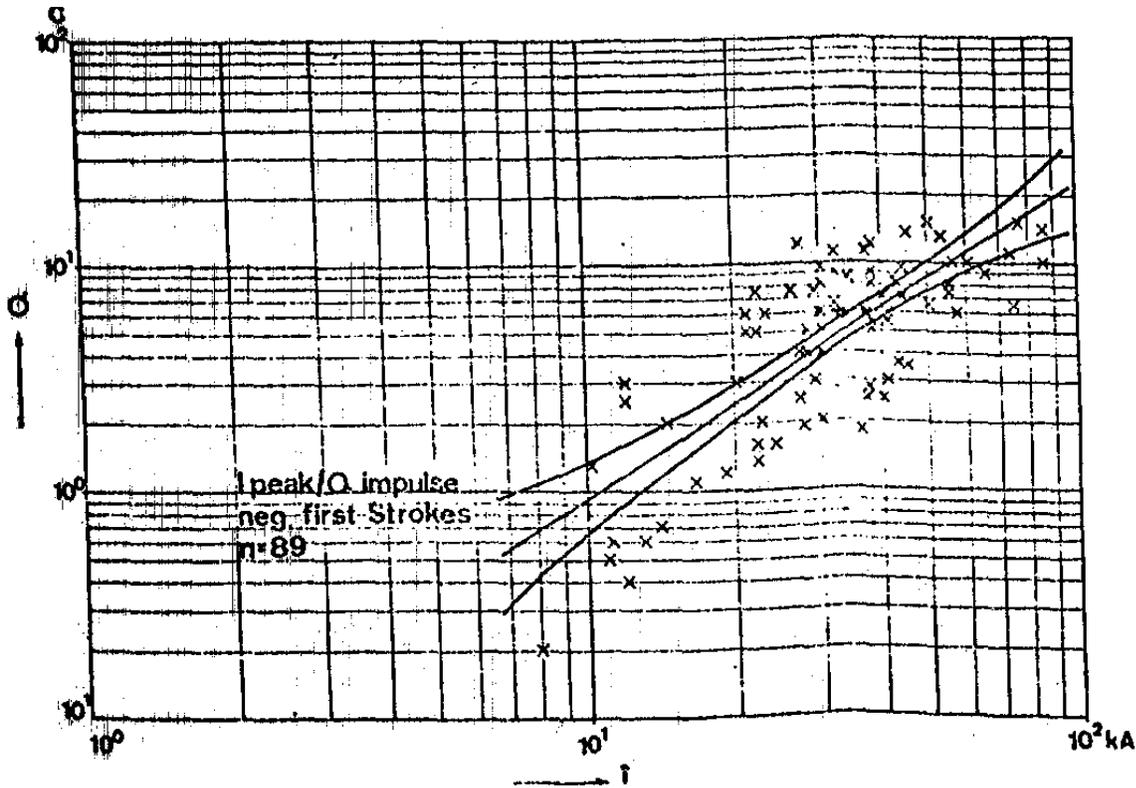


Figure 7.1-3. Scatter Plot of Impulse Charge, Q, Versus Return-Stroke Peak Current, I
(Note: Both Vertical and Horizontal Scales are Logarithmic - The Best Fit to Data, $I = 10.6 Q^{0.7}$, Where Q is in Coulombs and I is in Kiloamperes, was used in Deriving Equation (1) - Adapted From Berger⁸)

⁷ Protection Against Lightning. International Electrotechnical Commission Doc. No. 62305, January 2006.

⁸ Berger, K. *Mesungen und Resultate der Blitzforschung auf dem Monte San Salvatore bei Lugano, der Jahre 1963-1971*. Bulletin SEV 63 (1972): 1403-22.



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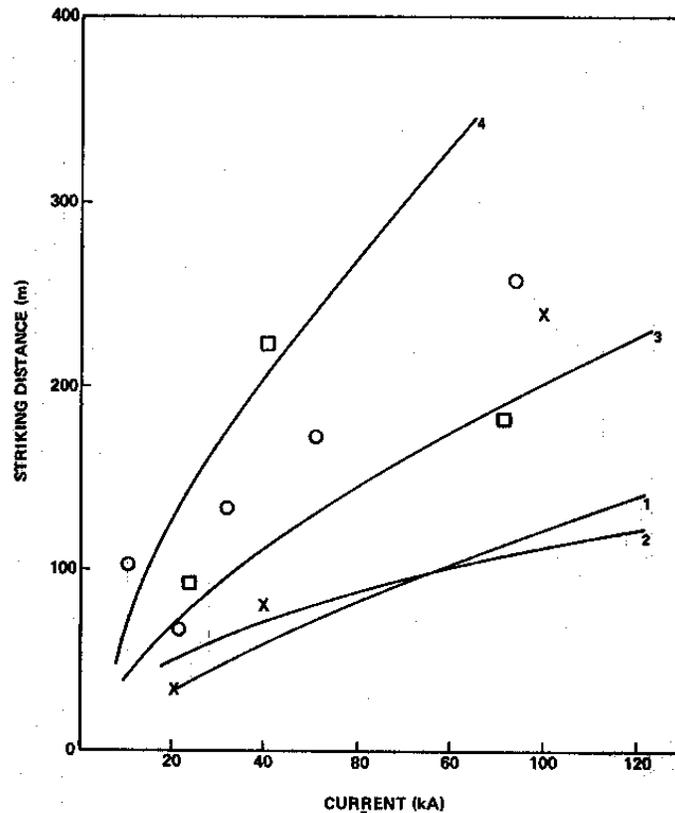


Figure 7.1-4. Striking Distance versus Return-Stroke Peak Current: Curve 1, Golde⁹; Curve 2, Wagner¹⁰ (1963); Curve 3, Love¹¹; Curve 4, Rühling¹²; X, theory of Davis¹³; 0, Estimates from Two-Dimensional Photographs by Eriksson¹⁴; □, Estimates from Three-Dimensional Photography by Eriksson¹⁵ (Adapted from Golde and Eriksson as Referenced Above)

⁹ Golde, R.H. "On the frequency of occurrence and the distribution of lightning flashes to transmission lines." *AIEE Trans.* 64(III) (1945): 902-10.

¹⁰ Wagner, C.F. "Relation between stroke current and velocity of the return stroke." *AIEE Trans.* 82: (1963): 609-617.

¹¹ Love, E. R. "Improvements on lightning stroke modeling and applications to the design of EHV and UHV transmission lines." M.Sc. Thesis, University of Colorado 1973.

¹² Rühling, F. "Modelluntersuchungen über den Schutzraum und ihre Bedeutung für Gebäudeblitzableiter." *Bull. Schweiz. Elektrotech. Ver.* 63 (1972): 522-528.

¹³ Davis, R. "Frequency of lightning flashover on overhead lines. *Gas Discharges and the Electricity Supply Industr.*" London: Butterworths (1962): 125-38.

¹⁴ Eriksson, A.J. "Lightning and tall structures." *Trans. S. Afr. Inst. Electr. Eng.* 69(8) (1978): 238-52.

¹⁵ Ibid.

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The EGM can be used for estimating lightning incidence to different elements (usually to the protected object) of a structure as follows:

1. Assume the spatial distribution of descending lightning leaders above all the capture surfaces (see Figure 7.1-1) and specify the ground flash density, N_g (typically $N_g =$ constant).
2. Find the striking distance, $r_s(I)$, and then the projection, $S(I)$, of the resultant capture surface of the element in question onto the ground surface.
3. Specify the probability density function of lightning peak currents, $f(I)$.
4. Integrate the product $N_g \times S(I) \times f(I) \times dI$ from 0 to I_{max} , to obtain the lightning incidence (number of strikes per year).

Alternatively, one can eliminate finding $S(I)$ in item (2) and entire item (4) from the outlined procedure using the Monte Carlo technique. It is important to note that the use of the RSM alone does not generally allow an estimate of lightning incidence to an element of structure (for example, to the Space Shuttle on the MLP), because such an estimate requires information on the spatial distribution of lightning leaders, which is not part of the standard RSM.

7.2 Monte Carlo Results

The preliminary Monte Carlo results were distributed on July 11, 2005. A second TEM to review these was deferred until October 5, 2005, due to the STS-114 launch and Agency post-flight analysis activities. The NESC experts reviewed these Monte Carlo results and provided comments prior to and at the TEM held on October 5, 2005. Key inputs from Dr. Rakov and Mr. Kithil are summarized in Appendix B.

The final Monte Carlo analysis report is included as Appendix C. Dr. Medelius presented final results of the Lightning TEMs to the Shuttle Engineering Review Board (SERB) on November 8, 2005. That presentation is provided as Appendix D. An expanded supplemental paper discussing lightning safety was submitted by Mr. Kithil on October 3, 2005, and is provided as Appendix E.

The detailed technical discussion of the June 21 and 22, 2005, TEM is provided verbatim from the NESC experts in Appendices F, G, and H.

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7.3 Lightning Incidence to Various Objects

This section briefly describes how cloud-to-ground lightning "decides" on its ground termination point. Ground flashes are normally initiated by stepped leaders that originate in the thundercloud. As the downward-extending leader channel (usually negatively charged) approaches the ground, the enhanced electric field intensity at irregularities of the Earth's surface or at protruding grounded objects increases and eventually exceeds the breakdown value of air. As a result, one or more upward-moving leaders are initiated from those points, and when it contacts a branch of the downward-moving stepped leader, the point of lightning termination on ground is determined. Grounded vertical objects produce relatively large electric field enhancement near their upper extremities, so that upward-moving connecting leaders from these objects start earlier than from the surrounding ground. Therefore, they serve to make the object a preferential lightning termination point. In general, the higher the object is, the greater the field enhancement and hence, the higher the probability that a stepped leader will terminate on the object. In the limit, when the height (field enhancement capability) of the object becomes so large that the upward-moving leader from the object tip can be initiated by in-cloud charges (or, more likely, by in-cloud discharge processes, as opposed to being initiated by the charge on the descending stepped leader), the object becomes capable of initiating upward lightning. The latter, as opposed to a "normal," downward lightning, would not occur if the object were not there. Ground-based objects, with heights ranging from about 100 to 500 meters, experience both downward and upward flashes with the proportion of these types of lightning being a function of object height. Eriksson derived the following equation for the annual lightning incidence N (yr^{-1}) to ground-based objects, including both downward and upward flashes:¹⁶

$$N = 24 \times 10^{-6} H_s^{2.05} N_g \quad (2)$$

where H_s is the object height in meters and N_g is the ground flash density in $\text{km}^{-2} \text{yr}^{-1}$. To do so, he employed:

- Observations of lightning incidence to structures of heights ranging from 20 to 540 meters in different countries,
- Corresponding local values of the annual number of thunderstorm days T_D , and
- An empirical equation relating N_g and T_D . For Pad 39B, $H_s = 106$ m, $N_g = 10 \text{ km}^{-2} \text{yr}^{-1}$, and N from equation (2) is about 3.4 yr^{-1} .

¹⁶ Eriksson, A.J. "The incidence of lightning strikes to power lines." IEEE Trans. PWRD-2 (1987): 859-70.

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Eriksson tabulated the observed percentage of upward flashes as a function of a free-standing structure's height, reproduced in Table 7.3-1.¹⁷ Eriksson and Meal fitted the data in Table 7.3-1 with the following expression:¹⁸

$$P_u = 52.8 \ln H_s - 230 \quad (3)$$

where P_u is the percentage of upward flashes and H_s is the structure height in meters. This equation is valid only for structure heights ranging from 78 to 518 meters, since for $H_s = 78$ m $P_u = 0$ and for $H_s = 518$ meters $P_u = 100$ percent. Structures with heights less than 78 meters are not covered by equation (2), because they are expected to be struck by downward flashes only. Structures with a height of greater than 518 meters are not covered, because they are expected to experience upward flashes only. For Pad 39B, $H_s = 106$ meters, and the percentage of upward flashes from equation (3) is 16 percent.

Table 7.3-1. The Percentage of Upward Flashes from Tall Structures (Adapted from Eriksson¹⁹)

| Reference | Structure height, meters | Percentage of upward flashes |
|--------------------------------------|--------------------------|------------------------------|
| Pierce (1972) | 150 | 23 |
| | 200 | 50 |
| | 300 | 80 |
| | 400 | 91 |
| McCann (1944) | 110 | 8 |
| | 180 | 24 |
| | 400 | 96 |
| Berger (1972) | 350 ^a | 84 |
| Gorin (1972); Gorin et al. (1976) | 540 | 92 ^b |
| Garbagnati et al. (1974) | 500 ^c | 98 |

^aAn effective height of 350 meters has been assigned by Eriksson to Berger's 70 meter high mountain-top towers to account for the enhancement of the electric field by the mountain whose top is 640 meters

¹⁷ Ibid.

¹⁸ Eriksson, A.J., and D.V.Meal. "The incidence of direct lightning strikes to structures and overhead lines." *Lightning and Power Systems*, London: IEE Conf. Publication No. 236 (1984): 67-71.

¹⁹ Eriksson, A.J. "Lightning and tall structures." *Trans. S. Afr. Inst. Electr. Eng.* 69(8) (1978): 238-52.

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above Lake Lugano (914 meters above sea level). Pierce assigned a different effective height of 270 meters to the Berger's towers.²⁰

^b50 percent of the flashes recorded in this study were classified as “unidentified.” The relative incidence of upward flashes is based upon analysis of only the identified data.

^cGarbagnati et al.'s towers were 40 meters high, located on mountain tops, 980 and 993 meters above sea level.²¹ Eriksson does not give any explanations of the assumed effective height of 500 meters.²²

In practice, structures having heights less than approximately 100 meters are often assumed to be struck by downward lightning only, and the upper height limit can be taken as 500 meters. Accordingly, the total lightning incidence N to a structure is the sum of the downward-flash incidence N_d and upward-flash incidence N_u if the structure height is in the range from about 100 to 500 meters, $N = N_d$ for structures shorter than 100 meters, and $N = N_u$ for structures taller than 500 meters. If both downward and upward flashes are expected, they are often treated separately in estimating the lightning incidence to an object, as described below.

7.3.1 Downward Flashes

When the incidence of downward lightning is estimated, it is common to ascribe an equivalent attractive (or exposure) area to the grounded object. The attractive area can be viewed as an area on flat ground surface that would receive the same number of lightning strikes in the absence of the object as does the object placed in the center of that area. In other words, in computing lightning incidence to a structure, the structure is replaced by an equivalent area on ground. For a free-standing structure whose plan-view dimensions are much smaller than its height (such as a mast, tower, or chimney), this area, A , is circular and is generally given by $A = \pi R_a^2$ where R_a is the equivalent attractive radius. For straight, horizontally extended structures (such as power lines or their sections), the equivalent attractive area is rectangular and is sometimes termed the "shadow zone" or "attractive swath." For example, if a power line has a length l , and an effective width b (usually taken as the horizontal distance between overhead shield wires or between the outer phase conductors), its equivalent attractive

²⁰ Pierce, E.T. “Triggered lightning and some unsuspected lightning hazards.” Stanford Research Institute, Menlo Park, California, (1971): 20 p.

²¹ Berger, K., and E. Garabagnati. “Lightning current parameters.” URSI Conference, Florence, Italy (1984).

²² Eriksson, A.J. “Lightning and tall structures.” *Trans. S. Afr. Inst. Electr. Eng.* 69(8) (1978): 238-52.

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area is generally estimated as $A = l(b + 2R_a)$ where R_a is generally thought to be approximately equal to the equivalent attractive radius for a free-standing structure of the same height.²³ Further, the local ground flash density N_g is assumed to be spatially uniform in the absence of the structure, so that the downward lightning incidence to the structure is found as

$$N_d = A N_g \quad (4)$$

Usually N_g is in $\text{km}^{-2} \text{yr}^{-1}$ so that A should be expressed in km^2 to obtain N_d in yr^{-1} (strikes per year).

The equivalent attractive radius R_a is usually assumed to be a function of structure height H_s and is generally expressed as

$$R_a = \alpha H_s^\beta \quad (5)$$

where α and β are empirical constants. The procedures used to obtain equation (5), from data on lightning incidence to structures of different height, is given (for example) by Eriksson.²⁴ In equation (5), both H_s and R_a are in meters, and different values of α and β have been proposed. For example, Whitehead et al. gave $\alpha = 2$ and $\beta = 1.09$ for transmission lines, while CIGRE Document 63 recommended $\alpha = 14$ and $\beta = 0.6$.²⁵ The attractive radius for individual strikes should depend on the charge carried by the descending leader, this charge being correlated with the associated return-stroke peak current. In this regard, equation (5) should be understood as representing the entire distribution of peak currents. In the EGM approach (Section 7.1), which is widely used for the estimation of lightning incidence in lightning protection studies (e.g., CIGRE Document), the equivalent attractive radius explicitly depends on the statistical distribution of lightning peak currents.²⁶

²³ Eriksson, A.J. "The incidence of lightning strikes to power lines." IEEE Trans. PWRD-2 (1987): 859-70. and Rakov, V.A., and A.O. Lutz. "A new technique for estimating equivalent attractive radius for downward lightning flashes." Proceedings of 20th Int'l Conf. on Lightning Protection, Interlaken, Switzerland, Paper 2.2 (1990).

²⁴ Eriksson, A.J. "Lightning and tall structures." Trans. S. Afr. Inst. Electr. Eng. 69(8) (1978): 238-52. and Eriksson, A.J. "The incidence of lightning strikes to power lines." IEEE Trans. PWRD-2 (1987): 859-70.

²⁵ Whitehead, J.T., et al. "Estimating lightning performance of transmission lines II-Updates to analytical model." IEEE Working Group Report, IEEE Trans. PWRD-8 (1993): 1254-66. CIGRE Document 63. Guide to Procedures for Estimating the Lightning Performance of Transmission Lines, October 1991.

²⁶ Eriksson, A.J. "The incidence of lightning strikes to power lines." IEEE Trans. PWRD-2 (1987): 859-70. and Rakov, V.A., and A.O. Lutz. "A new technique for estimating equivalent attractive radius for downward lightning flashes." Proceedings of 20th Int'l Conf. on Lightning Protection, Interlaken, Switzerland, Paper 2.2 (1990).

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Estimation of N_d from equation (3) implies a reasonably long-term value of ground flash density and yields a long-term average value of lightning incidence. For example, if a 60 meter tower is located in a part of Florida where $N_g = 10 \text{ km}^{-2} \text{ yr}^{-1}$, the long-term average downward lightning incidence will be about 0.5 yr^{-1} (assuming $\alpha = 2$ and $\beta = 1$). That is, the tower will be struck on average every other year. The use of equation (2) for Pad 39B would result in a lightning incidence value of about 1 yr^{-1} .

7.3.2 Upward Flashes

Once the incidence of downward lightning N_d is found from equation (4) using the concept of an equivalent attractive area, the incidence of upward flashes N_u can be determined by subtracting N_d from N given by equation (2). Recall that if the structure height is less than approximately 100 meters, it is usually assumed that $N_u = 0$. If only the percentage of upward flashes is sought, equation (3) can be used.

Upward flashes tend to develop from the highest point of the object, which is normally an air terminal of its Lightning Protection System (LPS). For this reason, upward flashes are usually of no concern in estimating the “shielding failure” mode of lightning interaction with the object.

7.4 Catenary Capability for Lightning Protection

A catenary or overhead shield wire (OHSW) is the preferred air terminal design for intercepting lightning at critical, high value facilities. Franklin Rods, another air terminal design, are considered inefficient since they do not begin functionality until the lightning threat is upon the structure to be protected. Air terminal designs such as Early Streamer Emitter (ESE) and Dissipation Array System/Charge Dissipation System (DAS/CTS) have been studied²⁷ with conclusions that their performance is greatly exaggerated by vendors.

Air terminal designs are one element of a comprehensive lightning protection system. See Table 7.4-1 for an introduction to other necessary ingredients in the family of components. See also KSC-STD-E-0012E “Facility Grounding and Lightning Protection, Standard For” August 1, 2001, for further information.

The Space Shuttle is at risk from direct lightning strikes while at the launch platform.

²⁷ Uman, M.A., and Rakov, V.A. “A Critical Review of Non-Conventional Approaches to Lightning Protection.” Transactions of the American Meteorological Society, December (2002).



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Table 7.4-1. Matrix of Lightning Protection Sub-Systems

| | Direct Strike | Indirect Strike | Exterior Location | Interior Location | People Safety | Structure Safety |
|-----------------------|---------------|-----------------|-------------------|-------------------|---------------|------------------|
| AIR TERMINALS | YES | N/A | YES | N/A | N/A | YES |
| DOWN-CONDUCTORS | YES | N/A | YES | YES | N/A | YES |
| BONDING | YES | YES | YES | YES | YES | YES |
| GROUNDING | YES | YES | YES | YES | YES | YES |
| SHIELDING | YES | YES | YES | YES | YES | YES |
| SURGE PROTECTION | YES | YES | YES | YES | YES | YES |
| DETECTION | YES | YES | YES | YES | YES | YES |
| POLICIES & PROCEDURES | YES | YES | N/A | N/A | YES | YES |

Apply these sub-systems as appropriate (YES/NO) to specific facilities or structures.

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7.4.1 General Observations

7.4.1.1 Magnitude of Lightning Threat

In 2004, there were some 56,206 ground lightning strikes in the KSC area. KSC has an average measurable flash density of about 17 strikes per square kilometer per year. A Bell Curve distributes most of the lightning within the June - September period, taking into account multiple ground strike points in sonic flashes.

7.4.1.2 Recorded Data

Rogowski Coils at the OHSWs have captured lightning characteristics - amplitude, polarity, waveform - for many years. On average, three to five strikes occur to each launch pad OHSW annually. Other helpful statistics which quantify the lightning threat are available from 45th Weather, Patrick AFB and from the NASA KSC Weather Office. In short, lightning that strikes the launch pad is severe and consequences from strikes to the Space Shuttle could be significant.

7.4.1.3 Theoretical Assumptions

When presented with various RSMs describing protective radii, the NESC and SSP lightning experts consensus was that areas not protected by the existing OHSW included the Space Shuttle. About 75 percent of the total structure is “enclosed” by the assumptions inherent in the RSM. However, it must be remembered that lightning is stochastic and irregular in conforming to theoretical models.

7.4.2 Conclusions

The KSC Pad 39B OHSW design ranks fifth behind designs used by other major space agencies.

- Russia – Baikonur employs twin towers at either side of the launch platform.
- France – CNES French Guiana uses four towers at corners of the launch platform.
- China – Jinqian uses two towers on opposite sides of the launch platform.
- United States (US) – US Air Force Space Launch Complex (SLC) 40 (decommissioned Titan IV) and 41 (Atlas V) use an overhead net design supported by four towers to obtain the most efficient design, and 37 (Delta IV) uses a two-tower system – one on each side of the vehicle, each having its own catenary wires.

Pads 39A/B should adopt a contemporary OHSW lightning protection treatment in keeping with recognized codes and standards as is consistent with proactive safety measures. Additional OHSWs are needed to provide effective lightning shielding for the Space Shuttle. The Study

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Group considered several alternative designs. At a minimum requirement, two new support towers are suggested. They should be located East of the exiting Pads and separated by at least 300 feet. Exact calculations as to tower locations, tower heights, tower distances from the pad, and so forth, will be performed by others. OHSW geometries also should be calculated by others.

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8.0 Findings, Root Causes, Observations, and Recommendations

8.1 Findings

- F-1 The existing Pad 39B lightning protection is inadequate. Pads 39A and 39B do not have contemporary OHSW lightening protection systems designed to recognized codes and standards.
- F-2. Personnel safety was only briefly discussed. When it was discussed, there were widely differing opinions regarding safety of the present configuration expressed.
- F-3. Secondary lightning effects were not discussed.
- F-4. Important lightning protection sub-systems such as bonding, grounding, and surge protection are not well-characterized at the Pad 39B site.

8.2 Causal Factors

When reviewed using techniques and analysis presently accepted today, the lightning protection system presently in place at Pad 39B for more than 25 years was not designed to provide adequate protection for the vehicle and personnel. Analysis with presently-accepted techniques shows varying degrees of vulnerability for the existing design.

8.3 Observations

- O-1. Caution notices were not in place at the catenary ground points.

8.4 Recommendations

These recommendations are directed to the KSC Ground Support Equipment Project Engineer's Office.

- R-1.** Convey risks and vulnerabilities of present system to SSP and anticipated launch service customers. (F-1)
- R-2.** Continue assessment of the present lightning system and prepare of design improvement alternatives for presentation to the SSP and anticipated launch service customers. (F-1)

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- R-3.** Study personnel safety, both from the perspective of a short term assessment and a longer term study. (F-2, O-1)
- R-4.** Review secondary effects protection provisions and their effectiveness. (F-3)
- R-5.** Review bonding, grounding, and surge protection lightning protection provisions and their effectiveness. (F-4)

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9.0 NESC Lessons Learned

The NESC lesson learned from this consultation is that additional definition of the scope of the activities would be helpful prior to initiation. The review of Monte Carlo analysis was appropriate and worthwhile. However, it was not initially anticipated in the contract provisions for the experts and increased the overall work required. For future consultations, perform the initial evaluation and allow for contract modifications to consultants.

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10.0 Definition of Terms (as required)

| | |
|--------------------------------|--|
| Catenary | A lightning protection wire system at Pad 39B consisting of a 1 inch stainless steel wire supported by an 80 foot insulating mast on top of the fixed support structure that runs from the mast in a North/south direction to grounds 1000 feet away on each side of the mast. |
| Corrective Actions | Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem. |
| Electrogeometrical Model (EGM) | An engineering method for estimating lightning incidence to various structures. In this method, one ascribes (explicitly or implicitly) to the ground and to objects on the ground the so-called capture surface, such that when the descending leader passes through that imaginary surface at a specific location, the leader is "captured" by a specific point on the ground or on a grounded object. The striking distance is needed for constructing the capture surface. |
| Finding | A conclusion based on facts established during the assessment/inspection by the investigating authority. |
| Lightning Leader | A lightning process that, in the case of downward cloud-to-ground discharges, originates in the thundercloud and extends toward the ground. The leader creates a conducting path between the cloud charge source and ground and determines the lightning strike point on ground or on grounded object. |
| Lessons Learned | Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result. |

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| Observation | A factor, event, or circumstance identified during the assessment and/or inspection that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur. |
| Problem | The subject of the independent technical assessment/inspection. |
| Recommendation | An action identified by the assessment/inspection team to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible C/P/P/O in the preparation of a corrective action plan. |
| Rolling Sphere Method (RSM) | A version of the EGM which is primarily used for placing lightning rods on ordinary structures. The geometrical construction of the capture surface in the RSM is accomplished simply by rolling an imaginary sphere of radius equal to the striking distance across the ground and across objects on the ground. Those points the rolling sphere touches can be struck by lightning (and hence have to be protected) - the smaller the prospective lightning peak current, the smaller the radius of the rolling sphere. |
| Root Cause | Along a chain of events leading to a mishap or close call, the first causal action or failure to act that could have been controlled systemically either by policy, practice, and/or procedure or individual adherence to policy, practice, and/or procedure. |
| Striking Distance | The distance from the tip of the descending leader to the object to be struck at the instant when the lightning strike point is thought to be uniquely determined. The concept of striking distance, which is assumed to be a function of lightning peak current, is the core of the EGM. |



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11.0 List of Acronyms

| | |
|-------|---|
| CCAFS | Cape Canaveral Air Force Station |
| EGM | Electrogeometrical Model |
| EMC | Electromagnetic Compatibility |
| ESE | Early Streamer Emitter |
| ET | External Tank |
| FSS | Fixed Support Structure |
| GOx | Gaseous Oxygen |
| GRC | Glenn Research Center |
| GSFC | Goddard Space Flight Center |
| IEC | International Electrotechnical Commission |
| IEEE | Institute of Electrical and Electronics Engineers |
| JSC | Johnson Space Center |
| kA | Kiloamperes |
| KSC | Kennedy Space Center |
| kV | Kilovolts |
| LaRC | Langley Research Center |
| LPS | Lightning Protection System |
| MLP | Mobile Launch Platform |
| NESC | NASA Engineering and Safety Center |
| NRB | NESC Review Board |
| OHSW | Overhead Shield Wire |
| RSM | Rolling Sphere Method |
| RSS | Rotating Support Structure |
| SE& I | Systems Engineering and Integration |
| SERB | Shuttle Engineering Review Board |
| SLC | Space Launch Complex |
| SPRT | Super Problem Resolution Team |
| SSP | Space Shuttle Program |
| TEM | Technical Exchange Meeting |

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13.0 Minority Report (dissenting opinions)

There were no minority opinions voiced during the conduct of the consultation.

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Appendix A. NESC Request Form (PR-003-FM-01)

| NASA Engineering and Safety Center Request Form | | |
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| Submit this ITA/I Request, with associated artifacts attached, to: nrbexecsec@nasa.gov , or to NRB Executive Secretary, M/S 105, NASA Langley Research Center, Hampton, VA 23681 | | |
| Section 1: NESC Review Board (NRB) Executive Secretary Record of Receipt | | |
| Received (mm/dd/yyyy h:mm am/pm) 5/18/2005 12:00 AM | Status: New | Reference #: 05-030-E |
| Initiator Name: Billy Stover | E-mail: Billy.R.Stover@nasa.gov | Center: KSC |
| Phone: (321)-861-8554, Ext | Mail Stop: | |
| Short Title: KSC Pad B Catenary Capability Analysis and Technical Exchange Meeting (TEM) Support Description: NESC was asked to support review of a lightning analysis done at KSC. SE&I has been struggling with this issue for awhile as one of the integrated hazards they're trying to document. The existing catenary wire system appears to provide protection for lightning strikes at a given energy level, but does not protect against lower-level strikes. No one has been able to determine what strike level is "acceptable" so upgrades to the catenary system may be required to fully protect the vehicle when the RSS is rolled back for loading and launch. Our role will be to assist in a review of the analysis done to determine lightning strike potential and recommend upgrades to reduce that potential. KSC has a very detailed analysis of what the Pad B Catenary system is really capable of. KSC is finalizing the TEM week and will be distribute information no later than 5/23. The purpose of the TEM will be to get the Shuttle Program E3 and lightning community to agree that this is a valid analysis and representation of what the actual lightning protection is at Pad B. Once an agreement is reached on that then will break out a lot of other things that the program has to go do to start closing the lightning story. Source (e.g. email, phone call, posted on web): email | | |
| Type of Request: Consultation | | |
| Proposed Need Date: | | |
| Date forwarded to Systems Engineering Office (SEO): (mm/dd/yyyy h:mm am/pm): | | |
| Section 2: Systems Engineering Office Screening | | |
| Section 2.1 Potential ITA/I Identification | | |
| Received by SEO: (mm/dd/yyyy h:mm am/pm): 5/18/2005 12:00 AM | | |
| Potential ITA/I candidate? <input type="checkbox"/> Yes <input type="checkbox"/> No | | |
| Assigned Initial Evaluator (IE): | | |
| Date assigned (mm/dd/yyyy): | | |
| Due date for ITA/I Screening (mm/dd/yyyy): | | |
| Section 2.2 Non-ITA/I Action | | |
| Requires additional NESC action (non-ITA/I)? <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No | | |
| If yes: | | |
| Description of action: Support the review of the lightning analysis for KSC Pad B Catenary Capability analysis and the Proposed TEM at KSC for Technical Review. This is related to Return-to-flight and was approved Out-of-Board by Ralph Roe on 5/18/2005. | | |
| Actionee: Tim Wilson | | |
| Is follow-up required? <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No If yes: Due Date: | | |
| Follow-up status/date: | | |



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| | |
|---|---------------------------------------|
| If no: | |
| NESC Director Concurrence (signature): | |
| Request closure date: . | |
| Section 3: Initial Evaluation | |
| Received by IE: (mm/dd/yyyy h:mm am/pm): | |
| Screening complete date: | |
| Valid ITA/I candidate? <input type="checkbox"/> Yes <input type="checkbox"/> No | |
| Initial Evaluation Report #: NESC-PN- | |
| Target NRB Review Date: | |
| Section 4: NRB Review and Disposition of NCE Response Report | |
| ITA/I Approved: <input type="checkbox"/> Yes <input type="checkbox"/> No | Date Approved: Priority: - Select - |
| ITA/I Lead: . Phone () - . x | |
| Section 5: ITA/I Lead Planning, Conduct, and Reporting | |
| Plan Development Start Date: | |
| ITA/I Plan # NESC-PL- | |
| Plan Approval Date: | |
| ITA/I Start Date | Planned: Actual: |
| ITA/I Completed Date: | |
| ITA/I Final Report #: NESC-PN- | |
| ITA/I Briefing Package #: NESC-PN- | |
| Follow-up Required? <input type="checkbox"/> Yes <input type="checkbox"/> No | |
| Section 6: Follow-up | |
| Date Findings Briefed to Customer: | |
| Follow-up Accepted: <input type="checkbox"/> Yes <input type="checkbox"/> No | |
| Follow-up Completed Date: | |
| Follow-up Report #: NESC-RP- | |
| Section 7: Disposition and Notification | |
| Notification type: - Select - | Details: |
| Date of Notification: | |
| Final Disposition: - Select - | |
| Rationale for Disposition: | |
| Close Out Review Date: | |



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Form Approval and Document Revision History

| | |
|-----------------|-------|
| Approved: _____ | _____ |
| NESC Director | Date |

| Version | Description of Revision | Office of Primary Responsibility | Effective Date |
|---------|-------------------------|----------------------------------|----------------|
| 1.0 | Initial Release | Principal Engineers Office | 29 Jan 04 |

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Appendix B. Key TEM Input Summaries: E-Mails of Dr. Rakov and Mr. Kithil

From: rakov@ece.ufl.edu

To: "Stover, Billy R" <Billy.R.Stover@nasa.gov>,
"Bowen, Barry C \KKSC\" <Barry.C.Bowen@nasa.gov>,
"Crawford, David E" <David.E.Crawford@nasa.gov>,
"Delgado, Hector N" <Hector.N.Delgado@nasa.gov>,
"Frank A. Fisher" <fafisher@lightningtech.com>,
"Garrett, Alma B \BBo\ \UUSA\" <alma.b.garrett@usa-spaceops.com>,
"George C. May" <george.c.may@boeing.com>,
"Hampton, John O \UUSA\" <john.o.hampton@usa-spaceops.com>,
"Hancock, Randy A" <Randy.Hancock-1@ksc.nasa.gov>,
"Jason Chai" <jason.c.chai@aero.org>,
"Lewis, Mark E" <Mark.E.Lewis@nasa.gov>,
"Lindholm, Judy A \UUSA\" <judy.a.lindholm@usa-spaceops.com>,
"Lindsay W Coffman" <Lindsay.W.Coffman@aero.org>,
"Madura, John T" <John.T.Madura@nasa.gov>,
"Magee, Tyrone J \BBoeing\" <Tyrone.Magee-1@ksc.nasa.gov>,
<Mark.Krome@nasa.gov>, <Matt.Mccollum@nasa.gov>,
"Medelius, Pedro J" <Pedro.Medelius-1@ksc.nasa.gov>,
"Myrsten, Randolph \UUSA\" <randolph.myrsten@usa-spaceops.com>,
<noel.b.sargent@nasa.gov>,
"Raffoul, George W " <George.W.Raffoul@boeing.com>,
"Richard Kithil" <rich@lightningsafety.com>,
"Robert A. Kichak" <robert.a.kichak@nasa.gov>,
"SCULLY, ROBERT C. \JJSC-EV\ \NNASA\" <robert.c.scully@nasa.gov>,
"Snyder, Gary P" <Gary.P.Snyder@nasa.gov>,
"Speigner, Jimmy O \AAerospace\" <SpeigJO@kscems.ksc.nasa.gov>,
"Stanton, Mark A \UUSA\" <Mark.A.Stanton@usa-spaceops.com>,
"Troutman, Dana R \UUSA\" <Dana.R.Troutman@usa-spaceops.com>,
"Vlad Rakov" <rakov@ece.ufl.edu>,
"Wheeler, Jeff D" <Jeffrey.D.Wheeler@nasa.gov>,
"Willingham, James T" <Terry.Willingham-1@nasa.gov>,
"Winters Katherine A GS-13 45 WS/DOR \PPAFB\" <Katherine.Winters@patrick.af.mil>,
"Mata, Carlos T" <Carlos.Mata-1@ksc.nasa.gov>

Date: Tue, 30 Aug 2005 17:50:15 -0400

Subject: RE: Lightning Monte Carlo Results

CC: "Abner, Charlie A" <Charles.A.Abner@nasa.gov>,

| | | | |
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"Cipolletti, John P \UUSA\" <John.P.Cipolletti@usa-spaceops.com>,
 "Sullivan, Steven J" <Steven.J.Sullivan@nasa.gov>,
 "Mata, Carlos T" <Carlos.Mata-1@ksc.nasa.gov>

Priority: normal

X-mailer: Pegasus Mail for Windows (v4.02)

X-Qmail-Scanner: uvscan: v4.3.20/vAug 30 12:29.

Carlos,

The updated Monte Carlo simulation results look good. About 15% (2 to 3 strikes per year, which is consistent with observations) of all the downward-lightning strikes within the 1 square kilometer are intercepted by the launch pad. Depending on configuration, 0 to 0.3% of all strikes are expected to terminate on the ET. Configuration 1 (RSS rotated back, GOx vent arm rotated back) is the worst case.

The expected number of strikes per year to the ET is 0.052, 0, 0, and 0.020 for Cases 1, 2, 3, and 4, respectively.

In other words, the ET is expected to be struck on average once in 19 years and once in 50 years for Cases 1 and 4, respectively. For Cases 2 and 3, the ET is not expected to be struck at all.

Now, the question of peak currents or charges that represent a threat to ET remains open. If some (smaller) strikes can be tolerated, then the number of potentially hazardous direct strikes will be less than that found from the Monte Carlo simulations.

On the other hand, the Monte Carlo simulations do not account for any flashovers from the structural elements of the launch pad to the ET.

Overall, I think that the updated Monte Carlo simulations do provide the necessary information to quantify the threat due to the most deleterious direct lightning strikes.

Regards,

Vlad

Dr. Mata described the five analysis cases as follows:

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We ran a total of 5 cases (four of them were run three times with some variants):

Case 1: Orbiter in launch configuration, RSS rotated back, LOX vent arm rotated back (three runs with max angles of 30, 40, and 60 degrees).

Case 2: Orbiter in launch configuration, RSS rotated back, LOX vent arm 2 meters from the ET (three runs with max angles of 30, 40, and 60 degrees).

Case 3: Orbiter parked, RSS covering the Orbiter, LOX vent arm 2 meters from the ET (three runs with max angles of 30, 40, and 60 degrees).

Case 4: Orbiter parked, RSS covering the Orbiter, LOX vent arm rotated back (three runs with max angles of 30, 40, and 60 degrees).

Case 5: Same as case 1 but with two auxiliary catenary wires protecting the stack.

From: R Kithil [mailto:rkithil@ix.netcom.com]

Sent: Wednesday, October 05, 2005 11:50 AM

To: 'Robert Kichak'

Cc: Timmy.R.Wilson@nasa.gov; rakov@ece.ufl.edu; rkithil@ix.netcom.com

Subject: Re: Input From Oct 5 Lightning TIM

Bob and Tim:

My summary of the meeting is:

1. Consideration of catenary issues has omitted positive lightning strike manifestations.
2. Only vertical lightning strikes are including in the EGM Model, upon which the computer simulations were based. What percentage of KSC lightning is less-than-vertical? Can NASA's LDAR archives look at this to get an approximation?
3. One strike to Space Shuttle every 15 years as a conclusion begs the question of "acceptable risk" (raised by Vlad Rakov).
4. It remains a Given that the present catenary design was conceived for the Apollo Project. Is NASA comfortable using old science for a new structure? What are the measures to be taken to enhance LP at Pads 39B after digestion of the study group's data?
5. We learned that MSFC (Jeff Anderson) is working up a lightning protection schema for the Next-Generation Space Craft. Will the present NESC study group be allowed input into those LP design considerations?

Thanks for letting NLSI participate in the Pad 39B catenary study.

Richard Kithil, Jr., Founder & CEO
National Lightning Safety Institute
891 N. Hoover Ave., Louisville CO 80027
Email: rkithil@lightningsafety.com

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Internet: www.lightningsafety.com
 Tel. 303-666-8817; Fax 303-666-8786
 A Non-Profit Agency Providing Objective
 Information about Lightning Hazards.

----- Forwarded message follows -----

From: rakov@ece.ufl.edu
 To: "Vlad Rakov" <rakov@ece.ufl.edu>,
 "Rich Kithil" <RKithil@lightningsafety.com>,
 "Noel Sargent" <noel.b.sargent@nasa.gov>,
 Robert Kichak <Robert.A.Kichak@nasa.gov>
 Date sent: Wed, 05 Oct 2005 14:25:25 -0400
 Subject: Re: Tomorrow's Lightning TIM
 Copies to: Timmy.R.Wilson@nasa.gov
 Priority: normal

Bob,

The KSC telecon meeting on Oct. 5 went well. I also had a separate phone conversation with Jason Chai, who missed the meeting but submitted written comments prior to it. Here are some observations.

1. The issue of vertical vs. non-vertical leaders has been discussed. I have commented on this issue several times before. The bottom line is that, in the updated Monte Carlo simulations, (1) descending leaders are initially vertical, because they do not "sense" the presence of any objects on ground and (2) vertical leaders become non-vertical when they come within tens to hundreds of meters of the prospective strike point, because they are attracted by grounded objects. I do not believe initially-non-vertical leaders should be considered because (1) there is no good way to specify lightning channel tortuosity (whatever you do it will be arbitrary; the way it was done by KSC is not correct) and (2) the difference it makes (30% or so in power-line studies) is less than the uncertainties involved in the electrogeometrical model.

2. Calculations were done for negative lightning only. They will additionally do positive lightning by the end of the month. I have sent them a paper that contains info needed for modeling positive lightning.

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3. All the results up to date are concerned with direct strike effects. This was clearly stated by Pedro, but needs to be in writing in all documents related to this project. I hope that possible flashovers, induced effects, surges arriving along the wires, and safety issues will be addressed at later stages of the project.

4. Mark Lewis stated that the next step will be risk assessment (to answer the question on what lightning incidence is acceptable; unfortunately, lightning elimination is not an option), which will have to involve forces outside the Lightning TIM.

Regards,

Vlad

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Appendix C. Monte Carlo Simulation Report

**DOCUMENT NUMBER
REVISION BASIC**

MONTE CARLO SIMULATION OF POSITIVE STRIKES TO THE KSC LAUNCH PADS

This document has NOT been reviewed for export control status.
Please replace this statement with the appropriate notice reflecting
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OCTOBER 31, 2005

ASRC AEROSPACE CORPORATION



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**MONTE CARLO SIMULATION OF POSITIVE STRIKES
TO THE KSC LAUNCH PADS**

Prepared by:

Dr. Carlos T. Mata, ASRC-10
Principal Investigator

Prepared by:

Dr. Pedro J. Medelius, ASRC-19
Chief Technologist

This Revision Supersedes All Previous Editions of This Document

OCTOBER 31, 2005



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| RECORD OF REVISIONS | | |
|---------------------|-------------|------------------|
| REV LTR | DESCRIPTION | DATE |
| | Basic Issue | October 31, 2005 |
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ABBREVIATIONS, ACRONYMS, AND SYMBOLS

A ampere
k kilo
m meter



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**MONTE CARLO SIMULATION OF POSITIVE STRIKES
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1. BACKGROUND

Kumar and Joseph use (1) to relate the lightning stroke current peak I to the striking distance r_s :

$$r_s = aI^c \tag{1}$$

where a ranges between 6 and 10 and the exponent c has a value between 0.6 and 0.8 (note that $a = 10$ and $c = 0.65$ are commonly used for negative strokes). They found the maximum bypass negative stroke (presumably when the sphere can sneak through the shielding and hit the aircraft) to be approximately 14 kA (Figure 1).

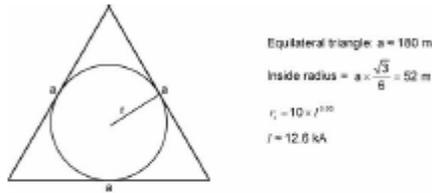


Figure 1. Geometry of study of Kumar and Joseph, showing the location of the towers and the size of the sphere that can sneak through the catenary wires. Note that we compute about 12.6 kA, and they estimate 14 kA.

They also obtained a maximum bypass positive stroke of 38 kA. So, (1) can be rewritten to reflect this as follows (see Figure 2):

$$10 \times (14)^{0.65} = a_{(+)}, (38)^{0.65} \tag{2}$$



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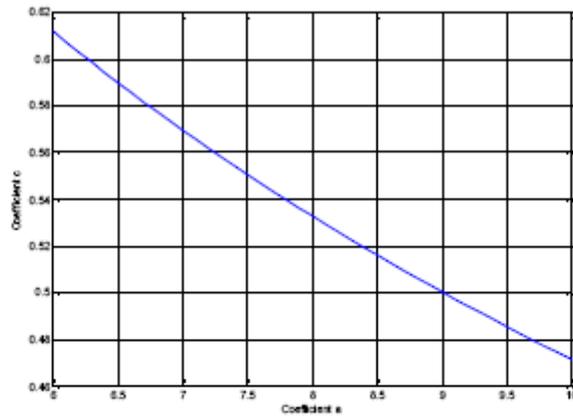


Figure 2. Coefficient c versus coefficient a as indicated by (2) when a ranges from 6 to 10.

From here we find $c_{(+)}$:

$$c_{(+)} = \frac{\log(10 \times (14)^{0.65}) - \log(a_{(+)})}{\log(38)} \quad (3)$$

We can now plot the striking distance as a function of positive stroke current peak and $a_{(+)}$ (see Figure 3).



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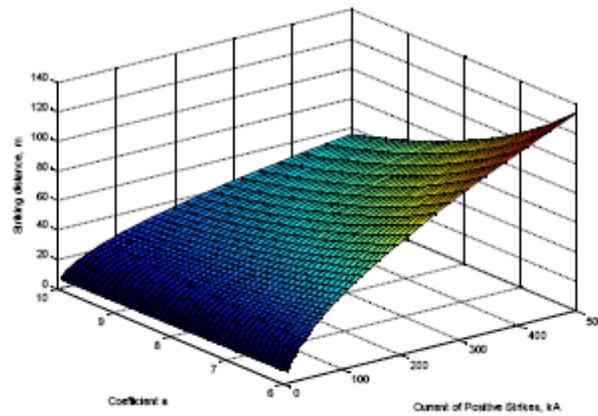


Figure 3. Striking distance as a function of positive stroke current peak and $\alpha_{(+)}$.

It is obvious from that Figure 4 the most severe case for positive strokes is given by

$$r_s = 10I^{0.4716} \quad (4)$$



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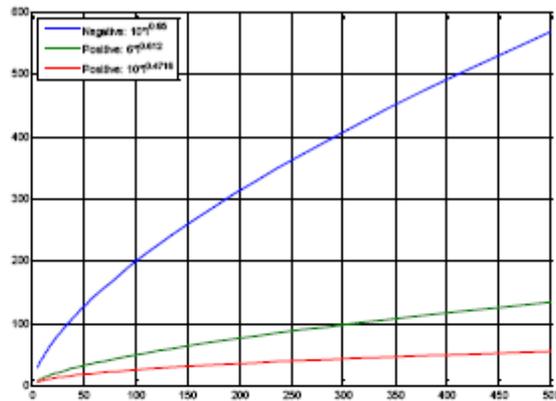


Figure 4. Striking distance for the commonly used equation for negative strokes and the two extreme cases shown in Figure 3.

Therefore, (4) will be used for the Monte Carlo simulation considering positive lightning strokes. Also, the current parameters used for positive strokes are as follows: 95 percent exceed 4.6 kA, 50 percent exceed 35 kA, and 5 percent exceed 250 kA [2]. Doing curve fitting we estimate sigma (using a lognormal cumulative distribution function with base e) and we obtain a sigma of approximately 1.2. Figure 5 shows the cumulative probability distribution function for a log-normal distribution with $\mu = 35$ kA and $\sigma = 1.2$.



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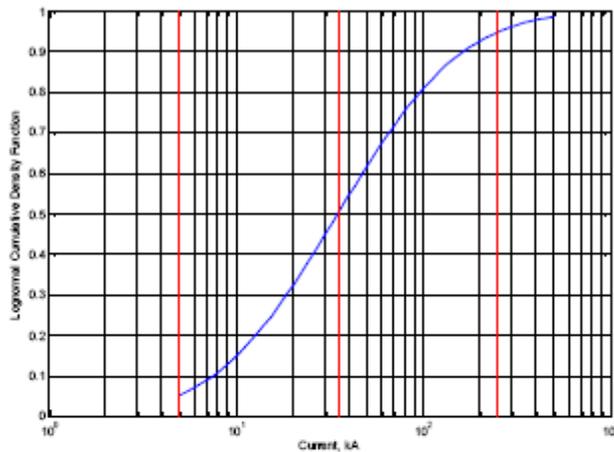


Figure 5. Lognormal cumulative distribution function of a dataset with $\mu = 35$ kA and $\sigma = 1.2$.

2. ASSUMPTIONS

The following are the assumptions used in the present study.

- a. The relationship between striking distance and stroke peak current is given by (4).
- b. The leaders travel vertically with step sizes equal to 10 percent of their corresponding striking distance.
- c. The leader will attach to any point that touches the surfaces of the sphere as it travels down (the sphere's radius is the striking distance). So, the last step of the leader can be in any direction (see Figure 6).



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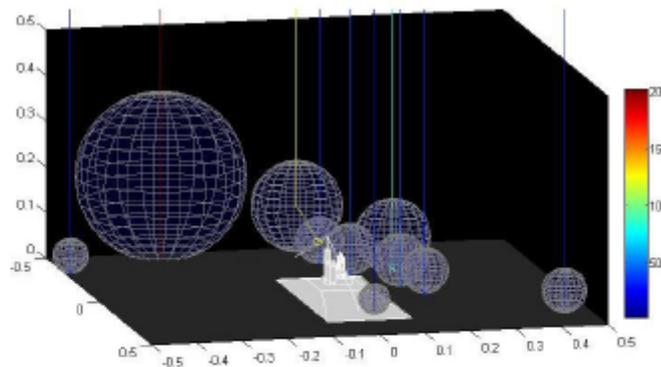


Figure 6. Positive strikes to the pad using spheres to illustrate the algorithm. Note the angle of inclination of the initially vertically traveling leader (yellow line) as it attaches to the catenary system.

- d. Positive strikes are assumed to be 10 percent of all strikes and we do not know the correction factor for multiple ground strike points for positive strikes. Therefore, we estimate that about 10% of the uncorrected ground flash density (or 1 flash/km²/year) is the frequency of occurrence of positive strikes at the pad. Nevertheless, data from the 45th Weather Squadron at Patrick Air Force suggest that this percentage is actually from 3-5%. So, we've used 5% or 0.5 positive flashes/km²/year.
- e. The area of study is 1 km² with the lightning mast at the (0,0) coordinate.
- f. The (x,y) origin of the leader is obtained from a random-number generator and they all originate at the same height (500 m).
- g. The stroke peak current is obtained from a lognormal random-number generator with $\mu = 35$ kA and $\sigma = 1.2$ (see Figure 5).
- h. The stack is assumed to be permanently at the pad.



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3. RESULTS

The following figures correspond to Monte Carlo simulations of the pads assuming leaders initially travel vertically with step sizes of 10 percent of their corresponding striking distances. Strikes to ground are represented as "x" and strikes to objects of interest are represented as "o." All strikes with a peak current equal to or greater than 200 kA are presented with the same red intensity. Colors of other peak currents correspond to the color bar shown in each figure (it is the same for all).

3.1 Case 1: launch configuration: RSS rotated back, GOX vent arm rotated back.

- ET received 1 strikes (0.20%), Min=48.9kA, Max=48.9kA, GeoMean=48.9kA, sigma=0.0000
- MLP received 2 strikes (0.40%), Min=8.4kA, Max=33.5kA, GeoMean=16.8kA, sigma=0.9527
- FSS received 0 strikes
- Catenary received 35 strikes (7.00%), Min=5.7kA, Max=441.4kA, GeoMean=48.2kA, sigma=1.2555
- pad_surface received 16 strikes (3.20%), Min=1.7kA, Max=73.8kA, GeoMean=17.8kA, sigma=0.8583
- SRBs received 0 strikes
- orbiter received 0 strikes
- rss_not_in_place received 0 strikes

Current distribution, Min=1.7kA, Max=603.4kA, GeoMean=32.3kA, sigma=1.1393 (See Figure 7).



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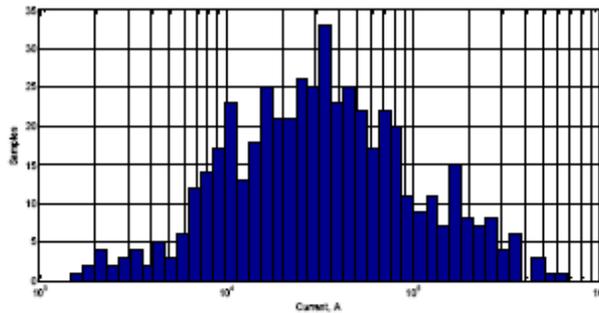


Figure 7. Histogram of the peak currents used for Case 1. Post-processing indicates $\mu=32.3\text{kA}$ and $\sigma=1.1393$.

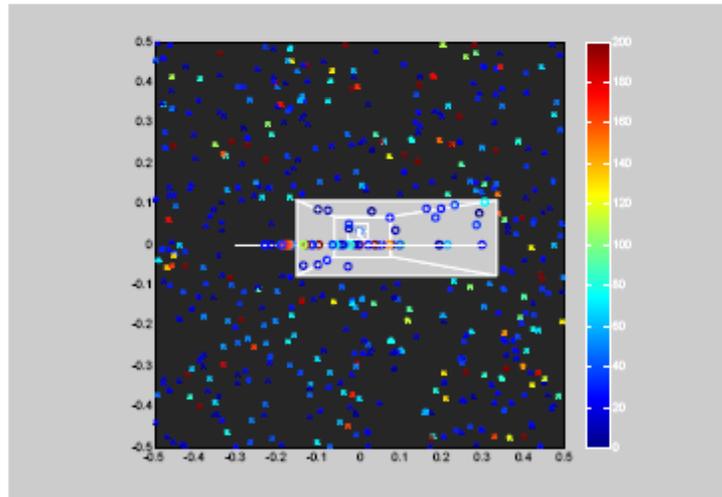


Figure 8. Pad seen from above, results for case 1.



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3.2 Case 2: launch configuration: RSS rotated back, GOX vent arm 2 m from ET

- ET received 0 strikes
- MLP received 0 strikes
- FSS received 0 strikes
- Catenary received 37 strikes (7.40%), Min=10.2kA, Max=425.1kA, GeoMean=41.0kA, sigma=0.7690
- pad_surface received 19 strikes (3.80%), Min=2.3kA, Max=278.9kA, GeoMean=22.0kA, sigma=1.2152
- SRBs received 0 strikes
- orbiter received 0 strikes
- rss_not_in_place received 0 strikes
- Gox_vent_arm received 2 strikes (0.40%), Min=22.4kA, Max=106.3kA, GeoMean=48.8kA, sigma=1.2154

Current distribution, Min=1.5kA, Max=928.3kA, GeoMean=33.9kA, sigma=1.1275 (See Figure 9).



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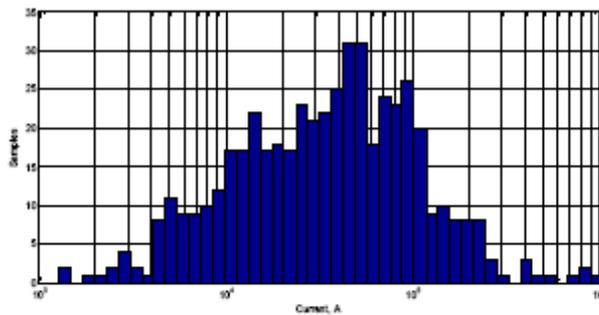


Figure 9. Histogram of the peak currents used for Case 2. Post-processing indicates $\mu=33.9\text{kA}$ and $\sigma=1.2075$.

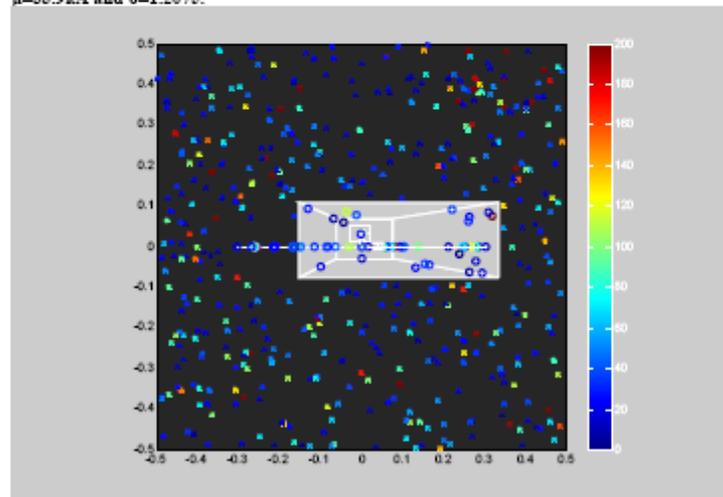


Figure 10. Pad seen from above, results for case 2.



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- 3.3 Case 3: RSS covering the orbiter, GOX vent arm 2 meters from ET
- ET received 0 strikes
 - MLP received 1 strikes (0.20%), Min=11.6kA, Max=11.6kA, GeoMean=11.6kA, sigma=0.0000
 - FSS received 0 strikes
 - Catenary received 27 strikes (5.40%), Min=7.8kA, Max=497.9kA, GeoMean=38.5kA, sigma=0.9882
 - pad_surface received 32 strikes (6.40%), Min=1.9kA, Max=327.5kA, GeoMean=22.0kA, sigma=1.4354
 - SRBs received 0 strikes
 - orbiter received 0 strikes
 - rss_in_place received 3 strikes (0.60%), Min=23.3kA, Max=73.9kA, GeoMean=49.6kA, sigma=0.4290
 - Gov_vent_arm received 1 strikes (0.20%), Min=28.0kA, Max=28.0kA, GeoMean=28.0kA, sigma=0.0000
- Current distribution, Min=1.7kA, Max=603.4kA, GeoMean=32.5kA, sigma=1.1361 (See Figure 11).



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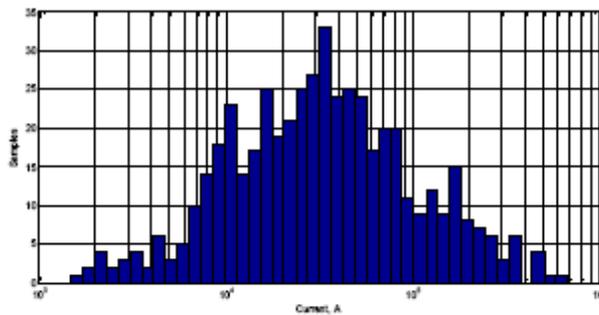


Figure 11. Histogram of the peak currents used for Case 3. Post-processing indicates $\mu=32.5kA$ and $\sigma=1.1361$.

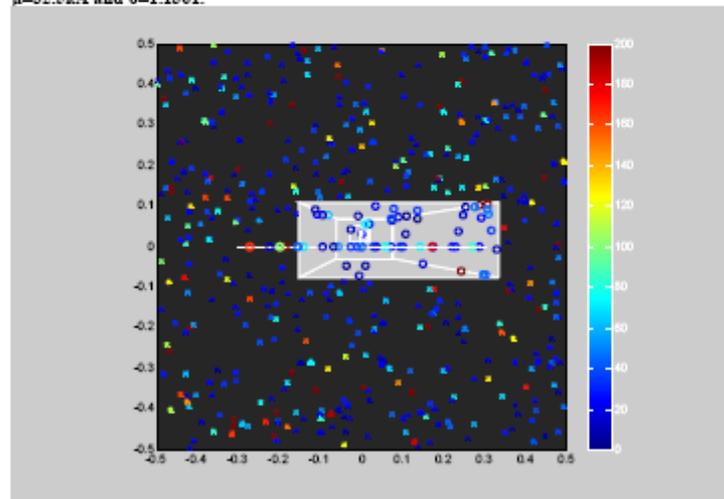


Figure 12. Pad seen from above, results for case 3.



3.4 Case 4: RSS covering the orbiter, GOX vent arm rotated back

- ET received 0 strikes
- MLP received 0 strikes
- FSS received 0 strikes
- Catenary received 47 strikes (9.40%), Min=1.9kA, Max=883.3kA, GeoMean=49.2kA, sigma=1.4751
- pad_surface received 28 strikes (5.60%), Min=2.4kA, Max=87.8kA, GeoMean=24.9kA, sigma=0.7654
- SRBs received 0 strikes
- orbiter received 0 strikes
- rss_in_place received 3 strikes (0.60%), Min=29.9kA, Max=264.9kA, GeoMean=90.3kA, sigma=1.1904

Current distribution, Min=1.5kA, Max=928.3kA, GeoMean=34.0kA, sigma=1.1289 (See Figure 13).

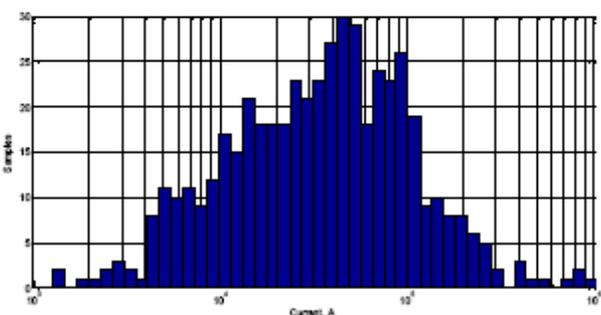


Figure 13. Histogram of the peak currents used for Case 4. Post-processing indicates $\mu=34.0\text{kA}$ and $\sigma=1.2289$.



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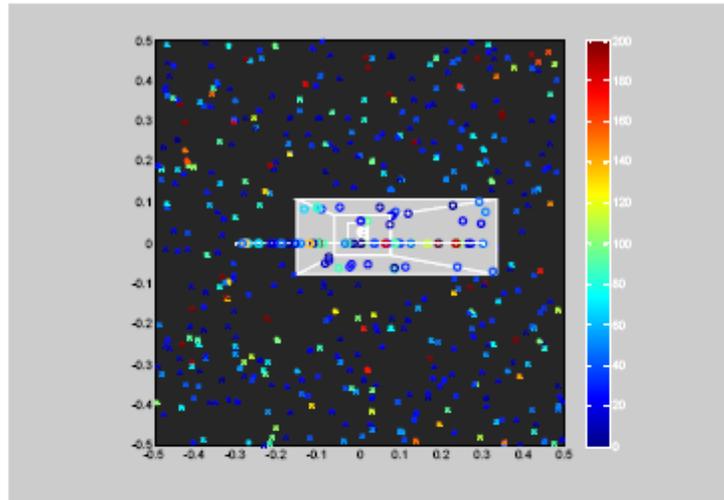


Figure 14. Pad seen from above, results for case 4.



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4. SUMMARY

Table 1 summarizes the results of the Monte Carlo simulation for both, negative and positive strikes. Note that the assumed overall ground flash density is 10 flashes/km²/year. The ground flash density correction for negative flashes is 1.7 (to account for flashes with multiple terminations) and the percent of positive strikes is 5%. Therefore, the ground flash density for negative strike is 17 flashes/km²/year¹ and the ground flash density for positive strikes is 0.5 flashes/km²/year.

Table 1 Expected number of years between strikes to structures of interest. Results are shown by flash polarity (negative and positive) and for the four cases that have been studied.

| Object | Case 1 | | Case 2 | | Case 3 | | Case 4 | |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| | Negative | Positive | Negative | Positive | Negative | Positive | Negative | Positive |
| ET | 19.230789 | 1000 | >1000 | >1000 | >1000 | >1000 | 50 | >1000 |
| MLP | 200 | 500 | 250 | >1000 | 333.33333 | 1000 | >1000 | >1000 |
| FSS | 188.88887 | >1000 | 333.33333 | >1000 | 500 | >1000 | 333.33333 | >1000 |
| Catenary | 0.5032713 | 28.571429 | 0.5181347 | 27.027027 | 0.408008 | 37.037037 | 0.5182108 | 21.276598 |
| Pad Surface | 2.3384488 | 82.5 | 2.4006388 | 52.831579 | 2.8595745 | 81.25 | 2.5008738 | 35.714288 |
| SRBs | 90.000091 | >1000 | 200 | >1000 | >1000 | >1000 | >1000 | >1000 |
| Orbiter | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 |
| RSS | 1000 | >1000 | 333.33333 | >1000 | 11.382838 | 333.33333 | 9.3457944 | 333.33333 |
| GOX Vent Arm | NA | NA | 14.285714 | 500 | 22.727273 | 1000 | NA | NA |

¹ Note that 95% of the overall ground flash density times 1.7 is 16.15 and not 17. Nevertheless, the simulations for negative strikes had already been run and we can assume that the results of the negative strike simulations using 16.15 flashes/km²/year will be within 5% of the results using 17 flashes/km²/year.

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[2] V.A. Rakov and M.A. Uman. 2003. *Lightning Physics and Effect. Cambridge University Press.* ISBN 0521583276

6. ACKNOWLEDGEMENTS

The authors will like to acknowledge the contribution of Dr. Vladimir Rakov who provided valuable information and direction. The authors also express their gratitude to the 45th Weather Squadron, who provided the data necessary for the conduction of the analysis.

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**Appendix D. Shuttle Engineering Review Board November 8, 2005
Presentation by Dr. Medelius**



Evaluation of the Effectiveness of Lightning Protection Systems at the LC-39 Launch Pads

Summary

Pedro J. Medelius, Ph.D.

Carlos T. Mata, Ph.D.



ASRC Aerospace Corporation
Kennedy Space Center

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Analysis Methodology

The analysis of the effectiveness of the lightning protection system was conducted using the following methods:

1. Rolling Sphere – provided insight into areas with inadequate lightning protection
2. “Equivalent Collection Method” described in International Standard IEC 61024-1 and Eriksson’s equation, widely used for distribution and transmission lines.
3. Monte Carlo Simulation: simulated **1000** years of lightning activity for various configurations.

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Results of Theoretical Analysis

Summary of Expected Number of Years Between Strikes to the Orbiter Stack

| | Launch Configuration | RSS next to Orbiter |
|--|----------------------|---------------------|
| Equivalent Collection and Eriksson's Equation Method | 5 years | 12.5 years |
| Rolling Sphere Method | 20 years | 50 years |

The calculations are based on the "Equivalent Collection Method" described in the International Standard IEC 61024-1; and on Eriksson's equation, widely used for distribution and transmission lines.

The Rolling Sphere method is widely accepted by the scientific community, and its use is recommended by International and National Standards:

- NFPA 780
- IEC 61024
- IEEE Std 998-1996

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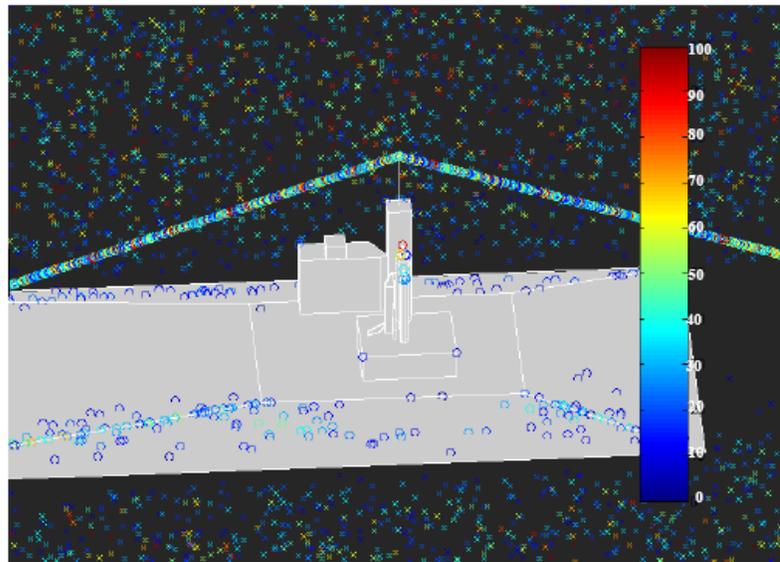
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Monte Carlo Simulation

Example: STS in launch configuration: RSS rotated back, GOX vent arm rotated back.
Monte Carlo Simulation: 1000 years, 17 strikes per year



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Monte Carlo Simulation

Summary for Positive and Negative Lightning Strikes

Expected number of years between strikes to structures of interest.

Results are shown by flash polarity (negative and positive) and for the four cases that have been studied.

Case 1: STS in Launch Configuration

Case 2: GOx Vent arm positioned over external tank

Case 3: Rotating Service Structure next to Vehicle and GOx Vent arm positioned over external tank

Case 4: Rotating Service Structure next to Vehicle

| Object | Case 1 | | Case 2 | | Case 3 | | Case 4 | |
|--------------|----------|----------|----------|----------|----------|----------|----------|----------|
| | Negative | Positive | Negative | Positive | Negative | Positive | Negative | Positive |
| ET | 19.2 | 1000.0 | >1000 | >1000 | >1000 | >1000 | 50.0 | >1000 |
| MLP | 200.0 | 500.0 | 250.0 | >1000 | 333.3 | 1000.0 | >1000 | >1000 |
| FSS | 166.7 | >1000 | 333.3 | >1000 | 500.0 | >1000 | 333.3 | >1000 |
| Catenary | 0.5 | 28.6 | 0.5 | 27.0 | 0.5 | 37.0 | 0.5 | 21.3 |
| Pad Surface | 2.3 | 62.5 | 2.4 | 52.6 | 2.7 | 31.3 | 2.6 | 35.7 |
| SRBs | 90.9 | >1000 | 200.0 | >1000 | >1000 | >1000 | >1000 | >1000 |
| Orbiter | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 |
| RSS | 1000.0 | >1000 | 333.3 | >1000 | 11.4 | 333.3 | 9.3 | 333.3 |
| GOX Vent Arm | NA | NA | 14.3 | 500.0 | 22.7 | 1000.0 | NA | NA |

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Monte Carlo Simulation

Summary of Expected Number of Years Between Strikes to the Orbiter Stack

Expected number of years between strikes to the STS (Orbiter, external tank, and SRBs) for the four cases that have been studied.

Case 1: STS in Launch Configuration

Case 2: GOx Vent arm positioned over external tank

Case 3: Rotating Service Structure next to Vehicle and GOx Vent arm positioned over external tank

Case 4: Rotating Service Structure next to Vehicle

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total |
|---------------|-------|-------|-------|-------|-------|--------|--------|--------|--------|-------|-------|--------|---------|
| | 0.40% | 0.82% | 3.26% | 1.97% | 5.24% | 24.59% | 19.29% | 29.53% | 12.10% | 2.37% | 0.33% | 0.11% | 100.00% |
| Case 1 | 3952 | 1939 | 488 | 804 | 303 | 65 | 82 | 54 | 131 | 671 | 4883 | 14589 | 16 |
| Case 2 | 49801 | 24429 | 6127 | 10131 | 3818 | 813 | 1037 | 677 | 1653 | 8456 | 61275 | 183824 | 200 |
| Case 3 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 |
| Case 4 | 12450 | 6107 | 1532 | 2533 | 955 | 203 | 259 | 169 | 413 | 2114 | 15319 | 45956 | 50 |

Note 1: Monthly data was derived from 15 years worth of historical data recorded by the 45th Weather Squadron

Note 2: The total column shows the estimated number of years between strikes if the STS is at the pad all year long

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Results

- Significant agreement was obtained among the results of the Monte Carlo simulation, the Rolling Sphere Analysis, and the theoretical calculations.
- The lightning mast and the catenary wire lightning protection system do not provide complete protection to the STS.
- The possibility exists for an eventual lightning strike attachment to the STS.
- The analysis also shows the possibility of lightning strikes to the MLP and the pad surface.
- An increased probability (once every 54 years) exists for an eventual lightning strike attachment to the orbiter stack during the peak lightning months (June - September).

Note: The analysis in this study has concentrated on direct lightning strikes to the Orbiter and structures of interest. The indirect effects caused by large electromagnetic fields are beyond the scope of this study.

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Recommendations

- SE&I should conduct risk analysis for flight hardware to determine whether additional facility lightning protection needs to be implemented or risk is acceptable as is.
- Update the KSC lightning policy to reflect the high likelihood of lightning strikes and its implications for personnel working on the LC-39 Launch Pads.
- Access possible risk mitigation strategies in parallel with the above SE&I action:
 - Additional catenary wire protection
 - Maintaining RSS rotated next to vehicle if thunderstorms are expected
- Review weather criteria rules and ground rules for propellant tanking, and for crew and support personnel access into the Pad area.

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Equivalent Collection Area

International Standard IEC 61024-1

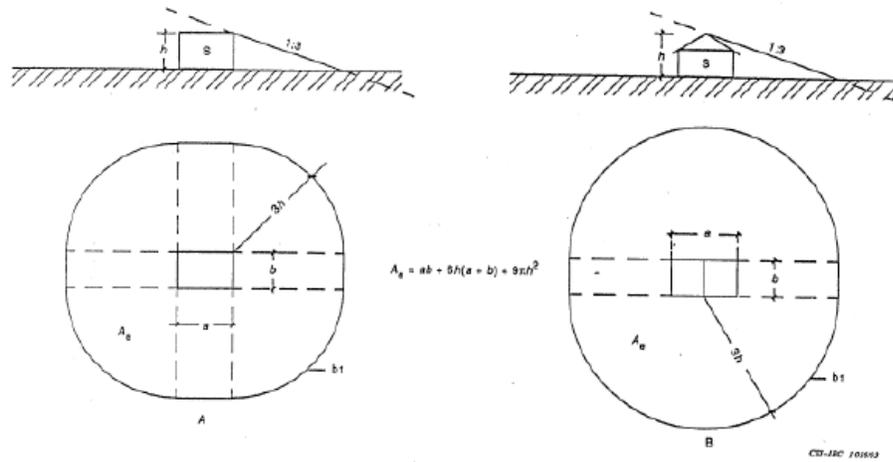


Figure 1 – Surface équivalente d'exposition d'une structure en pays plat
Equivalent collection area of a structure in flat country

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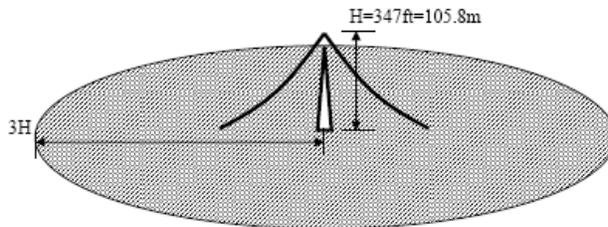
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Lightning Strike Frequency Using the Equivalent Collection Area



Equivalent collection area A_e (as per IEC 61024-1):

$$A_e = \pi r^2 = \pi(3H)^2 = 0.316km^2$$

Lightning strike frequency N_d (as per IEC 61024-1) :

$$N_d = N_g A_e C_1 = 10 \frac{\text{flashes}}{km^2 \text{ year}} \cdot 0.316km^2 \times C_1 = 3.16 \frac{\text{flashes}}{\text{year}} \times C_1$$

Where N_g is the average flash density in the region where the structure is located and C_1 is the **environmental coefficient** (equal to 1 for unshielded structures).

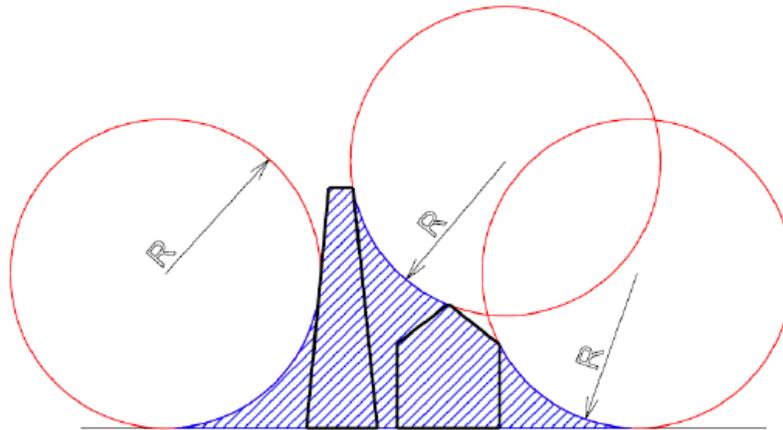


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Rolling Sphere Method



Shaded area represents the protected region

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Appendix E. Lightning Protection for NASA KSC Facilities: A Comprehensive Matrix Approach by R. Kithil

LIGHTNING PROTECTION FOR NASA KSC FACILITIES: A COMPREHENSIVE MATRIX APPROACH

by Richard Kithil, President & CEO
National Lightning Safety Institute (NLSI)
www.lightningsafety.com

1. SUMMARY.

For complex facilities at NASA's Kennedy Space Center where sensitive electrical systems/electronics or explosives or volatile substances are present, a decision matrix of lightning protection sub-systems should be employed with engineering emphasis according to separate site specificities. This paper suggests adoption of a comprehensive lightning safety planning process which can be applied to NASA environments.

2. LIGHTNING LOSSES AND RISK MANAGEMENT.

NASA recorded about 56,208 lightning strikes at the KSC property during 2004, including some 3-6 strikes at or on the Pad 39B Launch Tower. The US Department of Defense recorded some 75 lightning-induced explosions in its database over the 1926-1999 period (DDESB archives) at military or contractor facilities. The US Department of Energy has recorded 346 known lightning events to its USA sites during the 1990-2000 period (DOE-ORPS archives). In total, lightning is responsible for about \$4-5 billion annual losses in the USA (National Lightning Safety Institute, 1999). The phenomenon is arbitrary, capricious, random and stochastic: absolute lightning protection is impossible. If forecasts related to global warming are correct, it is expected that the number of lightning strikes will double or even triple by mid-century (Uman, 2001). Thus it is a prudent organizational policy to analyze facilities and operations so as to identify lightning vulnerability. Designs and operational means to mitigate potential accidents should be developed. For the lightning hazard, *safety should be the prevailing directive.*

3. LIGHTNING CHARACTERISTICS.

3.1. Physics of Lightning. Lightning's characteristics include current levels in excess of 200 kA (one percentile) with the 50% average being about 25kA, temperatures to 15,000 C, and voltages in the hundreds of millions. In addition to high temperatures, lightning has a strong magnetic component, generates X-Rays, produces nitrogen, and its associated close-in thunder can reach levels of up to ten atmospheres. The stages of lightning flashes to earth, as presently understood, follows an approximate behavior:

3.1.1 The downward Leader (high energy electrified gas plasma channel) from a thundercloud pulses toward earth.

3.1.2 Within a cone of influence, ground-level air terminators such as trees, blades of grass, corners of buildings, people, radio towers, lightning rods, power poles, sailing ship's rigging, etc.. etc. emit varying degrees of responsive induced electric activity. An early term for this observed behavior was St. Elmo's Fire.

3.1.3 Grounded objects may respond at breakdown voltage by forming upward Streamers. In this intensified local field some Streamer(s) can connect with some Leaders.



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3.1.4 Upon connection of Streamer-Leader the "switch" is closed and the current flows. Lightning flashes to ground are the result. A series of return strokes may follow.

3.2 Lightning Effects. When lightning strikes an asset, facility or structure, the return-stroke current will divide up among all parallel conductive paths between attachment point and earth. Division of current will be inversely proportional to the path impedance Z ($Z = R + XL$, resistance plus inductive reactance). The resistance term will be low assuming effectively bonded metallic conductors. The inductance, and related inductive reactance, presented to the total return stroke current will be determined by the combination of all the individual inductive paths in parallel. Essentially lightning is a current source. A given stroke will contain a given amount of charge (coulombs = amp/seconds) that must be neutralized during the discharge process. If the return stroke current is 50kA – that is the magnitude of the current that will flow, whether it flows through one ohm or 1000 ohms. Therefore, achieving the lowest possible impedance serves to minimize the transient voltage developed across the path through which the current is flowing [$e(t) = I(t)R + L di/dt$].

4. LIGHTNING PROTECTION DESIGNS.

Mitigation of lightning consequences can be achieved by the employment of a matrix approach, described in some detail below.

MATRIX OF RELEVANT LIGHTNING PROTECTION SUB-SYSTEMS

| | DIRECT STRIKE | INDIRECT STRIKE | EXTERIOR LOCATION | INTERIOR LOCATION | PEOPLE SAFETY | STRUCTURE SAFETY |
|-----------------------|---------------|-----------------|-------------------|-------------------|---------------|------------------|
| AIR TERMINALS | YES | NO | YES | NO | NO | YES |
| DOWN-CONDUCTORS | YES | NO | YES | YES | NO | YES |
| BONDING | YES | YES | YES | YES | YES | YES |
| GROUNDING | YES | YES | YES | YES | YES | YES |
| SHIELDING | YES | YES | YES | YES | YES | YES |
| SURGE PROTECTION | YES | YES | YES | YES | YES | YES |
| DETECTION | YES | YES | YES | YES | YES | YES |
| POLICIES & PROCEDURES | YES | YES | N/A | N/A | YES | YES |



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4.1 Air Terminals. Since Franklin's day lightning rods have been installed upon ordinary structures as sacrificial attachment points, intending to conduct/divert direct flashes to earth. Rods should not be located on explosives storage structures since this *integral air terminal design* does not provide protection for electronics, explosives, or people inside modern structures. Inductive and capacitive coupling from lightning-energized rods and conductors can result in significant voltages and currents on interior power and signal assets. Overhead shield wires (catenaries) and mast systems located above or next to the structure are suggested alternatives for critical facilities. These are termed *indirect air terminal designs*. Such methods presume to collect/divert lightning above or away from the sensitive structure, thus avoiding or reducing flashover attachment of unwanted currents and voltages to the facility and equipments.

Unconventional air terminal designs which claim the elimination or redirecting of lightning (various arrays and charge dissipators) or its preferential capturing (early streamer emitters - ESE) have received a very skeptical reception. See by example: NASA/Navy Tall Tower Study 1987; FAA Airport Study, 1989; T. Horvath "Computation of Lightning Protection" 1991; D. MacKerras et al, IEE Proc-Sci Meas. Technol, V. 144, No. 1 1997; National Lightning Safety Institute "Royal Thai Air Force Study" 1997; A. Mousa "IEEE Trans. Power Delivery, V. 13, No. 4 1998. Merits of radioactive ESE air terminals have been investigated and dismissed by reputable scientists (Golde, 1977) and are not allowed under today's European IEC 62305 guidelines.

4.2 Downconductors. Downconductor pathways should be installed outside of the structure. Rigid strap is preferred to flexible cable due to inductance advantages. Conductors should not be painted nor placed directly on building walls, since this will increase impedance. Gradual bends always should be employed to avoid flashover problems. Building structural steel also may be used in place of downconductors where practical as a beneficial subsystem which can emulate a quasi-Faraday Cage concept.

4.3 Bonding assures that unrelated conductive objects are at the same electrical potential. Without correct bonding, lightning protection will not work. All metallic conductors entering structures (ex. AC power lines, gas and water pipes, data and signal lines, HVAC ducting, conduits and piping, railroad tracks, overhead bridge cranes, roll up doors, personnel metal door frames, hand railings, etc.) should be electrically referenced to the same "mother" ground. Conductor connective bonding should be exothermal and not mechanical wherever possible, especially in below-grade locations. Mechanical bonds are subject to corrosion, to physical damage, and to loosening due to temperature differentials. HVAC vents that penetrate one structure from another should not be ignored as they may become troublesome electrical pathways. Frequent inspection and resistance measuring (maximum 1 milliohm per Federal Aviation Admin. FAA-STD-019d) of connectors to assure continuity is recommended. A number of bonds were sampled at KSC 39B in June 2005 and were found to be independent of one another.

4.4 Grounding. The grounding system must address low earth impedance as well as low resistance. A spectral study of lightning's typical impulse reveals both a high and a low frequency content. The grounding system appears to the lightning impulse as a transmission line where wave propagation theory applies. A considerable part of



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lightning's current responds horizontally when striking the ground: it is estimated that less than 15% of it penetrates the earth. As a result, low resistance values (25 ohms per NEC) are less important than volumetric efficiencies. Equipotential grounding is achieved when all equipment within the structure(s) is referenced to a master bus bar which in turn is bonded to the external grounding system. Earth loops and consequential differential rise times must be avoided. The grounding system should be designed to reduce AC impedance and DC resistance. The use of counterpoise or "crow's foot" radial techniques can lower impedance as they allow lightning energy to diverge as each buried conductor shares voltage gradients. Buried ground rings connected around structures are useful. Proper use of concrete footing and foundations (Ufer grounds) increases volume. Where high resistance soils or poor moisture content or absence of salts or freezing temperatures are present, treatment of soils with carbon, Coke Breeze, concrete, natural salts or other low resistance additives may be useful. These concepts should be deployed on a case-by-case basis where lowering grounding impedances are difficult and/or expensive by traditional means.

4.5 Corrosion and cathodic reactance issues should be considered during the site analysis phase. Where incompatible materials are joined, suitable bi-metallic connectors should be adopted. Joining of aluminum down conductors together with copper conductor wires is a typical error.

4.6 Transients and Surges. Ordinary fuses and circuit breakers are not capable of dealing with lightning-induced transients. Surge protection Devices (SPDs aka transient limiters) may shunt current, block energy from traveling down the wire, filter certain frequencies, clamp voltage levels, or perform a combination of these tasks. Voltage clamping devices capable of handling extremely high amperages of the surge, as well as reducing the extremely fast rising edge (dv/dt and di/dt) of the transient are recommended. Protecting the AC power main panel and protecting all relevant secondary distribution panels and protecting all valuable plug-in devices such as process control instrumentation, computers, printers, fire alarms, data recording & SCADA equipment, etc. is suggested. Protecting incoming and outgoing data and signal lines (modem, LAN, etc.) is essential. All electrical devices which serve the primary asset such as well heads, remote security alarms, CCTV cameras, high mast lighting, etc. should be included.

SPDs should be installed with short lead lengths to their respective panels. Under fast rise time conditions, cable inductance becomes important and high transient voltages can be developed across long leads. SPDs with replaceable internal modules are suggested. In all instances the use of high quality, high speed, self-diagnosing SPD components is suggested. They may incorporate spark gaps, diverters, metal oxide varistors, gas tube arrestors, silicon avalanche diodes, or other technologies. Avoid SPDs with internal potting compounds. Hybrid devices, using a combination of these technologies, are preferred. SPDs conforming to the European IEC Standards are tested to a 10 X 350 us waveform, while those tested to IEEE and UL standards only meet a 8 X 20 us waveform requirement. Very little attention to SPD installation was in evidence at Pad 39B.

Uninterrupted Power Supplies (UPSs) provide battery backup in cases of power quality anomalies...brownouts, capacitor bank switching, outages, lightning, etc. UPSs are employed as back-up or temporary power supplies. They should not be used in place of



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dedicated SPD devices. Correct IEEE Category A installation configuration is: AC wall outlet to SPD to UPS to equipment.

4.7 Detection. Lightning detectors, available at differing costs and technologies, are useful to provide early warning. Users should beware of over-confidence in detection equipment. They are not perfect and they do not always acquire all lightning data. Detectors cannot "predict" lightning. An interesting application is their use to disconnect from AC line power and to engage standby power, before the arrival of lightning. A notification system of radios, sirens, loudspeakers or other means should be coupled with the detector. See the NLSI WWW site www.lightningsafety.com/nlsi_lhm/detectors.html for a more detailed treatment of this subject. In this regard, detection equipment and warning criteria at KSC are in a state of excellence... perhaps the best in the entire country.

4.8 Testing & Maintenance. Modern diagnostic testing is available to "verify" the performance of lightning conducting devices as well as to indicate the general route of lightning through structures. With such techniques, lightning paths can be forecast reliably. Sensors which register lightning current attachments can be fastened to downconductors. Regular physical inspections and testing should be a part of an established preventive maintenance program. Failure to maintain and test any lightning protection system may render it ineffective. William Jafferis, retired Director of NASA's KSC Rocket-Triggered Lightning Test Program has noted, "if you don't test your lightning protection system, Mother Nature will test it for you."

4.9. Personal Safety. No place outside is safe from lightning. Direct and indirect effects from high currents voltages make timely evacuation to shelter a prudent and responsible mandate. Section 4 of the NLSI website www.lightningsafety.com contains a wealth of information on this topic. NASA KSC suspends activities prior to lightning's arrival. This is costly, yet NASA KSC recognizes safety as the prevailing directive.

5. CODES AND STANDARDS.

In the USA there is no single lightning safety code or standard providing comprehensive guidance. The most commonly-referenced USA commercial lightning protection installation standard is incomplete and superficial. US Government lightning protection documents should be consulted. The Federal Aviation Administration FAA-STD-019d is valuable. Other recommended federal codes include military documents MIL HDBK 419A, Navy NAVSEA OP5, NASA STD E0012E, MIL STD 188-124B, MIL STD 1542B, MIL B 5087B, Army PAM 385-84 and USAF AFI 32-1065. The IEEE 142 and IEEE 1100 books are very helpful. The European International Electro-Technical Commission IEC 62305 series for lightning protection is the single best reference document for the lightning protection engineer. Adopted by many countries, it is a comprehensive science-based document applicable to many design situations. Ignored in most Codes is the very essential electromagnetic compatibility (EMC) subject, especially important for explosives safety and facilities containing electronics, VSDs, PLCs, and monitoring equipment.

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6. CONCLUSION.

Lightning has its own agenda and may cause damage despite application of best efforts. Any comprehensive approach for protection should be site-specific to attain maximum efficiencies. In order to mitigate the hazard, systematic attention to details of bonding, grounding, shielding, air terminals, surge protection devices, detection & notification, personnel education, maintenance, and employment of risk management principles is recommended.

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Appendix F. Estimation of the Effectiveness of the Space Shuttle Launch Pad Lightning Protection System – Dr. Vladimir Rakov

Estimation of the Effectiveness of the Space Shuttle Launch Pad Lightning Protection System

Contribution to NESC Report on the Lightning TIM (KSC, June 21-22, 2005)

by V.A. Rakov

1. Introduction

I attended the Lightning TIM held at the Kennedy Space Center on June 21-22, 2005. The meeting included a tour of Pad B, a three-part presentation on the lightning protective system (LPS) of Pad B by Dr. Pedro Medelius (former University of Florida Ph.D. student), a talk on lightning detection and warning at KSC by John Madura, and a presentation on 3D simulation of lightning incidence to various structures by Frank Fisher. There was also time provided for discussion of presented materials. Additionally, I communicated in private with several TIM participants, in particular with Drs. Pedro Medelius and Carlos Mata (my former Ph.D. student), Mr. Rich Kithil, and Dr. Frank Fisher.

The structure of my report is as follows. I'll start, in Section 2, with general information on lightning incidence to various objects and then, in Section 3, give a review of the Electrogeometrical Model (EGM), a version of which called the Rolling Sphere Method (RSM) was employed by Dr. Pedro Medelius in his lightning incidence analysis. I'll show both advantages and limitations of this method. Then, in Section 4, I'll comment on the three-part presentation of Dr. Pedro Medelius and make suggestions on correcting and improving his analysis. Finally, in Section 5, I'll summarize my observations, findings, and recommendations for future work.

2. Lightning Incidence to Various Objects

I first briefly describe how cloud-to-ground lightning "decides" on its ground termination point. Ground flashes are normally initiated by stepped leaders that originate in the thundercloud. As the downward-extending leader channel, usually negatively charged, approaches the ground, the enhanced electric field intensity at irregularities of the Earth's surface or at protruding grounded objects increases and eventually exceeds the breakdown value of air. As a result, one or more upward-moving leaders are initiated from those points. When one of the upward-moving leaders from the ground contacts a branch of the downward-moving stepped

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leader, the point of lightning termination on ground is determined. Grounded vertical objects produce relatively large electric field enhancement near their upper extremities so that upward-moving connecting leaders from these objects start earlier than from the surrounding ground and, therefore, serve to make the object a preferential lightning termination point. In general, the higher the object, the greater the field enhancement and hence the higher the probability that a stepped leader will terminate on the object. In the limit, when the height (field enhancement capability, to be more exact) of the object becomes so large that the upward-moving leader from the object tip can be initiated by in-cloud charges or, more likely, by in-cloud discharge processes, as opposed to being initiated by the charge on the descending stepped leader, the object becomes capable of initiating upward lightning. The latter, as opposed to a "normal," downward lightning, would not occur if the object were not there. Ground-based objects with heights ranging from about 100 to 500 m experience both downward and upward flashes, with the proportion being a function of object height. Eriksson (1987a) derived the following equation for the annual lightning incidence N (in yr^{-1}) to ground-based objects, including both downward and upward (if any) flashes:

$$N = 24 \times 10^{-6} H_s^{2.05} N_g \quad (1)$$

where H_s is the object height in meters and N_g is the ground flash density in $\text{km}^{-2} \text{yr}^{-1}$. To do so, he employed (1) the observations of lightning incidence to structures of heights ranging from 20 to 540 m in different countries, (2) the corresponding local values of the annual number of thunderstorm days T_D , and (3) an empirical equation relating N_g and T_D . For Pad B, $H_s = 106$ m, $N_g = 10 \text{ km}^{-2} \text{yr}^{-1}$, and N from Eq. 1 is about 3.4 yr^{-1} .

Eriksson (1978a) tabulated the observed percentage of upward flashes as a function of a free-standing structure's height, reproduced in Table 1. Eriksson and Meal (1984) fitted the data in Table 1 with the following expression:

$$P_u = 52.8 \ln H_s - 230 \quad (2)$$

where P_u is the percentage of upward flashes and H_s is the structure height in meters. This equation is valid only for structure heights ranging from 78 to 518 m, since for $H_s = 78$ m $P_u = 0$ and for $H_s = 518$ m $P_u = 100\%$. Structures with heights less than 78 m are not covered by Eq. 1 because they are expected to be struck by downward flashes only, and structures with a height of greater than 518 m are not covered because they are expected to experience upward flashes only. For Pad B, $H_s = 106$ m, and the percentage of upward flashes from Eq. 2 is 16%.

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Table 1. The percentage of upward flashes from tall structures. Adapted from Eriksson (1978a).

| Reference | Structure height, m | Percentage of upward flashes |
|--------------------------------------|---------------------|------------------------------|
| Pierce (1972) | 150 | 23 |
| | 200 | 50 |
| | 300 | 80 |
| | 400 | 91 |
| McCann (1944) | 110 | 8 |
| | 180 | 24 |
| | 400 | 96 |
| Berger (1972) | 350 ^a | 84 |
| Gorin (1972); Gorin et al. (1976) | 540 | 92 ^b |
| Garbagnati et al. (1974) | 500 ^c | 98 |

^aAn effective height of 350 m has been assigned by Eriksson to Berger's 70-m high mountain-top towers to account for the enhancement of the electric field by the mountain whose top is 640 m above Lake Lugano (914 m above sea level). Pierce (1971) assigned a different effective height of 270-m to the Berger's towers.

^b50% of the flashes recorded in this study were classified as 'unidentified'. The relative incidence of upward flashes is based upon analysis of only the identified data.

^cGarbagnati et al.'s towers were 40 m high, located on mountain tops, 980 and 993 m above sea level (Berger and Garbagnati 1984). Eriksson (1978a) does not give any explanations of the assumed effective height of 500 m.

In practice, as stated above, structures having heights less than 100 m or so are often assumed to be struck by downward lightning only, and the upper height limit can be simply taken as 500 m. Accordingly, the total lightning incidence N to a structure is the sum of the downward-flash incidence N_d and upward-flash incidence N_u if the structure height is in the range from about 100 to 500 m, $N = N_d$ for structures shorter than 100 m, and $N = N_u$ for structures taller than 500 m. If both downward and upward flashes are expected, they are often treated separately in estimating the lightning incidence to an object, as described below.

Downward flashes. When the incidence of downward lightning is estimated, it is common to ascribe a so-called equivalent attractive (or exposure) area to the grounded object. The attractive area can be viewed as an area on flat ground surface that would receive the same number of

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lightning strikes in the absence of the object as does the object placed in the center of that area. In other words, in computing lightning incidence to a structure, the structure is replaced by an equivalent area on ground. For a free-standing structure whose plan-view dimensions are much smaller than its height (such as a mast, tower, or chimney), this area, A , is circular and is generally given by $A = \pi R_a^2$, where R_a is the equivalent attractive radius, discussed later. For straight, horizontally extended structures (such as power lines or their sections), the equivalent attractive area is rectangular and is sometimes termed the "shadow zone" or "attractive swath." For example, if a power line has a length l , and an effective width b (usually taken as the horizontal distance between overhead shield wires or between the outer phase conductors), its equivalent attractive area is generally estimated as $A = l(b + 2R_a)$, where R_a is the equivalent attractive distance generally thought to be approximately equal to the equivalent attractive radius for a free-standing structure of the same height (Eriksson 1987a; Rakov and Lutz 1990). Further, the local ground flash density N_g is assumed to be spatially uniform in the absence of the structure, so that the downward lightning incidence to the structure is found as

$$N_d = A N_g \quad (3)$$

Usually N_g is in $\text{km}^{-2} \text{yr}^{-1}$ so that A should be expressed in km^2 to obtain N_d in yr^{-1} (strikes per year).

The equivalent attractive radius (or distance) R_a is usually assumed to be a function of structure height H_s and is generally expressed as

$$R_a = \alpha H_s^\beta \quad (4)$$

where α and β are empirical constants. The procedures used to obtain Eq. 4 from data on lightning incidence to structures of different height is given, for example, by Eriksson (1978a, 1987a). In Eq. 4, both H_s and R_a are in meters, and different values of α and β have been proposed. For example, Whitehead et al. (1993) gave $\alpha = 2$ and $\beta = 1.09$ for transmission lines, while CIGRE Document 63 (1991) recommended $\alpha = 14$ and $\beta = 0.6$. The attractive radius for individual strikes should depend on the charge carried by the descending leader, this charge being correlated with the associated return-stroke peak current. In this regard, Eq. 4 should be understood as representing the entire distribution of peak currents. In the so-called electrogeometrical approach (Section 3), which is widely used for the estimation of lightning incidence in lightning protection studies (e.g., CIGRE Document 63, 1991), the equivalent attractive radius explicitly depends on the statistical distribution of lightning peak currents (e.g., Eriksson 1987a; Rakov and Lutz 1988, 1990).

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Estimation of N_d from Eq. 3 implies a reasonably long-term value of ground flash density and yields a long-term average value of lightning incidence. For example, if a 60-m tower is located in a part of Florida where $N_g = 10 \text{ km}^{-2} \text{ yr}^{-1}$, the long-term average downward lightning incidence will be about 0.5 yr^{-1} (assuming $\alpha = 2$ and $\beta = 1$), that is, the tower will be struck on average every other year. The use of Eq. 1 would result in a lightning incidence value of about 1 yr^{-1} .

Upward flashes. Once the incidence of downward lightning N_d is found from Eq. 3 using the concept of an equivalent attractive area, the incidence of upward flashes N_u can be determined by subtracting N_d from N given by Eq. 1. Recall that if the structure height is less than 100 m or so, it is usually assumed that $N_u = 0$. If only the percentage of upward flashes is sought, Eq. 2 can be used.

Upward flashes tend to develop from the highest point of the object, which is normally an air terminal of its LPS. For this reason, upward flashes are usually of no concern in estimating the “shielding failure” mode of lightning interaction with the object.

3. Electrogeometrical Model (EGM)

The attachment of the leader to the strike object is often described using the so-called electrogeometrical model (EGM), the core of which is the concept of a “striking distance”. This concept obscures some of the significant physics but allows the development of relatively simple and useful techniques for designing lightning protection systems for various structures. The striking distance can be defined as the distance from the tip of the descending leader to the object to be struck at the instant when an upward connecting leader is initiated from this object. It is assumed that at this time the lightning termination point is uniquely determined. For a given striking distance, one can define an imaginary surface above the ground and above objects on the ground (see Fig. 1) such that, when the descending leader passes through that surface at a specific location, the leader is “captured” by a specific point on the ground or on a grounded object. The geometrical construction of this surface can be accomplished simply by rolling an imaginary sphere of radius equal to the assumed striking distance across the ground and across objects on the ground, the so-called rolling sphere method (RSM) (e.g., Lee, 1978; NFPA 780). The locus of all points traversed by the center of the rolling sphere forms the imaginary capture surface referred to above. Those points that the rolling sphere touches can be struck, according to this approach; and points where the sphere does not touch cannot. Fig. 2 illustrates the rolling sphere method. The shaded area in Fig. 2 is that area into which, it is postulated, lightning cannot enter.



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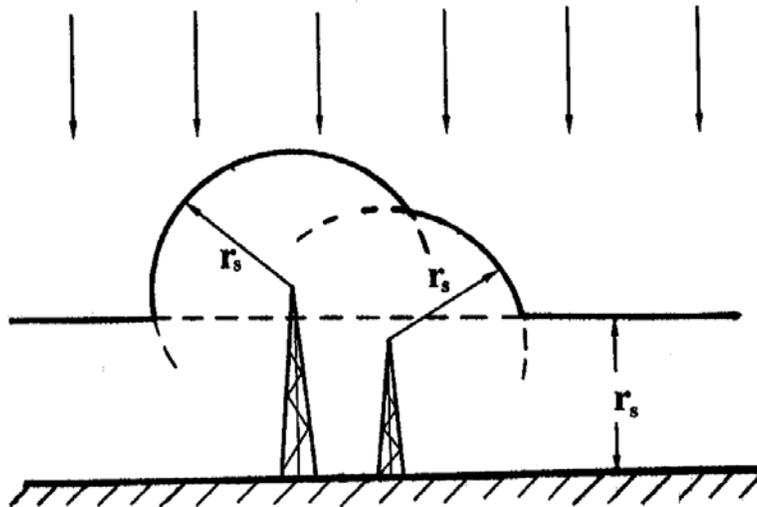


Fig. 1. Illustration of capture surfaces of two towers and earth's surface in the electrogeometrical model. r_s is the striking distance. Vertical arrows represent descending leaders, assumed to be uniformly distributed above the capture surfaces. Adapted from Bazelyan and Raizer (2000).

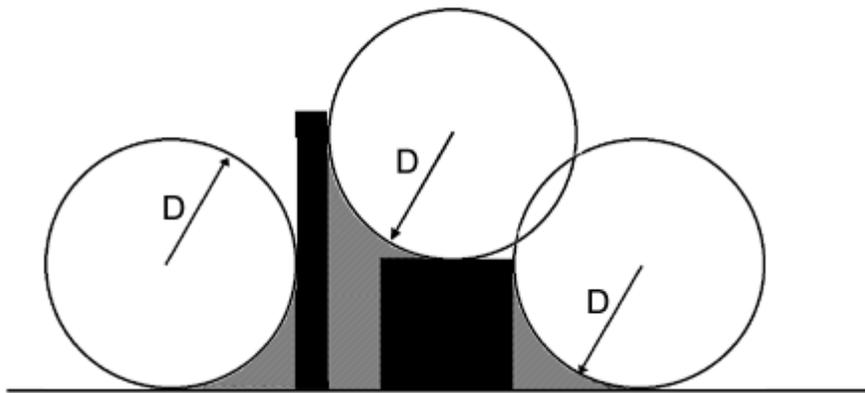


Fig. 2. Illustration of the rolling sphere method for two objects shown in black. D is the striking distance (same as r_s in Fig. 1.). Shaded area is that area into which, it is postulated, lightning cannot enter. Adapted from Szczerbinski (2000).

In the rolling sphere method, the striking distance is assumed to be the same for any object projecting above the earth's surface and for the earth itself. There are variations of the EGM in which the assumption of different striking distances for objects of different geometry is used (e.g., Eriksson 1987a,b). The main application of the rolling sphere method is positioning air terminals on an ordinary structure, so that one of the terminals, rather than a roof edge or

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other part of the structure, initiates the upward leader that intercepts the descending leader and, hence, becomes the lightning attachment point.

The striking distance is usually expressed as a function of prospective return-stroke peak current. The procedure to obtain such an expression typically involves assumptions of leader geometry, total leader charge, distribution of charge along the leader channel, and critical average electric field between the leader tip and the strike object at the time of the initiation of upward connecting leader from this object. This critical electric field is assumed to be equal to the average breakdown field from long laboratory spark experiments with rod-rod and rod-plane gaps, which varies with waveshape of applied voltage as well as with other factors such as the high-voltage generator circuitry. The typical assumed values range from 200 to 600 kV/m. As a result, one can obtain an expression relating the striking distance to the total leader charge. In the next step, the observed correlation (see Fig. 3) between the charge and resultant return-stroke peak current (Berger 1972) is used to express the striking distance, r_s , in terms of the peak current, I . The most popular striking-distance expression, included in many lightning protection standards, is

$$r_s = 10 I^{0.65} \tag{5}$$

where I is in kA and r_s is in meters. This and other expressions for the striking distance found in the literature are illustrated in Fig. 4. Given all the assumptions involved and large scatter seen in Fig. 3, each of these relationships is necessarily crude, and the range of variation among the individual expressions (see Fig. 4) is up to a factor of 3 or more. Therefore, there are considerable uncertainties in estimating the striking distance. On the other hand, there is satisfactory long-term (the RSM has been in the Hungarian Standard on Lightning Protection since 1962; Horvath, 2000) experience with the RSM as applied to placement of lightning rods on ordinary structures and with the EGM in general as applied to power lines. This experience is the primary justification for the continuing use of this method in lightning protection studies. In fact, as of today, the EGM is the best engineering tool for estimating lightning incidence to structures, which is indorsed by the IEEE and IEC (International Electrotechnical Commission).



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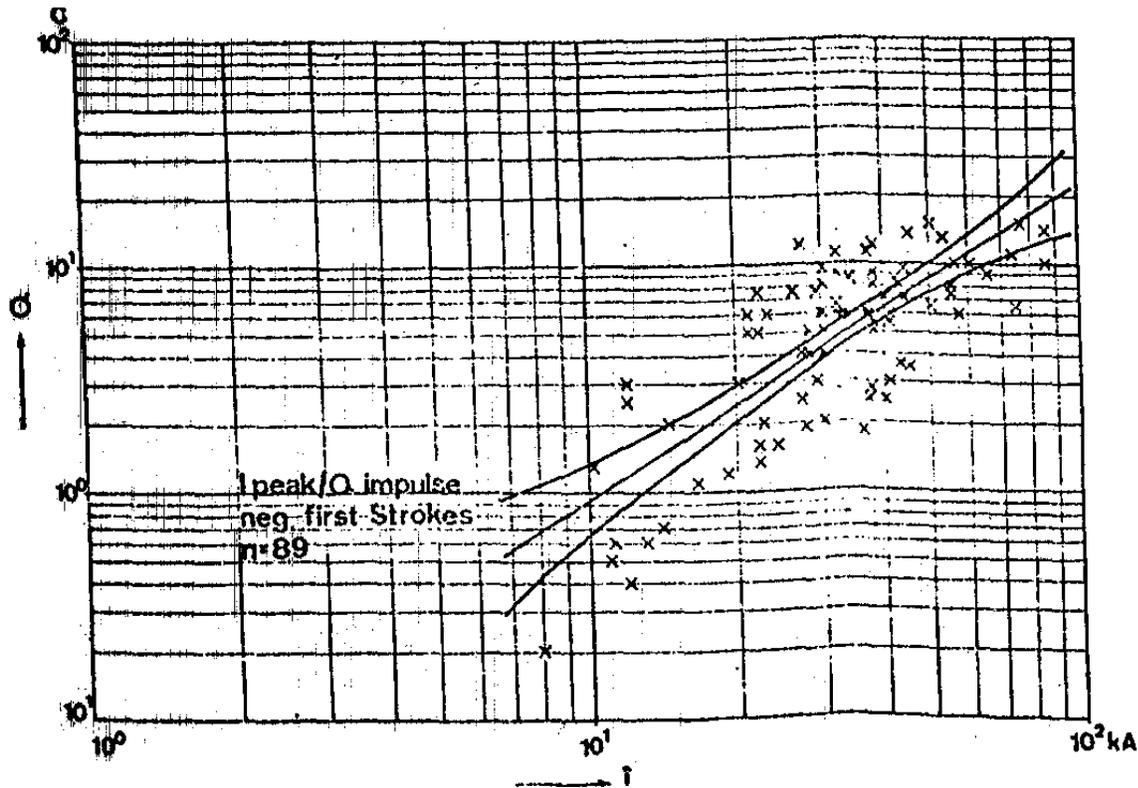


Fig. 3. Scatter plot of impulse charge, Q , versus return-stroke peak current, I . Note that both vertical and horizontal scales are logarithmic. The best fit to data, $I = 10.6 Q^{0.7}$, where Q is in coulombs and I is in kiloamperes, was used in deriving Eq. 5. Adapted from Berger (1972).



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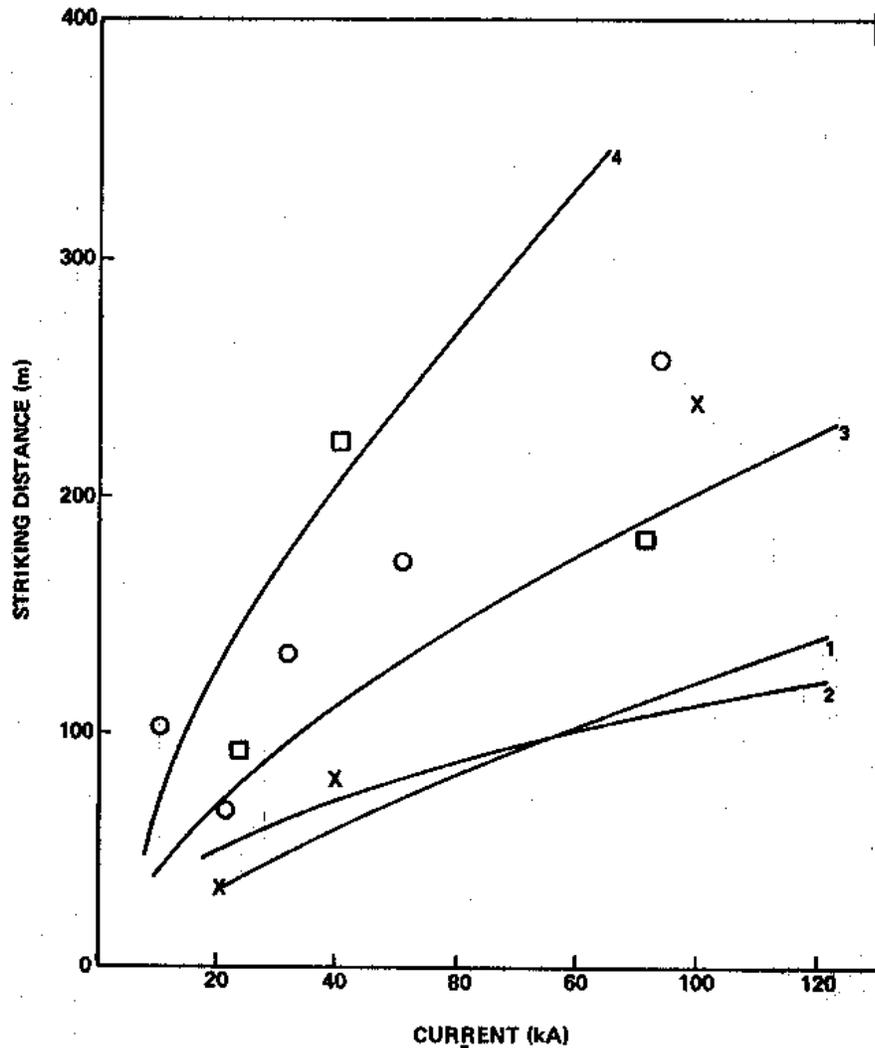


Fig. 4. Striking distance versus return-stroke peak current [curve 1, Golde (1945); curve 2, Wagner (1963); curve 3, Love (1973); curve 4, Ruhling (1972); x, theory of Davis (1962); o, estimates from two-dimensional photographs by Eriksson (1978); estimates from three-dimensional photography by Eriksson (1978). Adapted from Golde (1977) and Eriksson (1978).

The EGM can be used for estimating lightning incidence to different elements (usually to the protected object) of a structure as follows. One needs to (1) assume the spatial distribution of descending lightning leaders above all the capture surfaces (see Fig. 1) and specify the ground flash density, N_g (typically $N_g = \text{const}$), (2) find the striking distance, $r_s(I)$, and then the projection, $S(I)$, of the resultant capture surface of the element in question onto the ground

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surface, (3) specify the statistical distribution (the probability density function, to be more exact) of lightning peak currents, $f(I)$, and (4) integrate the product $N_g \times S(I) \times f(I) \times dI$ from 0 to I_{max} , to obtain the lightning incidence (number of strikes per year). Alternatively, one can eliminate finding $S(I)$ in item (2) and entire item (4) from the outlined procedure using the Monte Carlo technique. It is important to note that the use of the RSM alone does not generally allow one to estimate lightning incidence to an element of structure (for example, to the orbiter on the launch pad), because such an estimate requires information on the spatial distribution of lightning leaders, which is not part of the standard RSM.

4. Comments on Dr. Medelius' RSM Analysis

Overall, the presented analysis needs to be re-done to (1) replace the statistical distribution of peak currents with a more appropriate one (the one found in IEC or IEEE lightning protection standards), (2) account for the spatial distribution of lightning leaders in estimating the lightning incidence to the orbiter ("shielding failure" rate), and (3) consider positive lightning flashes that constitute about 10% of the overall lightning activity, but can be dominant in the dissipating stage of a thunderstorm, in cold season, and under some other meteorological conditions (Rakov 2003). Note that it is more difficult to protect against positive lightning, because it is associated with a smaller striking distance. Additionally, the probability of flashover from the launching structure (in particular, from the GOx Vent Arm) to the orbiter (ET) should be estimated. More specific comments are given below.

History and Background

Slide 3, Ground Flash Density Map. This map is based on the NLDN data for 1996-2000. According to this map, the ground flash density for the KSC area is about $10 \text{ km}^{-2}\text{yr}^{-1}$. The correction factor to account for multiple channel terminations on ground in Florida is 1.7 (Rakov and Uman 2003), resulting in $N_g = 17 \text{ km}^{-2}\text{yr}^{-1}$.

Slide 4, Cumulative Distribution of Peak Currents. The specified values of the median (27.7 kA) and standard deviation (0.461) are incorrect. The correct values found in CIGRE Document 63 (1991) are 31 kA and 0.484, respectively. I have provided the correct CIGRE distribution, as well as the IEEE distribution (having the same median value, 31 kA), to Dr. Carlos Mata. These distributions are reproduced in Fig. 5 below.

Slides 9-14. Cone of Protection Method. Catenary wires also provide lightning protection, while their protective effect is not shown in these slides.



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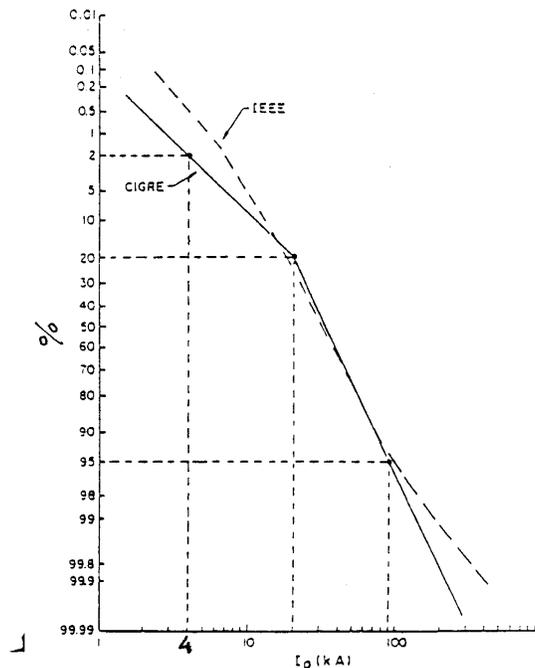


Fig. 5. Cumulative statistical distributions of peak currents (percent values on the vertical axis should be subtracted from 100% to obtain the probability to exceed the peak current value on the horizontal axis) for negative first strokes adopted by IEEE and CIGRE and used in various lightning protection standards. Adapted from CIGRE Document 63 (1991).

Findings and Analysis

Slide 7. Using Eriksson's Equation. The equivalent height equal to $H/2$ is arbitrary. I think $2H/3$ would be more appropriate (and more consistent with power line studies).

Slides 9 and 10. How often is the Space Shuttle Vehicle expected to be struck by lightning? These are very important slides, since they address the primary question of the meeting. In my view, combining the arbitrarily assumed "environmental coefficient C_1 " and results of RSM analysis is not a self-consistent approach. The use of the Monte Carlo technique, to account for the spatial distribution of lightning leaders, in conjunction with the RSM (EGM), as decided at the meeting, should fix this problem.

Slide 15. Rolling Sphere Method. It should be made clear that this slide is to illustrate the estimation of I_{max} (see the last paragraph of Section 3 above).

Slide 17. "Step Length" should be replaced with "Striking Distance".

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Slides 27-35. I have a problem understanding these illustrations of the RSM, as I stated during the meeting and discussed in private with Dr. Carlos Mata. The yellow sphere appears to be stationary, centered on the Shuttle, and to expand as the peak current increases. Perhaps these illustrations do convey the intended information, but they appear to be inconsistent with the RSM concept, in which the center of the sphere represents the tip of descending leader. This comment also applies to Slides 37-43, 45-52, and 54-58. The correct representation of the protected area based on the RSM is found in Slide 26, although the protective effect of the catenary wires in that slide seems to be neglected.

Slide 60. Summary of Analysis using Rolling Sphere Method (and elsewhere). The percentages for 150 kA and 60 kA are incorrect. The correct values are 1.6% and 15% (IEEE distribution), respectively. Further, the “% of strikes with adequate protection” does not account for the spatial distribution of lightning leaders. For example, 76% for 20 kA implies that 24% (100% - 76%) of all strokes will terminate on the orbiter, which is not correct, since some of the strokes with peak currents less than 20 kA will terminate on the LPS, leading to an increase in the “% of strikes with adequate protection”. The use of the Monte Carlo technique, to account for the spatial distribution of lightning leaders, in conjunction with the RSM (EGM), as decided at the meeting, should fix this problem.

Design Alternative: Parallel Catenary Wires

Slides 3-6 and 8-10. I think that two additional wires running in the west direction would make the LPS more balanced, both mechanically and electrically.

4. Summary

Overall, I think the meeting was well organized and did facilitate productive interaction (exchange of ideas) among the participants. From the technical point of view, in my opinion, the existing lightning protective system (apparently designed in 1970s) of the Space Shuttle Launch Pad is inferior to that of essentially any other major launch facility in the world. The modern approach to lightning protection of launch sites typically includes multiple (usually 3 or 4) towers supporting multiple horizontal conductors, with the overall structure approaching an imperfect Faraday cage. As an example, Fig. 6 shows the LPS of the Indian Satellite Launch Pad, in which the launch vehicle is surrounded by three 120-m towers separated by 180 m and interconnected by horizontal wires. For such an LPS in the region characterized by 50-90



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thunderstorm days per year a “shielding failure” (direct lightning attachment to the launch vehicle) is expected to occur once in about 500-1000 years.

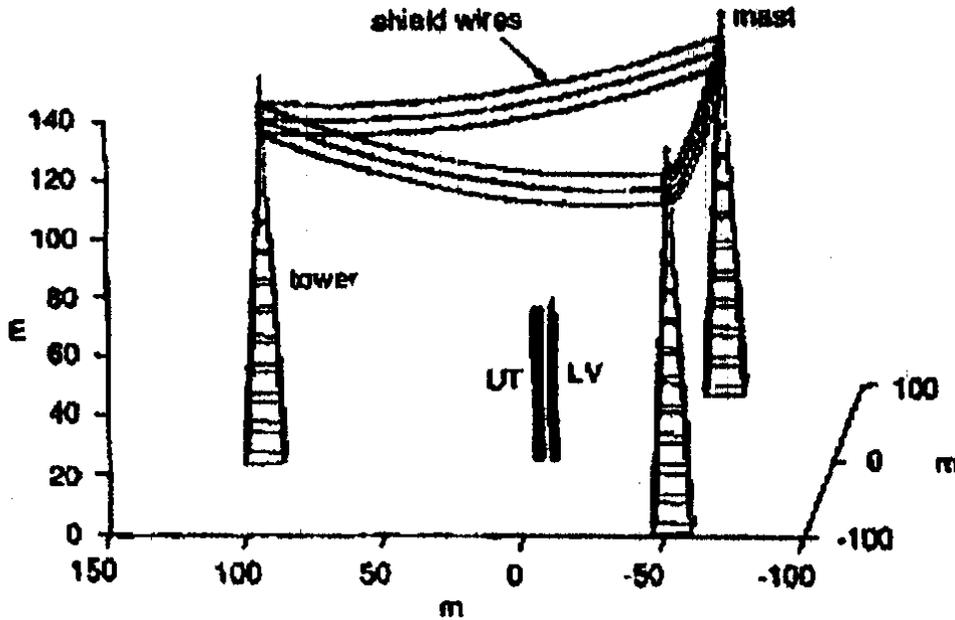


Fig. 6. An example of modern lightning protective system of a launch pad. LV = Launch Vehicle; UT = Umbilical Tower. Adapted from Kumar and Joseph (2003).

Given the high level of lightning activity in Florida and the number of operations (exposure), the likelihood of "shielding failure" for Pad B appears to be excessively high. On the other hand, I concur with Terry Willingham that it is necessary to obtain an estimate of consequences (as a function of peak current or charge transfer) of a direct lightning strike to the orbiter (loaded ET), in order to determine a meaningful acceptable "shielding failure" rate.

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Appendix G. KSC Launch Pad 39 A/B Catenary Capability for Lightning Protection – Richard Kithil

KSC Launch Pad 39 A/B Catenary Capability for Lightning Protection
 By Richard Kithil Jr., Founder & CEO
 National Lightning Safety Institute
www.lightningsafety.com
 Tel. 303-666-8817

- 1.0 Executive Summary. A catenary or overhead shield wire (OHSW) is the preferred air terminal design for critical, high value facilities. Air terminals are one member of the family of sub-systems used to achieve lightning protection. See "Matrix of Lightning Protection Subsystems" attached. The Pad 39 OHSWs, erected in 1966-67, are insufficient to offer satisfactory safety for the space shuttle. The space shuttle therefore is at risk from direct lightning strikes while at the launch platform.
- 2.0 Caveats. Not a part of this study were several key subjects:
- 2.1 Grounding and Bonding. All ground terminations must be bonded equipotentially to avoid unequal voltage rise times which cause upsets to electrical/electronic systems. Spot checks were conducted at Pad 39A on June 21, 2005 using an AEMC Model 3730 Ground Resistance Tester. Many grounds were not bonded in common. Common grounds are required by the National Electrical Code, section 250.50, NFPA-780 section 4.13.1.3 and by NASA KSC-STD-E-0012E, Appendix A.
 - 2.2 Personal Safety. No one is safe outdoors during nearby thunderstorms. While inside protective structures, it is very dangerous to be in contact with electrical equipment or any other potential conductors. For more information on this topic, refer to:
 - 2.2.1 www.lightningsafety.com Chapter 4.
 - 2.2.2 www.lightningsafety.noaa.gov
 - 2.3 I conducted discussions with KSC's Tyrone McGee about lightning protection to the loaded crawler should an equipment breakdown result in a stranded crawler/space shuttle along the transport runway. It was suggested to deploy two rubber-tired telescopic boom cranes so as to form an inverted "V" over the equipment. Rule-of-Thumb six foot minimum separation of the cranes from the space shuttle was recommended.
- 3.0 General Observations.
- 3.1 Magnitude of Lightning Threat. In 2004 there were some 56,206 ground lightning strikes in the KSC area. KSC has an average measurable flash density of about 17 strikes per square kilometer per year. A Bell Curve distributes most of the lightning within a 3-4 month June-September period.
 - 3.2 Recorded Data. Rogowski Coils at the OHSWs have captured lightning characteristics -- amplitude, polarity, waveform -- for many years. On average 3-5 strikes occur to each launch pad OHSW annually. Other helpful statistics which quantify the lightning threat are available from 45th Weather Patrick AFB and from the NASA KSC Weather Office. In short: lightning at the two



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launch pads is severe and consequences from strikes to the space shuttle could be extreme.

3.3 Theoretical Assumptions. When presented with various "Rolling Ball Methods" describing protective radii, the Study Group consensus was that areas not shielded by the existing OHSW included the space shuttle. About 75% of the total structure is "enclosed" by the assumptions inherent in the "Rolling Ball Method." However, it must be remembered that lightning often has its own agenda and is stochastic and irregular in conforming to man's wishes.

4.0 Specific Recommendations.

4.1 Additional OHSWs are needed to provide effective lightning shielding for the space shuttle. The Study Group considered several alternative designs. At a minimum requirement, two new support towers are suggested. They should be located East of the existing Pads and separated by at least 300 ft. Exact calculations as to tower locations, tower heights, tower distances from the pad, etc. will be performed by others. OHSW geometries also should be calculated by others.

4.2 Existing one inch stainless steel wires are over-designed. Consider the IEEE standard for spans up to 300 meters using "3/8 inch, seven strand, galvanized, 1300 metric" as satisfactory for purposes at KSC.

5.0 Conclusion. The KSC Pad 39 OHSW design ranks fourth behind designs used by other major space agencies. Russia – Baikonur employs twin towers at either side of the launch platform. France – CNES French Guiana uses four towers at corners of the launch platform. China – Jinqian uses two towers on opposite sides of the launch platform. US Air Force at SLC 40 uses an elaborate overhead net design supported by four towers to obtain the most efficient of designs.

Pads 39A/B should adopt a contemporary OHSW lightning protection treatment in keeping with recognized codes and standards as is consistent with pro-active safety measures.

6.0 References.

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(signed electronically)

Richard Kithil, Jr.
Founder & CEO
National Lightning Safety Institute

June 22, 2005



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MATRIX OF LIGHTNING PROTECTION SUB-SYSTEMS

Apply these sub-systems as appropriate (YES/NO) to specific facilities or structures.

| | DIRECT STRIKE | INDIRECT STRIKE | EXTERIOR LOCATION | INTERIOR LOCATION | PEOPLE SAFETY | STRUCTURE SAFETY |
|-----------------------|---------------|-----------------|-------------------|-------------------|---------------|------------------|
| AIR TERMINALS | YES | NO | YES | NO | NO | YES |
| DOWN-CONDUCTORS | YES | NO | YES | YES | NO | YES |
| BONDING | YES | YES | YES | YES | YES | YES |
| GROUNDING | YES | YES | YES | YES | YES | YES |
| SHIELDING | YES | YES | YES | YES | YES | YES |
| SURGE PROTECTION | YES | YES | YES | YES | YES | YES |
| DETECTION | YES | YES | YES | YES | YES | YES |
| POLICIES & PROCEDURES | YES | YES | N/A | N/A | YES | YES |

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Appendix H. Assessment of June 21 & 22, 2005 Lightning TIM – Noel Sargent

Assessment of June 21 & 22, 2005 Lightning TIM

The material presented at this TIM represents the state-of-the-art for evaluating the adequacy of lightning protection for tall structures. The personnel involved have both the knowledge and experience to ensure both accurate definition and complete examination of the issue. The summary draft dated June 24 succinctly captures the conclusions and forward actions, so in my opinion there is no need for me to repeat these.

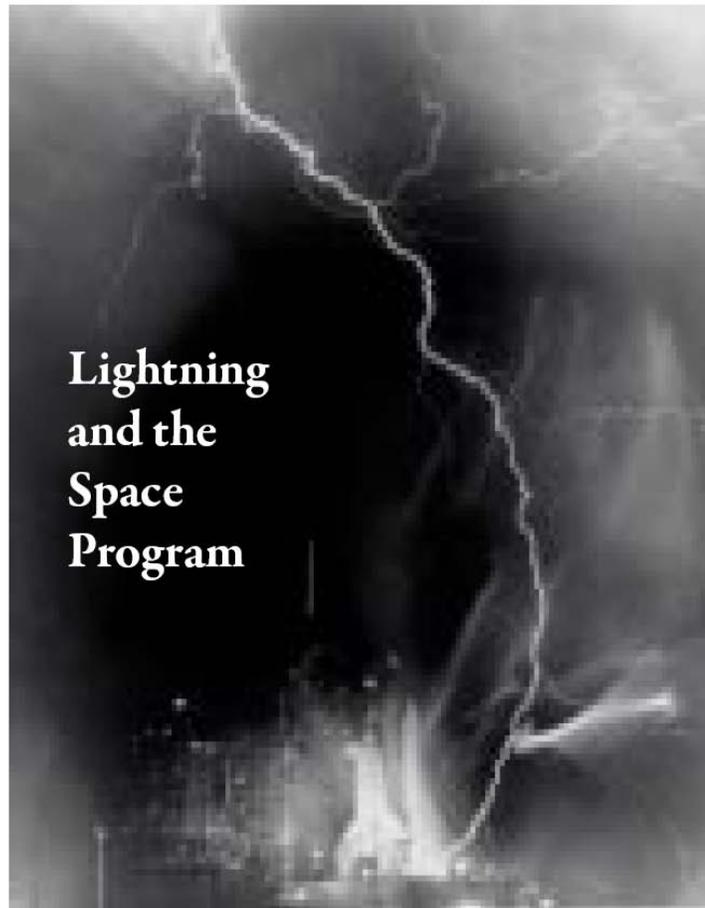
Because of my present involvement in ISO Space Systems EMC standards through GRC and the NASA Office of the Chief Engineer, I think it is important to document the standards and tools used in arriving at the conclusions of this study. This is particularly important now, as NASA will soon enter a new phase of man-rated vehicle development and supporting facility design. Traditionally NASA has used Military Standards as guidance in tailoring its own standards and program requirements. Relative to lightning, many of these military documents do not reflect the newest design and analysis techniques, or have been replaced with civil (SAE & RTCA) or international (IEC) standards. I am suggesting the work of this panel serve both NASA and secondarily the custodians of relevant Military Specifications (MIL-STD-1542B dated 15NOV91, & MIL-STD-1757 replaced with SAE ARP 5416) dealing with lightning protection of aerospace ground and flight systems. Many of the individuals providing input to the lightning and EMC standards process are also part of this lightning TIM activity.

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Appendix I. NASA Facts – Lightning and the Space Program

NASA Facts

National Aeronautics and Space Administration



Lightning and the Space Program

www.nasa.gov



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Lightning protection systems

Kennedy Space Center operates extensive lightning protection and detection systems in order to keep its employees, the 184-foot-high space shuttle, the launch pads, payloads and processing facilities from harm. The protection systems and the detection systems incorporate equipment and personnel both at Kennedy and Cape Canaveral Air Force Station (CCAFS), located southeast of Kennedy.

Predicting lightning before it reaches Kennedy

Air Force 45th Weather Squadron – The first line of defense for lightning safety is accurately predicting when and where thunderstorms will occur. The Air Force 45th Weather Squadron provides all weather support for Kennedy/CCAFS operations, except space shuttle landings, which are supported by the National Atmospheric and Oceanic Administration (NOAA) Spaceflight Meteorology Group at Johnson Space Center.

Information provided by the 45th Weather Squadron includes lightning advisories and warnings critical for day-to-day shuttle and payload processing, as well as launch day weather data essential in helping NASA determine when it is safe for the space shuttle to lift off. The 45th Weather Squadron has developed several techniques to forecast lightning and has teamed with many universities to improve thunderstorm prediction.

The 45th Weather Squadron operates from Range Weather Operations at CCAFS, a center for the forecasting and detection of thunderstorms and other adverse weather conditions. RWO houses the Meteorological Interactive Data Display System, which processes and displays data from the National Centers for Environmental Prediction, weather satellite imagery and local weather sensors to help forecasters provide the most accurate, timely and tailored support possible for Kennedy operations.

Among the local sources of weather information are two weather radars that can identify and track storms within a 150-mile range of Cape Canaveral, and the Wind Information Display System, a network of towers with wind, temperature and moisture sensors. Wind measurements can reveal some of the conditions that can cause thunderstorm development.

Lightning Detection Systems – The Launch Pad Lightning Warning System, Lightning Detection and Ranging system and the Cloud to Ground Lightning

Surveillance System provide data directly to the Range Weather Operations on atmospheric electrical activity. These systems, along with weather radar, are the primary Air Force thunderstorm surveillance tools for evaluating weather conditions that lead to the issuance and termination of lightning warnings.

The Launch Pad Lightning Warning System comprises 31 electric field mills uniformly distributed throughout Kennedy and Cape Canaveral. They serve as an early warning system for electrical charges building aloft or approaching as part of a storm system. These instruments are ground-level electric field strength monitors. Information from this warning system gives forecasters information on trends in electric field potential and the locations of highly charged clouds capable of supporting natural or triggered lightning. The data are valuable in detecting early storm electrification and the threat of triggered lightning for launch vehicles.

The Lightning Detection and Ranging system, developed by Kennedy, detects and locates lightning in three dimensions using a "time of arrival" computation on signals received at seven antennas. Each part of the stepped leader of lightning sends out pulses, which the system receives at a frequency of 66 MHz (equal to TV channel 3). By knowing the speed of light and the locations of all the antennas, the position of individual steps



This is one of the 31 electric field mills that compose the Launch Pad Lightning Warning System. They are called mills because they have a rotating, four-bladed shield much like arms of a windmill. The shield contained in the bottom of the round housing alternately exposes and covers metal sensing plates, resulting in an alternating current proportional to the atmospheric electric field.



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of a leader can be calculated to within 100-meter accuracy in three dimensions. The system provides between one and 1,500 points per flash.

For many years, this was the only system in operational meteorology able to provide detailed information on the vertical and horizontal extent of a lightning flash, rather than just the location of its ground strike. Lightning Detection and Ranging detects all lightning, including cloud-to-cloud and in-cloud as well as cloud-to-ground.

The Cloud to Ground Lightning Surveillance System detects, locates and characterizes cloud-to-ground lightning within approximately 60 miles of the Range Weather Operations. Electromagnetic radiation emitted from lightning is first detected by the system's six direction finder and time-of-arrival antennas, located in Orange and Brevard Counties. Lightning positions are computed using triangulation and time-of-arrival from as many sensors as possible and relayed to a color display video screen in the center. Once lightning-producing cells are identified and located, the forecaster can more easily predict just where the next lightning bolts will hit.

The 45th Weather Squadron also has an extremely active program to educate its customers and the general public on lightning safety.

Kennedy lightning policy

Kennedy pioneered a two-phase lightning warning policy. In Phase I, an advisory is issued that lightning is forecast within five nautical miles of the designated site with a desired lead-time of 30 minutes. The 30-minute



Attached to the wing of a Cessna Citation aircraft are cloud physics probes that measure the size, shape and number of ice and water particles in clouds. The plane is also equipped with field mills, used to measure electric fields. The plane was flown into anvil clouds in the KSC area as part of a study to review and possibly modify lightning launch-commit criteria.

warning gives personnel in unprotected areas time to get to protective shelter and gives those working on lightning-sensitive tasks time to secure operations in a safe and orderly manner.

A Phase II advisory is issued when lightning is imminent or occurring within five miles of the designated site. All lightning-sensitive operations are terminated until the Phase II advisory is lifted.

This two-phase policy provides adequate lead-time for sensitive operations without shutting down less sensitive operations until the hazard becomes immediate. Because it is essential that no lightning go unwarned, there is a false-alarm rate of about 40 percent. Improved forecasting tools may enable the false-alarm rate to be reduced without compromising safety.

The lightning policy is defined by the Kennedy Lightning Safety Assessment Committee. This group is also responsible for seeing that all structures at Kennedy, as well as the space shuttle, are adequately protected. Structures that particularly need protection against lightning include those containing ignitable, explosive or flammable materials, and personnel.

Protection at the pad

Some Kennedy facilities that incorporate extensive lightning-shielding devices include the service structures at Launch Pads 39A and 39B, the Vehicle Assembly Building and the Orbiter Processing Facility.

An 80-foot-tall fiberglass mast on top of the fixed service structure at each pad is the most visible means of protecting the structure itself, the shuttle while it is on the pad, and the enclosed launch equipment. The mast supports a 1-inch stainless steel cable that runs over its top. This cable stretches 1,000 feet in two directions, and each end is anchored and grounded. Its appearance is similar to that of a suspension bridge tower and its supporting cables.

A 4-foot-high lightning rod on top of the mast is connected to the cable. The rod's purpose is to prevent lightning current from passing directly through the space shuttle and the structures on the pad. Any strikes in this area would be conducted by the cable, called a "catenary wire" because of its shape, to the grounded anchor points.

Other grounding systems in the Launch Complex 39 area include a network of buried, interconnected metal rods called the "counterpoise" that run under the launch pads and surrounding support structures. All structures in the area are grounded, including the Vehicle Assembly Building.



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Space Shuttle Endeavour clears the lightning mast and attached catenary wire as it hurtles into space on mission STS-111 to the International Space Station June 5, 2002. The mast and wire provide the primary lightning protection system for the orbiter while it is on the pad. Mission STS-111 is the 18th flight of Endeavour and the 110th flight overall in NASA's space shuttle program.

Additional protection devices at the pads include a grounded overhead shield cable to protect the crew emergency egress slidewires, attached to the fixed service structure. Grounding points on the pad surface connect the pedestals that support the mobile launcher platform to the pad counterpoise. The platform itself has electrical connections in its twin tail service masts that make contact with the space shuttle. These connections complete the system that conducts any lightning-related electrical discharges safely away from the space plane. Most other launch pads at CCAFS have similar overhead wire lightning protection systems.

Overhead gridwire systems protect hypergolic fuel and oxidizer storage areas at the pads. The huge 900,000-gallon liquid hydrogen and oxygen tanks at each pad are constructed of metal and do not need overhead protection since they provide their own grounds.

Away from the pad, the shuttle is well protected from both inclement weather and lightning when it is in the Vehicle Assembly Building. This 525-foot-high structure, one of the largest in the world, has its own system of 11 lightning conductor towers rising 25 feet high on its roof. When lightning hits the system, wires conduct the charge to the towers, which then direct the current down the sides of the building and into its foundation pilings that are driven into bedrock.

After leaving the building, the space shuttle is vulnerable to lightning strikes as it is transported to the launch pad. This trip takes about six hours. The primary method of reducing lightning risk is by scheduling rollout during periods of very low lightning probability – typically in the late night and early morning hours.

Launch pad detection systems

A lightning measuring system is located at the launch pads so that any electrical activity in the immediate area can be continually observed, recorded and assessed. Data gathered by its sensors and cameras is sent directly to the Launch Control Center so NASA personnel can determine when it is safe to launch the shuttle.

One of the monitors closest to the shuttle is the Catenary Wire Lightning Instrumentation System. This system senses lightning currents in the wire and evaluates them to see what potential they may have for causing damage to sensitive electrical equipment. The current sensors are located at each end of the catenary wire, and they detect and record lightning strikes to provide potential damage assessment data for the lightning instrumentation system.

Another launch pad monitoring system, the Lightning Induced Voltage Instrumentation System, detects and records any transient electrical impulses that might occur in space shuttle electronic systems or on the vehicle's skin. The system is installed in the mobile launcher platform and monitors conditions while the shuttle is on the way to the launch pad via the crawlerway and at the pad itself. Voltages and currents may be induced by nearby lightning even if the pad is not directly struck.

The electromagnetic fields from the intense lightning currents are enough to cause currents to flow in nearby conductors.

Data recorded by both systems are compiled and sent to the Launch Control Center through the computers of the Lightning and Transients Monitoring System.

A new Sonic Lightning Locator being tested at the



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shuttle launch pads precisely determines the strength and exact location, to within 5 meters, of any lightning strikes within the immediate area of the pad. This helps shuttle engineers assess the need to conduct additional tests on sensitive systems after nearby lightning events. The sonic lightning locator uses an electric field detector and an array of acoustic detectors to locate the lightning contact point with great precision.

Visual detection of lightning activity is also essential. A network of video cameras positioned to observe the fixed service structure's lightning mast and the top of the shuttle's external tank are linked to television monitors in the Launch Control Center. Any lightning flashes can be seen on the screen and recorded for later analysis. These data, along with the launch pad protection systems, help verify and calibrate the lightning detection systems.

Does it all work?

The elaborate lightning detection and protection systems at Kennedy have proven their worth the hard way. The lightning masts at Launch Pads 39A and 39B are struck about five times per year, sometimes with a space shuttle on the pad. There has been no damage to any equipment.

In 1983, lightning struck the launch pad with the shuttle on the pad before three of the four launches. To this date, no NASA-Kennedy employee has ever been injured by lightning – due in part to the lightning protection policy and education programs.

Thanks to the extensive weather and electric field detection systems, no space shuttle has ever been endangered by lightning during launch although several launches have been delayed due to observed and forecast weather conditions.

Lightning research by NASA, other governmental agencies

Kennedy Space Center needs to protect space shuttles and other launch vehicles, payloads, associated ground processing equipment and facilities, and its personnel. Therefore, it has performed extensive research into lightning and its causes, and how to detect and forecast it. This information is applied toward improved lightning warning and protection systems.

For more than 20 years, Kennedy has hosted international projects to study thunderstorms and atmospheric electricity. The three largest programs have been the Thunderstorm Research International Project

conducted in the mid-1970s, the Rocket Triggered Lightning Program conducted from the mid-1980s to 1992, and the Convection and Precipitation/Electrification program of 1991.

Additionally, three programs using aircraft with electric field measurement capability have been conducted at Kennedy. The first occurred around the time of the Apollo-Soyuz program to safely enhance launch availability for short-launch-window docking missions.

The second was an Airborne Field Mill Program in the early 1990s that studied revising our lightning launch-commit criteria, to safely relax them based on better understanding of the actual hazards. It was conducted by NASA's Langley Research Center, Marshall Space Flight Center and Kennedy, Stanford Research International, and New Mexico Technological University.

Finally, the latest airborne field mill program flew missions in 2000 and 2001. The data from that program is still being analyzed, but has already led to modified lightning launch-commit criteria and improved launch safety.

Many investigators from other governmental agencies, leading universities, utilities and international organizations conducted ground-based and airborne lightning experiments supporting Kennedy's program. The French government was a major participant in the Rocket Triggered Lightning Program and it pioneered this type of research along with the United States.

Other NASA centers are heavily involved in lightning-related research. NASA-Langley scientists studied aircraft-triggered lightning by flying specially instrumented and weather-hardened aircraft directly through thunderstorms in Virginia and Oklahoma. Much of what we know about this phenomenon was discovered through work with an F-106B fighter airplane.

During eight years of research, the airplane was struck by lightning more than 700 times. Nearly all of these strikes were triggered by the aircraft's motion through the intense thunderstorm-electric field, rather than as the result of intercepting a natural lightning bolt. The Federal Aviation Administration and the Air Force have conducted similar experiments to determine how to better protect aircraft electronics.

Marshall, in conjunction with Langley and Kennedy, measured electric fields aloft in the early 1990s using airborne field mills to assess what weather conditions pose a threat of triggered lightning during space vehicle launches.

Similar measurements were made in 2000 and 2001



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by a team led by Kennedy that included scientists from Marshall, the University of North Dakota, the National Center for Atmospheric Research, NOAA and others.

Scientists from the University of Arizona, New Mexico Tech and other universities are examining Kennedy/CCAFS ground-based field mill data for additional clues concerning what conditions are safe and which are hazardous. This will help design launch rules providing maximum opportunity to launch without compromising safety.

Marshall has investigated thunderstorms by flying over them with U-2 aircraft, and is also investigating lightning via satellite. Its Optical Transient Detector is able to detect and locate lightning from orbit over large regions.

The detector is a highly compact combination of optical and electronic elements that represents a major advance over previous technology by gathering lightning data in daytime as well as night. Some of its most important science results are the first-ever consistent

lightning climatology covering most of the globe, and contributing to the use of lightning data in severe weather forecasting.

The detector, and its follow-on, the Lightning Mapper, enables more accurate estimates of the energy and current associated with the global electrical circuit.

Lightning — one of the most violent forces of nature

At any instant, there are more than 2,000 thunderstorms taking place throughout the world. These storms combine to produce about 100 lightning flashes per second, each one with an average of 300 million volts, currents ranging up to 20,000 amps, and temperatures over 50,000 degrees Fahrenheit. Extreme lightning can reach a billion volts, over 200,000 amps, and over 54,000 degrees Fahrenheit.

A moderate-sized thunderstorm at its peak can generate several hundred megawatts of electrical power,



Lightning is at once beautiful and fearsome. Here, a cloud-to-ground strike is caught in the act as it zaps a tree.



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equivalent to the output of a small nuclear power plant. With so much energy being released, there is little wonder that lightning has considerable potential to cause damage.

Lightning on other planets

These giant electric sparks are not unique to Earth. Among the mystifying and gargantuan storms that rage throughout Jupiter's atmosphere, one familiar phenomenon – lightning – was captured by cameras on NASA's Voyager I planetary explorer spacecraft. Both Voyager I and II detected electrical signals from Jupiter characteristic of lightning. This discovery was the first hard evidence that such violent electrical discharges take place on other planets. The Galileo spacecraft also photographed what appear to be visible lightning flashes in Jupiter's atmosphere. Electrostatic discharge detection on Saturn and Uranus by Voyager 2, along with radio signals associated with lightning picked up by the Pioneer Venus orbiter and Russian Venera probe, may indicate that lightning is commonplace in our solar system.

Lightning-like electrostatic discharges in the dust storms of Mars have been hypothesized.

Lightning helps maintain atmospheric charge, aids plants

Lightning on other planets may be too "far out" for some people. For others, the fearsome flashes and explosions that accompany a midsummer night's thunderstorm here on Earth often seem a little too close to home.

During a power blackout from a lightning strike, it's hard to remember that some good does come from the powerful bursts of electrical energy. When lightning bolts discharge, they ionize the air and produce nitrogen oxide. According to recent studies, this process could generate more than 50 percent of the usable nitrogen in the atmosphere and soil. Nitrogen is an essential plant fertilizer.

Lightning also plays a critical role in forests' natural cycles by helping generate new growth.

Areas that are burned by lightning-triggered fires are cleared of dead trees so that seedlings have the space and soil to take root. The global array of thunderstorms serves as a worldwide circuit of electrical generators.

Through the activity of the lightning they produce, these generators continually maintain and renew the atmosphere's positive electrical charge.



An artist's concept of the descent module of NASA's Galileo interplanetary probe shows the probe plunging through Jupiter's atmosphere. The probe carried instruments designed to investigate lightning in the Jovian atmosphere. Launched from KSC Oct. 18, 1989, Galileo arrived at the planet in 1995, and after eight years of data gathering, disintegrated as it fell toward the surface.

Nature takes its toll, though

With so many bolts of lightning, it's no wonder that people and structures are hit. Each year, about 100 people are killed and about 245 are injured in the U.S. by the number two storm-related killer.

Lightning-generated fires destroy more than 30,000 buildings at a loss of hundreds of millions of dollars yearly. The average total economic impact of lightning is more than \$5 billion in the U.S. each year.

Airplanes and spacecraft are subject to the tremendous electrical forces that can build up in the atmosphere. According to the Federal Aviation Administration, commercial aircraft are struck an average of once every 3,000 flight hours, or about once a year. However, only one U.S. airliner was confirmed as lost to lightning, in 1963.

Because of an airplane's metal construction, lightning flows along its fuselage rather than penetrating it.

Almost all lightning strikes on aircraft cause only superficial damage, and passengers are protected from



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injury. With the advent of new composite materials for airframes and digital fly-by-wire control systems, newer aircraft may be more vulnerable than statistics would suggest.

Spacecraft are more vulnerable than aircraft. On March 26, 1987, an Atlas Centaur rocket and its satellite were lost when the unmanned NASA vehicle was struck by lightning that it triggered itself.

Two earlier triggered strikes that temporarily disabled the electrical systems on the Apollo 12 spacecraft onboard a Saturn V rocket on Nov. 14, 1969, prompted NASA to develop ways to protect its launch vehicles, and to create a better system to predict when and where lightning might strike.

Reducing lightning damage

NASA, the Department of Defense, NOAA, the FAA, various research and industry groups, and several foreign governments continue to investigate the ways lightning develops, better ways to predict its occurrence, and the means to reduce damage when it does strike.

To attempt to predict where the next strikes will occur, a National Lightning Detection Network has been established across the U.S. The network plots the strike location of each cloud-to-ground flash.

The Kennedy-developed precise three-dimensional Lightning Detection and Ranging system was commercialized under a Space Act agreement between NASA and Global Atmospherics, Inc (a Vaisala Inc. subsidiary).

This system allows the forecaster to view the height and horizontal extent of each lightning flash and not just the point-of-ground contact. Unlike the National Lightning Detection Network, the system can also detect in-cloud and cloud-to-cloud flashes.

The Lightning Detection and Ranging system has contributed much to our understanding of lightning, including the distribution of lightning strike distances, and the use of lightning in severe weather forecasting. Soon, satellites that observe the whole planet will supplement ground detectors to increase coverage of thunderstorm activity.

Meteorologists can use this data to alert people in potential strike areas. The more accurate the prediction of where and when lightning will occur, the better chance of reducing or eliminating the damage it causes. Kennedy and CCAFS use a two-phase lightning policy (described on page 3).

Ground equipment needs most protection

Since lightning tends to strike the highest local point, special care must be taken to protect tall structures from direct strikes. These structures are often power lines, microwave relay towers used in telephone communication, buildings filled with sensitive electrical equipment, or even launch pads.

Without protection, a lightning strike can cause power line surges and arcing, electrical fires and electrical or structural damage. The lightning does not have to hit a facility directly to cause damage. Voltages and currents induced by nearby strikes can burn out or damage components of modern electronic circuits.

The National Fire Code standards for lightning protection (NFPA-780) for structures call for a pathway, or conductor, that will safely redirect a lightning bolt's electrical energy to the ground. Circuit breakers, fuses and electrical surge arrestors provide additional protection.

Sometimes even this equipment is not sufficient to prevent damage. Studies, including results from the Rocket Triggered Lightning Program, have shown that lightning strikes result in rapid current surges (reaching an initial peak within a millionth of a second) with such high peak current (over 20,000 amperes on average) that conventional protection methods are unable to save complex electronic systems from damage.

Utilities and high-technology industries, among others, are investigating ways to better protect vital electrical equipment.

Better protection begins with better knowledge of lightning

Although lightning has been known to be a discharge of electrical energy since Ben Franklin's kite-flying days, the way electrical charges build up and discharge in clouds is still not fully understood, even now in the 21st century. Researchers at Kennedy and others throughout the world attempt to answer these questions so improved means to detect and measure the charges can be developed.

A lightning bolt is the transfer of an electrical charge between regions inside a cloud, between clouds, from cloud to air, from cloud to the ground, or (more rarely) from the ground to air.



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For such a transfer to take place, the two types of charges must be separated so the cloud is electrified. Exactly how the charges become separated and where in the cloud they are located are still not completely clear.

Is a thundercloud like a generator?

However the details may turn out, it is well understood that thunderstorms separate electrical charges. Usually, a positive charge is pumped aloft while a negative charge accumulates near the lower-middle part of the storm. A small amount of positive charge may collect near the base of the storm cloud. It takes energy to separate the charge, and this energy comes from the rapidly rising air currents in the storm. Thus, like a generator, a thunderstorm converts mechanical energy to electrical energy.

Convection and thunderstorms

A thunderstorm is a natural heat engine. On a typical summer day over Florida, the air is loaded with moisture and the land surface is hot. As the land heats the air near the surface, it expands, becomes less dense (lighter) and begins to rise.

As it rises, the air expands further, this time due to the lower pressure higher in the atmosphere, rather than due to heating. In fact, as the air expands in the lower pressure, it cools because its internal energy is spread out over a larger volume. When moist air cools enough, it can no longer hold all the water it contained when it was warm. If it were on the ground, dew and fog might form. Aloft, the excess water condenses out as a patch of fog in the sky, which we call a cloud.

When water condenses, it releases heat to its surroundings, just as when it evaporates, it absorbs heat (which is why a wet towel cools you on a hot day). The heat released when a cloud forms makes the air rise even more vigorously until a cloud is thousands of feet high. The cloud can continue to grow as long as it has a good source of warm, moist air at its base. As it grows, it eventually becomes tall enough for the air in the cloud to cool below the freezing point (0° C).

Surprisingly, water in the parts of the cloud cooler than 0° does not actually freeze until it gets considerably colder: -10° C to about -20° C. Liquid water colder than 0° is called "super-cooled" water. At temperatures below -10° to -20°, water vapor condenses directly to ice ("subliming" rather than "condensing"). As we will see, it is

the mixture of ice and super-cooled water that probably accounts for most thunderstorm electrification.

Cloud droplets are too small to fall as rain, but turbulence in the cloud causes droplets and ice crystals to collide. Droplets may coalesce, and when a super-cooled droplet collides with an ice crystal, it will freeze to the crystal, thus enlarging it. Soon these larger ice crystals begin to fall through the super-cooled water and collect it, growing as they go. When they have fallen enough for the temperature to rise above 0°, they melt, becoming raindrops.



The lightning event begins when lightning strikes the 3,000-foot copper wire being trailed from the 3-foot-tall rocket. The wire is then vaporized as it follows the path to a lightning rod attached to the launcher. As the wire burn dissipates, it creates an effect called "rosary bead lightning." This can be the prelude to natural lightning restrikes. The initiation of a wire burn can also induce natural intercloud lightning during the event, as seen in this sequence.



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Sometimes a small ice pellet will become coated with water and then be blown back up higher by a sudden updraft. Later it can fall again and gather even more water. This can happen several times if the updrafts and turbulence are strong enough. Then some really large ice particles can form and they may not melt before hitting the ground. These large ice particles are called hail.

Precipitation charging theory

The most widely accepted explanation of how thunderstorms separate the charge is based on laboratory experiments and atmospheric observations with aircraft and radar. The tests show that when ice crystals and super-cooled water droplets collide, if they don't coalesce, the pieces that are scattered after the collision are charged. Which pieces get which kind of charge, positive or negative, depends on the temperature. But at temperatures typical of the electrically active part of thunderstorms, the smaller pieces usually get the positive charges. These smaller, lighter fragments will be carried aloft by the updrafts while the negatively charged, larger, heavier remnants fall. This results in charge separation and an upward transport of the positive charge.

Mechanics of a lightning strike

It is a fact of nature that positive and negative electrical charges attract each other. The strength of this attraction is called the "electric field." When enough charge has been separated, the force of attraction overcomes the electrical resistance of the air and a giant spark (lightning!) can occur.

Most lightning occurs within or between clouds. The destructive cloud-to-ground lightning bolt occurs much less frequently and can carry either a positive or a negative charge. Of the two, negative lightning is the most common type (about 94 percent). The process involved in generating a lightning stroke explains why lightning usually seeks out and strikes the highest point on the surface.

First, a long series of negatively charged branches about 50 yards long, called stepped leaders, emerges from the cloud and approaches the ground. During the approach, the stepped leader causes electric fields on the ground to increase in strength. Positive ions gather around pointed objects as small as pine needles and grass blades, then flow upward toward the stepped leader as several 50-yard sparks, called upward streamers.

When the stepped leader and upward streamer touch, the cloud-ground circuit closes, and a huge, rapid

surge of current flows up the ionized stepped leader channel from ground to cloud. The grounded object serves as the focal point of the positive ion flow. That object, such as a tree or a golfer with an upraised club, is considered "struck" by lightning.

The huge upward surge of current is called the return stroke. It heats the channel to over 50,000 degrees Fahrenheit almost instantly. This lights up the channel, which we see as lightning, and generates a large pulse of sound as the super-heated air rapidly expands, which we call thunder. Usually the return stroke doesn't neutralize all the charge in that region of the cloud, and a dart leader races down the lightning channel to the ground, initiating another return stroke.

There are usually three to four return strokes per lightning flash, separated by about a tenth of a second. This is near the limit of human perception and explains why lightning appears to flicker. Lightning with as few as fifty return strokes has been observed. The entire event is called a lightning flash.

Positive lightning carries a positive charge to the ground. It makes up less than 4 percent of a storm's lightning strikes and typically takes place at the end of a storm. However, the positive lightning strike has potential to cause more damage.

It generates current levels up to twice as high and of longer duration than those produced by a negative bolt. It's the long-duration, or "continuing current" components, of lightning that causes heating and burning, and metal punctures. For that reason, scientists are especially interested in developing ways to detect the areas of a thunderstorm that develop positive bolts.

Triggered lightning — a bolt from the gray?

The phrase "a bolt from the blue" originated from observations of a seemingly inexplicable phenomenon — a flash of lightning on a day without a storm cloud nearby. This event would be startling under any circumstances, but imagine the shock of seeing such a bolt strike the 363-foot-high Apollo 12/Saturn V rocket while it was more than a mile above Kennedy (Nov. 14, 1969). Perhaps being in an airliner as it was "zapped" by lightning at 20,000 feet would be more of a scare, though. While not really bolts from the "blue," because they occur inside of clouds, they occur in clouds that otherwise do not contain lightning.

Why are rockets and airplanes struck in these circumstances? It was first thought that they just "got in



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the way” of a lightning bolt jumping from a positive- to a negative-charged area of a thundercloud. Later research provided evidence that the buildup of strong electric fields at certain points of the aircraft were the culprit.

Such concentrated fields of electrical energy can develop before lightning occurs. When an aircraft or a rocket enters such a high electric field, electrical fields are compressed, and they concentrate around the sharp edges and protuberances of the vehicle.

If the electrical fields around the airplane’s sharp and protruding parts build up to where there is an electrical breakdown of the air, lightning leaders form at two or more locations on the airplane. The aircraft also contributes to the conducting path between a positive and a negative electrical field, triggering the resultant lightning bolt.

In the case of Atlas Centaur-67, a lightning strike changed some data in the rocket’s computer, which caused it to steer the rocket sideways and begin breaking up in flight. Range Safety then destroyed the out-of-control rocket, March 26, 1986.

Lightning Safety

Lightning is the second leading cause of storm-caused deaths in the U.S., killing more people than tornadoes or hurricanes. Only floods kill more than lightning. Lightning also inflicts lifelong debilitating injuries on more than it kills.

Public education is the key to prevention. Lightning safety is best taught as a multi-level process of decreasing levels of protection. No place outside is safe when thunderstorms are within several miles.

The first and best level of lightning safety, Level-1, is to avoid the threat. Use the weather forecast and know your local weather patterns to plan your outdoor activities to avoid the lightning.

Level-2 is to use the “30-30 Rule” while outdoors. If there are 30 seconds or less between lightning and its thunder, go inside. Wait 30 minutes or more after the last thunder before going outside. The safest, most accessible place to avoid lightning is a large, fully enclosed

building with wiring and plumbing, such as a typical house. While indoors, avoid using corded telephones, electrical appliances and wiring, and plumbing. If a solid building is not available, a vehicle with a solid metal roof and metal body offers some protection.

Level-3 of lightning safety is getting into dangerous territory. If you must be outside and thunderstorms are near, avoid the most at-risk locations or activities. Avoid high elevations or open areas. Do not go under trees to keep dry. Avoid tall, isolated objects. Avoid swimming, boating and fishing. Avoid open-cockpit farm or construction equipment.

Level-4 should be used only as a desperate last resort. If you’ve made several bad decisions and find yourself outside, in an at-risk location, and thunderstorms are threatening, some procedures can reduce, but not eliminate the threat.

Level-5 is first aid. All lightning deaths result from cardiac arrest or stopped breathing from the cardiac arrest. CPR or rescue breathing is the recommended first aid, respectively.

Further lightning safety information is available from the National Weather Service lightning safety Web site, www.lightningsafety.noaa.gov.

The future of lightning prediction, detection and research

As society becomes more dependent on computers and other electronic devices, more effective ways must be developed to protect this equipment against high-voltage shock. Future aircraft made of nonconductive composite materials, that “fly-by-wire” or by computer command instead of manual hydraulic systems, will need advanced protection systems. As the global population expands, the increase of people and property calls for improved lightning prediction and detection through advanced weather equipment and methods.

As one of the more lightning-sensitive residents of the “lightning capital of the United States,” Kennedy will continue to apply its technical expertise to support these efforts.



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COVER PHOTO: A tremendous lightning bolt that appeared to impact Pad A in this dramatic photograph actually smashed into the ground well to the north. If the strike had occurred over the pad, it would have gone to ground through the one-half-inch stainless steel catenary wire, which is suspended over the pad from north to south. The wire is supported by the lightning mast, visible to the left and above the orbiter Challenger.

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