NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ANALYSIS OF
APOLLO 12 LIGHTNING INCIDENT

PREPARED BY

MARSHALL SPACE FLIGHT CENTER

KENNEDY SPACE CENTER

MANNED SPACECRAFT CENTER

FEBRUARY 1970

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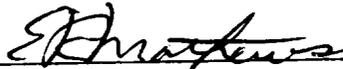
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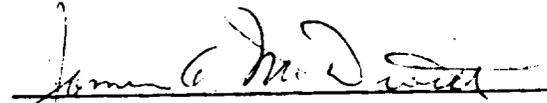
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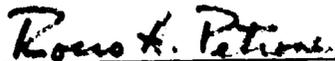
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PREFACE

Appreciation is extended to the following personnel for their expertise and help in the understanding of the Apollo 12 lightning incident at the special December meeting of the American Geophysical Union in San Francisco, California.

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To other participants of this meeting, a special thanks is given for their analytical contributions and consultations which were graciously offered during the analysis of the phenomena associated with the lightning incident.
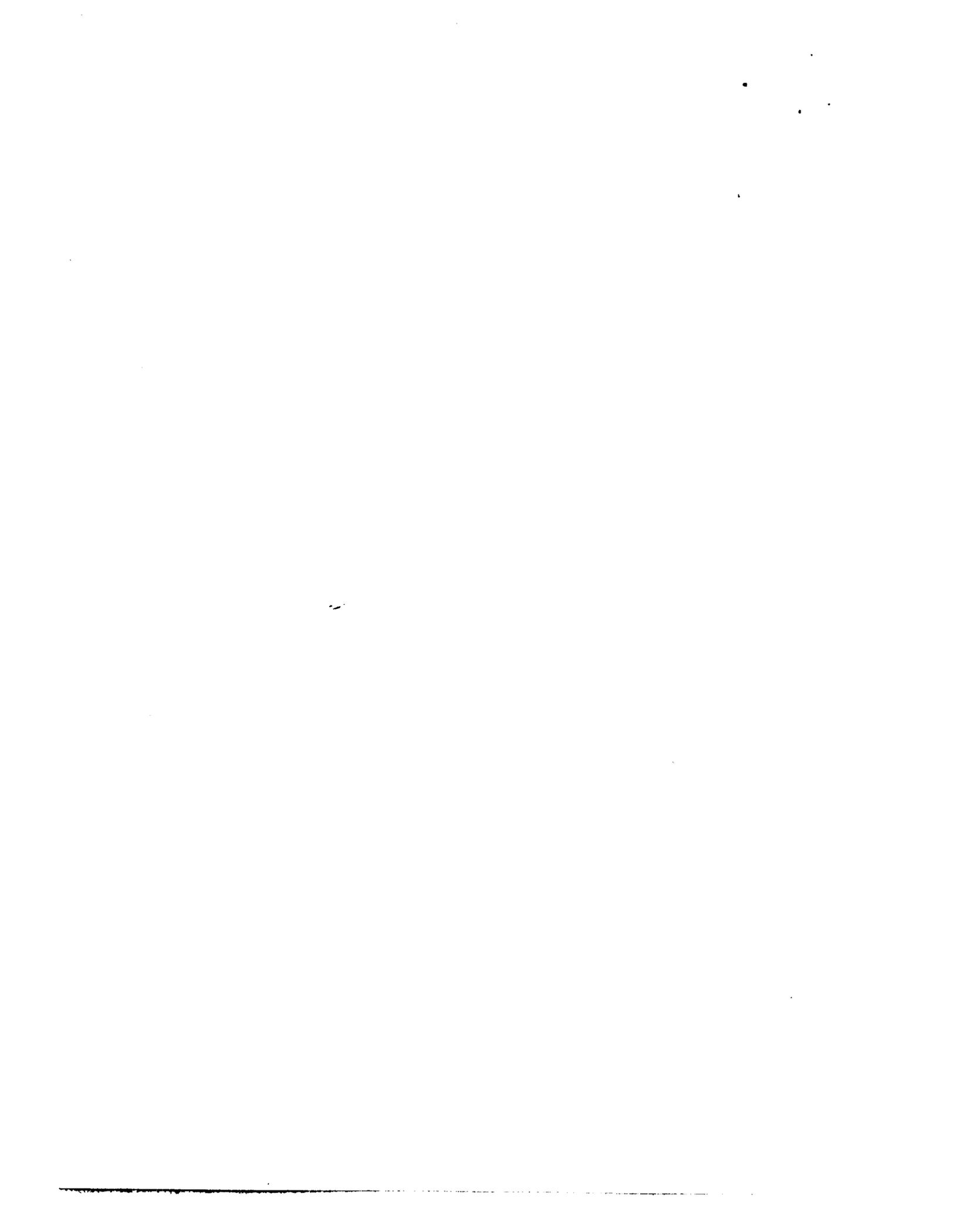
SUMMARY

The Apollo 12 space vehicle was launched on November 14, 1969, at 11:22 a.m. e.s.t. from launch complex 39A at Kennedy Space Center, Florida. At 36.5 seconds and again at 52 seconds, a major electrical disturbance was caused by lightning. As a result, many temporary effects were noted in both the launch vehicle and spacecraft. Some permanent effects were noted in the spacecraft and involved the loss of nine non-essential instrumentation sensors. All noted effects were associated with solid-state circuits, which are the most susceptible to the effects of a discharge.

Analysis shows that lightning can be triggered by the presence of the long electrical length created by the space vehicle and its exhaust plume in an electric field which would not otherwise have produced natural lightning. Electric fields with sufficient charge for triggered lightning can be expected to contain weather conditions such as the clouds associated with the cold front through which the Apollo 12 vehicle was launched. The possibility that the Apollo vehicle might trigger lightning had not been considered previously.

The Apollo space vehicle design is such that a small risk of triggered lightning is acceptable. In accepting this minimal risk for future flights, launch rule restrictions have been imposed with respect to operations in weather conditions associated with potentially hazardous electric fields.

INTRODUCTION

Before the Apollo 12 flight, the only consideration of the effects of lightning on the space vehicle was for the period prior to flight. The methods and procedures used to cope with possible lightning prior to launch have been in existence since the inception of the launch complex. The possibility of the vehicle becoming involved with lightning after lift-off was not a launch consideration, unless natural lightning activity was actually present in the launch complex area.

This report discusses the significant elements of the lightning incident during the Apollo 12 launch. The report is addressed to what happened and why, and what meteorological conditions could produce lightning with the presence of the launch vehicle. This report also recommends action for minimizing the possibility of creating a similar incident on future Apollo flights. An assessment of the spacecraft and launch vehicle electrical design to determine the effects of lightning is included.

The investigative results represent the combined efforts of the appropriate personnel at the Manned Spacecraft Center, the Marshall Space Flight Center, and the Kennedy Space Center. The primary contributions to the understanding of the physics associated with the incident and of how to apply the present knowledge of atmospheric electricity to the Apollo Program have been provided by recognized experts in the field. A number of authorities on atmospheric electricity have enthusiastically and voluntarily provided consultation and literature in this area.

LIGHTNING PHOTOGRAPHS

Two lightning incidents occurred on Apollo 12 as evidenced by the onboard data. The first incident, at 36.5 seconds, was recorded photographically at many locations around the launch complex.

Four motion picture cameras recorded lightning discharge channels near the launch tower. These photographs, together with video-tape records from the abort advisory television camera (figs. 1 and 2), show two discharge channels. The duration of each scan in figure 1 is 1/60 second with 1 millisecond between scans. These photographs were obtained from video-tape records of the actual event. The bright lightning channel apparently saturated the vidicon tube in scan b, and the tube remained saturated for scans c and d. The image began decaying in scan e and required four scans for total decay. Scan f shows the second lightning channel, which developed approximately 60 milliseconds after the first. One of the channels, located about 1500 feet from the launch umbilical tower, showed pronounced downward branching and appeared to last 50 milliseconds in the motion picture photographs. Another channel, partly obscured by steam and clouds and about 100 feet from the launch umbilical tower, also lasted about 50 milliseconds. One frame from each of the motion picture cameras that recorded the lightning strike at 36.5 seconds are shown in figure 3.

Table I shows the types of cameras used together with films, lens openings, and shutter opening angles. All cameras were operated at a speed of 24 frames per second. Figure 4 shows the camera sites and the approximate locations of where the channels contacted the ground.

TABLE I.- APOLLO 12 LIGHTNING STRIKE CAMERA DETAIL

Camera number	Channel and number of frames exposed	Distance from center of launch pad, ft	Direction camera facing, deg	Camera[a] and f-stop	Focal length, mm	Shutter opening angle, deg	Film
E-100	Main channel 1 frame	120	130	16-mm f-stop 11	10	36	Color, ASA 160 high-speed daylight Ektachrome EF
E-102	Main channel (branch only) 1 frame	1200	90	16-mm Mitchell f-stop 16	25	40	Color, ASA 160 high-speed daylight Ektachrome EF
D-120	Obscured channel 2 frames	1308	30	16-mm f-stop 11	18	170	Color, ASA 16 low-speed, daylight Ektachrome reversal
Nevada all sky camera[b]	Main channel 2 frames	1308	30	35-mm f-stop 6.3		30	Color, ASA 64 5254 negative Ektachrome

[a] All cameras operated at 24 frames per second.

[b] Nevada all-sky camera photograph is a 360-degree view looking straight up. This camera and the photograph in figure 3 were provided through the courtesy of Dr. O. Richard Norton, Curator of Fleischmann Atmospherium-Planetarium, Desert Research Institute, University of Nevada, Reno, Nevada.

Note: Each scan has 1/60 - second exposure time with one millisecond between each scan.

(a)

(b)

(c)

(d)
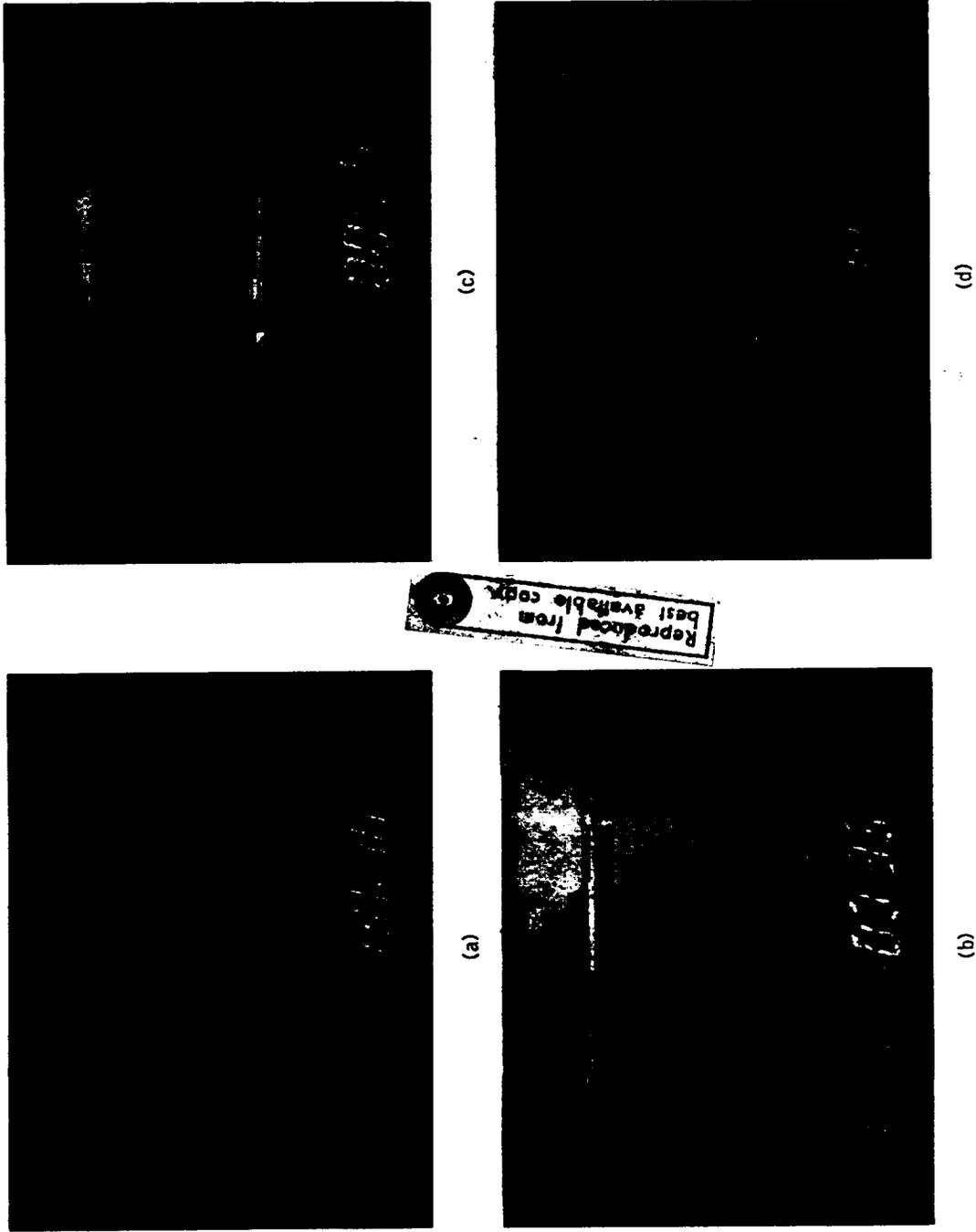
Figure 1.- Sequence photographs of television scans of the lightning strike at 36.5 seconds.

Note: Each scan has 1/60 - second exposure time with one millisecond between each scan.

(e)

(f)

(g)

(h)
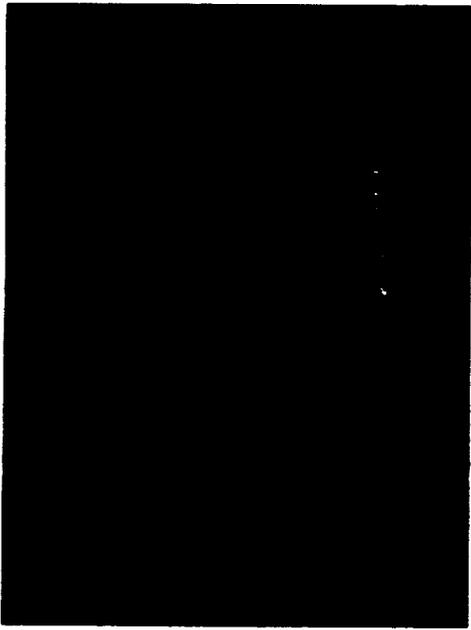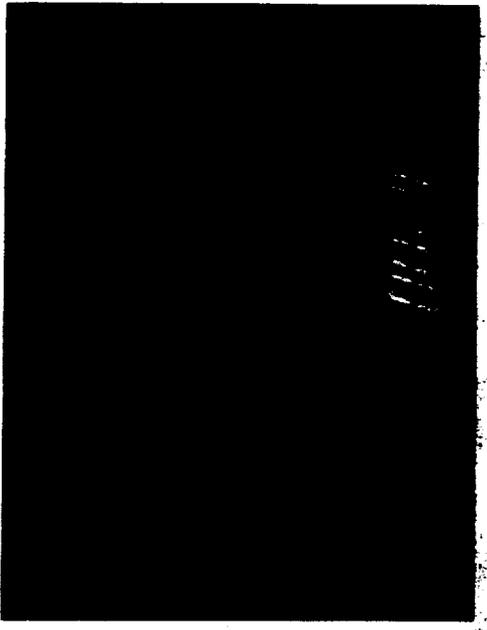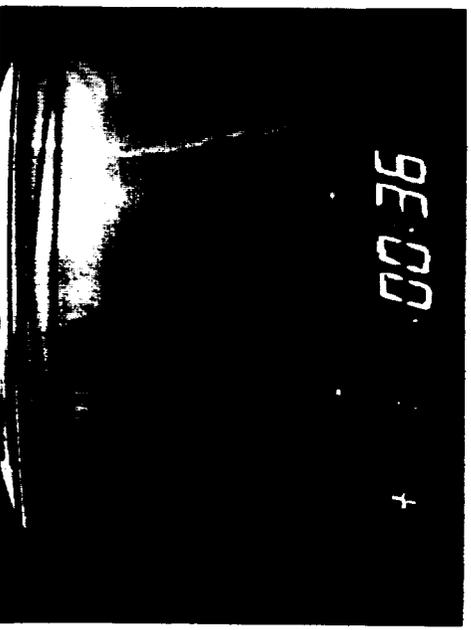
Figure 1.- Concluded.

Note: See Table I for camera details.

Figure 2.- Lightning recorded at launch complex by camera D-120.

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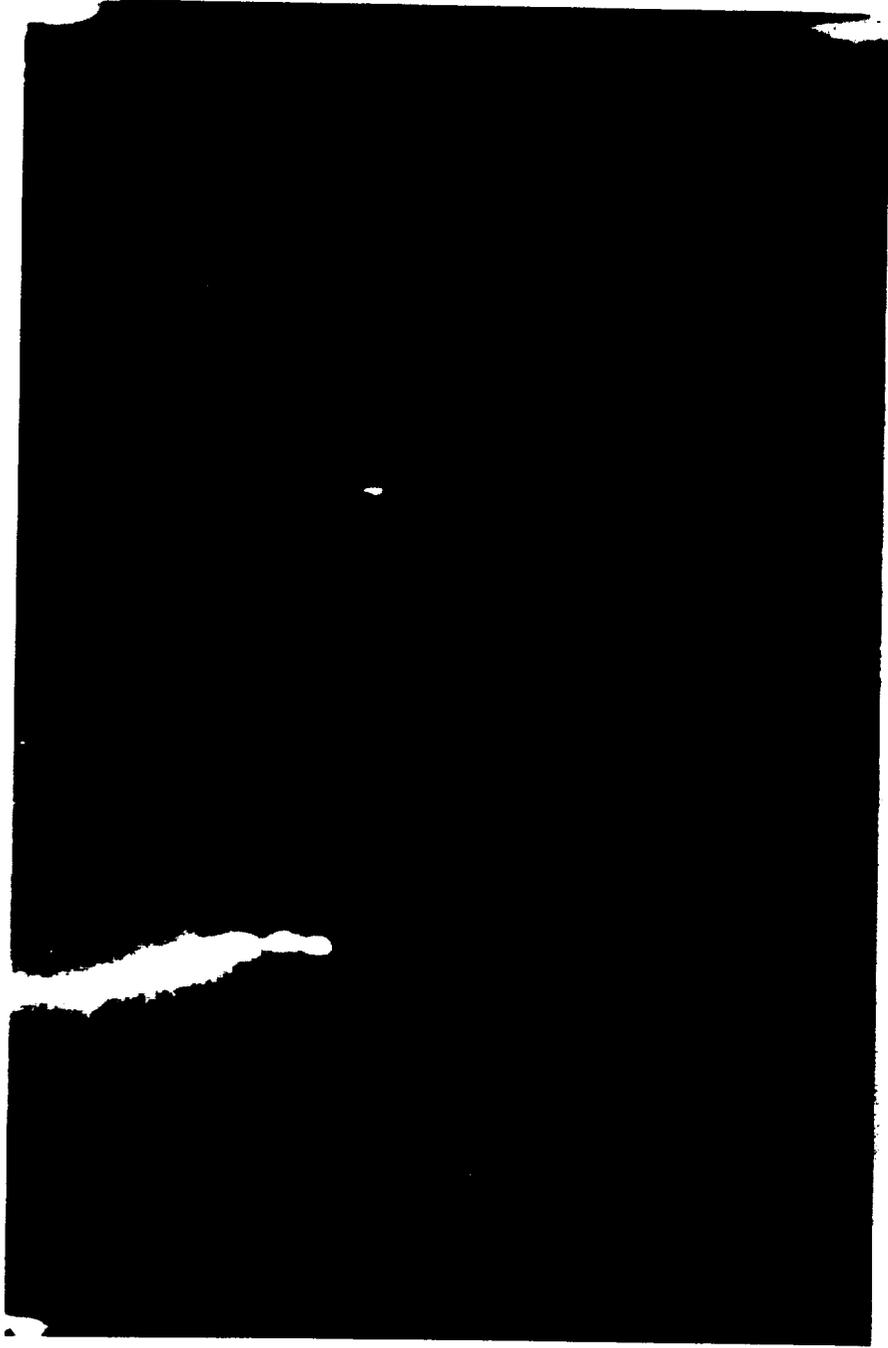
Note: See table I for camera details.

(a) Camera E-100.

Figure 3. - Additional photographic evidence of lightning discharge.

(b) Camera E-102.

Note: See table I for camera details.

Note: See table I for camera details.

(c) Nevada all-sky camera.

Figure 3.- Concluded.
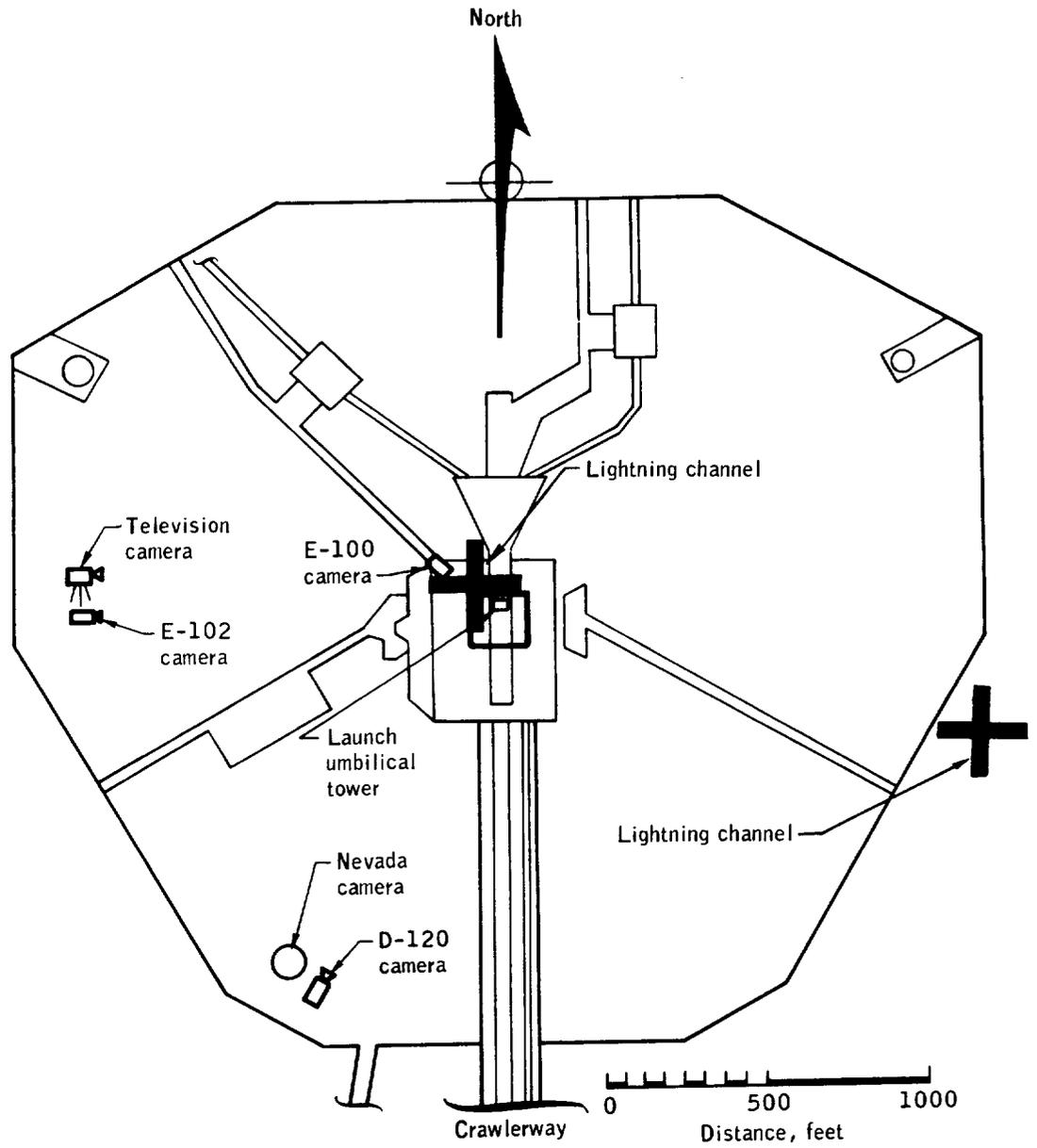
Figure 4.- Camera locations and lightning channels on launch complex 39A.

ATMOSPHERIC ENVIRONMENT

On November 13, the day before the Apollo 12 launch, an intense low-pressure trough in the upper atmosphere had evolved over the east central United States from the Great Lakes down the Mississippi Valley into the Gulf of Mexico. A surface cold front related to this upper air circulation extended from the Atlantic, just west of Bermuda, across northern Florida and westward along the Gulf Coast. A broad band of cloudiness and precipitation, punctuated by numerous thunderstorms, spanned the central part of Florida from the east coast far out into the Gulf of Mexico and lay over the launch area during the afternoon and evening. A weak low-pressure wave, traveling eastward along the cold front, traversed the northern part of Florida during the day and retarded the southward movement of the front.

During the night of November 13, the band of inclement weather pushed southward into Florida, however, thunderstorms had ended in the launch area early in the evening. No precipitation or weather of consequence identified the front, either by visual observation or by radar, and although clouds covered all of the state between the band of intense thunderstorms and the frontal area, only scattered light showers occurred during the early morning hours of November 14. However, soon after daybreak, a nearly solid line of precipitation echoes appeared on radar displays, providing positive identification of the cold front activity.

At the time of launch (11:22 a.m. e.s.t.), the cold front was passing through the Kennedy Space Center. Radar echoes extended across Florida from northeast of the Cape Kennedy area and averaged 20 miles in width, although in places the band of echoes was 30 miles wide. Tops of the cumulus congestus clouds reached a maximum of 23 000 feet within a range of 30 miles, according to radar operators' reports. Winds aloft were southwest or west-southwest from 3000 to 50 000 feet, and speed ranged from 36 knots at 3000 feet to a maximum of 90 knots at 47 000 feet. The general weather conditions in the vicinity of the launch complex were highly variable with clouds reported between 800 and 1500 feet and the overcast between about 2000 and 10 000 feet. There were light rainshowers with southwest winds. Detail weather conditions in the area are shown in table II. Less than an hour after launch, the precipitation had ended in the launch complex area and the skies were clearing as the cold front moved southeastwardly during the remainder of the day. The frontal location 4 hours prior to launch is shown in figure 5.

After lift-off, the vehicle was observed until it was obscured by the low cloud ceiling. An electrical discharge to the launch complex was observed about 36.5 seconds after lift-off. At that time, and again at 52 seconds, sferics equipment indicated discharges as the space vehicle

TABLE II.- WEATHER CONDITIONS AT LIFT-OFF

Station	Air Force - Cape Kennedy	KSC - Manned Spacecraft Operations Building	Air Force - KSC Mila Substation
Location with respect to launch complex 39A	10 miles south-southeast	6 1/2 miles southwest	5 miles west
Clouds	1 500 ft scattered E 7 000 ft broken 11 000 ft broken higher overcast	800 ft broken 4 000 ft broken 10 000 ft overcast	E 2 100 ft overcast
Visibility	8 miles - light rain-showers	7 miles - rainshowers	4 miles - rainshowers
Winds	12 knots, gusts to 19 knots from 200°		5 knots from 290°
Temperature	70.7° F	69° F	68° F
Dew point	66.4° F	64° F	65° F
Pressure	1005.4 mb		1008.1 mb
Relative humidity		84 percent	92 percent

Note: Additional meterological data

Launch complex 39A winds at lift-off
60 foot reference level — 13.3 knots from 280°
530 foot reference level — 14.5 knots from 265°

Freezing level
2 3/4 hours after lift-off: 12 382 feet
16 hours prior to lift-off: 12 428 feet

Cloud top observations
Aircraft and radar reports for tops in Cape Kennedy area ranged from 18 000 to 23 000 feet

was ascending through the clouds. No lightning had been observed prior to lift-off nor was any lightning visually observed after the 36.5-second incident. The lightning was recorded on film and is discussed in the lightning photography section of this report. At 36.5 seconds, the vehicle was at about 6400 feet, and at 52 seconds the vehicle was at about 14 400 feet.

Traces of the potential gradient measurements taken by eight radioactive devices (fig. 6) during the final countdown period are shown in figure 7. The instrumentation description is given in Appendix A. The traces in figure 7 show a variability in frequency and magnitude of the potential gradient at the point of measurement and are indicative of rapidly and highly fluctuating electric fields above the launch complex area. It should be noted that the devices are calibrated in the laboratory. No additional corrections, such as for wind or exposure, have been applied to the data. The tabulated potential gradient readings were as follows:

Site no.	Indicated potential gradient at lift-off	Potential gradient range, (11:00 to 11:22 a.m. e.s.t.)
1	0	+3 — 0
2	+5	+6 — -15
3	-3	-1 — -5
4	0	0 — -3
5	+5	+5 — -9
6	-1	0
7	0	0 — -3
8	+1	+6 — -11
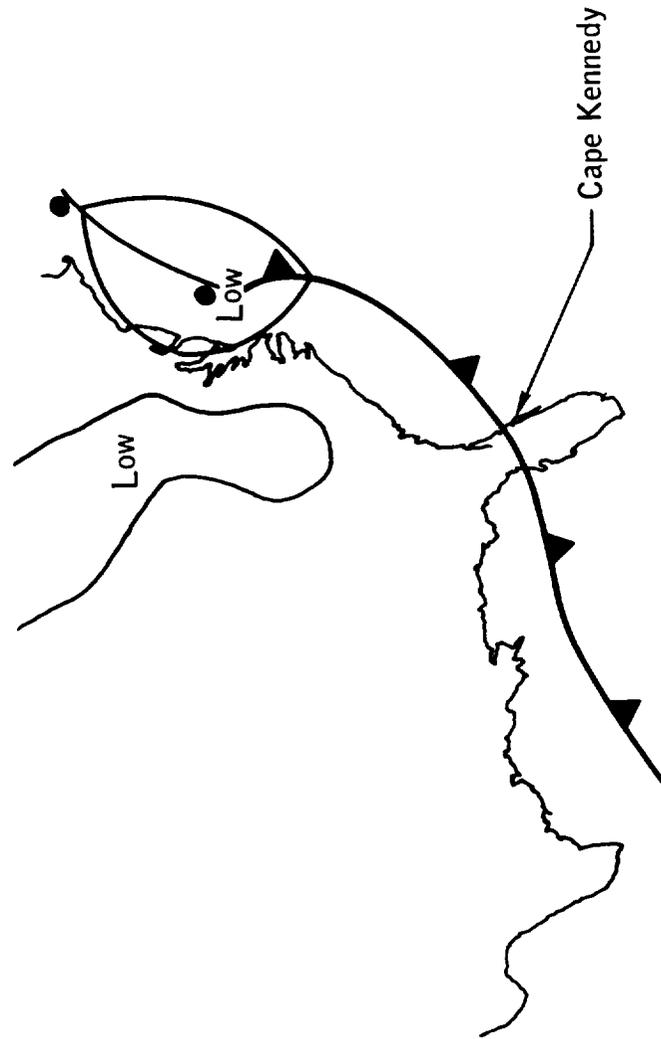
Figure 5.- Frontal location four hours prior to launch.
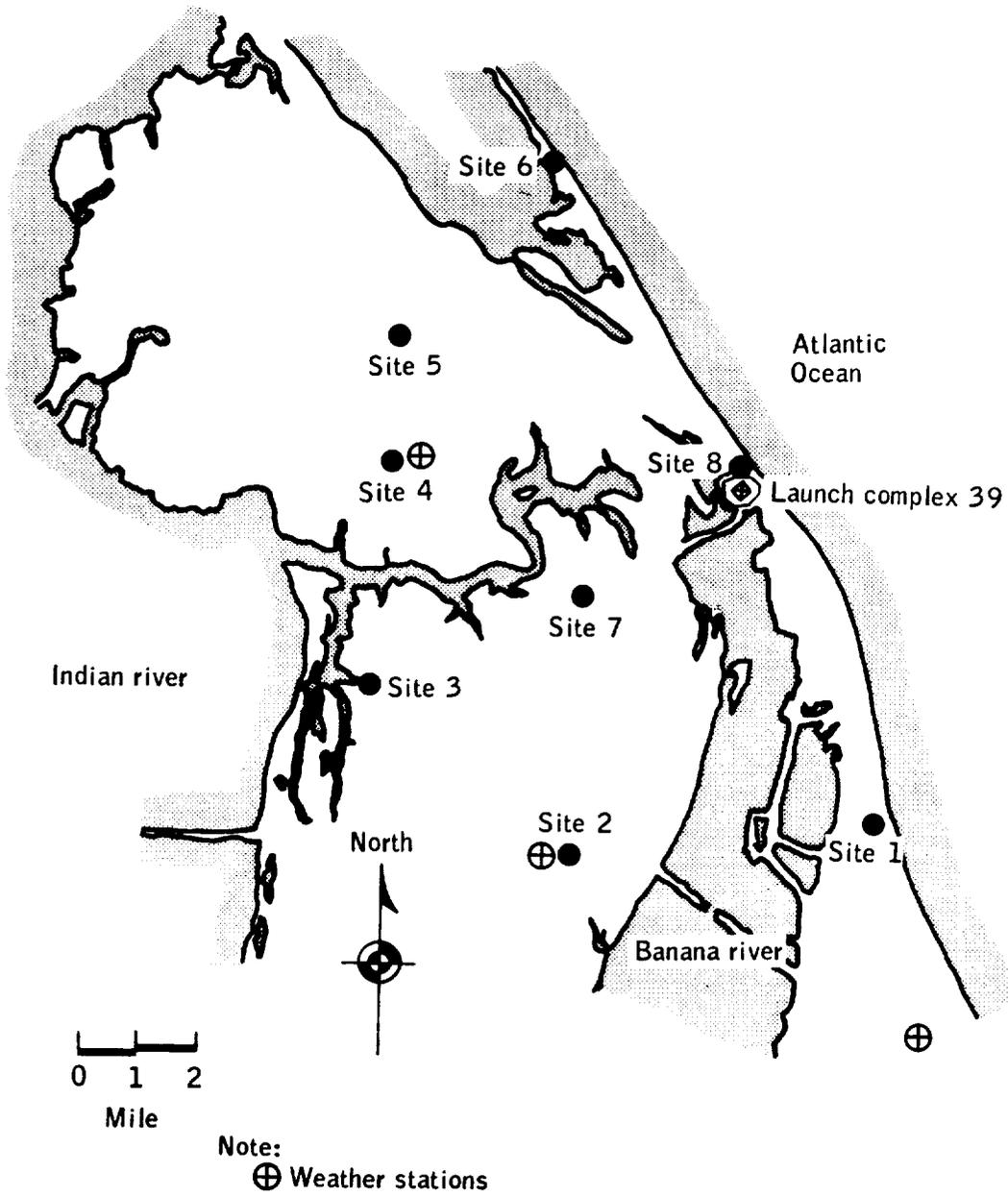
Figure 6.- Location sites for lightning instrumentation.

Figure 7. - Potential gradient recordings during launch day.
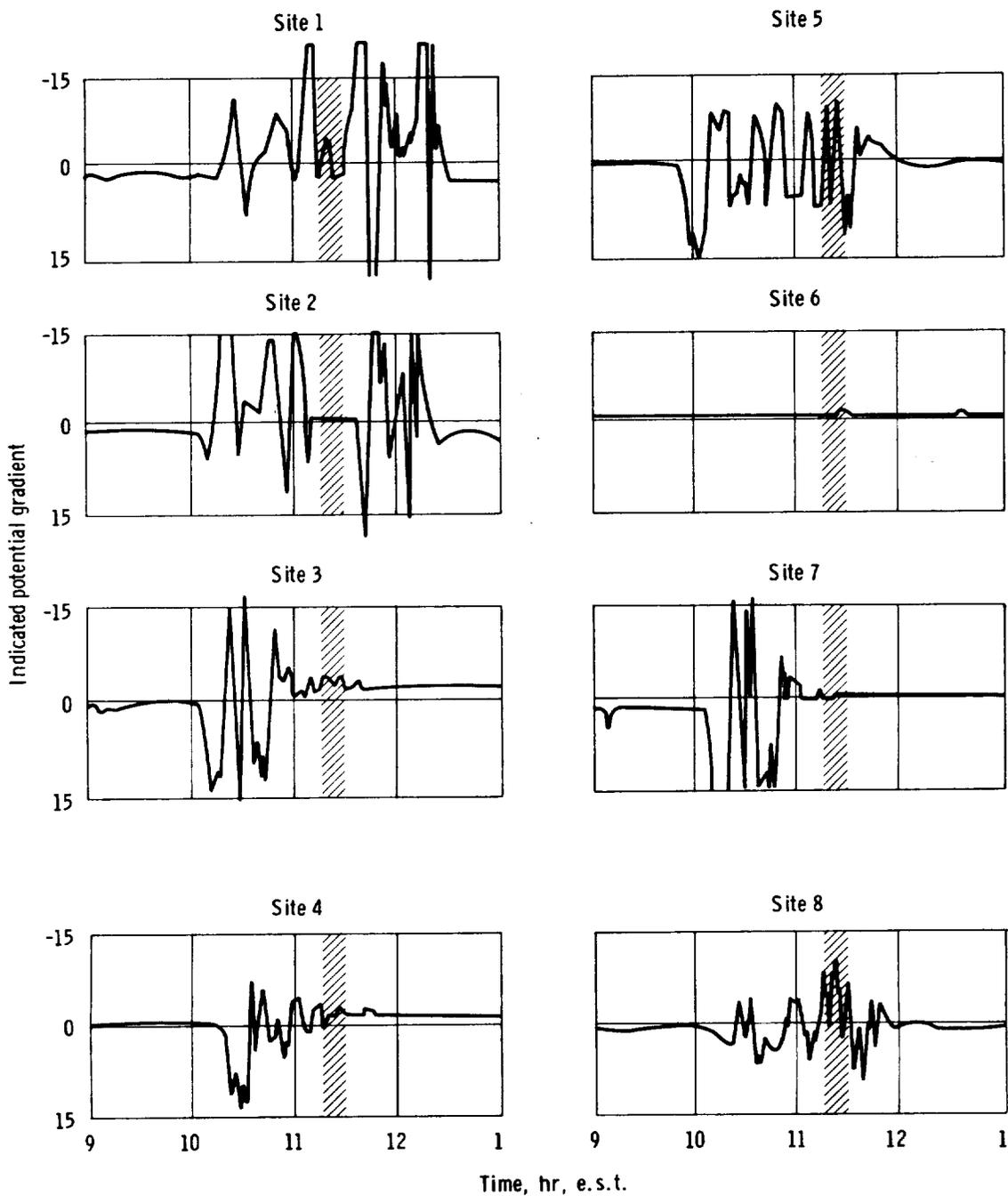
Note: These data show trends of the potential gradient during launch day.

Time of launch; width of band indicates time uncertainty of the trace.

EFFECTS ON SPACE VEHICLE

Spacecraft

There were many spacecraft indications of effects from the discharge at 36.5 seconds. Also, at about 52 seconds, similar types of indications were noted but to a lesser degree. Most of the effects were temporary except for the permanent damage sustained by nine data measurements. None of the conditions, including the loss of measurement parameters, had any impact on the overall operation of the mission.

The many temporary conditions included momentary interruption of communications, disturbances on instrumentation measurements, illumination of many warning lights and alarms in the crew compartment, disconnection of the three fuel cells from the buses, loss of attitude reference (tumbling) by the inertial platform, and disturbances to the timing system and clocks. Some of the more significant spacecraft effects will be discussed to permit an understanding of the mechanism which enabled the electrical discharge to affect the systems.

Fuel cells.- At about 36.5 seconds, the fuel cells were abruptly and automatically disconnected from the spacecraft power buses, with the resultant alarms normally associated with total fuel cell disconnection. The basic elements that are typical for each of the three fuel cells associated with the automatic fuel cell disconnection circuitry and switches are shown in figure 8. Automatic disconnection of the fuel cells takes place when sufficient current flows through the shunt. If the current exceeds a certain value, the integrating circuit within the disconnect circuitry will gate ON the silicon controlled rectifier. For example, if 300 amperes were applied through the shunt, the integrating circuit would require between 1 and 3 seconds to reach the threshold of the circuit and gate ON the silicon controlled rectifier. Once the rectifier is gated ON, current will flow from the bus to the motor-driven switch, which requires 0.1 second to disconnect the fuel cells from the bus. The likelihood of a high current flow through the shunt causing the disconnect can be ruled out for several reasons but primarily because the fuel cells simply cannot supply the energy levels required by the integrating circuit to gate ON the silicon controlled rectifier in a time frame of milliseconds.

A silicon controlled rectifier has the characteristic of being sensitive to the rate of voltage change (dV/dt) on the anode (power side). The rectifiers in the disconnect circuit will gate ON without a gating signal if 500 V/microsecond is imposed on the anode or if the anode voltage exceeds 200 volts. The rate of voltage rise for a lightning discharge is consistent with the 500 V/microsecond value. If the turn on mechanism was due to exceeding 200 volts (breakover voltage) on the rectifier anode,
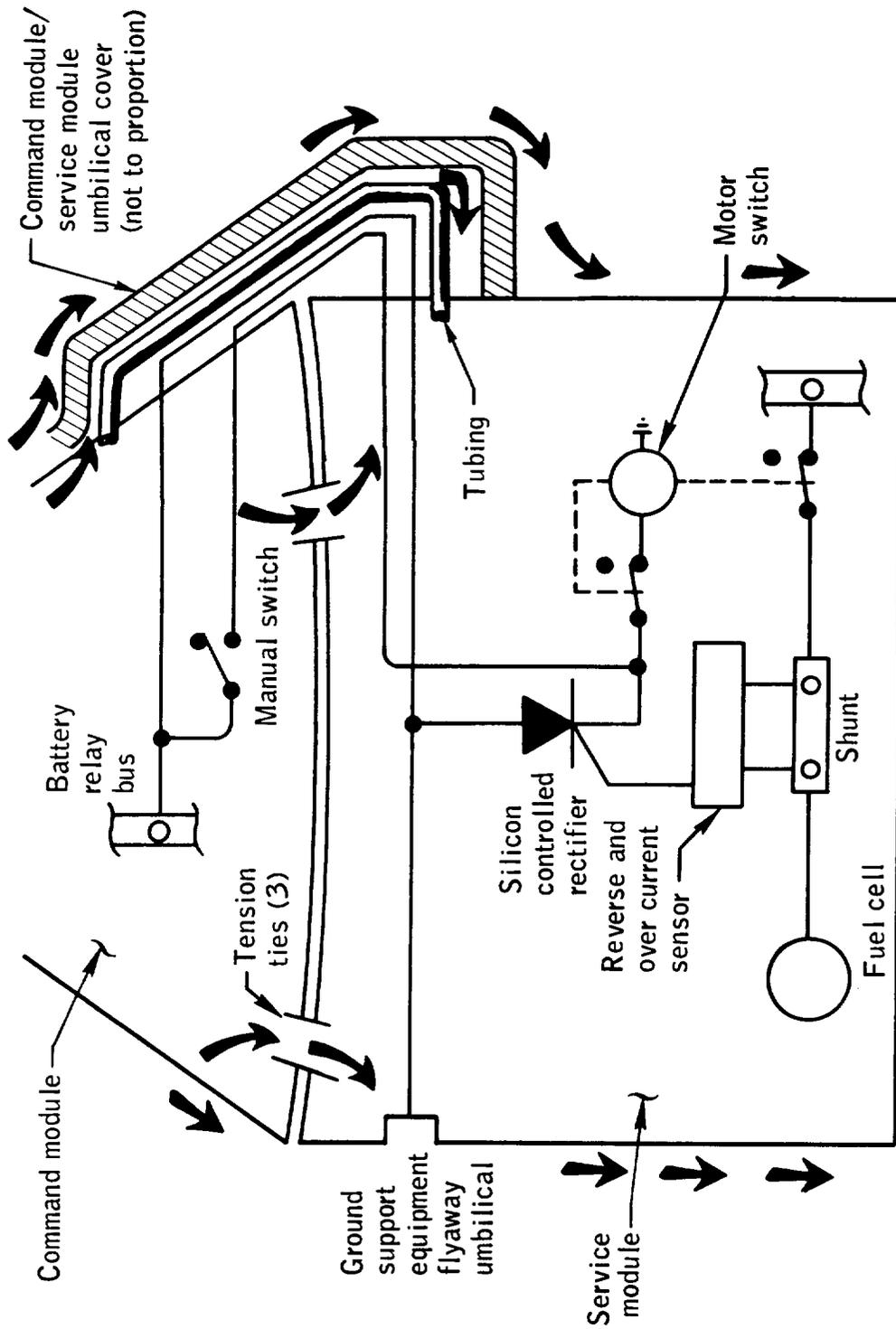
Figure 8.- Fuel cell disconnect circuitry.

it is likely that the rectifier would have been damaged. However, the rectifiers were not damaged as verified by the successful reconnection of fuel cells to the buses. This characteristic provides the suspected mechanism (as dV/dt) for initiating the fuel cell disconnects. Figure 8 shows two methods in which a high rate of potential change could have been imposed on the power line to the rectifier. The most likely method would be induction as a result of the discharge transient through the conducting path of the structure in the area of the umbilical cover. The other is a direct input through a wire connected to an exterior umbilical.

There was no indication of any damage to the disconnect system or to the fuel cells. The fuel cells were manually reconnected to the buses and operated properly for the remainder of the mission.

As a result of the fuel cell disconnection, the main bus load of 75 amperes was being supplied only by entry batteries A and B, and the main-bus voltage dropped momentarily to approximately 18 or 19 volts but recovered to 23 or 24 volts within a few milliseconds. The low dc voltage on the main buses resulted in the illumination of the undervoltage warning lights, dropout of the signal conditioning equipment, and a lower voltage input to the inverters. The momentary low voltage input to the inverters tripped the ac undervoltage sensor and caused the ac bus 1 fail light to illuminate. The transient that affected the silicon controlled rectifiers in the fuel cell disconnect circuitry also affected the silicon controlled rectifiers in the ac overload circuits in the same manner. This further substantiates the method by which the lightning affected the systems.

Instrumentation.- The nine sensors which failed consisted of five thermocouples and four pressure/temperature transducers. These devices are all located in the same general plane of the service module. Four of the thermocouples which failed were mounted on the exterior skin of the service module and were to be used to determine the relative sun angle; however, these are not required for mission success as alternate methods of determining sun angle are available. The diodes and resistors in the bridge circuits within these thermocouples can be overstressed by potentials as low as 100 volts. The thermocouple locations expose the circuit directly to the discharge, and the lack of shielding makes the system highly susceptible to induction. The fifth failure was a thermal measurement located on the nuclear particle analyzer, which is of the same design as the four thermocouples discussed previously.

The remaining four sensors which failed were used to measure propellant quantities in the service module reaction control system. These sensors detect pressure and temperature through a semiconductor strain gage mounted on a pressure-sensing diaphragm on each of the four propellant tanks. In addition to the diodes and resistors which can be affected by potentials, the gage itself is very sensitive to current, particularly

because of the 1-mil wire attached to the semiconductors. Alternate means of determining propellant quantity were available; therefore, these failures had no effect on the mission.

After the discharge at 36.5 seconds the computer data showed that the computer register containing the coupling display unit X-axis and Y-axis readouts changed. The coupling display unit provides the computer with the inertial measurement unit gimbal angles, in digital form. Since the gimbal angles did not change, the most likely cause was the coupling display unit circuitry, which is inherently sensitive to low-voltage transients between chassis and signal ground. These conditions have been experienced previously in ground tests. The computer data also indicated that five computer restarts had taken place. These were most probably caused by the voltage drop when the fuel cells disconnected from the bus. Fail alarms noted in the fail register were caused by the coupling display unit activity.

Guidance system.- The 52-second discharge also affected the guidance system. When data were recovered several seconds after the discharge, the inertial measurement unit gimbals were driving at approximately 35 deg/sec, indicating the platform had tumbled. Also, a number of bits in the computer channels had been set, and all were associated with gimbal lock, coarse align, loss of attitude, etc.

The most likely cause of the tumbling condition was the setting of high-order bits in the coupling display unit as a result of the voltage transients introduced into the circuits. At 52 seconds, however, the Z-axis coupling display unit (middle gimbal) was also affected such that the readout exceeded 85 degrees. At 85 degrees the computer, sensing impending gimbal lock, will automatically change the platform to the coarse align mode. Under these conditions, the inertial measurement unit/coupling display unit servo loop becomes unstable and continuously drives the gimbals.

A simplified functional diagram of the system is shown in figure 9. In the launch configuration, switch 3 is closed and the computer receives gimbal angle data from the coupling display unit. These data are compared to the planned launch trajectory, and the angle differences are displayed to the crew through the coupling display unit error counter. Switches 1 and 2 are open for launch, but are closed when the computer enters the coarse align mode. Normally in this mode, the computer supplies the angle data that the coupling display unit error loop must null by driving the gimbals, but the coupling display unit will not affect the angles requested by the computer. However, when switch 3 is closed (launch configuration) and switch 1 and 2 are also closed, a condition exists in which the computer-requested gimbal angles will continuously be changed by the readout so that the error loop cannot be nulled. If there is a large difference

Analog
gimbal
angles

Digital
gimbal
angles

Inertial
measurement
unit

Coupling display
unit readout
counter

3

Desired
angle

1

Gimbal
torquing
signal

2

Coupling display
unit error
counter

To attitude
error display

Gimbal
alignment
angle
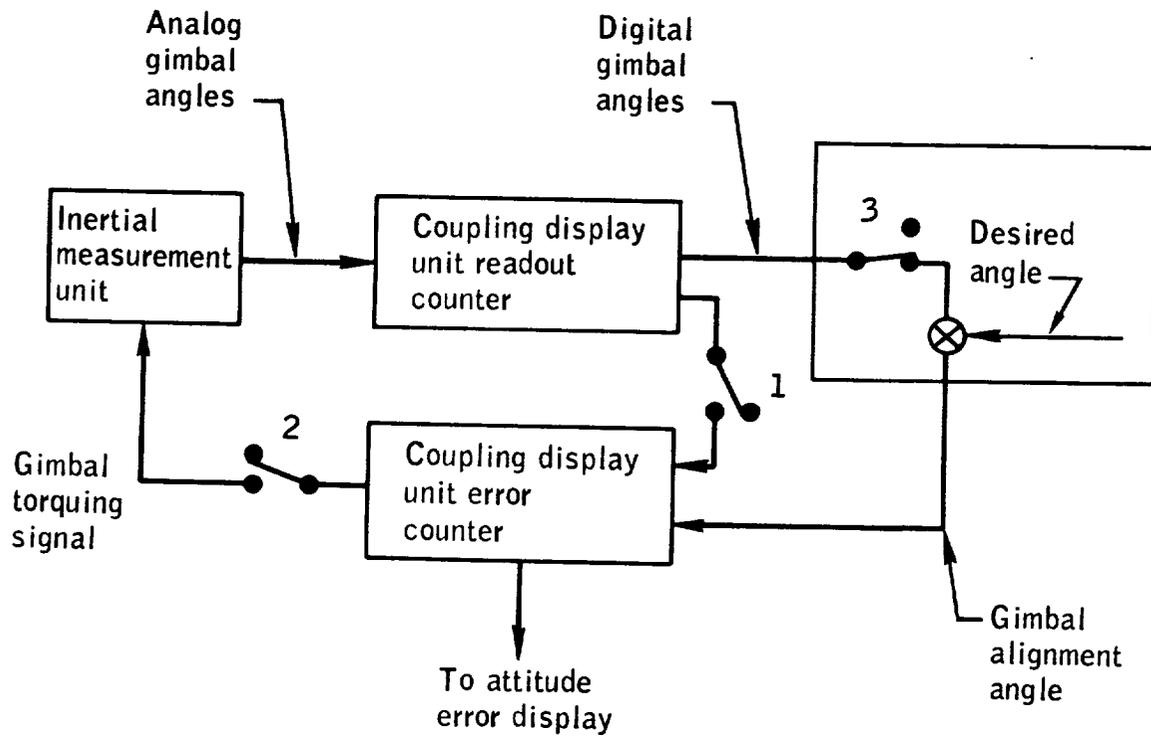
Figure 9.- Simplified functional diagram of the computer/
inertial measurement unit interface.

between the coupling display unit and platform angle when entering coarse align, regardless of the computer output, the platform will become unstable. This condition has been demonstrated in a bench test of the system simulating the observed conditions.

The lunar module instrumentation system does not operate during launch, consequently any transient effects on that vehicle would be unknown. Permanent effects may be detectable when the instrumentation system is activated later in the flight. However, because of the lunar module location inside the adapter, no effects would have been expected. In any event, the checkout of the lunar module enroute to the moon, as well as the normal operation of all systems during the mission indicated no systems had been affected.

Launch Vehicle

From initial quick-look data, the only effects on the launch vehicle were minor disturbances on three continuous channel piezoelectric vibration measurements at about 36.5 seconds. A detailed investigation of the data, conducted until 21 days after launch, showed 109 of 1477 measurements indicating transient disturbances during the 36.5-second discharge period. No measurements were lost in the launch vehicle as a result of the lightning strike.

Launch vehicle data system indications.- Launch vehicle telemetered data were examined in detail in the 36.5-second and 52-second time periods to determine the effects that could be attributed to lightning or a static discharge. Forty-five measurements in the instrument unit experienced a disturbance in the 36.5-second time period. S-IVB data systems experienced disturbances at this time on all 15 single sideband telemetry channels and on 45 pulse code modulated data samples. Three piezoelectric vibration measurements on the S-II stage were also affected at this time with one disturbance noted on the S-IC. At 52 seconds, a disturbance was noted on one S-II piezoelectric vibration measurement. All of the disturbances noted were transients of variable amplitudes. No pattern was apparent either in geometrical location or in the magnitude of the disturbance other than most measurements affected were located on the upper two stages of the vehicle. There was no damage or subsequent data degradation noted. The nature and randomness of the transients are characteristic of effects caused by a massive external electrical disturbance.

The telemetered Q-ball output appeared normal throughout the entire active period of flight; however, the telemetered measurements of the Q-ball did not agree with launch wind profile information. A simple laboratory test is being considered to determine whether a high electric field could contribute to an error in the output from the Q-ball transducers.

Launch vehicle data adapter/digital computer indications.- Two deviations were observed by the launch vehicle digital computer during the initial boost phase of flight at approximately 36 seconds. The Z (downrange) accelerometer A and B counters disagreed and the Y (pitch) gimbal reading failed a reasonableness test at this time.

At 36.6 seconds, the pitch gimbal crossover detection counter reading changed 2.8 degrees over one minor loop computation cycle time (40 milliseconds). This value exceeded the reasonableness test value of 0.4 degree and was properly rejected by the computer. The computer utilized the previous gimbal angle reading, and returned to normal gimbal angle processing. Subsequent readings were reasonable.

At 37.01 seconds, the A and B counters of the Z (downrange) accelerometer differed by nine counts (0.45 meters per second). Both counters were reasonable, but the B counter was closer to the established force to mass ratio profile. The launch vehicle digital computer flight program accelerometer error processing properly selected the B reading.

The computer operated normally by going into the alternate mode of operation when the deviations were noted in the signals from the platform. The redundant signals were within the required tolerances and the computer transferred back into its normal mode of operation with no change in the operation of the flight program. The guidance errors which were observed just prior to the vehicle orbiting the earth do not appear to be correlated with the pitch gimbal reasonableness test failure or the downrange accelerometer counter disagreement which occurred at the time of the lightning phenomena.

These deviations have been closely correlated with an electrical impulse that passed from the top of the vehicle through all stages, 36.5 seconds after lift-off.

Launch Complex

A complete investigation showed no ground support equipment abnormalities which could be attributed to the lightning discharge.

CAUSE OF DISCHARGES

There is general agreement in the scientific community involved with atmospheric electricity that the Apollo 12 lightning discharges at 36.5 and 52 seconds were triggered by the presence of the Apollo 12 vehicle. One other suggestion which has been discounted, is worthy of discussion and that is, as the vehicle ascended, it generated sufficient static electricity to produce a discharge.

The discussion that follows has been extracted from analyses performed by several authorities in atmospheric electricity. A specific detailed analysis is contained in Appendix B.

Electrostatic Discharge Theory

An estimate of the amount of energy expended in the discharge channels observed at 36.5 seconds can be compared with that which might be produced by static electrification of the space vehicle. Photographs show that the channels to the ground at 36.5 seconds have the appearance of normal lightning. The intensity of light from the channels is comparable to that of natural lightning. A lightning detector 8 miles from the launch complex and an electric field detector 11 miles from the complex both recorded signals similar to those of natural lightning. The assumption can then be made that the energy of the discharge must have been characteristic of natural lightning, which is in the range 10^5 to 10^6 joules per meter of channel length and corresponds to a total energy of at least 10^8 joules. If this energy was supplied by static electrical charge accumulated on the vehicle, the energy would be $0.5\ Q^2/C$, where C is the capacitance and Q is the charge on the vehicle. At 6400 feet, the capacitance of the vehicle depends on the electrical length and diameter assumed for the exhaust plume. The length of the vehicle is 364 feet. If it is assumed that the electrically conducting exhaust plume broadens to 50 feet and is up to 5 times the length of the vehicle, the vehicle will behave electrically like an ellipsoid with a 50-foot minor axis and a 1900-foot major axis. The capacitance of this object for this exhaust plume length is about 10^4 picofarads.

Corona discharge limits the field strength at the vehicle surface to about 2×10^6 V/m. Then, the maximum charge which can accumulate on the vehicle is about 10^{-2} coulombs. The corresponding electrostatic energy is no more than 10^4 joules, which is 4 orders of magnitude less than the energy observed. For this reason, static electrification cannot be considered the source of the discharge at 36.5 seconds.

Vehicle-Triggered Lightning Theory

In order for the vehicle to trigger a lightning discharge, electrified clouds are required. Just prior to the launch of Apollo 12, the available instruments did not show any lightning activity in the area; however, the electric field meters showed the existence of electric charges in the clouds overhead (fig. 7). These clouds extended from about 1000 feet to above 20 000 feet, and rain was falling from them. The zero-degree isotherm was at an altitude of about 12 400 feet, so that ice was forming in the clouds. Rain and ice formation are nearly always associated with strong electrification of clouds. Thus, while the space vehicle was not launched into an active thunderstorm, it was launched into clouds which contained significant amounts of electric charge. The electric field meters showed (fig. 7) an oscillatory pattern, indicating that electric charges in the clouds were distributed in a complex way.

A space vehicle can initiate lightning from an electrified cloud because of its effect on the electric field lines in the atmosphere. The space vehicle is an excellent electrical conductor which may be effectively extended by the presence of the exhaust plume. The launch of such a vehicle has the effect of suddenly introducing a long electrical conduction path into the atmosphere where no such path existed before. This, in turn, produces a distortion in the electric field equipotential lines such that the electric field or potential gradient is greatly increased at the top of the vehicle and below the exhaust plume. At the top of the vehicle, the field may be increased by a factor of several hundred as illustrated in figure 10.

When the enhanced electric field becomes sufficiently large (about 3×10^6 V/m for air at sea level, less at high altitudes), electrical breakdown will occur and may be propagated either up or down, or both ways. Following the initial breakdown, a discharge may develop in a manner similar to natural lightning.

There is ample experimental evidence that the rapid injection of a conductor into a region of high electric field processes can trigger lightning discharges. Newman (references 2, 3, and 4) has shown that lightning strokes may be triggered by firing a small rocket trailing a grounded wire into the base of thunderstorm clouds at sea. Another example is a lightning discharge triggered by a water plume from an underwater explosion. Lightning discharges to tall structures can also be induced by electrical breakdown at the top of the structure. The Apollo 12 discharge at 36.5 seconds probably propagated both ways from the vehicle. The direction of propagation near the ground was determined by the downward direction of branches which were photographed. The Apollo 12 discharge is similar to other induced lightning because of the rather long duration seen at the ground.
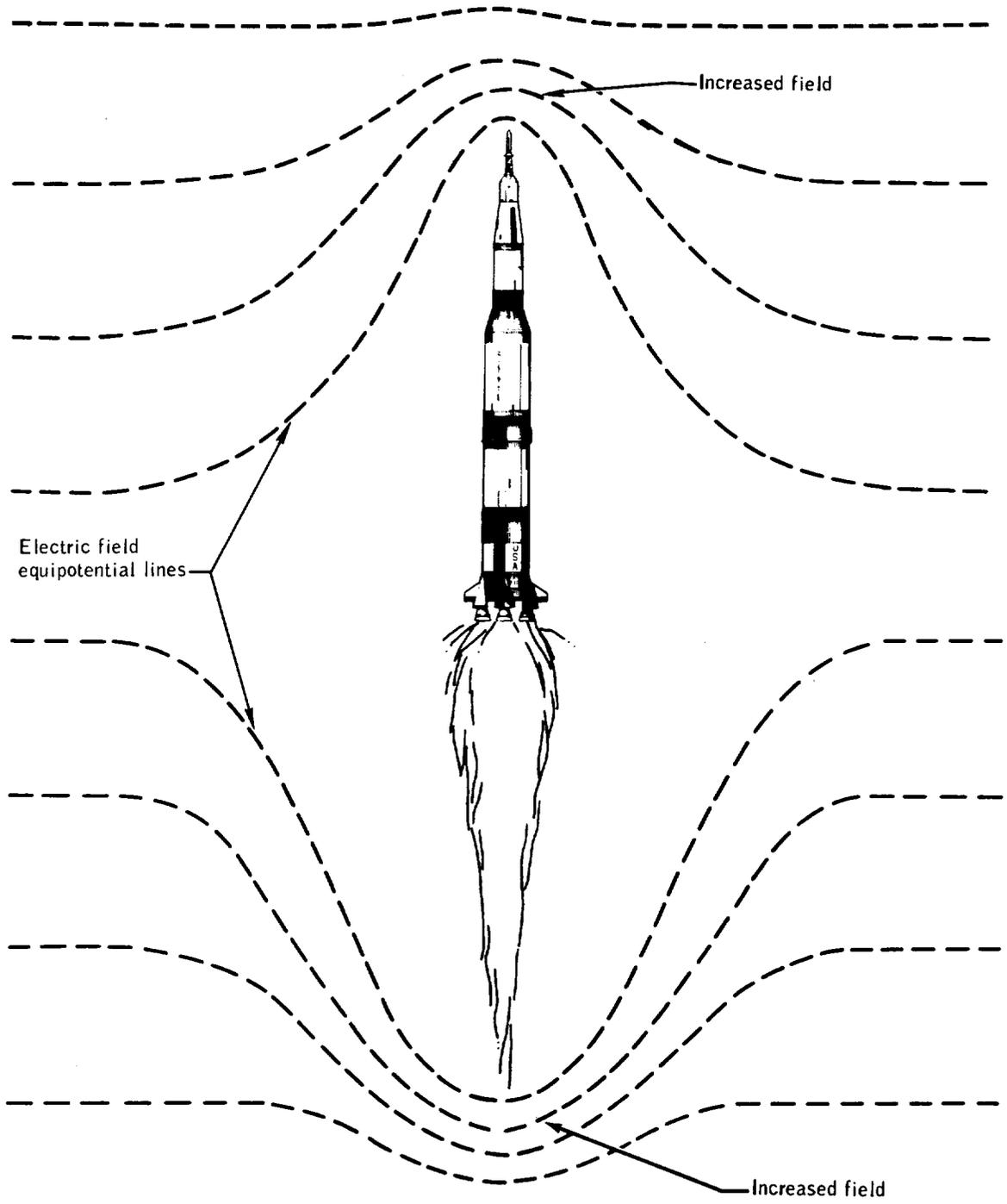
Figure 10.- Enhancement of electric fields at each end of the space vehicle.

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An indication of what might have been the discharge current at the vehicle is shown in figure 11. This estimate is based on the nature of the lightning recorded on film and on currents measured during other triggered discharges and natural lightning.
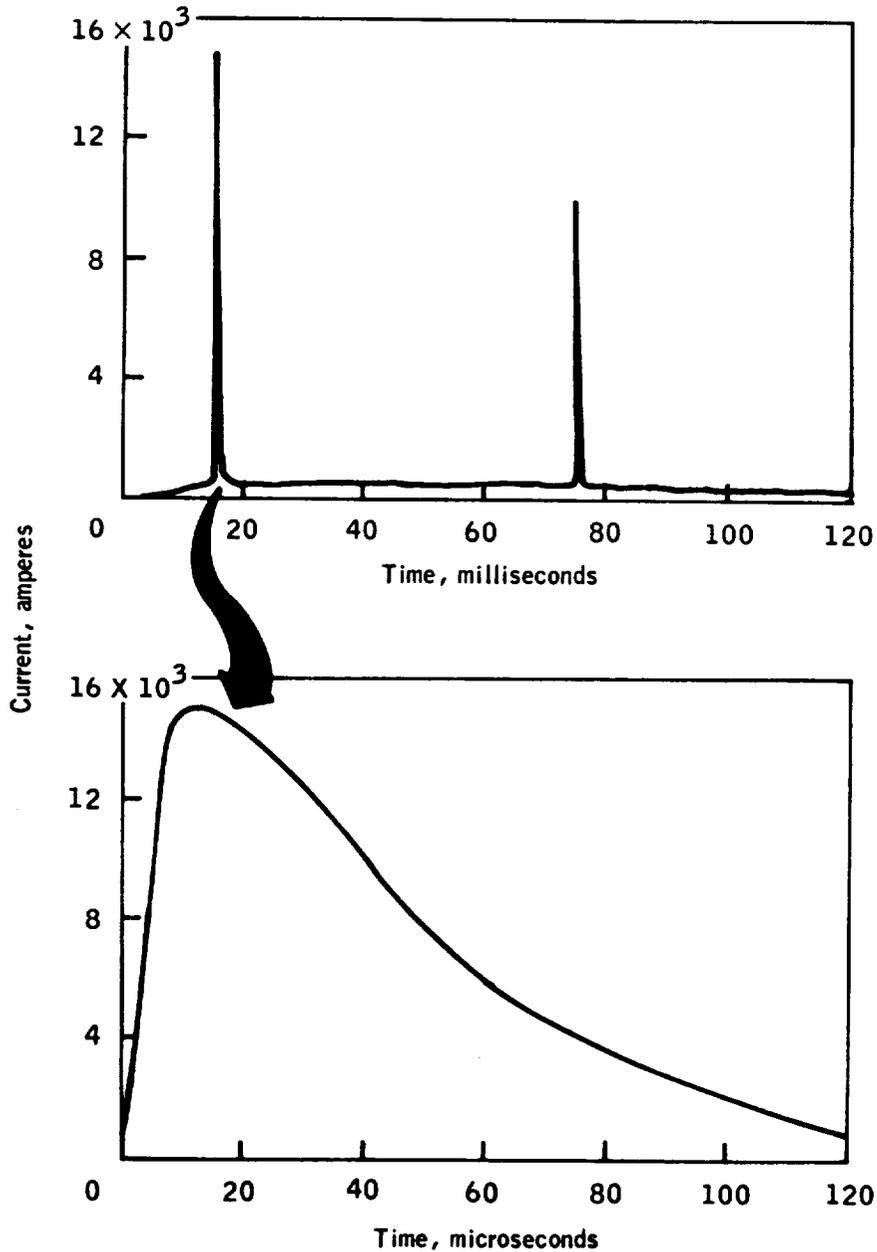
Figure 11.— Probable current characteristics of the discharge at 36.5 seconds seen at the space vehicle.

FLORIDA METEOROLOGICAL CONDITIONS ASSOCIATED
WITH ELECTRIFIED CLOUDS

Because of the high frequency of thunderstorm occurrence in the
Cape Kennedy area, a comprehensive review has been performed of typical
conditions associated with potentially dangerous electric fields. This
basic information was required prior to definition and evaluation of
realistic launch rules. The frequency of thunderstorm conditions in the
Eastern Test Range area is shown in figure 12 (see reference 5.)

Note: All values shown are in percent.
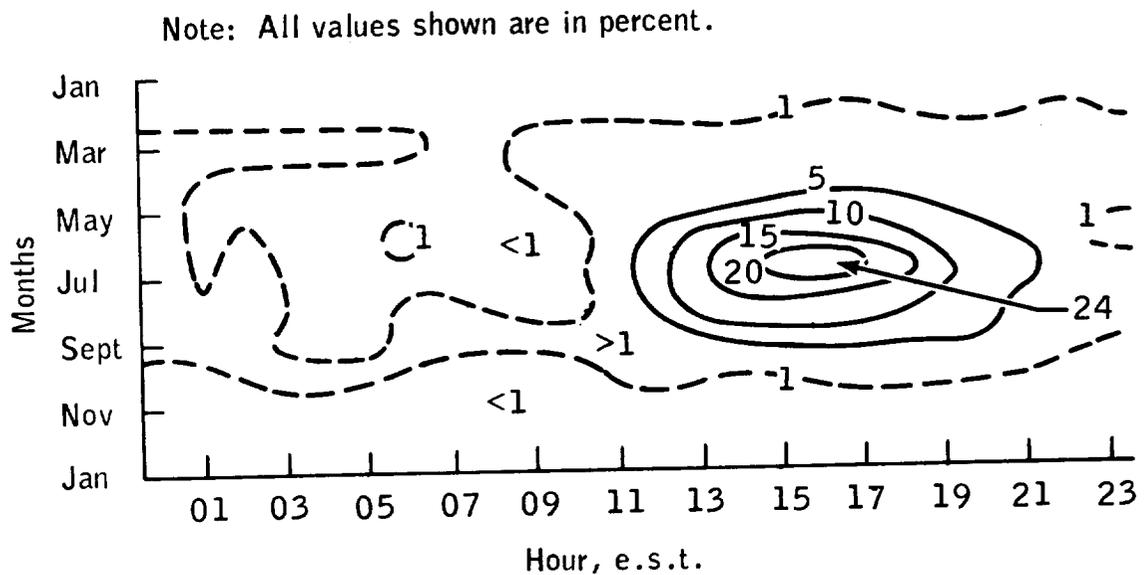
Figure 12.- Probability of thunderstorm occurrence by months plotted
against time of day in the Cape Kennedy area.

Any thunderstorm, regardless of the associated atmospheric condi-
tions, creates natural lightning situations. Even when thunderstorms
(either fully developed or decaying) are located outside the launch com-
plex area, the associated cloud anvil may create a hazard. On occasion,
lightning from such anvils has been observed traveling to ground outside
the cloud.

There are three other cloud conditions that may produce high electric fields. The first system of concern relates to the movement of cold fronts, or squall lines, without thunderstorms but producing rain or rain showers and extending vertically above 10 000 feet. As indicated by the Apollo 12 incident, such conditions can cause high potential gradients of such a magnitude that cloud discharges may take place when a man-made discharge path is introduced (reference 6). Such situations develop even when natural lightning phenomena would not normally occur nor be anticipated. While fronts through the Cape Kennedy area are often not active with respect to thunderstorms, during the period of November through March, about 4 to 6 fronts per month can be expected (about 80 percent cold fronts.)

Deep middle cloud layers, 6000 feet or more in thickness and with or without rain falling to the ground, is the second condition of concern. Such clouds would normally be based at least 8000 feet above ground. They are usually associated with large-scale cyclonic circulations and may extend outward several hundred miles from the circulation center. These conditions may or may not produce thunderstorms. Although the potential gradients may be quite high, natural lightning rarely occurs. However, cloud discharge may take place when a man-created discharge path is introduced.

The third system is quite common to the Cape Kennedy area and is associated with showers falling from cumulus clouds moving in from the ocean. Such clouds may have vertical developments of 10 000 to 25 000 feet with high electric fields.

In summary, several meteorological situations common to the Cape Kennedy area can create electrical hazards even though natural lightning may not exist.

Effects of Atmospheric Conditions on Launch Window

Certain meteorological phenomena are indicative of environmental conditions related to increased atmospheric electrical activity. To evaluate the occurrence of these conditions at Cape Kennedy, the past weather records were analyzed and the frequencies of occurrence of specific phenomena were determined. The results of this analysis are applied here to obtain an insight to the probability at each hour of conditions which are indicative of increased electrical activity in the atmosphere.

The analysis also includes determinations of conditions at hours subsequent to each unfavorable hour to determine the improved chances gained with the passage of time in a launch window.

Criteria

The criteria selected for this analysis which might be considered in establishing an unfavorable launch situation at Cape Kennedy are:

L_1 = wind ≥ 28 knots at 60-foot reference level

L_2 = thunderstorm with both a ceiling and precipitation

The criteria which also might be considered indicative of increased atmospheric electrical activity are:

L_3 = precipitation without a thunderstorm

L_4 = cumuliform type cloud ceiling ≤ 4000 feet except any ceiling ≤ 4000 feet is unfavorable if precipitation is reported.

Designation of the criteria as L is arbitrary. (See figure 13.)

A wind of ≥ 28 knots is designated for L_1 since it is approximately the same limitation used for previous Apollo launches.

Criterion L_2 is specified as shown based on the consideration that a thunderstorm not close enough to produce a ceiling or precipitation at the station is not indicative of a launch through a cumulonimbus clouds.

Criterion L_3 is established based on the premise that any precipitation must be considered indicative of increased electrical activity. The criterion excludes thunderstorm precipitation since this is included in criterion L_2.

The basis for criterion L_4 is that the occurrence of cumuliform (vertical motion) type clouds in sufficient quantity to produce a ceiling at the reporting point is indicative of increased electrical activity whether or not precipitation is occurring. A previous analysis, not included here, showed that the base of cumuliform clouds at Cape Kennedy was almost never above 4000 feet, hence 4000 feet was selected as the ceiling limitation. Criterion L_4 includes cases of ceiling 4000 feet with precipitation when cumuliform clouds are not reported since, as noted above, any reported precipitation is considered indicative of increased atmospheric electrical activity.

The intent of this analysis is to illustrate the degree of degradation in launch probability with the addition of further atmospheric constraints. The constraint of no flight through a thunderstorm when added to the current Apollo launch ground wind constraint does not significantly influence the fall, winter, and spring launch probabilities. The primary influence of thunderstorms on launches occurs during the summer months.

However, a constraint for no launch during rain (which is a strong indicator of high potential gradients in the clouds) adds two to four percent to the delay probability. This may not be critical depending upon launch window. When consideration is given to the launch window, the launch delay probabilities are reduced as the length of the launch window increases; for example, the delay probability becomes about one-half that shown in figure 13 for a 3-hour launch window.
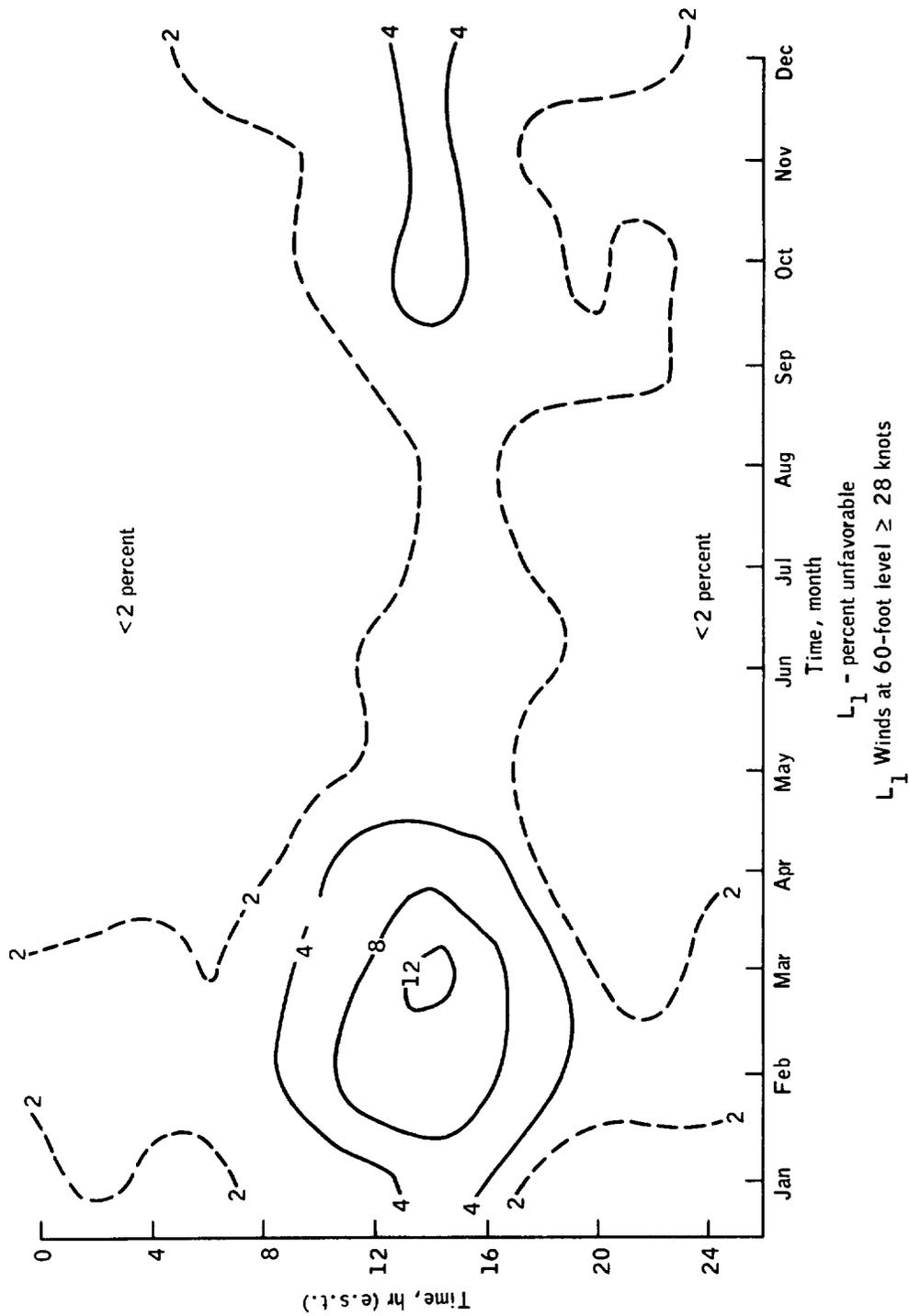
Figure 13.- Probability of weather conditions affecting launch.

(a) Effect of winds only.

L_1 - percent unfavorable
L_1 Winds at 60-foot level $\geq$ 28 knots

Time, month

34

L_1UL_2 - percent unfavorable
L_1 Winds at 60-foot level $\geq$ 28 knots
L_2 Thunderstorm with both ceiling and precipitation
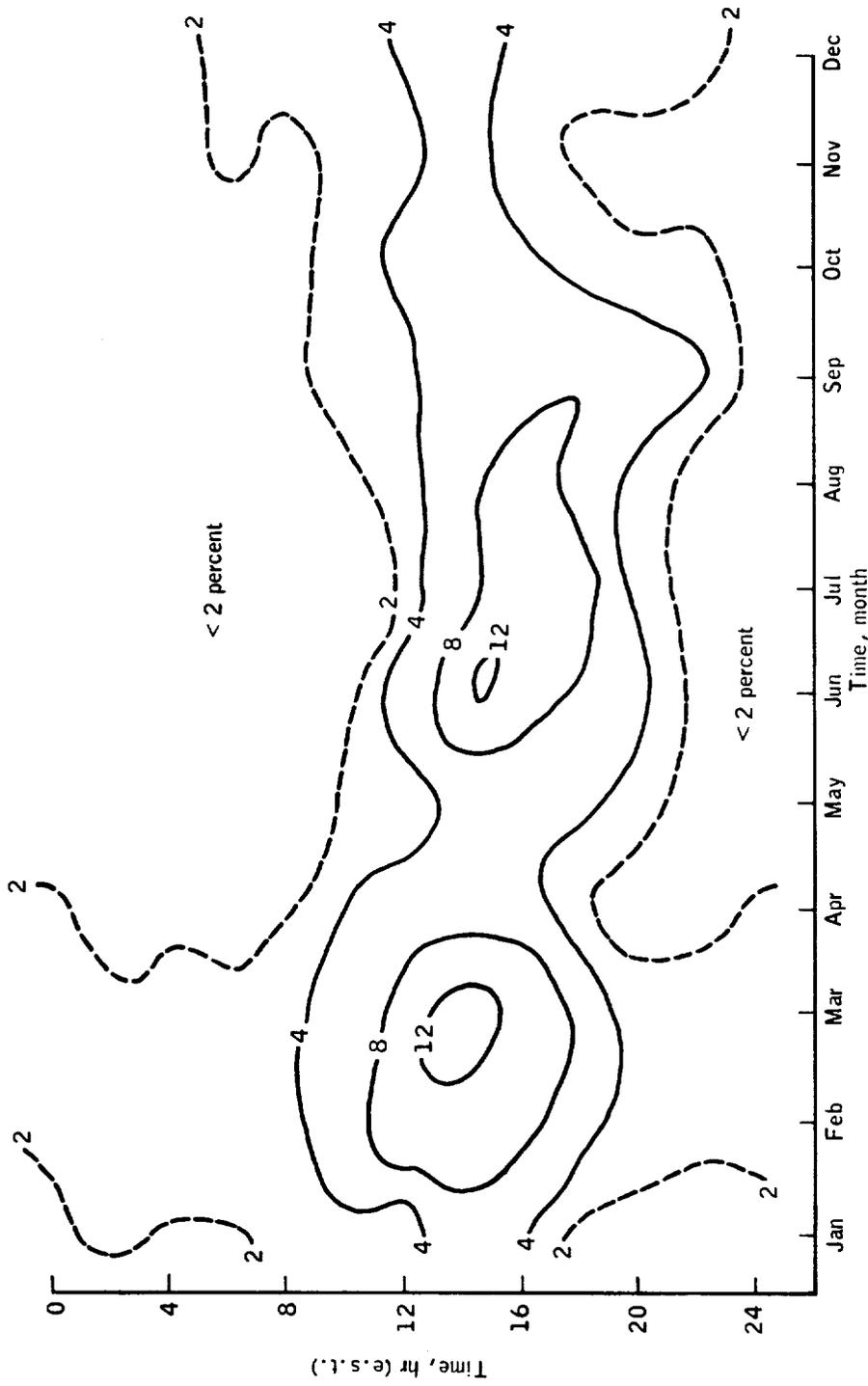
(b) Winds and thunderstorms.

Figure 13.- Continued.

$L_1UL_2UL_3$ – percent unfavorable

L_1 Winds at 60-foot level $\geq$ 28 knots

L_2 Thunderstorm with both ceiling and precipitation

L_3 Precipitation without thunderstorms

(c) Winds, thunderstorms, and all precipitation.
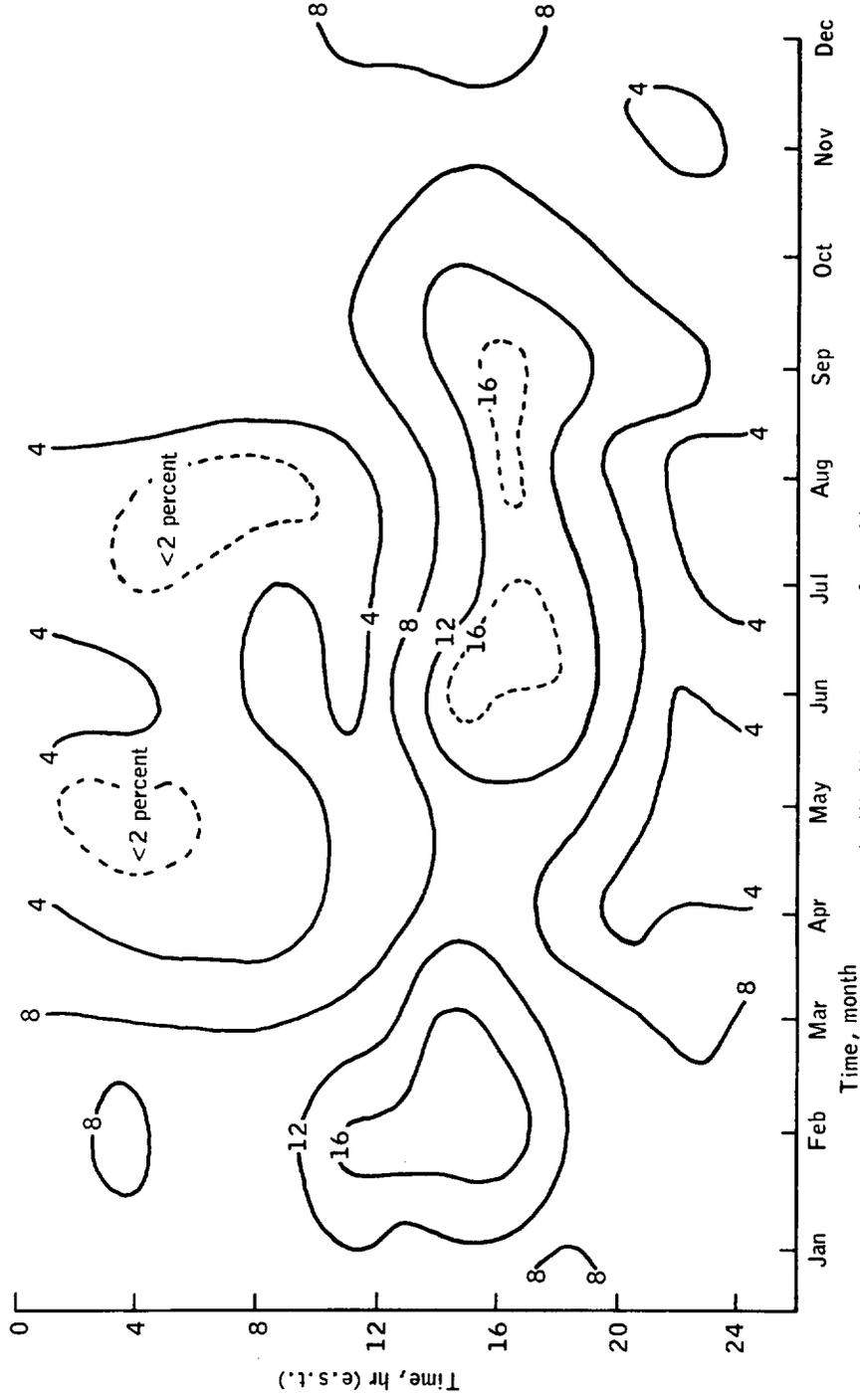
Figure 13.– Continued.
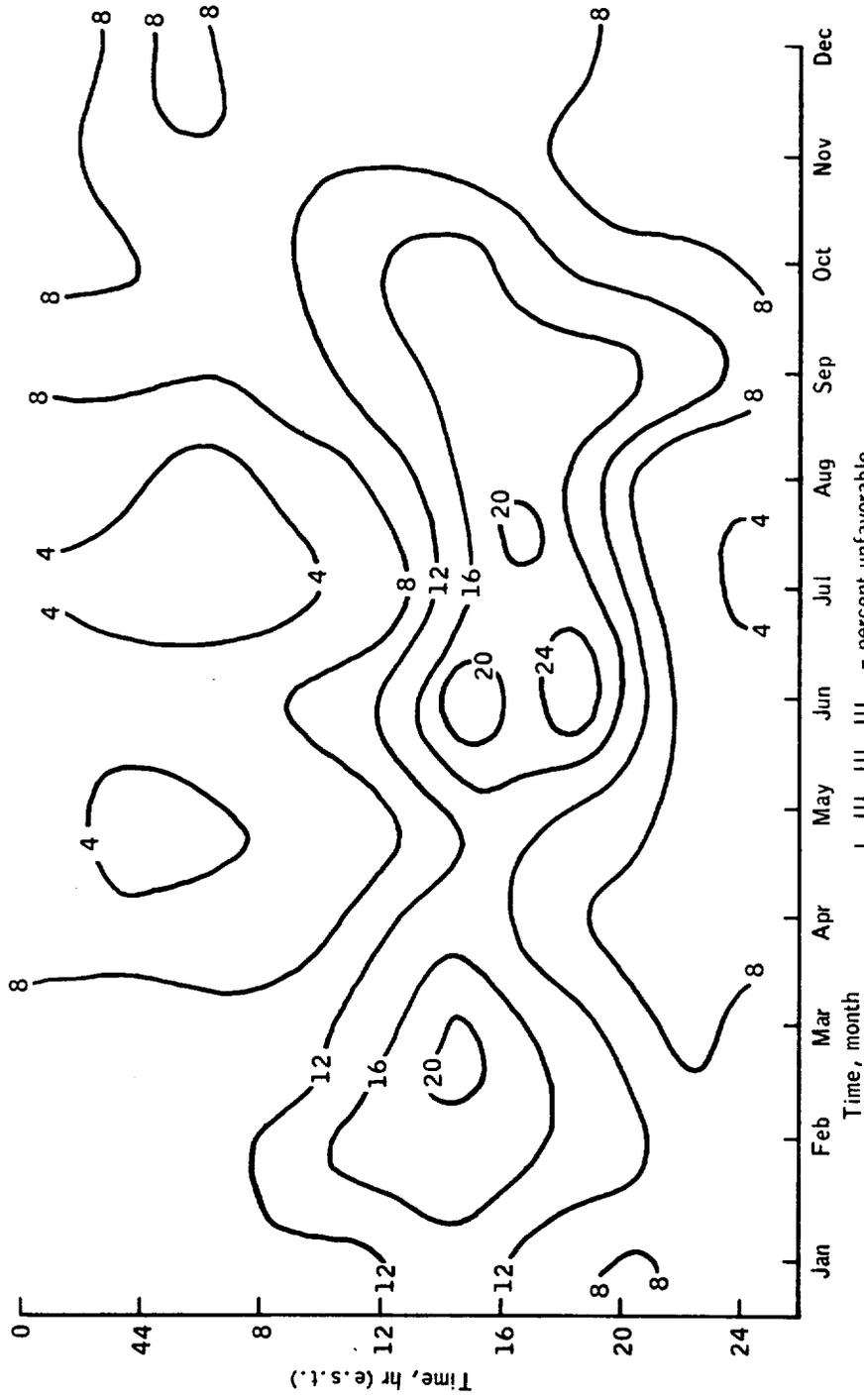
$L_1UL_2UL_3UL_4$ - percent unfavorable
L_1 Winds at 60-foot level $\geq$ 28 knots
L_2 Thunderstorm with both ceiling and precipitation
L_3 Precipitation without thunderstorm
L_4 Cumuliform ceiling $\leq$ 4000 feet, any ceiling $\leq$ 4000 feet, if precipitation

(d) Winds, thunderstorms, all precipitation, and clouds ceilings.

Figure 13.- Concluded.

VEHICLE DESIGN CONSIDERATIONS

There are two basic effects of lightning on the launch vehicle and spacecraft systems. The first is the induction of electric current into the circuitry and is produced by the flow of current through the basic vehicle structure with the induced potential proportional to the rate of change of current. This condition may cause an inadvertent function or even permanent damage. This leads to the second basic effect of lightning: the damage that may result from the energy dissipation along the current flow path (I^2R). The damage along the conducting path can vary from discoloration to explosive destruction of the material depending on the current level and duration in relation to the physical dimensions of the material. This damage may result whether the current is induced or introduced directly into the system by the discharge.

The launch vehicle was designed for operation in hazardous electric fields. The spacecraft design, on the other hand, incorporated good design practices to guard against electrical discharges; however, the specific design did not in all areas, consider operations in hazardous electric fields. The question is, how immune is the present design of the spacecraft systems to the effects of electrical discharges of the type experienced on Apollo 12? · Moreover, are there any systems or components which could be affected such that an unsafe condition would be created? To this end, the systems of the spacecraft and launch vehicle were reassessed for operation under the influence of triggered electrical discharges associated with clouds.

The Crew Safety Panel reassessed the ordnance system and the automatic abort system of the vehicles. The findings of the panel are reflected in the discussions which follow.

Spacecraft

Structural bonding.- The current associated with an electrical discharge of a cloud will seek the easiest path to discharge the potential. For an Apollo launch vehicle directly involved with the discharge, the path of current flow would be on the vehicle outer metallic skin, which provides a continuous low resistance conductive path from bow to stern. Bonding between basic structure and structural ties to metal components insures a continuous low resistance path. The bonding is measured and verified to meet requirements of 0.01 ohm between major assemblies of the spacecraft systems. Two flyaway umbilicals do not have covers. The main bus power during ground checkout for both the lunar module and command and service modules are provided through these umbilicals and this circuitry has an interrupt function. However, all of the other functions on these umbilicals are not protected and therefore, do provide a possible path for induced voltages.

Emergency detection system.- The emergency detection system has been assessed previously from the safety standpoint. A discharge in flight would not be expected to have a direct effect on the system such that an automatically initiated abort would inadvertently occur or such that a required automatic abort would be prevented from taking place. Calculations given in Appendix C are based on conservative assumptions and indicate that induction into the system would probably not cause any change. A secondary effect that was also considered occurred on Apollo 12 when the inadvertent disconnection of the fuel cells caused the battery bus to momentarily drop (see fig. 14). Note that the voltage level did not drop below the required level for the time delay relays in the system. The operational configuration of the battery system supporting the emergency detection system on Apollo 12 is considered to be safe for future flights.

Ordnance circuits.- The circuit designs employ safety features for protection against induced voltages, inadvertent operation, and static discharges. These ordnance systems are considered safe from initiation and reasonably secure from dudding as a result of electrical discharges.

All spacecraft ordnance functions are initiated by a single standardized initiator of the hot-wire type — Single Bridge Wire Apollo Standard Initiator. The pyrotechnic charge in this device is initiated by passing a current through the bridge wire; the resulting heat ignites the charge which is in intimate contact with the wire. The resultant heat and pressure output of the initiator in turn ignites the booster charge in the cartridge to perform the desired function. Firing current is supplied by special batteries used only for ordnance systems. Figure 15 shows a simplified schematic of the initiator and firing circuit; shielding is not shown. Two switch closures in series are necessary to fire the initiator.

There are three ways that induction from lightning may cause an initiator to fire:

a. Induced voltage across wires A and B

b. Induced voltage from wire A or B to the initiator case

c. Induced voltage to pull in the firing relays.

In the first item, wires A and B are shorted by the normally closed contacts on the firing relay. If both wires are subjected to the same induced voltage, however large (ignoring any shielding), no current will flow through the bridge wire. In considering a differential induction on wire A and B, the canard deploy circuit was analyzed because of its close proximity to the skin over a long distance and the current density
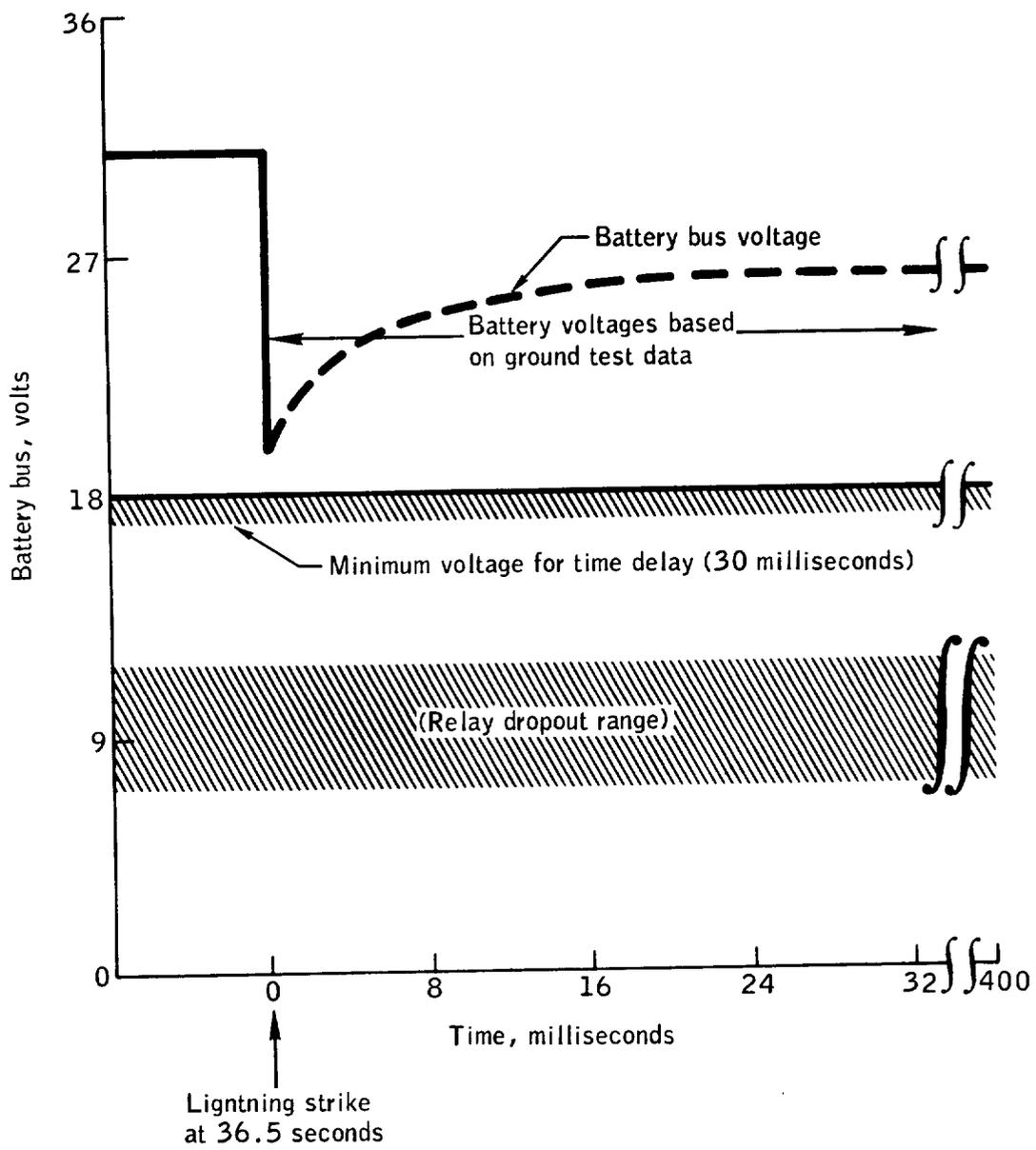
Figure 14.- Battery bus voltage and emergency detection system relay and timer voltage limits.

Spark gap

Initiator case

Explosive

Bridge wire

Insulation

A

B

To pyrotechnic bus

To control logic
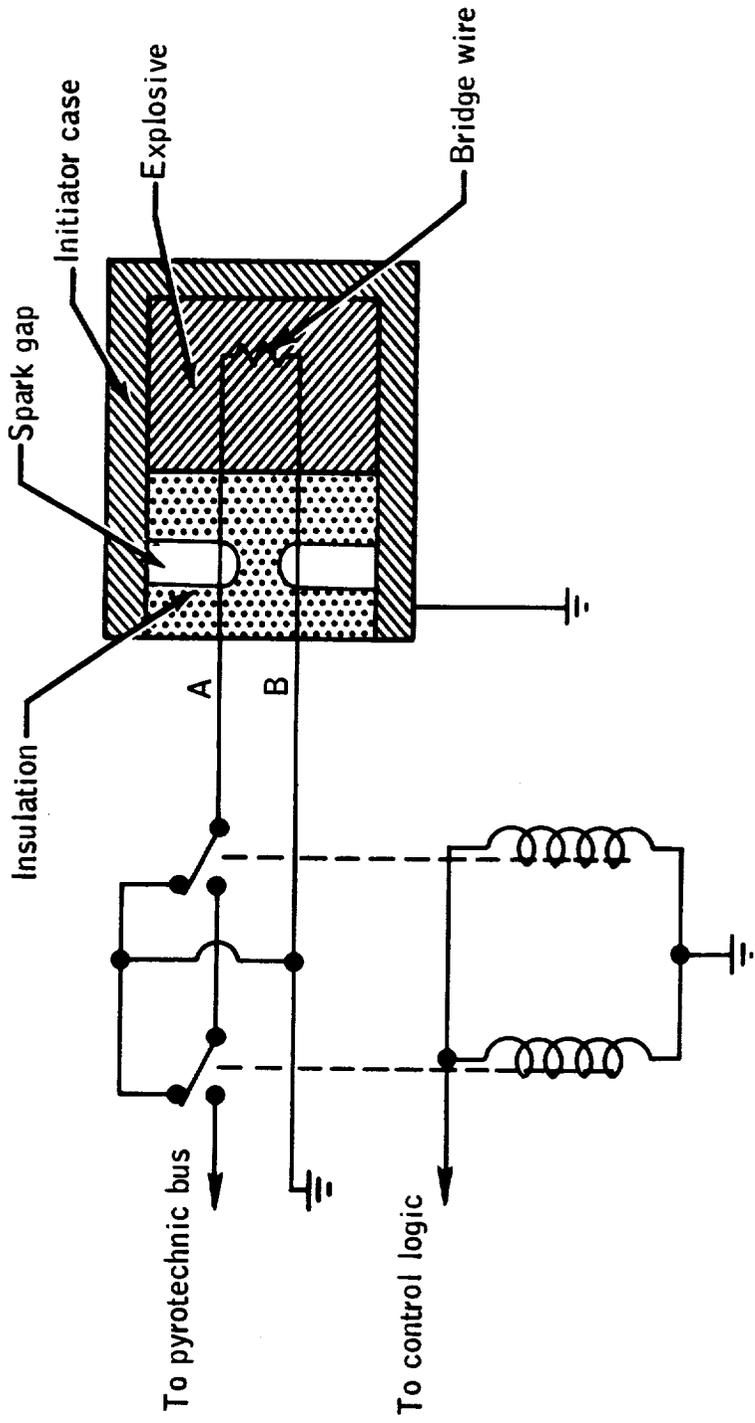
Figure 15.- Simplified schematic of the hot wire initiator.

is probably greatest on the tower due to the relatively small cross sectional area. The details of the analysis are given in Appendix C. The very conservative assumptions show a pulse energy of about 25 watts for 10 microseconds. Based on the steady-state ignition characteristics, the initiators should not fire. The initiators were tested to 1225 watts without firing.

The second item requires a potential between the initiator case and wire A or B. Again taking very conservative assumptions, a potential of 420 volts could exist from wire to case. Note in Figure 15 a spark gap is provided and is the lowest resistance path in the circuit. A potential of 1200 volts is necessary to cause a spark jump at this point. Each initiator is subjected to 25 000 volts to insure that the spark jump does not cause ignition.

The possibility listed in the third item can be ruled out as very unlikely since power for milliseconds is required to pull in these relays; induction from lightning can last for microseconds.

Solid-state components.- From two standpoints, the most susceptible areas in electrical circuits to lightning-type discharges are solid-state devices. First, the lightning-induced effects which occur for time durations of microseconds are well within the response time of these components; consequently, induction might initiate functions. Secondly, permanent damage might also result if the induced voltage exceeds a relatively low value. Examples of these conditions happened on Apollo 12. Initiation of functions through solid-state devices was believed to be the basic cause of the fuel cell disconnect, most caution and warning alarms, and the tumbling of the platform. Damage to solid-state devices in the measurements which failed are believed to be the effects of induced voltage in the circuit.

The experience with ground testing on the spacecraft has shown that induced effects into certain solid-state circuits, such as those associated with the caution and warning alarms, the coupling display unit readouts, pulse code modulation, etc., have occurred in the electromagnetic environment associated with normal activation and operation of systems. It is not surprising to experience similar situations with the electromagnetic environment associated with lightning. At this time, no practical changes can be made to the spacecraft to further protect these components.

Spacecraft guidance computer.- There is no practical procedure to eliminate the mechanism which led to the platform tumbling. However, because there is no requirement to align during launch, and the coarse-align mode inhibits the manual takeover of the S-IVB guidance, a software change is planned for Apollo 13 to prevent activation of the coarse-align mode during launch. A gimbal-lock indication, either real or caused by coupling

display unit transients, will still be displayed to the crew but will be ignored when the spacecraft digital autopilot is in the launch-vehicle configuration. Further software changes to provide protection against transients are being considered for Apollo 14.

Launch Vehicle

Even though there were no definite lightning protection requirements in the design specification of the vehicle, high voltage discharge protection was considered throughout the vehicle design. For example, a low resistance bonding requirement according to specification MIL-B-5087B between stages, covers on umbilicals after umbilical disconnect, not allowing the use of non-conductive surfaces in the vehicle, and suitable grounding on the vehicle protuberances such as cable tunnels were used in the design and construction of the vehicle.

Bonding.- The electrical bonding between stages causes the outer skin of the vehicle to act as the carrier of the discharge from the lightning phenomena. This aids in the protection of the internal equipment and electrical networks. Total compliance to MIL-B-5087B or better implies the ability to withstand skin currents up to 200 000 amperes without physical damage, but rigorous determination of the upper limit by tests or analyses is not practicable. The lack of direct data would cause the vehicle integrity (particularly with respect to digital systems) to be questionable to a sufficient degree to warrant a complete systems test in the event of any visible lightning strike when the vehicle is on the pad. The vehicle incorporates a two-wire direct current electrical system design which reduces the possibility of an induced transient voltage in the electrical networks. With the aid of these two design features, no electrical equipment was critically damaged in the launch vehicle.

Abort system.- The original concept utilized in the design of auto abort system was to prevent an erroneous abort. The system has no single point failures within the emergency detection system which would cause an inadvertent abort nor prevent an abort when an actual emergency arises. This is insured by the use of triple redundant circuitry, two out of three voting in auto-abort sensing circuits and automatic abort initiation circuits.

All the auto abort system located in the launch vehicle is shielded by the vehicle skin. This acts as a large metal can which provides a path for the discharge from the lightning phenomena. The relay circuitry is located in the emergency detection system distributor which is a metal box, within the large metal can, that is grounded to the vehicle structure. The relay coils are mounted in metal cans which are structurally grounded to the emergency detection system distributor. This system utilizes relay logic having 30-millisecond timers that provide a delay in the spacecraft to prevent any transient voltage from activating the auto abort system.

This system has three hot wires routed through separate cables from the instrument unit to the spacecraft to maintain six relays in the energized position until either the auto abort bus is energized or spacecraft separation occurs.

Ordnance.- The exploding bridge wire ordnance is designed specifically to prevent any response to random fields and electrostatic discharges. Operation of the exploding bridge wire ignitors requires a unique set of high energy parameters with a special "trigger" to assure predictable operation. The energy is derived from a capacitor which is normally uncharged and requires 1.5 seconds to achieve operating levels. Lightning discharges normally persist through time periods one to two orders of magnitude less than one second. Compliance with MIL-I-6181D and MIL-B-5087B (ASG) causes the units to be shielded through 360 spherical degrees and prevents the system from being ground driven in addition to the protection afforded by the vehicle structure.

All of the ordnance in this portion of the vehicle utilizes the exploding bridge wire method of ignition except the ordnance to start the F-I engines. The F-I engine start ordnance uses a hot wire ignition; however, it utilizes the same protective circuits to prevent erroneous ignition as does the exploding bridge wire. The requirements to ignite the exploding bridge wire detonators are 600 to 1200 volts dc with approximately 1000 amperes at a fast rise time of 0.1 microsecond. Two input signals are required for the exploding bridge wire firing unit to produce the ignition conditions for the exploding bridge wire detonators. The first signal applies power to the charging circuitry which charges a capacitor to 2300 volts dc. Charging time is 1.5 seconds. The second signal triggers an electronic switch causing the storage capacitor to discharge through a discharge tube in series with the detonator wire creating a high current to explode the wire. The charged capacitor will bleed off the charge to a safe 300 volts within 15 seconds if the input power is removed. If the trigger signal is received before the capacitor is fully charged, the charging circuit is cut off, thereby preventing detonation from the firing unit. The detonator does not contain heat-sensitive explosives and is not sensitive to static discharges, RF energy, or inadvertent application of ground or vehicle power.

If a stray current from lightning did get into the networks that command the exploding bridge wire firing unit, it is believed the solid state components would no doubt be destroyed before the capacitor could charge up, preventing a firing of the detonators. The cable from exploding bridge wire firing unit to the detonator is a maximum of forty-eight inches in length, and is covered with six to eight interwoven wire shieldings to eliminate any induced voltage to the detonators.

Launch vehicle design capability summary.- The probability of lightning damage to the vehicle hardware is deemed negligible. The computer

influence due to a lightning strike may be subtle and varied in flight. The built-in programming checks and computer system redundancies are such that no degrading first order effects due to lightning are known. The auto abort system has been designed to provide an adequate safety margin and no changes are considered necessary.

The probability of initiating launch vehicle ordnance by means of a lightning strike is virtually nonexistent while the probability of duding is deemed negligible.

Launch Complex

This section assesses the physical structures and associated equipment which make up the launch complex and determines the safety of the complex while a vehicle is undergoing checkout prior to lift-off.

Several years ago, a study was completed to determine if a cone of protection could be provided for protecting the Saturn V space vehicle from direct lightning strokes at the launch complex. At that time, the 1:1 cone and 2:1 cone concepts were considered to be most effective (fig. 16). The concept has been re-examined since the Apollo 12 incident.

In the cone concept, the tallest structure represents the height of the apex of a cone having a finite base dimension. Structures within the volume of the cone will be protected by the tallest structure intercepting the lightning stroke. To be specific, a 1:1 cone of protection would include all other structures whose topmost points lay within a cone having a base radius equal to the height of the tallest structure. Adequacy in the 1:1 cone of protection is based upon historical data involving lightning strokes as well as laboratory testing. In laboratory tests, simulated lightning strokes could not be made to violate the 1:1 cone of protection. However, the 1:1 cone of protection does not prevent the flow of current on or through the vehicle should lightning strike the launch umbilical tower.

When a stroke hits the launch umbilical tower lightning mast, the stroke current will flow from the mast into the crane, through a sliding contact on the crane into the structual steel of the launch umbilical tower, and then into the ground grid through the supporting pedestals for the launch umbilical tower. There are no special conductors through the launch umbilical tower because the massive steel structure is capable of carrying the lightning currents. However, there are lightning conductors connecting the framework of the launch umbilical tower to the supporting pedestals and along the pedestals to the grounding system, although the pedestals themselves are sufficient for carrying the lightning currents to ground.

Δh

Δh

2Δh

h

2Δh

Δh

Δh
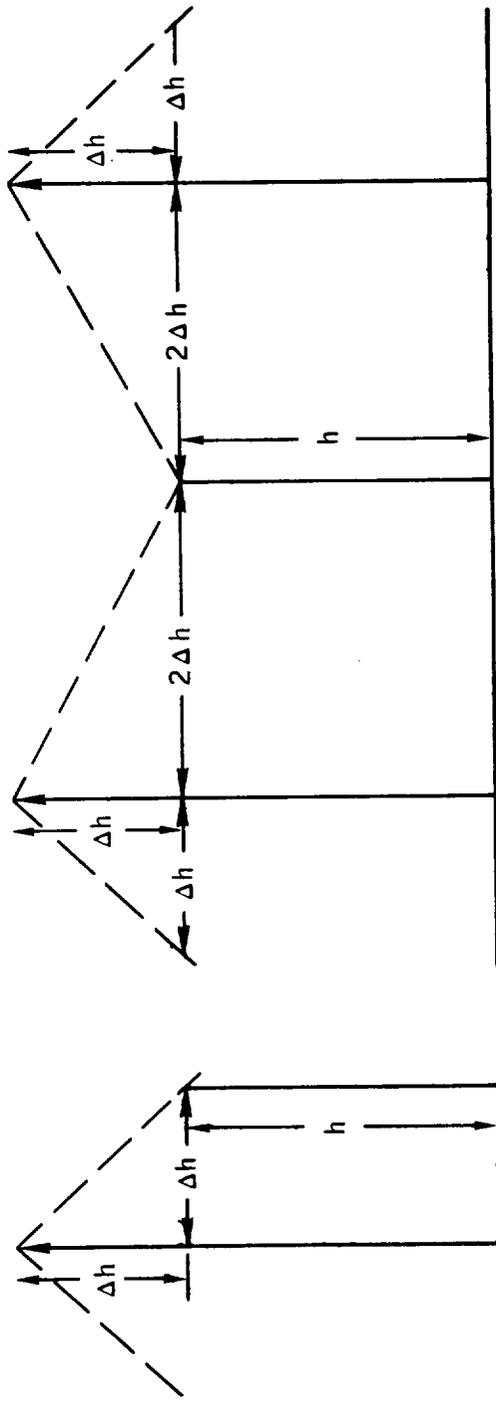
2:1 cone (two or more towers)

b.

Δh

Δh

h

1:1 cone (one tower)

a.

Figure 16.- Cone of protection criteria.

When the launch umbilical tower and vehicle are in transit to the complex, there is a path to ground from the launch umbilical tower through the crawler which drags a chain on the ground over a buried counterpoise.

In addition to passing through the legs of the tower, currents would be flowing in metallic materials that extend up and down the launch umbilical tower and also in the loop created by the launch umbilical tower/swing arms/vehicle. These currents would be mainly due to magnetic coupling from the main stroke path. To minimize the effects of induced currents on electrical equipment on the launch umbilical tower and in the vehicle, cables running up and down the tower have overall shields and are enclosed in metal trays with covers and the trays are bonded to structure.

External cables on the various launch umbilical tower levels are provided with overall shields which are grounded to the launch umbilical tower structure. Also the cables that extend across the swing arms to the vehicle have overall shields. To minimize personnel and equipment hazard created by potential differences (caused by high-resistance paths and different levels of magnetic flux), metallic structures have been bonded together and grounded to the structure.

In recognition of the various current paths available, a re-evaluation was performed relative to the present ground network. The results of this evaluation indicates that some minor changes are desirable.

The analysis of electrical cabling in critical launch support systems revealed that shielding to the control cables was not grounded. This will be corrected by providing a grounding to cable shields. The affected systems include the egress elevator, fly-away swing arms, damper arms, etc.

In addition, a study is being made on the possibility of grounding arms 3, 9 and the damper arm. There is no "classical" grounding between these arms and the launch umbilical tower, and there is no contact between the arms and the skin of the vehicle. It is likely that the results of this analysis will be the installation of grounding straps from the arms to the launch umbilical tower.

Historical data of lightning strokes on the launch umbilical tower indicate that only two strokes have ever occurred. On May 27, 1966, at approximately 1550 hours, a lightning stroke terminated on launch umbilical tower 1 at pad A at launch complex 39. Vehicle 500F was on the pad at the time. Analysis of magnetic link instrumentation indicated a peak current of 50 000 amperes. Damage was limited to the anemometer which was mounted on the same mast as the lightning terminal. During the period from May 28 to June 21, 1966, a smaller stroke occurred. A peak current of 6000 amperes was experienced. No damage was detected.

Re-examination of the space vehicle systems with Marshall Space Flight Center and Manned Spacecraft Center verifies that if a strike should occur to the launch umbilical tower, no significant hazard to the crew would be initiated by the space vehicle or its associated ground support equipment. Therefore, upon completion of ingress, the crew should remain on board, should lightning conditions develop. However, the mission rule essentially states that the Launch Director will give consideration to flight egress should thunderstorms occur in the immediate area. This present mission rule is considered adequate.

A discussion of the instrumentation used for monitoring lightning strikes is contained in Appendix A. No new instrumentation is planned at this time for indicating a hazardous electrical environment for flight; however, an evaluation of the lightning warning system at Kennedy Space Center is being conducted. To improve the Launch Director's real time information regarding actual strikes, the following four changes are being made:

a. The present remote launch umbilical tower strike counter indications for display in the Launch Control Center to provide real time readout capability

b. The launch umbilical tower corona current detection readout available for display in the Launch Control Center

c. New instrumentation to indicate stroke current, in real time, for display in the Launch Control Center

d. A differential voltage measurement system will be added to the launch umbilical tower pedestal to detect high current density distribution points on the launch umbilical tower. The data will be displayed at the Launch Control Center.

Retest requirements to determine launch readiness should lightning strike the launch umbilical tower have also been studied. Present information dictates that a confirmed strike on the launch umbilical tower would necessitate reverification on a component and systems level. The time line for accomplishing such retests are the objective of further study and will not be addressed in this report.

CONCLUSIONS

As a result of the analysis of the Apollo 12 lightning incident, the following conclusions are made:

1. The Apollo 12 lightning incident pointed out that atmospheric electrical hazards must be considered in greater depth for future Apollo flights.

2. The multiple effects observed in the spacecraft and launch vehicle at about 36.5 seconds and 52 seconds were caused by cloud-to-ground and intracloud lightning discharges, respectively.

3. The lightning was most probably triggered by the presence of the effective electrical conduction path created by the space vehicle and its exhaust plume in an electric field which would not otherwise discharged.

4. The available data show the discharge had most characteristics of an average natural lightning discharge. Typical natural discharges to ground produce peak currents on the order of 10 000 amperes and transfer about 20 coulombs of charge to ground.

5. Analysis of the spacecraft design to withstand triggered lightning effects indicates the following:

   a. The designs of the ordnance systems are reasonably safe.

   b. The normal bonding practices followed provide the required first-order protection to all systems.

   c. The automatic abort system is considered reasonably safe from improper operation.

   d. Solid-state devices are most susceptible, and some effects may be expected which may jeopardize mission success should a discharge occur.

6. Analysis of the launch vehicle design to withstand triggered lightning effects indicates the following:

   a. The probability of lightning damage to the vehicle hardware is deemed negligible.

b.   The computer influence from a lightning strike may be subtle and varied in flight. The built-in programing checks and the computer system redundancies are such that no degrading first-order effects will result from the lightning.

c.   The automatic abort system has been designed to provide an adequate safety margin and no changes are necessary.

d.   The probability of initiating launch vehicle ordnance by means of a lightning strike is virtually nonexistent while the probability of dudding is deemed negligible.

7.   Review of the present launch complex design and past analyses relative to lightning protection shows that the design concept is adequate.

CORRECTIVE ACTION

The corrective action is based on the previous conclusions and analysis within the report.

1. The problem of launching the Apollo spacecraft into electric fields which could be discharged by the presence of the spacecraft has been evaluated and the solution which will be followed is to minimize the probability of a lightning discharge by avoiding flight operations into conditions which may contain high electric fields. The Apollo spacecraft design has an inherent degree of protection from the effects of lightning. This protection is considered sufficient without hardware modifications to accept a low risk which can be provided by certain additional launch restrictions. The probability of meeting a launch window is estimated to be reduced a few percent by the launch restrictions for avoiding potentially hazardous electric fields. These launch restrictions are based upon meteorological conditions at Kennedy Space Center.

2. No changes are necessary to the launch vehicle for triggered lightning discharge. As a result of the tendency of a space vehicle to encourage electrical discharges where a natural lightning discharge would not exist, and because of the possible danger to the mission that results from this tendency, some additions will be made to the present launch vehicle system background data for Apollo mission rules to minimize the triggered lightning risks.

3. The launch restrictions which will satisfy the low risk requirement of the spacecraft and the lesser restrictions of the luanch vehicle are delineated in the following launch rules which shall apply.

a. No launch when flight will go through cumulonimbus (thunderstorm) cloud formation. In addition, no launch if flight will be within 5 miles of thunderstorms cloud or 3 miles of associated anvil.

b. Do not launch through cold-front or squall-line clouds which extend above 10 000 feet.

c. Do not launch through middle cloud layers 6000 feet or greater in depth where the freeze level is in the clouds.

d. Do not launch through cumulus clouds with tops at 10 000 feet or higher.

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APPENDIX A

LIGHTNING AND RELATED INSTRUMENTATION

Six types of ground instrumentation at eight locations (fig. 3 in basic report) are available in the Kennedy Space Center area for monitoring lightning and weather conditions, and these were used during the Apollo 12 launch operations. A composite schematic of the overall system is shown in figure A-1.

Eight radioactive device stations provide the primary instrumentation used for the determination of electric field intensity. The basic principle of operation of the radioactive device assumes that the ionization of the air close to the conductor (see fig. A-2) is partly carried away by the field or is returned to the sensor, depending upon polarity, until an equilibrium current flow is established by the atmospheric field. The output is used to calculate the potential gradient and is recorded.

Eight corona current detection system stations are used for indicating high atmospheric potential gradients and are located in conjunction with the radioactive devices (see fig. A-3). The corona current detector consists basically of a 4-foot whip antenna connected to a micromicroammeter. This detector measures the corona current leakage caused by large fields present at the detector. This information is available in real time.

Two sferic (atmospheric) monitoring stations are used to locate the position of lightning activity (see fig. A-4). Storm location, as a function of time, is used for forecasting movement. The sferic monitoring systems use directional loop antennas to receive the RF signals generated by lightning. Two fixed-loop antennas oriented at right angles to each other are used to determine compass direction of lightning strokes. It is necessary to use a two-station solution to determine location of the lightning activity. The sferic monitoring system is primarily suited for locating and tracking storm activity 20 to 50 miles away. This system can not accurately locate nearby strokes, since a single stroke can be over a mile long.

The lightning discharge counters count the number of times each arrester has received a lightning stroke. These counters are used in conjunction with a lightning rod at the top of the launch umbilical tower and require no external power for operation. The stroke counter consists of a resistor with a shunting airgap, a capacitor, and a five-digit cyclometer dial and associated counter. The information obtained by this instrumentation is recorded manually to provide historical data.

The magnetic link lightning detectors also are used in conjunction with the lightning rod located atop the launch umbilical tower to provide historical data. Through the use of cobalt alloy slugs, the peak lightning currents can be calculated by measuring the change in residual magnetism contained in these slugs. There are three slugs located at 5, 10, and 24 inches from the lightning arrestor. If only one stroke is received, the current of that stroke can be determined.

The FPS-77 weather radar system located at Cape Kennedy Air Force Station is used to locate and track cloud buildup. This radar operates at 5500 megacycles and has a maximum range of 200 miles. The plan position indicator data are available.
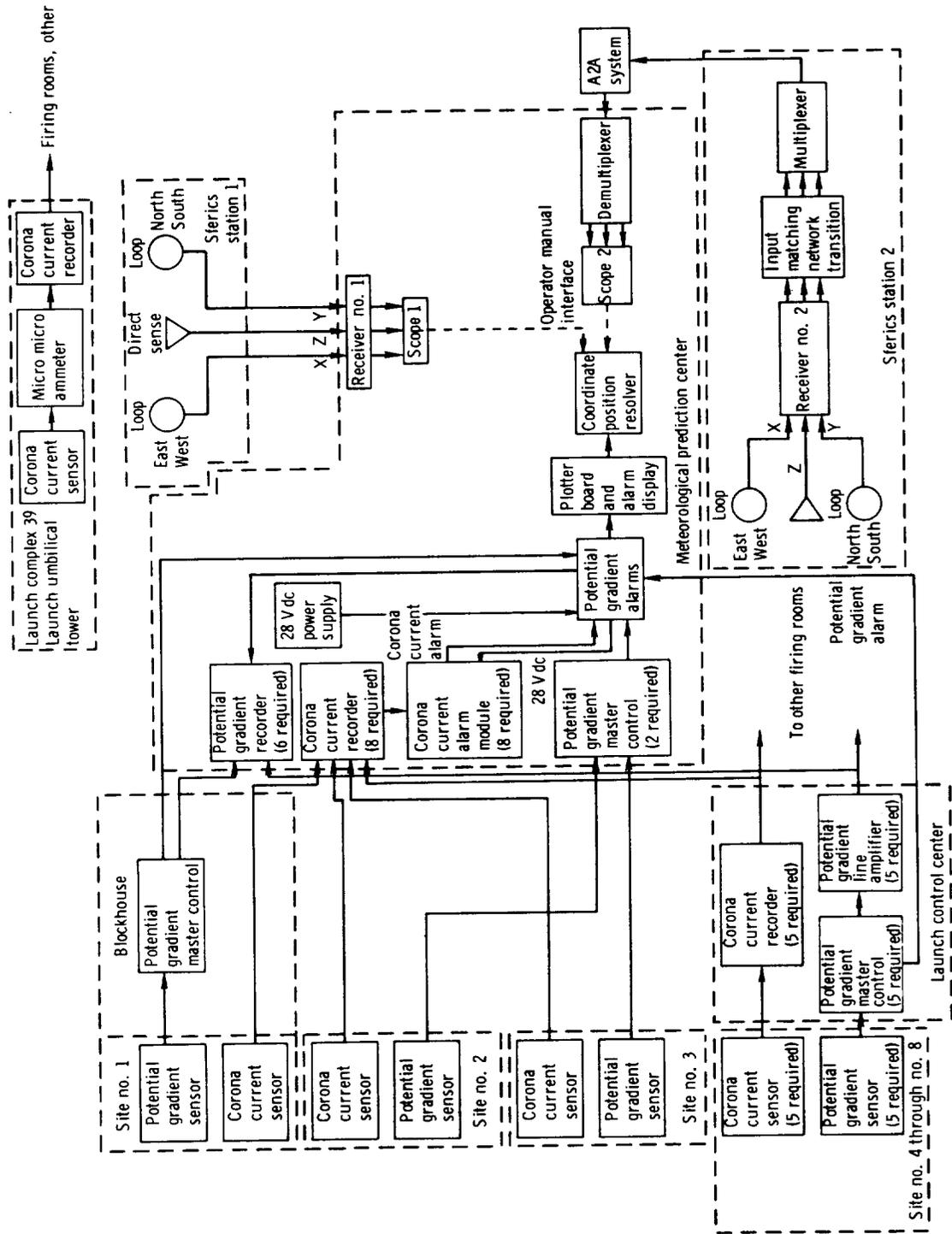
Figure A-1. - Composite schematic of lightning instrumentation system.
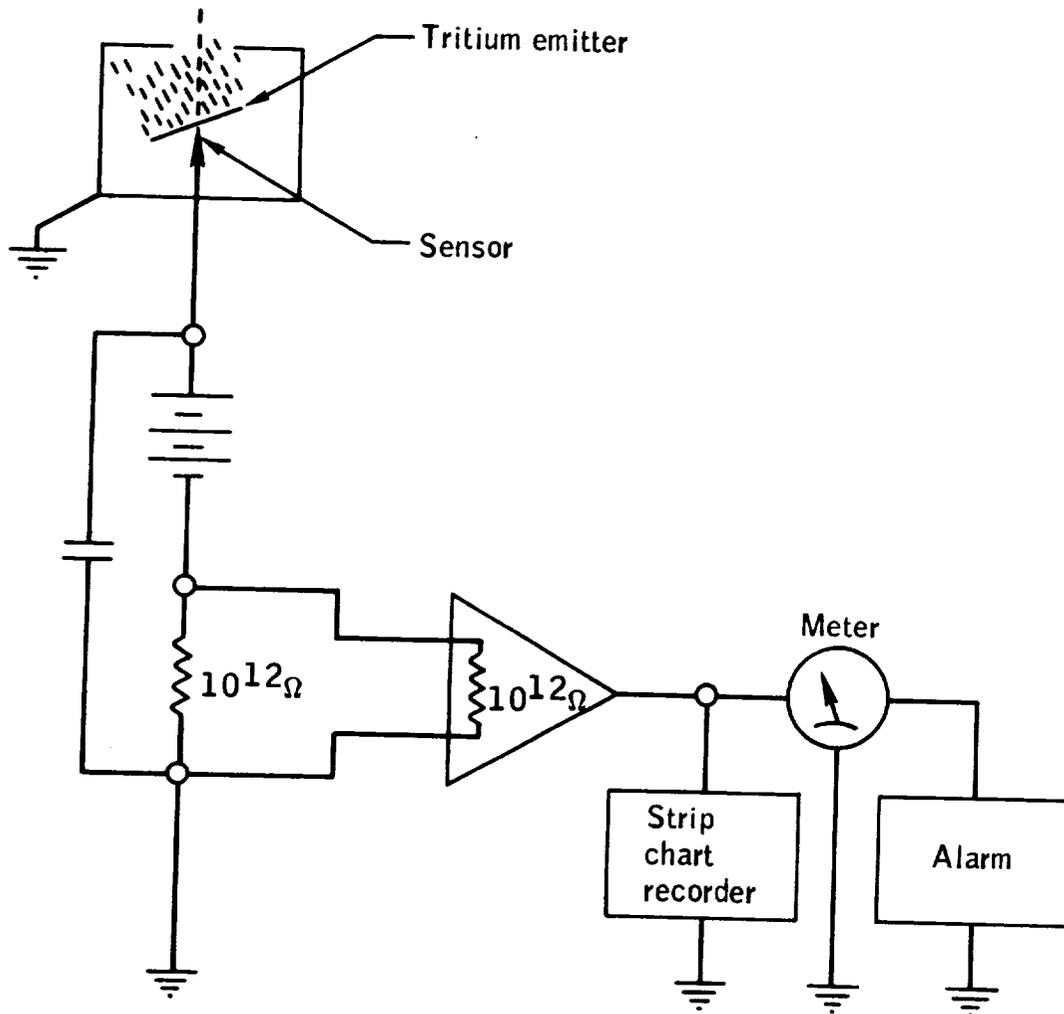
Figure A-2.- Potential gradient (radioactive device) functional schematic.

Whip antenna

R_1

Direct current
operational
amplifier

Recorder
and
alarm
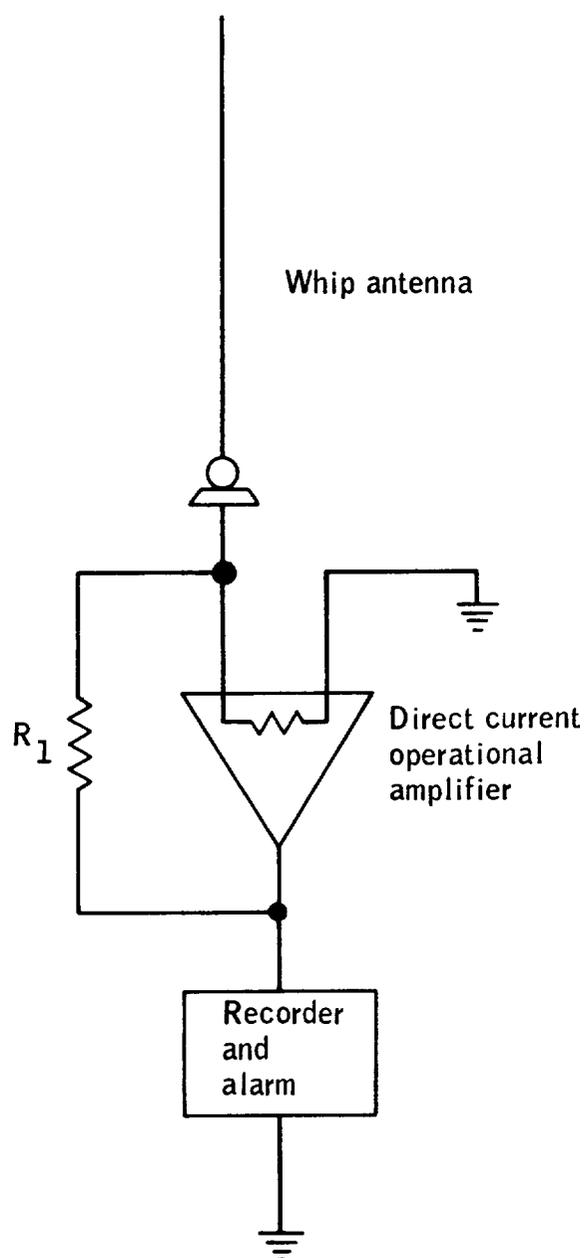
Figure A-3.- Corona current detection system functional schematic.

Vertical whip antenna

East-west
loop antenna

North-south
loop antenna

Sense circuit
(blanking circuit
removes 180°
ambiguity)

Oscilloscope

Scope
horizontal
deflection
circuits

Oscilloscope
vertical
deflection
circuits
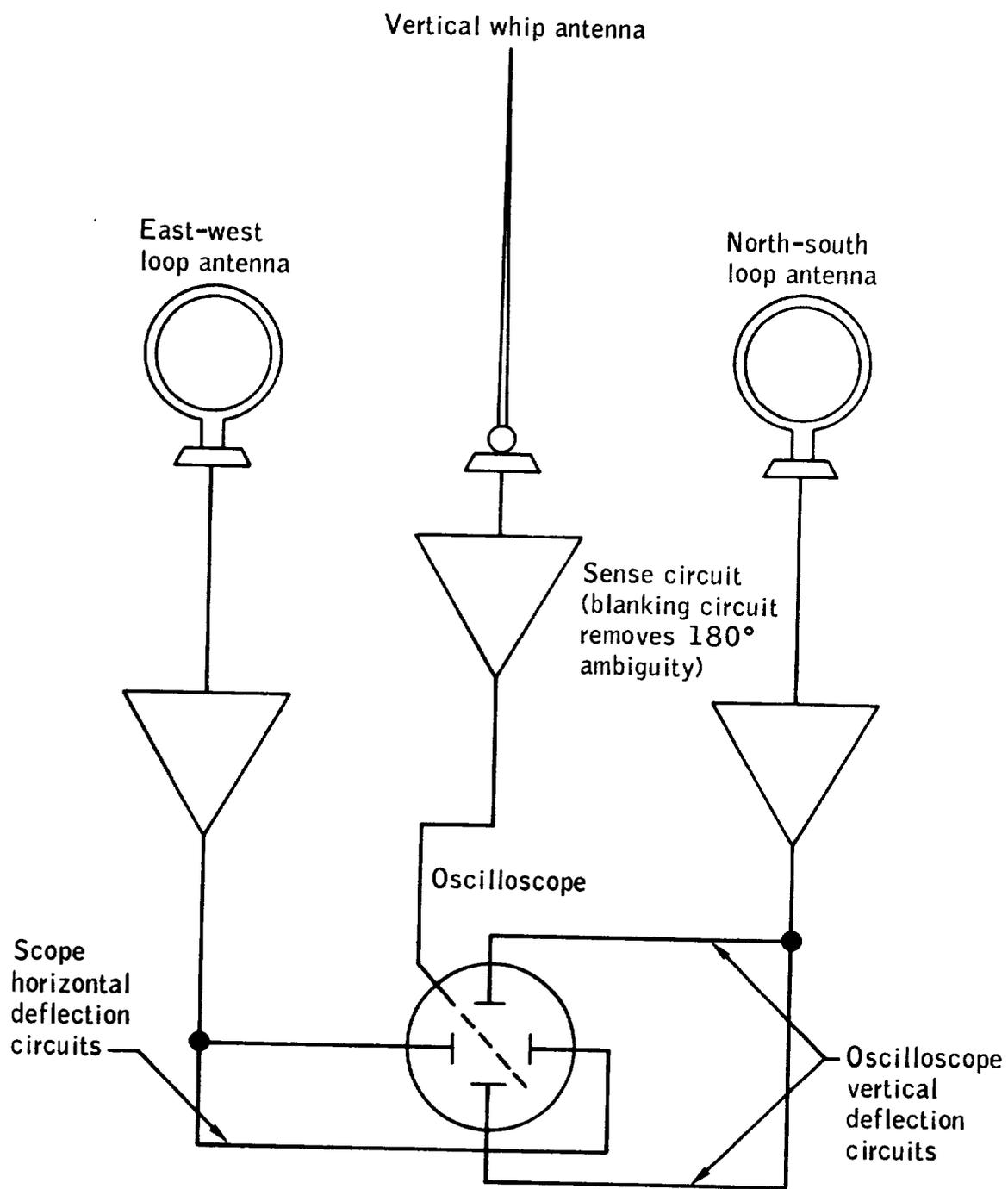
Figure A-4.- Sferic receiver functional schematic.

APPENDIX B

TECHNICAL NOTE*

EXPLORATION OF SOME HAZARDS TO NAVAL EQUIPMENT AND

OPERATIONS BENEATH ELECTRIFIED CLOUDS

by

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INTRODUCTION

The Apollo 12 launch at Cape Kennedy will probably be remembered as one of the most exciting interactions of weather with a public event in recent times. Thirty-six and one-half seconds after launch, at an altitude of 6400 feet, the Saturn V vehicle was struck by lightning. At the same time, no less than four cameras photographed a stroke to ground which hit near the launch pad. The astronauts reported seeing a bright flash, and later told of "feeling" the stroke. The fuel cells were disconnected from the main power bus, an undervoltage condition prevailed, and numerous alarms and warning lights were activated in the command module. Signal conditioning equipment dropped out for a period of about 60 seconds. About nine temperature and pressure sensors were permanently damaged.

At 52 seconds after launch a second major disturbance occurred. The space craft was now at an altitude of 14,400 feet, 2,000 feet above the freezing level. This time no visible evidence of lightning was photographed, but a spherics receiver at the ground was saturated. Equipment malfunctions were again noted (battery power was in use at this time), most noteworthy of which was the tumbling of the inertial measurement unit in the spacecraft. Fortunately, the inertial unit was not providing guidance at this time.

It is important to note that the Apollo 12 was not launched into a thunderstorm, or cumulonimbus cloud. For six hours prior to launch, and for a similar period afterward, no lightning strokes were observed or recorded, and no thunder was heard. Electric field meters in the area

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registered electric field magnitudes which are indicative of disturbed weather, but the Arthur D. Little lightning flash counter at nearby Patrick AFB showed no strokes except the one associated with the lightning at 36.5 seconds after launch. It is most probable, therefore, that the passage of the vehicle through an electrified cloud incapable of producing lightning on its own, triggered the lightning flashes at 36.5 seconds and 52 seconds after launch.

There is additional evidence, from an analysis of the telemetry signals, that several other electrical disturbances of smaller magnitude occurred both before and after the two major events.

The Apollo 12 event brings to mind a similar occurrence involving the testing of depth charges by the Navy in Chesapeake Bay (Young, 1961). In this instance, a plume of water thrown up by the explosion to a height of about 240 feet triggered a lightning discharge from the cloud above. Additional triggered lightning events have been reported associated with underwater explosions during offshore seismic explorations. A more complete description of the Chesapeake Bay event, along with a description of laboratory experiments of simulated triggered lightning has been published (Brook et al, 1961).

The Apollo 12 and Chesapeake Bay events cover the two most important situations which may be encountered in Naval Operations under electrified clouds. The similarity of the rapid emergence of a water plume after an underwater explosion to the launching of a Polaris missile is obvious. An aircraft flying through an electrified cloud would be expected to interact with the cloud in a manner similar to the Apollo 12 event. [An excellent analysis entitled "Electrical Behavior of an Airplane in a Thunderstorm" has been prepared for the FAA by Bernard Vonnegut (1965)]. Whether or not the triggered lightning reaches ground, and thereby exposes the rocket or aircraft to the destructive current and rate of rise of current observed in return strokes, is not a function of the vehicle, but of electrical conditions existing in the cloud. We shall discuss some of these considerations in what follows.

SOME PROPERTIES OF LIGHTNING

For purposes of this report, and in the interests of brevity, we shall classify lightning discharges into three types.

1. Intracloud lightning. Lightning which does not connect to ground, although dissipating amounts of electric charge and energy similar to those that do, does not generally involve currents greater than 1,000 to 2,000 amperes with maximum rates of rise probably not exceeding 100-500 amperes per microsecond. The average total duration of these currents does not exceed 3 milliseconds.

2. <u>Discrete lightning strokes to ground</u>. Lightning which reaches ground involves a low current leader followed by a return stroke with an average peak current value of 20,000 amperes, and with a rate of rise of about 10,000 amp/micro sec. The current falls to half value in about 40 microseconds and is essentially at zero value after several hundred microseconds. On the average, there are about 3 or 4 strokes to each discharge, with a time between strokes of about 40 milliseconds. The first stroke in a discharge usually carries the largest current.

3. <u>Long continuing-current lightning strokes to ground</u>. About one out of 5 or 6 strokes to ground is initiated by a leader followed by a discrete return stroke in which the current does not fall to zero value after a few hundred microseconds, but which continues at an average current value of about 185 amperes for an average duration of about 175 milliseconds. Continuing currents of 250 amperes lasting for about 0.25 sec are not uncommon.

Summarizing, high currents and high rates of rise of current are not expected from intracloud strokes; rates of rise of the order of 10,000 amp/microsecond are to be expected from discrete return strokes, each involving from 1 to 5 coulombs of charge; long continuing-current strokes involve high rates of rise as well as persistent currents of about 185 amperes for periods of about 0.2 sec bringing from 12 to 40 coulombs of charge to earth. In terms of energy, the continuing currents involve at least an order of magnitude greater energy release than do ordinary discrete return strokes.

THE NATURE OF THE LIGHTNING STROKES TRIGGERED BY APOLLO 12 AND BY THE UNDERWATER EXPLOSION

The underwater explosion and the Apollo 12 are unique events in that data on the duration of the strokes are available from movie film. In the case of Apollo 12, at least seven successive frames of the TV video camera film show the return stroke channel fully illuminated. The exposure time for each frame was 1/60 sec, and the time between frames was 1 msec. Although it is possible that each frame recorded a separate, discrete stroke, such an event appears to us to be highly improbable. We believe that the stroke triggered by the Apollo spacecraft was a long continuing current stroke, and that about 20 coulombs of charge passed through the vehicle structure in 0.12 seconds.

In the case of the triggered stroke in Chesapeake Bay, the evidence is again very strong that the discharge involved two or three long continuing current strokes. In this instance, the luminosity persisted

throughout 65 frames taken at a rate of 64 frames per second. The duration of this current was somewhat greater than 1 sec, and probably involved a total charge of 100 coulombs or more.

It would be folly to conclude on the basis of only two events that triggered lightning discharges to ground tend to be continuing current discharges. But other considerations also favor this view. Without going into too much detail, we point out that discrete lightning discharges must originate from regions of relatively high charge density, for the linear dimension of the charged volume appears to be of the order of 300 to 500 meters. Similar measurements on continuing current discharges give values for the linear dimension about 3 times greater. Since the volume is proportional to the cube of the linear dimension, cloud volumes associated with continuing currents are about 27 times greater than volumes storing charge for discrete strokes. On the other hand, the ratio of the charges in continuing currents to discrete strokes is measured to be from 2:1 to 6:1. Assuming that the charged volumes are at approximately the same potential, the capacity of the volume drained by the continuing current is approximately 3 times as large, consistent with the 2 to 6 times greater charge stored. But the currents are roughly in the ratio of 50 to 1. It is therefore apparent that the effective impedance of the current source is approximately proportional to the volume in which it is stored. It is this consideration which leads us to believe that triggered lightning probably involves volumes of charge whose density is considerably below that which would lead to a natural discharge, and would therefore exhibit a current consistent with the notion of a high internal impedance.

There is obviously much about long continuing-current lightning, and the disposition of charge in clouds which we do not understand. But one fact regarding the effective destructive potential of the long continuing currents is known. It has recently been shown, through correlated photographic and electric field measurements, that the long continuing current strokes are the prime cause of lightning-associated forest fires. Not only do they exhibit high rates of current rise in their initial phase, but they persist long enough to cause considerable I^2R heating damage.

ON THE MECHANISM OF TRIGGERING LIGHTNING DISCHARGES

There is no doubt that considerable ionization is present in the high temperature gases; the important question is how long do free electrons persist in sufficient numbers to render the exhaust gases conducting in the appropriate sense. In lightning return strokes, where the temperature may reach 30,000°K, the air is almost fully ionized, and electron densities decay to values of approximately 10^2 cm^{-3} in about 50 milliseconds. The reason they persist for so long a time is that recombination is slow until the channel cools to about 3000°K. The temperature in a rocket

exhaust is about a factor of 5 or 6 less than in the lightning channel, and one expects therefore that free electron densities are initially very much less, and that their lifetime will also be much less. At any rate, one can estimate with confidence that electron densities will effectively be zero after a time of the order of ten milliseconds following combustion. Certainly, in this sense, the absence of luminosity should be a good sign of the absence of free electrons.

On the other hand, there is no doubt that the rocket exhaust leaves behind a trail of small and large ions, and that the net charge in this trail is probably not zero. But these ions, which are elementary charges attached to particulate matter, cannot be thought of as constituting a conductor in the same sense as free electrons, since the mobility of the ions is more than an order of magnitude less than that of free electrons.

The presence of tons of particulate matter in the exhaust trail may influence the path of a lightning stroke in other ways: The net space charge left behind on combustion products may influence the course of the leader by providing an attractive or repulsive electric field. Also, the presence of materials in the exhaust may lower the ionization potential of the air by acting as a "sensitizer". For example, sodium has an ionization potential of 5.12 eV as compared to nitrogen or oxygen atomic or molecular species which ionize at from 12 to 15 eV. If the mechanism of progression of the leader involves photoelectric ionization ahead of it, then the lightning leader may be "led" down the exhaust trail in this way.

In general, one need not look for exotic mechanisms by which to trigger a lightning discharge if even moderate electric fields are present, such as are found in many electrified clouds not producing lightning. Consider a rocket such as the Saturn V, which is itself more than 100 meters long, and the luminous exhaust tail which at low altitudes appears to be at least 4 or 5 times the length of the vehicle. About 600 meters is probably a good estimate for the total effective length of this conductor. If a thin conductor of this length is injected rapidly into a region of electric field, it will tend to concentrate the field lines at its extremities, and if the concentration factor is large enough, the electric field at these points will exceed the breakdown field of air. The conductor will then go into corona, and if the electric field is strong enough, the corona streamers will continue to propagate out along the field lines.

To estimate the concentration factor of a long conductor in a uniform electric field, we can approximate its shape by a prolate spheroid. The problem is then one of finding the electric field distribution at the surface of the conductor extremities in terms of the ambient electric

field E_o. For a vehicle such as the Apollo 12 plus its luminous tail, we calculate that the electric field at the tip of the rocket head is given approximately by

$$E = E_o \left\{ \left(n_o \right) \left(n_o^2 - 1 \right) \left[\frac{1}{2} \ln \left(\frac{n_o + 1}{n_o - 1} \right) - \frac{1}{n_o} \right] \right\}^{-1} ,$$

where $n_o = \left(1 - b^2/c^2 \right)^{-\frac{1}{2}}$, and b and c are the semiminor and semimajor axes, respectively. Setting E equal to the breakdown field E_{br}, the ambient field E_o becomes the critical field E_c at which breakdown ensues. Thus $KE_c = E_{br}$, where the enhancement factor K is given by

$$K = \left\{ \left(n_o \right) \left(n_o^2 - 1 \right) \left[\frac{1}{2} \ln \left(\frac{n_o + 1}{n_o - 1} \right) - \frac{1}{n_o} \right] \right\}^{-1}$$

In Table 1, we have listed the critical field values corresponding to dimensions of rocket vehicles such as Apollo 12, and to other smaller vehicles which may be deployed in various naval operations.

Table 1. Concentration factor $E/E_o = K$, critical field E_c, for equivalent semimajor axis c, and semiminor axis b, at a pressure altitude of 6,000 feet, where the breakdown field is assumed to be 24000 V/cm.

c(Meters)	b(Meters)	$E/E_o = K$	E_{crit}(Volts/cm)
11	1	57	420
27	0.5	790	30
100*	5*	320*	75*
300	5	950	25

*The Apollo 12 was capped with a hemisphere of radius 10 cm. This curvature is greater than the maximum curvature for the ellipsoid assumed. Both the concentration factor K and the critical field E_{crit} were calculated in this instance using the higher value for the curvature. The maximum curvature at the tip of a prolate spheroid is related to the c/b ratio by $c/r = c^2/b^2$, where r is the radius at the tip.

Field values larger than 20 V/cm have been reported for clouds only several thousand feet thick. We see clearly that a long conductor injected into an electric field of only moderate intensity (25 V/cm) will concentrate the lines of force sufficient to produce breakdown. Magnitudes of electric fields observed in clouds are discussed in another section of this report.

For the benefit of the reader who may want to calculate enhancement factors for c/b ratios other than those given in Table 1, we have plotted in Figure 1 a curve of enhancement factor K vs the ratios $c/r = c^2/b^2$. Here r is the radius of curvature at the ends of the prolate spheroid.

When an exposed conductor at rest emits corona, a space charge which acts to reduce the field, is formed around the emitting point. This action serves to limit the flow of current and exhibit further breakdown. In the presence of wind the space charge is carried off, and higher currents can flow that again tend to reduce the field below breakdown. When the wind speed gets high enough, or when the conductor is a rocket moving at more than about 100 m/sec, the air motion relative to the point can be greater than the electron drift velocities. Consequently, the exposed
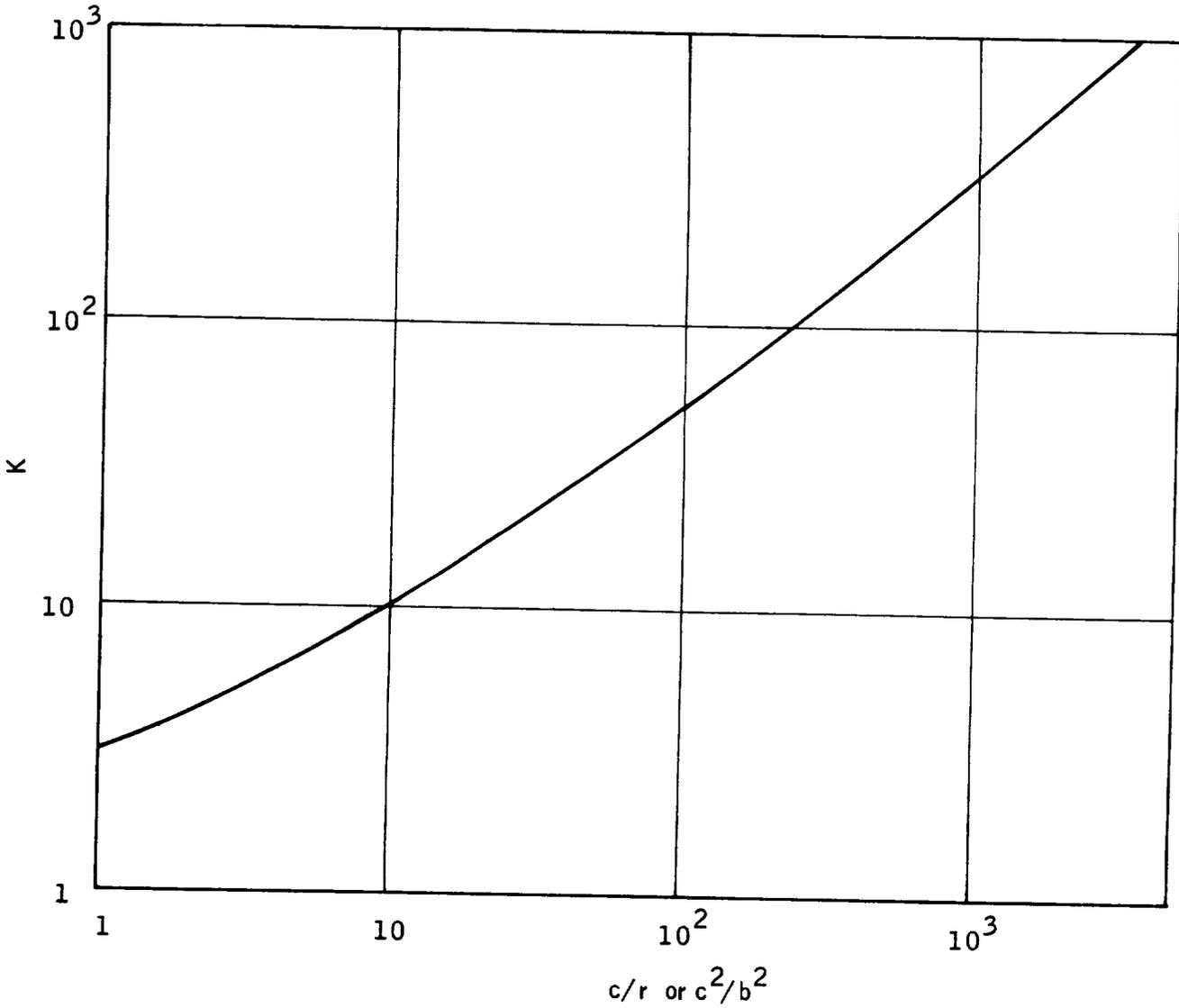
Figure 1. The electric field enhancement factor "K" at the top of a vertical, prolate ellipsoid versus the ratio of the height of the half ellipsoid c to the radius of curvature of the tip of r.

$$K = E_{tip}/E_{undisturbed} = \left\{ n\left(n^2 - 1\right)\left[\tfrac{1}{2}\ln\left(\frac{n + 1}{n - 1}\right) - \tfrac{1}{n}\right]\right\}^{-1}$$

where $\qquad n = \left[1 - r/c\right]^{-\frac{1}{2}} = \left[1 - b^2/c^2\right]^{-\frac{1}{2}}$

and b and c are the semi minor and semi major axes of the ellipsoid respectively.

point is no longer shielded from the high field by the emitted charges, and a lightning discharge may be initiated.

Whether or not a vehicle such as Saturn V will become involved in a lightning discharge depends also upon the amount of charge stored in the neighboring cloud volume. We have seen that the initiation of corona is highly probable in moderate electric fields; once corona occurs the discharge will continue if the charge density at the tip of the streamer can be maintained at a high enough value. Once a streamer forms and propagates into the charged volume, another streamer will also propagate from the other end of the vehicle. The formation of a streamer and the maintainance of a breakdown field at the streamer tip requires that charge be continually fed into the growing streamer to charge its increasing capacity. If the cloud capacity is large enough, the flow of charge from it necessary to maintain the breakdown field at the streamer tip will not lower appreciably the potential of the region, and the developing streamer will be led along the lines of force to either another charged volume of opposite sign in the cloud, or to ground. On the other hand, if the amount of charge available or remaining in the cloud is not sufficient to maintain the streamer tips at breakdown, the discharge will cease.

Numerous investigations have been made on the amount of electrical energy which various types of structures can withstand without damage. The energies shown in Table 2 have been calculated as available from a volume of cloud for various electric field values at its surface. For simplicity, a volume of uniform charge density in the form of a sphere of radius a has been assumed.

Table 2. Available Energy W, in Joules, from space charge stored in a spherical volume of cloud of radius a, with electric field, E_a, at its surface.*

$E_a \left(V\ m^{-1} \right)$	a (Meters)	W (JOULES)
10^2	10^2	0.67
10^2	3×10^2	18
10^2	10^3	6.7×10^2
10^2	3×10^3	1.8×10^4
10^4	10^2	6.7×10^3
10^4	3×10^2	1.8×10^5
10^4	10^3	6.7×10^6
10^4	3×10^3	1.8×10^7
10^6	3×10^2	1.8×10^9
10^6	5×10^2	8.1×10^9
3×10^6	3×10^2	1.6×10^{10}
3×10^6	5×10^2	7.5×10^{10}

*Natural lightning stroke energies are in the range of 10^8 to 10^{10} Joules

THE EFFECT OF CHARGE ON THE ROCKET IN THE ABSENCE

OF AN EXTERNAL ELECTRIC FIELD

A rocket may become charged in the absence of external fields by various mechanisms. The maximum charge will be acquired when the electric field at the point of largest curvature exceeds the breakdown field.

We can estimate the total energy available under these conditions from an estimate of the capacity of the vehicle, using a value of 2.4×10^6 V/M for the breakdown field.

The capacity of a rocket can be estimated by again approximating its shape with a prolate spheroid. The capacity is given approximately by

$$C = 4\pi E_o c \left[\text{arc tanh} \left(1 - b^2/c^2 \right)^{1/2} \right]^{-1}$$

To find the maximum charge which can be acquired by the rocket we calculate the maximum value of the field at its surface; this value occurs at the ends of the prolate spheroid:

$$Q_{max} = 1.1 \times 10^{-10} E_{max} b^2.$$

Since E_{max} will be the breakdown field, we can set $E_{Br} = 2.4 \times 10^6$ V/M, corresponding to breakdown at a pressure height of 6,000 feet. Thus, $Q_{max} = 2.64 \times 10^{-4} b^2$. The maximum energy which can be stored on the rocket is then given by $W = \frac{1}{2} Q^2/C$.

In Table 3 we give the values calculated for capacity, maximum charge, and maximum energy for the four rocket dimensions calculated previously.

Table 3. Maximum charge Q, capacity C, and maximum energy W, for effective rocket dimensions c (semimajor axis) and b (semiminor axis).

c (Meters)	b (Meters)	C (Farads)	Q_{max} (Coulombs)	W_{max} (Joules)
11	1	4×10^{-10}	2.7×10^{-4}	91
27	0.5	6.4×10^{-10}	6.7×10^{-5}	3.5
100	5	3×10^{-9}	6.7×10^{-3}	7500
300	5	7×10^{-9}	6.7×10^{-3}	3200

It is obvious that the maximum charge which can be carried by a rocket is trivial compared with the charge transferred by lightning which varies from 3 to 40 coulombs. In addition, the amount of electrical energy stored on a rocket is at least 5 orders of magnitude less than is involved in lightning flashes.

On the other hand, charge stored on a rocket entering a region of electric field will lower the threshold for breakdown and the triggering of lightning. Unfortunately, there are no available measurements of the charge carried by rockets to estimate this effect. Similarly, there are no values available for the atmospheric electric perturbations caused by the firing of a rocket and its passage through the atmosphere.

METHODS OF SENSING HIGH ELECTRIC FIELDS IN CLOUDS

For several reasons, the electric field intensities seen at the earth's surface are generally smaller than those encountered within clouds: The charge within and around clouds usually occurs in both polarities so that the electric field seen at the surface of the earth is the superposition of opposing fields. The observed field intensity therefore usually has an appreciably lower magnitude than that produced by either polarity of charge alone. Furthermore, each charge in the atmosphere and its image within the earth comprise an electric dipole; the intensity of the electric field decreases with the cube of the distance from the observer to the dipole.

Another field reducing effect is the formation of a screening layer of charge at the edge of clouds caused by capture of ions moving from the clear air under the influence of the electric fields produced by charges within the cloud.

For these reasons the electric fields seen at the surface of the solid earth are rarely much in excess of 100 V cm^{-1} even at the time just before lightning occurs nearby. On the other hand, immediately after a discharge, the field may be reversed and exhibit values of a thousand volts/cm^{-1}, decaying in a few seconds to the value observed before lightning occurred.

From various measurements it appears that electric field intensities within electrified clouds may often be as great as several thousand volts cm^{-1}. With data from sparks produced in the laboratory, one would expect that fields as great as 10^4 V cm^{-1} may be necessary to initiate lightning naturally within such clouds.

To sense the intensity of electric fields within clouds several techniques may be used:

1. <u>Penetrations with instrumented rockets</u>.

Dr. W. P. Winn of the National Center for Atmospheric Research has devised and used successfully electric-field sensitive instruments which are carried on spinning rockets to altitudes of about 20,000 feet above sea level. The radial components of any electric field vector produce a displacement current in the rockets. As the rocket rotates a sinusoidal signal is generated which is proportional to the external electric field and essentially is unaffected by charge on the rocket. The signal is telemetered back to earth with a low-power FM transmitter using the rocket itself as the antenna. In preliminary measurements, electric field intensities of up to 700 V cm^{-1} have been observed in electrified clouds. The maximum electric fields measured during the same period at the surface of the earth just below these clouds did not exceed 100 V cm^{-1}.

2. <u>Measurement from instrumented aircraft</u>.

Airplanes may be equipped with devices to measure the intensity and direction of the atmospheric electric field, but this is a difficult problem inside thunderstorm clouds. A large part of the difficulty arises from charge that the aircraft acquires in flight by the action of the engines, collisions with particulate matter (aerosol particles, cloud droplets, rain and snow) and by point discharge under high electric fields.

The presence of an airplane distorts and concentrates the atmospheric electric field so that extensive adjustments and calibrations are necessary to use the instruments in clear air. Within electrified clouds the difficulties of interpreting the measurements are even more formidable due to the charge transfers between the moving plane and cloud particles, and, if point discharge occurs from propellors, wing tips, or jet exhausts, the calibrations made in clear air may no longer be valid.

To measure the atmospheric electric fields with an airplane one must provide in essence two field sensing devices for each component of the electric field and then subtract their adjusted outputs. This process requires the installation and operation of 6 field sensing devices for measurement of the 3 field components, although some recent ingenious devices designed by Dr. H. Kasemir of ESSA, Boulder, have reduced this number to three.

Indications of high electric fields within clouds have been obtained with aircraft by Gunn and Fitzgerald who report values as great as 3,000 V cm^{-1}.

3. Balloon-borne sensors.

Many of the difficulties encountered in determination of the electric field intensities within clouds arise from the motion of the vehicle transporting the instruments. These difficulties can be minimized by the use of balloons, free or captive, to carry field measuring devices into electrified clouds. Measurements made in this manner are limited to one region or one penetration of a cloud but this limitation may be acceptable for research purposes.

During the summer of 1969, in an effort to determine the range of maximum electric fields within clouds, C. B. Moore mounted an electric field mill inside a spherical electrode from a Van de Graaff high-voltage supply. The mill was recessed, facing downward, in the re-entrant portion of the electrode so that no sharp points protruded to produce corona at low fields. Signals from the field mill were pre-served on a small portable tape recorder also mounted within the sphere, thus eliminating the telemetry antenna which is usually a good source of corona. This instrument was carried into electrified clouds be-neath a captive balloon and obtained indications of electric field intensities at the surface of the sphere in excess of 12,000 V cm^{-1}. The conducting sphere concentrates external fields by a factor of 3; the field intensity indicated also varies with the angle θ that the external field E_o makes with the suspension axis of the sphere. The resultant of these two factors is to produce an indicated intensity

$$E_{Indicated} = 3E_o \cos\theta.$$

If we assume a vertical external field and correct for the concen-trating effects of the housing, the measurements made during the summer

of 1969 indicate undisturbed electric field intensities in the clouds in excess of 4,000 V/cm.

These measurements with a single mill could not discriminate between the field indication produced by external electric fields and those arising from charge trapped on the spherical electrode. The measurements will be repeated with a new system that uses two improved field mills in a similar spherical housing from which one mill will look vertically, as at present, while the other will look horizontally. The whole system will be caused to rotate slowly so that a modulation on the horizontally looking mill will be produced that is proportional to the horizontal component of the external field multiplied by the cosine of the azimuth angle. The horizontal component of the electric field will then be given by a sinusoidally varying function superimposed on a D.C. component, the D.C. component resulting from any net charge collected on the surface of the sphere. The measured values of the vertical and horizontal electric field components and the self-charge-induced D.C.-offset will permit both correction of the magnitudes of the field components and a determination of the charge collected on the instrument.

This instrument is not suitable for use in naval operations but can be invaluable in the collection of information about cloud electrification.

4. Radar sensing of electric fields in rain clouds.

The introduction of measuring instruments into electrified clouds distorts the natural electric fields; often the field intensity measured is limited by the presence of the instrument which itself causes dielectric breakdown of the air and the release of charge resulting in spurious readings. To measure the maximum fields that exist in clouds one needs to sense — remotely and without the introduction of instruments — the presence of the electric field within clouds.

One method now under investigation for accomplishing this is the measurement of the distortion of raindrops in clouds. Raindrops are deformed in the direction of the electric field. Water drops are essentially good conductors containing sufficient charge carriers, even when neutral, to polarize in the presence of a field. The action of the field is to cause positive charge to move in one direction and negative charge to move in the opposite direction. When the field is sufficiently intense these forces cause physical deformation of the drop along the field direction such that an elongated drop is produced. If the intensity of the field is increased sufficiently, the drop can actually be disrupted by the action of the electric forces.

The drop distortion in a volume of cloud can be sensed with a radar. A raindrop illuminated by a microwave pulse of electromagnetic

radiation reflects or "back-scatters" radiation that is roughly pro-
portional to the drop dimension in the direction of the incident
electric vector. If the incident electric vector is rotated through
a complete turn about the line of sight, the back scattered radiation
will vary in intensity as the direction of the electric vector is first
along the maximum drop dimension and then along the minimum dimension.
From measurements of the cloud reflectivity and the amplitude of the
"cross-polarized" back scatter it appears that the magnitudes and di-
rections of the electric fields in clouds may be inferred by remote
means. This procedure has promise, and a radar with polarization di-
versity is now under construction at New Mexico Tech.

Another radar technique for remote sensing of electric fields is
also presently under development. Raindrops are excited into oscil-
lation as they fall, and the changing cross section of a vibrating drop
appears as a true amplitude modulation of the back scattered radar
signal. This effect has been demonstrated in the laboratory with drops
freely suspended in a vertical wind tunnel. The natural frequency of
vibration is related to the drop size, surface tension, and also to the
electric field, since the electric field produces a stress on the drop
surface in opposition to surface tension forces, thus altering the
effective spring constant. Studies of how the presence of an electric
field alters the drop vibrational frequency are underway. The shift in
the drop vibrational spectrum, for example, before and after a light-
ning stroke, may be used to infer electric field values.

COMPARISON OF CONTINENTAL AND MARITIME ATMOSPHERIC ELECTRIC FIELDS.

The energy that can be released by a lightning discharge from an
electrified cloud increases with the cloud volume and with the square of
the maximum electric field. Over the land the atmospheric electric field
measured at the surface is limited by discharge currents arising from
grounded points. Under high electric fields, exposed conducting points
such as grass, trees, and structures concentrate the electric field to
such an extent that air around the points becomes ionized. This permits
electric currents to flow from the earth and acts to reduce the electric
stress. When the electric field intensity exceeds about 10 or 15 V cm^{-1},
currents in excess of one microamphere can flow from each point. As a
result, electric field intensities in the air near the earth beneath
thunderstorms are limited and rarely exceed values in excess of 100 V cm^{-1}
Perhaps for this reason repeated attempts at New Mexico Tech to trigger
lightning by injecting wire-trailing rockets into thunderstorms over land
have been unsuccessful. The Apollo 12 vehicle is the only rocket of which
we are aware that has triggered lightning at low altitudes over land
surfaces.

In contrast to this are the successful initiations of lightning by Dr. M. M. Newman of the Lightning and Transients Institute who fired wire-trailing rockets from a small vessel off the Florida coast. The resulting lightning was often initiated when the rocket was no higher than 100 meters above the water; this suggests to us the existence of a high electric stress over the water surface.

It is perhaps worth noting that evidence is also available from antiquity that indicates the presence of especially high electric fields over water surfaces during disturbed weather: St. Elmo's fire is one result of intense point discharge. It is true that point discharge can occur without much visible luminosity, but noticeable St. Elmo's fire is indicative of intense point discharge and very high electric fields.

Our measurements of the point discharge currents from the mast of an LSM operating on the Atlantic Missile Range indicate values that are ten times those flowing from a similar installation on the beach of Grand Bahama Island. From these observations we may infer that the electric field intensities under thunderstorms over water surfaces are similarly enhanced. To investigate this effect further, we have attempted the direct measurement of electric fields beneath thunderstorms over the ocean with instrumented aircraft. The field intensities encountered were much higher than those over land, but the data were confused by saturation of the measuring instruments in the very high fields and by the effects of splashing raindrops which charged the aircraft.

Better measurements are needed, but we know enough to state that the potential for the triggering of lightning and for the release of stored charge is much higher over the oceans than it is over land. For this reason, a large rocket injected from beneath a water surface into a region of high electric field has a high probability of initiating lightning and becoming part of the conducting channel.

The apparent absence of corona points over the ocean surface probably accounts for the existence of high fields, but there is no adequate description of the atmospheric electric processes over the ocean during disturbed weather. In general, little is known about thunderstorms over oceans: we know nothing about the distribution of charge or the polarity. In addition, we don't know whether such thunderstorms are electrically more vigorous because of the low point discharge emission, or whether they are less vigorous because of it.

The atmospheric electric state produced by convective clouds over the water and its possible effects on ocean launching sites can at best be a subject of speculation at the present time. Definitive studies in electrified clouds and in the air above the oceans are sorely needed. Such studies should include instrumented aircraft flights over, through, and

under clouds, instrumented rocket penetrations, and studies of the sequence of electrical events as seen from the surface beneath oceanic thunderstorms. Measurements of the visual and radar thickness of clouds should be correlated with the electric field and other measurements to help develop criteria useful for establishing minimum hazard situations.

SUGGESTIONS FOR MINIMIZING HAZARDS IN OPERATIONAL PROCEDURES UNDER ELECTRIFIED CLOUDS

1. On the basis of the Apollo 12 experience, it is mandatory that the electronic sensing and computing elements of guidance systems be made immune to lightning transients.

2. Although no lower limit to cloud thickness can presently be given, we might guess that vehicle penetration into clouds less than 6,000 to 8,000 feet thick constitutes a minimal hazard situation.

3. Whenever possible, probing by aircraft or small sensing rocket penetration into clouds thicker than 5,000 feet should precede vehicle launches.

4. Whenever possible, radar evaluation of rate of echo growth as a measure of potential convective and electrical activity should be made.

5. Short range sferics detectors and lightning flash counters should be employed to warn of the occurrence of nearby lightning. Lightning transients may be detectable even from below the ocean surface.

6. The measurement of point discharge current at the surface (as a simple means of detecting high electric fields before lightning has occurred) should be made in all cases when clouds are present.

SUGGESTION FOR DESIRABLE STUDIES

1. Development of remote sensing techniques for the study of electric fields in clouds over the ocean must be implemented. The technique of cross polarization analysis of radar returns is promising. Similarly, optical polarization measurements of cloud surface reflected light may be indicative of electric fields strong enough to orient crystals near the surface. Such a technique could be utilized both from surface measurements as well as from aircraft. Other means of remote measurements of fields in clouds should be explored. Particular attention should be given to the exploration of new methods suitable to ocean vessel utilization.

2. Further development of small rocket probing techniques is needed. This method may well be the only simple technique available for measuring electric fields in clouds in times of emergency. In addition to the development of instrumentation, a program using these rockets to uncover electric field intensity versus cloud thickness relationships should be undertaken.

3. Lightning triggering experiments over the ocean should be made with the intent of exploring the possibility of relieving the electric stress in clouds prior to a launch. A trailing wire on a rocket might be used. Again, cloud thickness and electric field measurements should be made simultaneously. The nature of the triggered, lightning stroke and continuing currents over the ocean should be studied using high-resolution field-change instruments and high-speed cameras.

4. The charge carried on operational vehicles should be measured during test firings, along with the space charge left behind and the conductivity in the rocket exhaust.

5. A determination of the maximum electric fields existing over the ocean surface should be made for all weather conditions. We suggest that, since surface vehicles distort the electric field and often produce corona by their presence, a submarine would be ideal for such measurements. Great care should be taken to eliminate point discharge from the measuring instrument and its support.

6. Laboratory studies, using modeling tanks with water surfaces in various stages of agitation, should be initiated to study the electrical behavior of water surfaces under high electric stress.

7. A very general study of thunderstorm properties over the ocean and how they differ from storms over land is needed. Such information is essential in projecting what we now know about storms over land to ocean situations.

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APPENDIX C

CIRCUIT ANALYSIS

This appendix is an analysis of spacecraft circuitry.

Automatic Abort System Circuit Analysis

The emergency detection system wire routing in both the service module and spacecraft adapter is in close proximity to the skin (see fig. C-1), and therefore could be considered susceptible to induced voltage and current in the emergency detection system voting circuit. The analysis assumes a lightning current of 10 000 amperes with a 1 μsec rise time with a duration of 10 μsec. A further assumption is that 10 percent of the total current is concentrated under the emergency detection system wiring in the spacecraft adapter. With these conservative assumptions, the model for the emergency detection system voting logic power circuit inductive coupling is as follows:
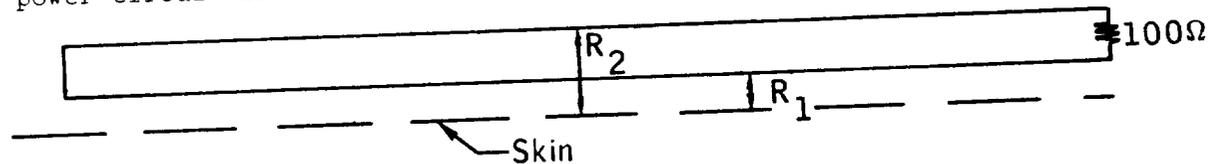
The induced electromotive force ε in the circuit is determined by

$$\varepsilon = \frac{\mu_o l}{2\pi} \times \ln \frac{R_2}{R_1} \frac{di}{dt}$$

where $\mu_o = 4\pi \times 10^{-7}$

$l = 30$ feet $= 9.15$ meters

$R_2 = 3$ centimeters

$R_1 = 0.3$ centimeters

By applying the limiting factor

$$\frac{di}{dt} = \frac{1 \times 10^4 \text{ amperes} \times 0.1}{1 \times 10^{-6} \text{ sec}} = 1 \times 10^9 \frac{\text{ampere}}{\text{sec}}$$

then

$$\varepsilon = \frac{4\pi \times 10^{-7}(9.15)}{2\pi} \times \ln \frac{3}{0.3} \times 10^9 = 42 \times 10^2 \text{ volts}$$

therefore

$$I = \frac{42 \times 10^2}{1 \times 10^2} = 42 \text{ amperes for 10 } \mu\text{sec}$$

This voltage level may result in insulation breakdown, however, because of the short duration, the operation of the emergency detection system should not be affected. The closed relay contacts in the instrument unit would not be affected by the 42 amperes for 10 μsec.

Ordnance Circuit Analysis

The effect that an electrical discharge would have on the pyrotechnic system was evaluated in the following areas: voltages induced on the single bridgewire Apollo standard initiator (pin to pin or pin to case) and voltages induced on the pyrotechnic initiating circuitry itself causing inadvertent operation. The design characteristics of the system are shown in table C-I.

The following analysis indicates the probable magnitude of the induced voltage and currents in the initiator circuitry. The canard deploy system was selected the most susceptible circuit because the initiator wiring is in close proximity to the skin for a long length (see fig. C-2) and the current density is greatest on the tower since the skin cross sectional area is the least of the complete stack.

The following compensating factors were used to provide a more realistic analysis.

a. The current will not be concentrated under the initiator circuit (10 to 1 reduction)

b. Shielding will provide attenuation at the frequency assumed for the electrical discharge (10 to 1 reduction)

c. The initiator circuitry has twisted wires which provide a cancelling effect (10 to 1 reduction).

The model for the canard deploy initiator circuit inductive coupling is as follows:

Analysis (pin to pin):
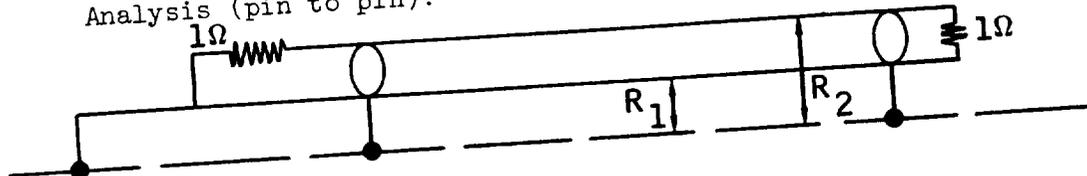
The induced electromotive force ε in the circuit is determined by

$$\varepsilon = \frac{\mu_0 \ell}{2\pi} \ln \frac{R_2}{R_1} \frac{di}{dt}$$

where $\mu_0 = 4\pi \times 10^{-7}$

$\ell = 26$ feet $= 7.8$ meters

$R_2 = 0.6$ centimeters

$R_1 = 0.3$ centimeters

By applying the limiting factors

$$\frac{di}{dt} = \frac{1 \times 10^4 \text{ amperes} \times 10^{-3}}{1 \times 10^{-6} \text{ sec}} = 1 \times 10^7 \frac{\text{ampere}}{\text{sec}}$$

then

$$\varepsilon = \frac{4\pi \times 10^{-7}(7.80)}{2\pi} \times \ln \frac{0.6}{0.3} \times 10^7 = 10.8 \text{ volts}$$

If the line resistance and inductance are neglected, the voltage will divide equally between the fuse resistor and the initiator or approximately 5 volts. This represents a power of approximately 25 watts for 10 μsec.

The pulse energy non-susceptibility of the initiators has been demonstrated to 1225 watts for 10 μsec.

The probability of inadvertent operation of the pyro initiating circuits is remote since all wiring is within the command module and is not in close proximity with the external skin. Even if the induced voltage was of sufficient magnitude, the duration of electrical discharge (microseconds) and induced voltage is not sufficient to pull in relays (milliseconds).

TABLE C-I.- SINGLE BRIDGEWIRE APOLLO STANDARD INITIATOR CHARACTERISTICS

Max no-fire current - 1 amp for 5 minutes
Max no-fire power   - 1 watt for 5 minutes
Max all-fire current - 3.5 or greater
Continuity current - 25 applications of 50 ma for 1 min each
Thermal - 400° F for 1 hour
Insulation resistance - 2 megohms at 250 volts dc
Dielectric strength - 200 vac for 1 minute
Electrostatic sensitivity - 25 000 v discharge from 500 mmf
  capacitor

Dudding characteristic

Ignition mix precludes dudding. No dud experienced in all tests
  to date.
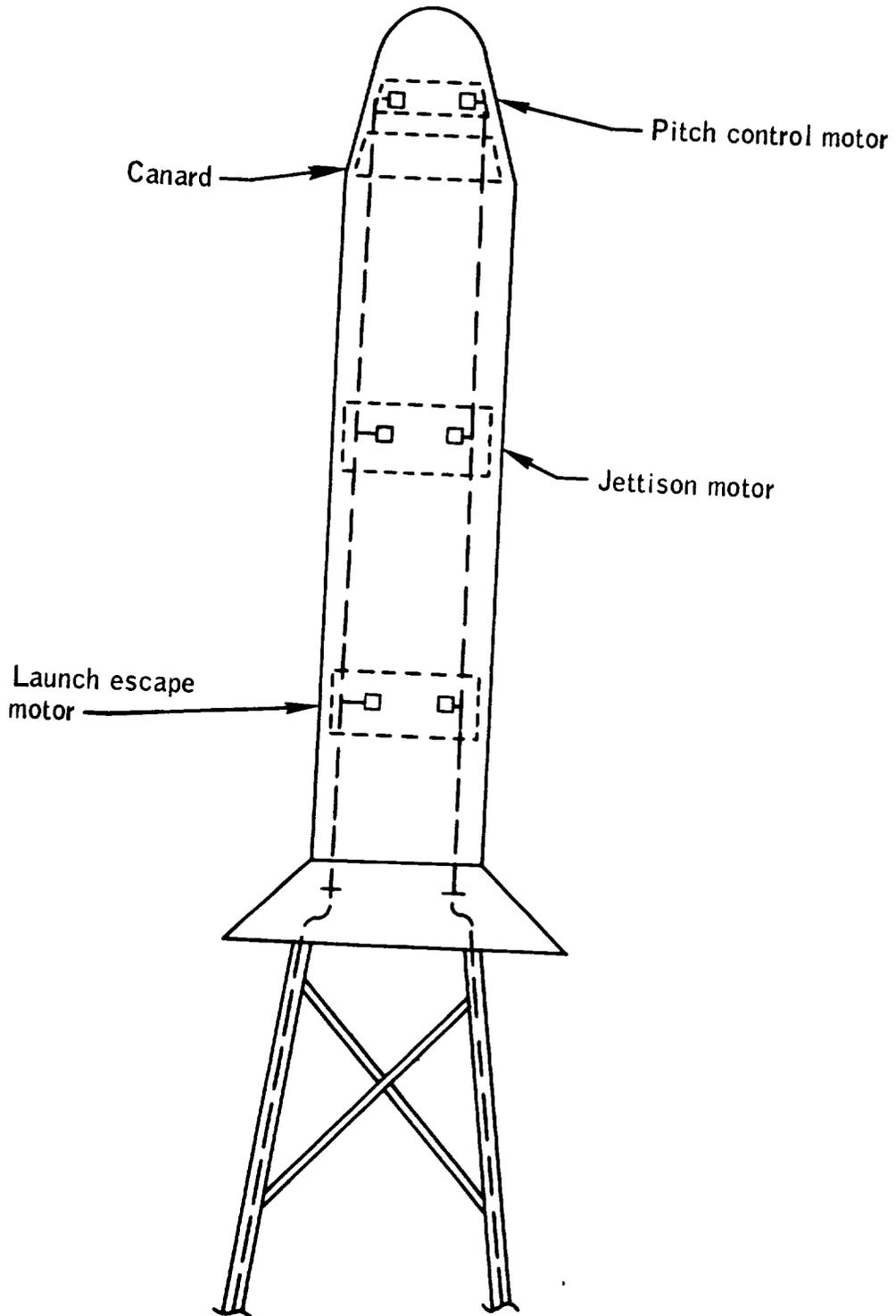
Figure C-2.- Tower pyrotechnic wire routing.