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ATMOSPHERIC ELECTRICITY CRITERIA GUIDELINES FOR USE IN SPACE VEHICLE DEVELOPMENT

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The accidental triggering of lightning discharges by the Apollo 12 space vehicle shortly after launch initiated a detailed study of these discharges as they relate to space vehicle missions. About this time, two new books were published on atmospheric electricity [1,2]. From the information resulting from the conferences, technical meetings, discussions with the professionals in the field of atmospheric electricity, and publications evaluating the Apollo 12 discharge incident [3,4], Chapter IX, entitled "Atmospheric Electricity," of NASA TM X-53872 [5] has been revised. Since the revision to NASA TM X-53872 will not be completed for publication until late spring 1971, information on atmospheric electricity is presented in this report so that it will be available for use in current space vehicle design and operational studies.

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SUMMARY

The accidental triggering of lightning discharges by the Apollo 12 space vehicle shortly after launch initiated a detailed study of these discharges as they relate to space vehicle missions. About this time, two new books were published on atmospheric electricity [1,2]. From the information resulting from the conferences, technical meetings, discussions with the professionals in the field of atmospheric electricity, and publications evaluating the Apollo 12 discharge incident [3,4], Chapter IX, entitled "Atmospheric Electricity," of NASA TM X-53872 [5] has been revised. Since the revision to NASA TM X-53872 will not be completed for publication until late spring 1971, information on atmospheric electricity is presented in this report so that it will be available for use in current space vehicle design and operational studies.

I. INTRODUCTION

Atmospheric electricity must be considered in the design, transportation, and operation of space vehicles. The effect of the atmosphere as an insulator and conductor of high voltage electricity, at various atmospheric pressures, must also be considered. Space vehicles not adequately protected can be damaged by (1) a direct lightning stroke to the vehicle while on the ground or after launch, (2) current induced in the vehicle from the electromagnetic field generated in a nearby object struck by lightning, and (3) a large buildup of the atmospheric potential gradient near the ground as a result of charged clouds nearby. Also high voltage systems not properly designed could arc or break down at low atmospheric pressures.

The vehicle can be protected by (1) ensuring that all metallic sections are connected electrically (bonded) so that the current flow from a lightning stroke is conducted over the skin without any gaps where sparking would occur or current would be carried inside (MIL-B-5087B (ASC)), 15 October 1964, and later amendments [6] give requirements for electrical bonding); (2) protecting objects on the ground, such as buildings, by a system of lightning rods and wires over the outside to carry the lightning stroke to the ground; (3) providing a cone of protection (as shown in reference 7) for the lightning protection plan for

Saturn Launch Complex 39; (4) providing protection devices in critical circuits [8]; (5) using systems which have no single failure mode; i.e., the Saturn V launch vehicle uses triple redundant circuitry on the auto-abort system, which requires two out of three of the signals to be correct before abort is initiated [3]; and (6) appropriate shielding of units sensitive to electromagnetic radiation.

If lightning should strike a space vehicle ready for test or flight, or a large metallic object nearby such as the test stand or gantry, sufficient system checks should be made to insure that all electronic components and subsystems of the vehicle are functional.

II. THUNDERSTORM ELECTRICITY

On a normal day without clouds, the potential gradient in the atmosphere near the surface of the earth is relatively low (~ 300 v/m), but when clouds build up, the potential gradient near the surface of the earth will increase. If the clouds become large enough to have water droplets of sufficient size to cause rain, the potential gradient between the cloud and ground may be sufficient to result in a lightning discharge (~ 1,000,000 v/m).

1. Potential Gradient

The earth can be considered as a large capacitor, the earth's surface being one plate, the ionosphere the other plate, and the atmosphere the dielectric. The earth is negatively charged.

a. Fine-Weather* Potential Gradients

The fine-weather electrical field intensity (potential gradient) measured near the ground is on the order of 100 to 300 volts/meter and is positive; i.e., the earth is negatively charged and the atmosphere above the earth is positively charged. The fine-weather value of 100 to 300 volts/meter will vary some in time at a specific location and will also be somewhat different at various locations. These variations in fine weather will be caused by variations in wind speed and direction, amount of particulate matter in the atmosphere (dust, salt particles, etc.), atmospheric humidity, and instrument location and exposure [9]. The fine-weather potential gradient decreases with altitude, reaching a value near zero at 10 kilometers. This fine-weather

*The term "fair weather" is also used with the same meaning.

potential on a 100-meter-high vehicle could result in a 10,000 volt, or greater, potential between the ground and top, if the vehicle is not grounded.

b. Potential Gradients with Clouds

When clouds develop, the potential gradient increases. Because of the potential gradient, on days when scattered cumulus clouds occur, severe shocks can result from the charge induced along a metal cable on captive balloons. Similarly induced charges on home television antennas have exploded fine wire coils in television sets. Such equipment damage can be prevented by installing lightning arresters with air gaps small enough to discharge the current before it discharges within the equipment.

c. Potential Gradients During Thunderstorms

If the cloud development reaches the cumulo-nimbus type of cloud, lightning discharges result when the potential gradient at some location between the base and the ground reaches a value equal to the critical value when electrical breakdown of the air occurs. Laboratory data indicate this value to be as much as 10^6 volts/meter at normal sea-level atmospheric pressure. Electrical fields measured at the surface of the earth are much less than 10^6 volts/meter during lightning discharges because of several effects: (1) Most clouds have centers of both polarities which tend to neutralize values measured at the surface. (2) Each charge in the atmosphere and its image within the earth comprise an electrical dipole, and the intensity of the electrical field decreases with the cube of the distance to the dipole. (3) The atmospheric electric field measured over land at the surface is limited by discharge currents arising from grounded points, such as grass, trees, and other structures, which ionize the air around the points, thus reducing the electric stress. For these reasons, the measured electrical field at the surface never is more than about 15×10^3 volts/meter. The potential gradient values indicated by measuring equipment at the surface will show only the high values of proper sign when the charged cloud is directly overhead. As the distance of the projection of the charged center of the cloud on the ground becomes greater, the readings of the measuring equipment become lower, reaching zero at some distance, and then changing to the opposite sign at greater distances [1,9].

d. Coronal Discharge

As the atmospheric potential gradient increases, the air surrounding exposed sharp points is increasingly ionized. If the ionization is sufficient, coronal discharges may occur. The induced charge from a nearby lightning stroke may aid such a discharge, which may be quite severe when lightning storms or cumulus development are within about 16 km (10 miles) of the launch pad.

2. Characteristics of Lightning Discharges

The lightning discharge to ground which appears to the eye as a single flash, is usually made up of 3 or 4 strokes. These strokes are preceded by a leader stroke of lesser intensity. A summary of the characteristics of various types of lightning discharges are given in Table 1. (Also, see references 4 and 10.)

a. Lightning Characteristics for Design

Based on the latest information (see Table 1), the following summary of lightning characteristics should be considered in design:

(1) On the Launch Pad or During Ground Transportation

(a) An average peak current of 20,000 amperes can be expected. The peak current flow is reached 6 microseconds after start of stroke, with a fall to one-half the peak value in 24 microseconds. A total flash charge of 20 coulombs is transmitted to the earth with 90 percent of the current flow, after the initiation of the first stroke. Additional strokes will have currents at less than 1,000 amperes, and the peaks of the current will be at 40-millisecond intervals.

(b) The maximum peak current will not be greater than 100,000 amperes 98 percent of the time. This peak current flow is reached in 10 microseconds after start of the stroke, and the current then falls to one-half the peak value in 20 microseconds. A total stroke charge of 100 coulombs is transmitted to the earth, with 95 percent of the current flow, after the initiation of the first stroke, at less than 5000 amperes.

(2) Inflight Triggered Lightning

The space vehicle while in flight should be capable of withstanding an electrical discharge from triggered lightning. The characteristics of such a discharge is an average peak current of 20,000 amperes. The peak current flow is reached in 6 microseconds after the start of the stroke, with a fall to one-half the peak value in 24 microseconds. After the current reaches 185 amperes, it will remain at this level for at least 175 milliseconds (17,500 microseconds) before falling to zero. There will be only one stroke in the discharge, called a long-continuing-current discharge (see references 3, 4, 6, 10 and 11).

b. Surges from Lightning Discharge

If an electrical line, antenna, or other metallic object is struck by a lightning discharge, there will be a surge of current through the object. If the object is grounded and is of sufficient size, then

Table 1. Characteristics of Lightning Discharges

Type of Lightning	Average Peak Current per Stroke (amperes)	Maximum Rate of Rise of Current (amperes/micro-seconds)	Average Amount of Charge Transferred		Average Total Duration of Stroke (milli-seconds)	Average Number of Strokes (unitless)	Average Time between Strokes (milliseconds)	Remarks
			Per Stroke (coulombs)	Total (coulombs)				
Intercloud Lightning								
Leader	No Information							
Return stroke	1000-2000	100-500	1-5	1-5	3	1		
Discrete Lightning Strokes to Ground								
Leader	100		5	5	20	1		
Return Stroke	20,000	10,000	1-5	4-20	0.3	3 to 4	40	Peak current exceeding 100,000 amperes have been measured about 2% of the time.
Long Continuing Current Lightning Strokes to Ground								
Leader	100		5	5	20	1		
Return Stroke	20,000	10,000	12-40	12-40	200	1		Average current value of 185 amperes for long periods (175 milli-seconds).

characteristics currents equal to the current in the lightning discharge as given in paragraph 2a will be conducted through the object to ground. If the object is not grounded, then the current flow will be less in relation to the resistance of the object and the ground. Metallic objects whose cross sections are too small to carry the current from a lightning stroke may be melted or vaporized.

c. Ground Current

When lightning strikes an object, the current will flow through a path to the true earth ground. The voltage drop along this path may be great enough over short distances to be dangerous to personnel and equipment [8]. Cattle and humans have been electrocuted from the current flow through the ground and the voltage potential between their feet while standing under a tree struck by lightning.

d. Radio Interference

When an electrical charge produces a spark between two points, electromagnetic radiation is emitted. This discharge is not limited to a narrow band of frequencies, but covers most of the electromagnetic radiation spectrum with various intensities. Most static heard in radio reception is related to electrical discharges, with lightning strokes contributing a large percentage of the interference. This interference from lightning strokes is propagated through the atmosphere in accordance with laws valid for ordinary radio transmission and may travel great distances. With the transmission of interference from lightning strokes over great distances, certain frequencies remain prominent, with 30 kc being the major frequency. Interference with telemetering and guidance needs to be considered only when thunderstorms are occurring within 100 km (60 miles) of the space vehicle launch site. Thunderstorm locations can be obtained from supporting meteorologists.

3. Frequency of Occurrence of Thunderstorms

According to standard United States weather observing procedure, a thunderstorm is reported whenever thunder is heard at the station. It is reported along with other atmospheric phenomena on the standard weather observer's form WBAN-10 when the time thunder is heard and ends 15 minutes after thunder is last heard. Notice that this type of reporting of thunderstorms may be a report of one or more thunderstorms during a period. For this reason, these types of observations will be referred to as "thunderstorm events"; i.e., a period during which one or more thunderstorms is reported (heard). Because of the method of reporting thunderstorms, most analyses of thunderstorm data are based on the number of days per year in which thunder is heard one or more times on a day, i.e., "thunderstorm days." More detailed studies of frequencies of thunderstorms occurring in the Cape Kennedy Area have been made [13].

a. Thunderstorm Days per Year (Isokeraunic Level)

The frequency of occurrence of "thunderstorm days" (number of days per year on which thunder is heard) is an approximate guide to the probability of lightning strokes to earth in a given area. The number of thunderstorm days per year is called the "isokeraunic level." A direct lightning stroke is possible at all locations of interest, but the frequency of such an occurrence varies between the locations (see Table 2 and references 7, 8, and 12).

b. Thunderstorm Occurrence per Day

In a study made using the WBAN-10 data (which reports a thunderstorm when thunder is heard [13]), frequencies were computed of the number of days which had 0, 1, 2, ..., thunderstorms reported; i.e., none or more "thunderstorm events." Tables 3 and 3a taken from reference 13, give this information.

c. Thunderstorm "Hits"

There were sufficient data for the summer months (June, July, August) at Cape Kennedy, Florida to make an analysis of the frequency of occurrence of "thunderstorm hits" [13]. Thunderstorm hits are defined as:

(1) A thunderstorm actually reported overhead, or

(2) a thunderstorm first reported in a sector and last reported in the opposite sector. This is assuming thunderstorms move in straight lines over small areas. Tables 4 and 4a from reference 13 list this information.

4. Frequency of Lightning Strokes to Earth

Although reliable representative data concerning the number of thunderstorms actually passing over Cape Kennedy (or the launch site) are available, the data have not been directly related to the number of lightning strokes to the launch pad. But in another study [7], it has been determined that, if the isokeraunic level is multiplied by 0.23, an estimate of the stroke frequency to the earth per square mile can be obtained. For the 0.2 square-mile launch area of Saturn Launch Complex 39, there are an estimated four strokes per year or nearly one stroke for the month of August. The probable number of strokes per year to buildings of different heights will increase with height (see Table 5).

Table 2. Frequency-of-Occurrence of "Thunderstorm Days" (Isokeraunic Level)

Location	Mean Number of Days Per Year for Thunderstorms		Monthly Distribution (percent of annual)											
			January	February	March	April	May	June	July	August	September	October	November	December
Huntsville	70	% No. Days	1 0.70	3 2.10	6 4.20	8 5.60	11 7.70	19 13.30	22 15.40	18 12.60	9 6.30	1 0.70	1 0.70	1 0.70
River Transportation and New Orleans	75	% No. Days	3 2.25	3 2.25	5 3.75	5 3.75	8 6.0	16 12.0	21 15.75	20 15.0	10 7.5	3 2.25	3 2.25	3 2.25
Gulf Transportation	90	% No. Days	1 0.90	1 0.90	4 3.60	2 1.80	9 8.10	18 16.20	24 21.60	23 20.70	12 10.80	4 3.60	1 0.90	1 0.90
Eastern Test Range	70.09	% No. Days	0.77 0.54	1.94 1.36	4.28 3.00	4.02 2.82	9.73 6.82	18.55 13.00	21.27 14.91	20.23 14.18	13.22 9.27	3.89 2.73	1.18 0.82	0.92 0.64
Panama Canal Transportation	100	% No. Days	1 1.0	1 1.0	4 4.0	2 2.0	9 9.0	18 18.0	24 24.0	23 23.0	12 12.0	4 4.0	1 1.0	1 1.0
Western Test Range and West Coast Transportation	6	% No. Days	9 0.54	11 0.66	19 1.14	13 0.78	7 0.42	4 0.24	3 0.18	7 0.42	8 0.48	8 0.48	3 0.24	8 0.48
Sacramento	4	% No. Days	6 0.24	16 0.64	12 0.48	15 0.60	9 0.54	6 0.24	3 0.12	3 0.12	10 0.40	12 0.48	5 0.20	3 0.12
Wallops Test Range	41	% No. Days	1 0.41	2 0.82	5 2.05	7 2.87	13 5.33	19 7.79	24 9.84	18 7.38	7 2.87	2 0.82	1 0.41	1 0.41
White Sands Missile Range	35	% No. Days	1 0.35	1 0.35	3 1.05	6 2.10	14 4.90	19 6.65	24 8.40	18 6.30	9 3.15	3 1.05	1 0.35	1 0.35

Table 3. Frequencies of the Observed Number of Days that Experience x Thunderstorm Events at Cape Kennedy, Florida for the 11-year Period of Record January 1957 through December 1967.

x	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Spr.	Sum.	Fall
0	335	295	308	299	266	187	177	185	228	311	321	334	873	549	860
1	4	9	20	18	43	77	80	89	54	17	6	3	81	246	77
2	2	4	9	10	25	40	47	30	33	9	3	2	44	117	45
3		2	3	3	3	17	26	24	12	4		2	9	67	16
4			1		3	6	9	10	3				4	25	3
5					0	2	2	3					0	7	
6					1	1							1	1	
n	341	310	341	330	341	330	341	341	330	341	330	341	1012	1012	1001

Table 3a. Relative Frequency of Days that Experienced at Least One Thunderstorm Event at Cape Kennedy, Florida.

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Spring	Summer	Fall
.018	.048	.097	.094	.220	.433	.481	.457	.309	.088	.027	.021	.137	.458	.141

Table 4. Frequencies of the Observed Number of Days that Experience x Thunderstorm Hits at Cape Kennedy, Florida for the 11-year Period of Record January 1957 through December 1967.

x	June	July	August	Summer
0	293	305	300	898
1	27	24	30	81
2	5	6	7	18
3	3	3	2	8
4 or more	2	3	2	7
TOTAL	330	341	341	1012

Table 4a. Relative Frequency of Days that Experienced at Least One Thunderstorm Hit at Cape Kennedy, Florida.

June	July	August	Summer
.112	.106	.121	.113

Table 5. Estimate of the Number of Lightning Strokes per Year for Various Heights (Eastern Test Range) [7]

Height (m)	Height (feet)	Number of Lightning Strokes (per year)
30.5	100	0.4
61.0	200	1.1
91.4	300	2.3
121.9	400	3.5
152.4	500	4.4
182.9	600	5.3
213.4	700	5.8

III. STATIC ELECTRICITY

A static electric charge can accumulate on an object from its motion through the atmosphere containing raindrops, ice particles, or dust. If not grounded, an unmoving object can also accumulate a charge from wind-borne dust or salt (often as nuclei too small to be visible) or rain or snow particles striking the object. This charge can build up until the local electric field at the point of sharpest curvature exceeds the breakdown field. The quantity of maximum charge will depend on the size and shape of the object (especially if sharp points are on the object). Methods of calculating this charge are given in reference 4.

If a charge builds up on an ungrounded space vehicle on a launch pad, any discharges which occur could ignite explosive gases or fuels, interfere with radio (telemetering) communications, or cause severe shocks to persons. Static electric charges occur more frequently during periods of low humidity and can be expected at all geographical areas.

IV. ELECTRICAL BREAKDOWN OF THE ATMOSPHERE

The atmosphere of the earth at normal sea-level pressure (101,325 newtons m^{-2}) is an excellent insulator, having a resistance greater than 10^{16} ohms for a column one square centimeter in cross section and one meter long. When there is a charge in the atmosphere, ionization takes place, thus reducing the conductivity of the air. This charge can be from either cloud buildups or electrical equipment. If the voltage is increased sufficiently, the ionization will be high enough for a spark discharge to occur.

The breakdown voltage (voltage required for a spark to jump a gap) for direct current is a function of atmospheric pressure. The breakdown voltage decreases with altitude until a minimum of 327 volts mm^{-1} at an atmospheric pressure of 760 newtons m^{-2} (7.6 mb), representing an altitude of 33.3 km. Above and below this altitude, the breakdown voltage increases rapidly [14], being several thousand volts per millimeter at normal atmospheric pressure (see figure 1).

The breakdown voltage is also a function of frequency of an alternating current. With an increase of frequency, the breakdown voltage decreases. A more complete discussion can be found in NASA SP-208 [15].

Several measures can be taken to prevent arcing of high voltage in equipment:

(1) Have equipment voltages off at the time the space vehicle is going through the critical atmospheric pressures. Any high voltage capacitors should have bleeding resistors to prevent high voltage charges remaining in the capacitors.

(2) Eliminate all sharp points and allow sufficient space between high voltage circuits.

(3) Seal high voltage circuits in containers at normal sea-level pressures.

(4) Have materials available to protect, with proper use, against high voltage arcing by potting circuits.

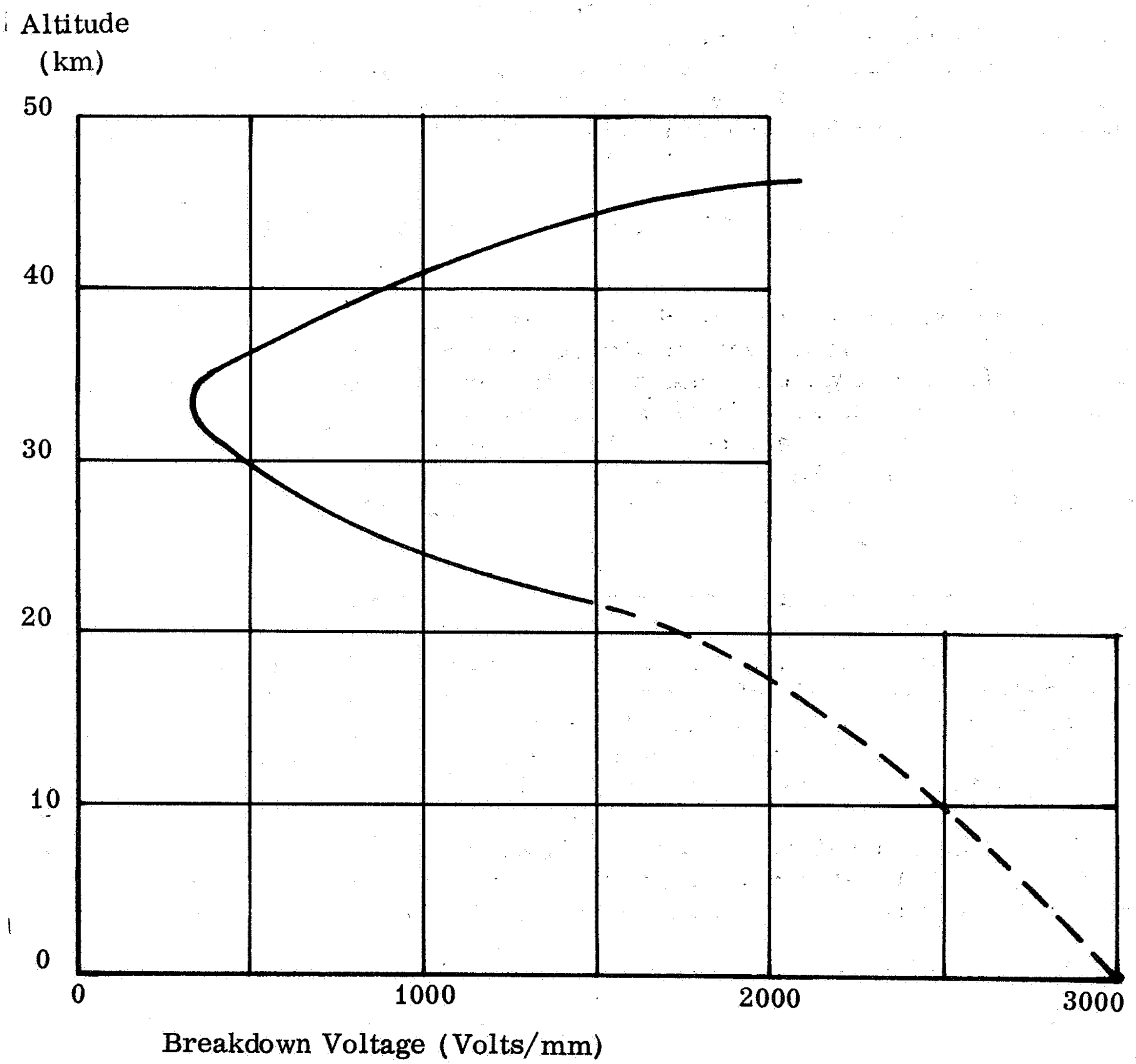

Figure 1. Breakdown Voltage vs Altitude

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FOR USE IN SPACE VEHICLE DEVELOPMENT

By Glenn E. Daniels

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commision programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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