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LONG LINE LOITER: POTENTIAL SHOCK HAZARDS OF AN AIRBORNE ELECTRICALLY CONDUCTIVE LINE

Eric J. Jumper, et al

Aerospace Medical Research Laboratory
Wright-Patterson Air Force Base, Ohio

June 1973

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JUNE 1973

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23

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When a conductive line is towed in a circling-line maneuver by a fixed-wing aircraft, a potential static electricity hazard is developed. This condition is described and analyzed herein. Peak current surges expected for systems with and without ground contact during fair weather conditions are presented. Protection equipment and procedures recommended include grounding the line, the use of special gloves, and avoidance of inclement weather.

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i

FOREWORD

The research in this report was conducted from March 1970 to April 1971 by the Flight Environments Branch, Human Engineering Division, Aerospace Medical Research Laboratory under Project 7184, "Human Performance in Advanced Systems."

The authors acknowledge the contributions of Mr. John J. Earshen of Cornell Aeronautical Laboratories, Inc., for his concern and assistance in the analysis of the problem. Also acknowledged is Mr. C. Austin of the Avionics Laboratory, Wright-Patterson AFB, and Captain Doug Lockie, Aeronautical Systems Division, Wright-Patterson AFB, for their help and suggestions; Mr. B. C. Dixon, Lear Siegler, Inc., for the design of test apparatus; Technical Sergeant Roland W. Fancher, Aerospace Medical Research Laboratory, Flight Environments Branch, for his ideas and assistance; and Lt. Col. John Simons, Chief, Flight Environments Branch, for his encouragement and help.

This technical report has been reviewed and is approved.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION I

INTRODUCTION

Because of the increasing interest in the use of the circling line phenomena for such applications as rescue and communication, electrically conducting long lines may become common in these programs. The Navy is studying the GARD (Ground Anchor Retrieval Device) rescue system, which employs an OV–10 and a steel cable to rescue a downed airman[ref [illegible]]. The Aerospace Medical Research Laboratory is developing an application requiring the use of electrical wire[ref 2 through 7].

Until November 1969, no electrically conducting lines had been flown by the Aerospace Medical Research Laboratory and the solution to static electrical problems had been to allow the line to touch ground and discharge.

On 13 November, a ½-inch, hollow-core-woven nylon line, 2,000-pound test, containing #18 gage wires was flown. 2,500 feet of line was deployed with the aircraft at 1,500 feet AGL (Above Ground Level). The aircraft held a tight orbit, allowing the end of the line to stall and touch the ground. The usual precaution of allowing the line to ground out was taken. After the ground personnel had come in contact with the line, the line continued discharging at short and nearly regular intervals. The amount of each shock was not the same and it wasn't until two severe shocks were felt that the test was abandoned.

This report covers investigations of the cause of the phenomena, its dangers, and special handling requirements.

SECTION II

ANALYSIS AND METHODS

A. LINE CHARACTERISTICS

Initially it was assumed that the interaction of nylon rubbing on polyethylene insulation on the wires was causing the line to charge (the wires were acting as capacitors) and discharge rapidly along its entire length.

On the assumption that the line was the main contributor, a new line was designed and constructed, using 3/8-inch, hollow-braided polyethylene line with 4 strands of D–2 field telephone wire. The insulation on the wire was also polyethylene. If the charge was due to the interaction of the line and the wire insulation, the no-slip arrangement of the polyethylene on polyethylene interface might solve the problem.

The first test with this line was flown with only 2,400 feet of line. Because of the line length and high winds, it was necessary to maintain the aircraft at 500 feet AGL and to keep the line in contact with the ground. This condition was judged to be potentially unsafe and the test was discontinued. During the ground contact, however, the line was handled in the aircraft and the static electricity did not evidence itself. It was assumed that the problem had been solved, and construction was continued to increase the line length to 3,600 feet.

A second flight with 3,600 feet of line was flown with ease from 2,000 feet AGL. At first, no static electricity was evident, but after handling the line for several minutes a shock was felt by a ground crewman and the tests were terminated. It appeared that as soon as the ground crewman was the only link between the line and the ground, the line would begin to discharge at near regular intervals. The jolts did not appear as large as those felt from the nylon line, but were judged of sufficient magnitude that special handling rules should be formulated.

Although the insulation-line interaction may have compounded the problem, the static electricity phenomena appeared to be associated with the conductive feature of the line rather than its construction.

B. BACKGROUND INVESTIGATION

The biggest diffierence between the flights described was the altitude above the ground at which the aircraft was flying. Consequently an investigation was begun to determine if atmospheric potential might possibly be the prime contributor to the static electricity phenomena.

1. Atmospheric Electricity Considerations:

Investigation into the electrical nature of the atmosphere yielded the following simple model for fair weather conditions. The earth can be considered as electrically negative and the atmosphere increasingly positive vertically to about 80 km, the beginning of the ionosphere. The potential across this 80 km is maintained at about 400K volts. Because the conductivity of the atmosphere increases rapidly with altitude, the field strength is not uniform at 5 V/meter as might be expected, but is generally greatest near the surface and decreases with altitude. Measurements taken in recent years by Clark in 1958, and Kraakevik and Hoppel in 1967 indicate that the atmospheric conductivity increases exponentially up to about 6 km above the surface. $\sigma = \sigma_0 e^{\alpha z}$ where σ_0 is the conductivity at the surface, and z is the height. Characteristics above 6 km will not be discussed. The charging and discharging current can be considered to flow between the ionosphere and the earth's surface just equal to the total charging current.

This model can be analyzed as follows: Consider the electrical field strength at any altitude to be uniform in a plane perpendicular to the local vertical. Then

$$\mathbf{E} = -\frac{dV}{dZ}$$

Where **E** = Field Strength (volts/m)
V = Atmospheric Potential at Altitude Z (volts)
Z = Altitude (m) **(1)**

The conduction current is related to the atmospheric conductivity and field strength as follows:

$$i = \sigma \mathbf{E}$$

Where **i** = Conduction Current (amperes)
σ = Atmospheric Conductivity (m/ohm) **(2)**

Adopting the exponential model for conductivity shown above and assuming that the conduction current is constant during discharge, equation 2 becomes, for altitudes up to 6 km.

$$\mathbf{E} = E_o e^{-\alpha z}$$

Where E_o = Field Strength at Zero Altitude (volts/m)
($E_o = i/\sigma_o$, or $i = \sigma_o E_o$) **(3)**

Note in equation 3 that E_o, α are constant for specified atmospheric conditions. Clark, and Kraakevik and Hoppel give the following average values for fair weather conditions.

$$\alpha = 2.5\ (10)^{-4}\ m^{-1}$$
$$E_o = 100 \text{ volts/m}$$ **(4)**

Using equations 3 and 4, the potential at any altitude h less than 6 km with respect to ground is approximated by

$$V(h) = -\int_0^h 100\, e^{-2.5z \cdot 10^{-4}}\, dz \text{ [volts]}$$ **(5)**

Equation 5 is plotted in figure 1.

Note that these figures are for fair-weather conditions and the values could increase by orders of magnitude in the presence of deteriorating or adverse weather. Measurements show that deteriorating weather as far as 16 miles away has an effect on the local field

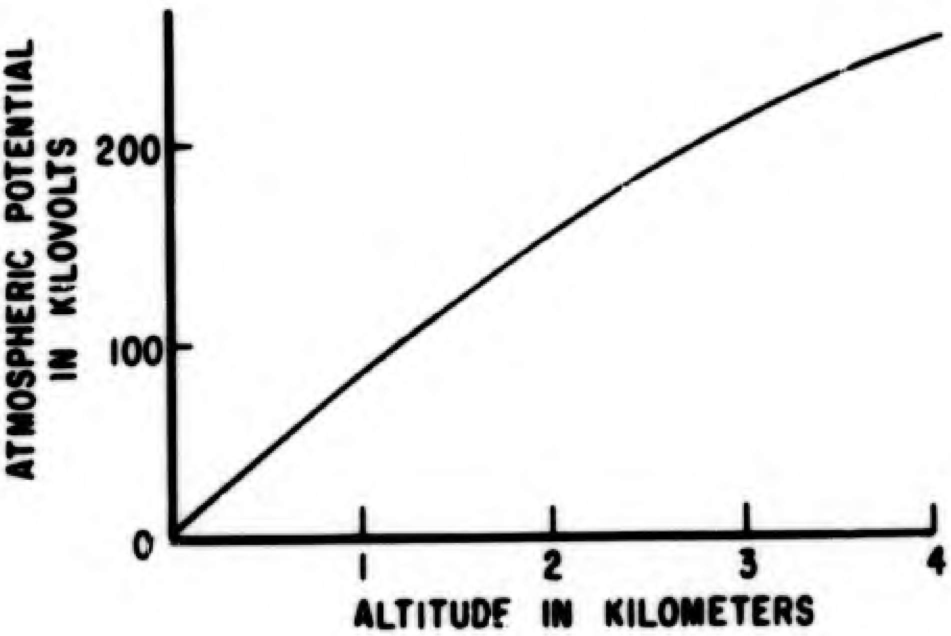

Figure 1. Atmospheric Potential vs Altitude

2. Nonatmospheric Electricity Charging:

a. Triboelectric Charging

Triboelectric charging, sometimes called frictional charging, is produced by the interaction of dissimilar materials coming in contact with one another. In our case the aircraft might become charged by such materials as dust, sand, snow, or moisture particles. The charging current magnitude depends upon the material, its mass and particle density, and the velocity at which these particles strike the aircraft. The charging currents are usually very small. When measured for helicopters at altitudes of less than 50 feet AGL, where charging particles are more likely to be present, currents are generally less than +50 microamperes. Extreme charging currents, however, in cases where blade downwash creates clouds of dust, currents of 100–200 microamps are likely to occur. In these cases, potentials at the helicopter have been recorded in excess of 10^6 volts.

At altitudes at which circling-line maneuvers are generally performed, very little electrical potential charge is caused by triboelectric charging. The mechanism must be considered, however, in cases where dust or sand have been carried to higher altitudes by atmospheric disturbances, or on dry days when small snow particles are likely to be suspended at flight altitudes[ref. 11]

b. **Precipitation:**

Of more concern is precipitation charging. Heavy rain, especially from cumulonimbus clouds, snow and other forms of precipitation can be charged and produce positive or negative charging currents in the order of 100 microamperes or more. Charging times to maximum voltage are extremely short[(ref 11)].

c. **Self-Generating:**

Aircraft engine exhaust, especially from turbine engines, is also a charging source but its charging rate is usually small enough to ignore in smaller aircraft; however, it should be considered when dealing with aircraft in the C–130 class[(ref 11)].

These charging mechanisms are present to some degree at all times; however, the magnitude of these factors in the ideal weather and small aircraft conditions in which we flew was probably very small. These are considered negligible in any analysis that follows.

3. **Steady-State Hazards**

a. **Potential Hazards:**

The following set of conditions are considered steady-state conditions:

Aircraft— (1) The aircraft is in straight and level flight, and no transient maneuvers (climbs, turns, airspeed changes, etc.) have occurred within the last few minutes or are anticipated to occur during the time period to be considered.

(2) The aircraft is in a continuous turn, during which the end of the line is not in a transient (see line parameters below). During this turn the aircraft is maintained at approximately the same altitude.

Line— The line is considered in steady state when the end of the line remains on the ground or off the ground at approximately the same altitude during the time period under consideration.

Weather— The weather conditions are "fair" as described under Atmospheric Electricity Considerations.

Under the foregoing conditions, there is no danger from any surge currents or high voltage differential within the line/aircraft system as long as a good electrical bond exists between the aircraft and the line. The hazards then would only be associated with those steady-state currents that would be induced by the altitude difference between the aircraft and the end of the line.

b. Analysis of the Steady-State Conditions:

The steady state condition was examined without and with ground contact as follows (see figure 2):

CASE I, No ground contact:

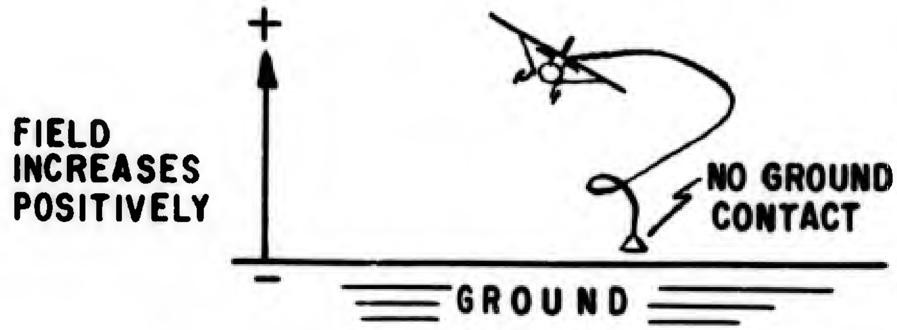

Figure 2. Case I, Line Not in Ground Contact

In the no-grounded case (figure 2), the system (A/C and line) potential with respect to ground is predominately that of the atmospheric potential at the aircraft altitude. The atmospheric potential is distorted approximately as shown in figure 3, increasing the electrostatic field intensity at the end of the line (ref. 10,12).

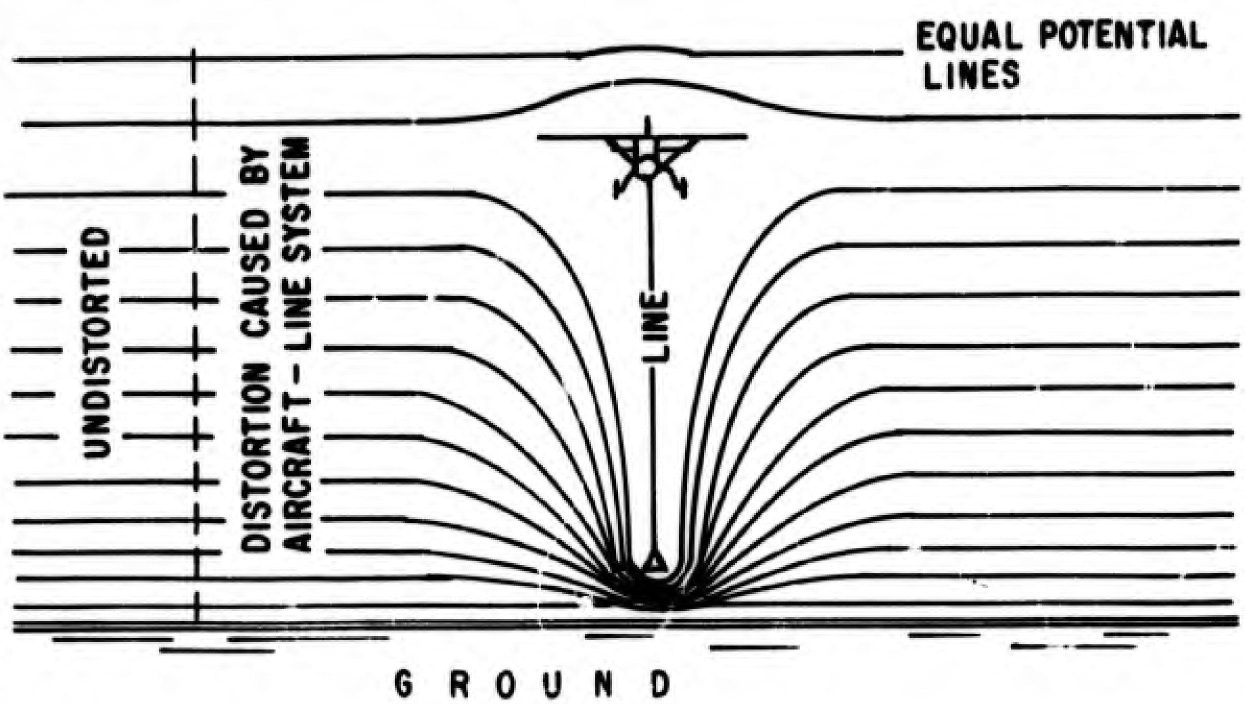

Figure 3. Atmospheric Distortion

The electrical circuit then can be represented as shown in figure 4. The amount of atmospheric distortion depends on the amount of system charging and discharging current and the adequacy of aircraft-line bond. The charging current in this case comes from the line and its end, while the discharging current originates mainly at the aircraft (although the line can contribute as a discharging source). The amount of current flowing in the system appears to depend on the physical makeup of the system components, and the atmosphere distortion concept and subsequent circuit diagrams assumes that the A/C is the only discharging source. This assumption is quite valid in those cases that we are concerned.

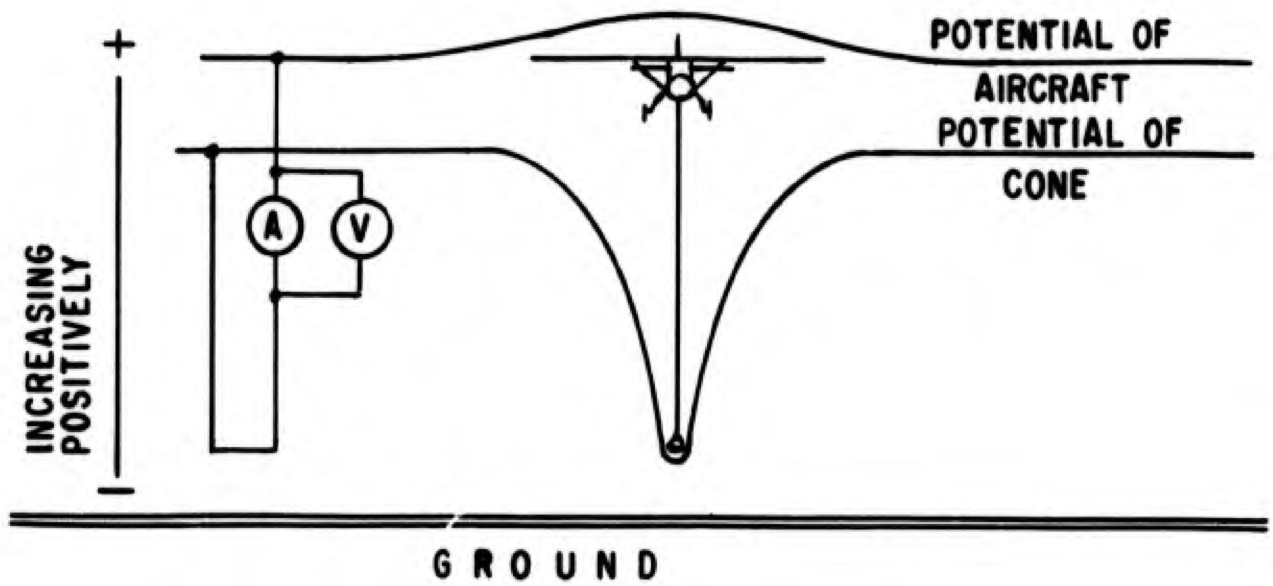

Figure 4. Circuit Diagram for Case I

CASE II: Steady-State Ground Contact:

In the ground contact case (figure 5) the atmospheric distortion is reversed from that of the no contact case, and the system becomes primarily negative with respect to the atmosphere as shown in figure 6.

In this case, a high electrostatic field intensity is placed on the aircraft end of the system. The subsequent circuit diagram is shown in figure 7.

The aircraft is assumed to be a better discharging source than the line. Since the line is grounded, the major influence is the discharge capability of the aircraft since the ground has an unlimited supply of charge available.

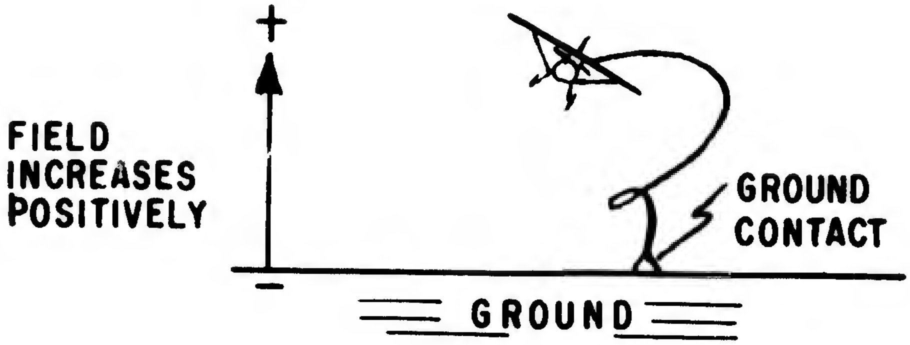

Figure 5. Case II Grounded-Line

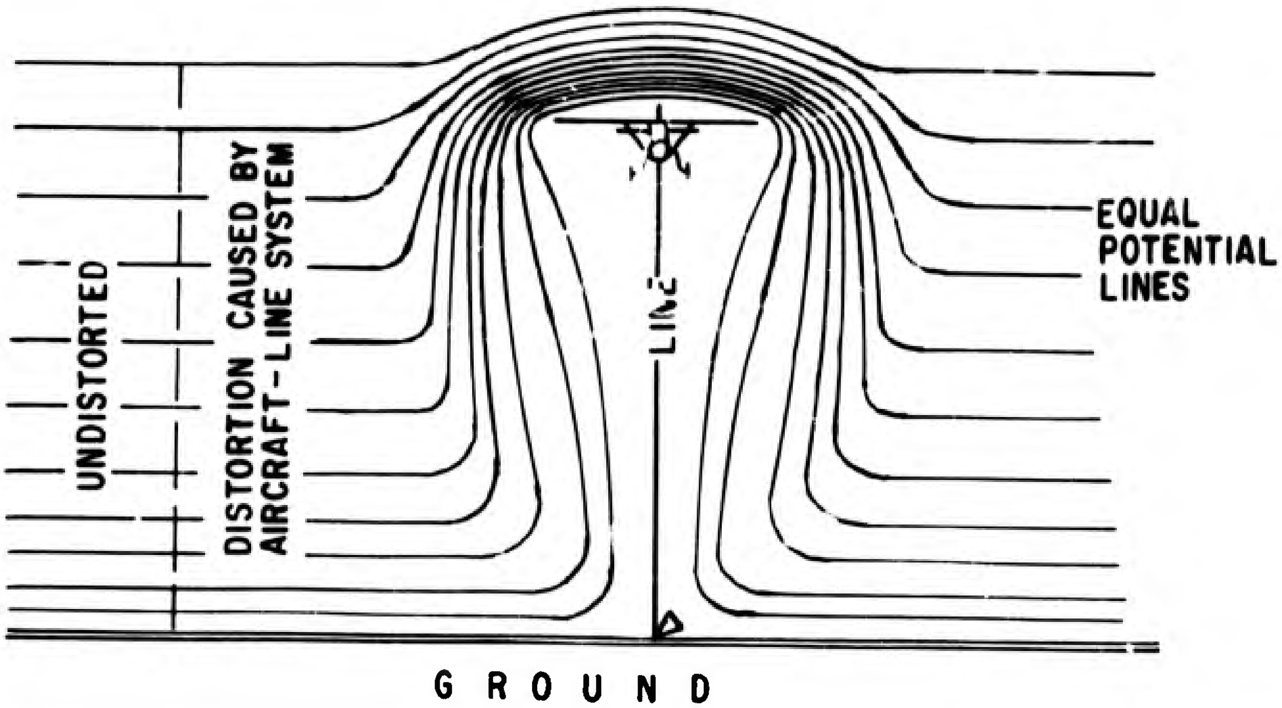

Figure 6. Case II Atmospheric Distortion

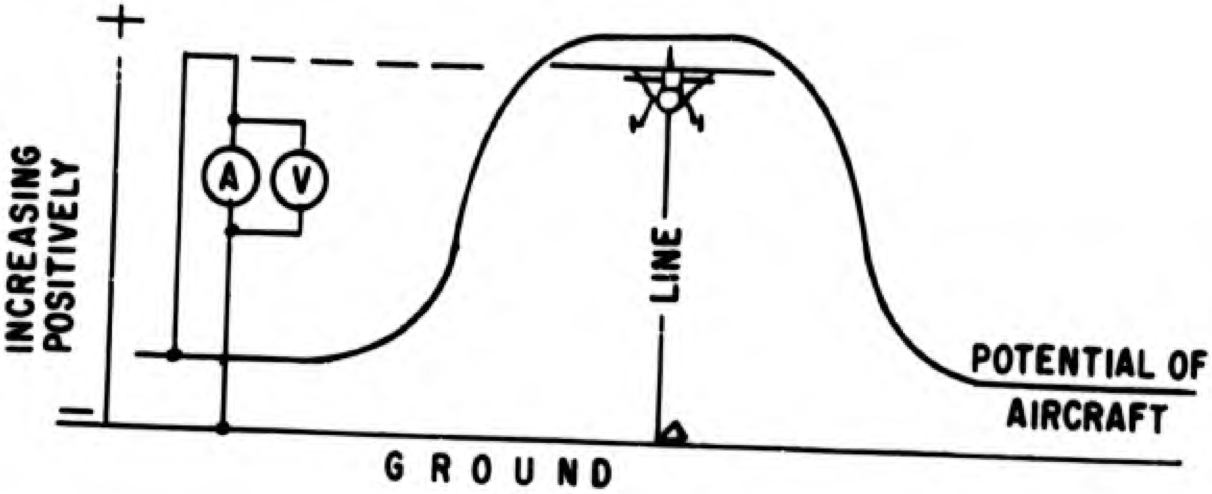

Figure 7. Case II Circuit Diagram

c. Experimental Investigation of Steady-State Hazards

An experimental flight test was conducted to measure the steady-state current that could be expected from a small-engine aircraft operating from 1,000 to 3,000 feet AGL on a fair-weather day.

(1) Test Equipment: The following test equipment was used.

(a) Aircraft—Cessna 206.

(b) Line—3,600 feet of 2,000-pound (breaking strength) polypropelene floater rope with four conductors as described earlier.

(c) Line End—The end of the line was fastened to a 2 by 2-inch-square, ⅛-inch-thick aluminum plate and bolted to a 10 by 16-inch fiberglass cone weighted to 20 pounds. (see figure 8.)

(d) Resistor Box—a resistor box (see figure 9) was fabricated to give seven selections of resistance ranging from 2 megohms to 400 megohms.

The line was placed in series with the resistance selected in the resistance box and the volt ohmmeter was connected across the resistance. Figure 9 shows the line coming into the box at Point A. The box is grounded to the aircraft, and all other grounds grounded to the box. In order to deploy the line in flight, it was packed into two packing barrels prior to the flight. The arrangement is shown in figure 10 depicting the total arrangement, including the weighted cone, prior to takeoff.

Figure 8. Line Bolted to Fiberglass Cone

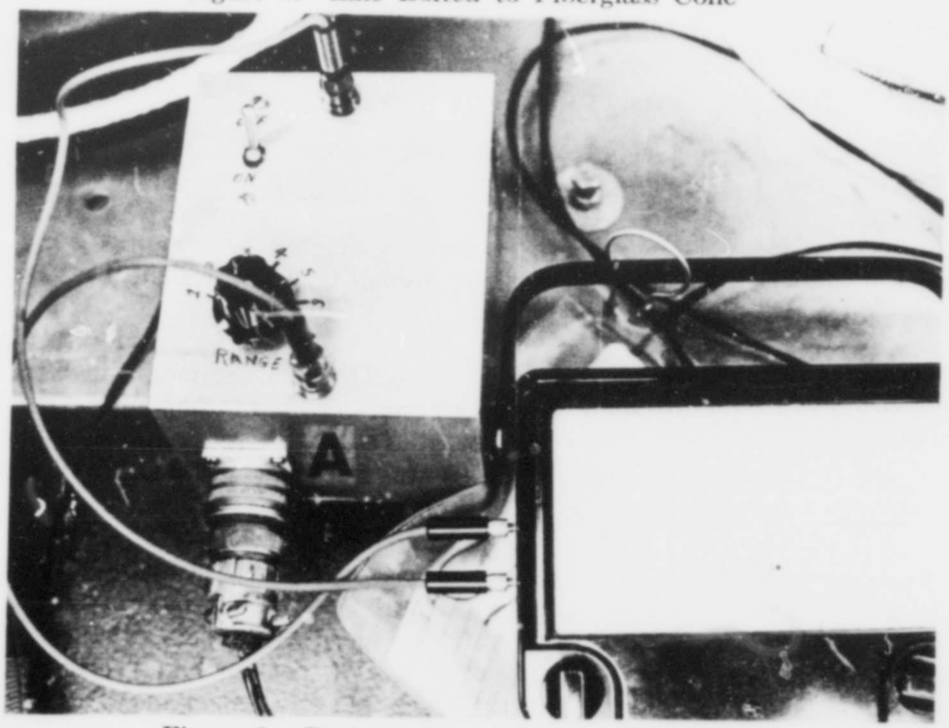

Figure 9. Resistor Box and Volt Ohmmeter

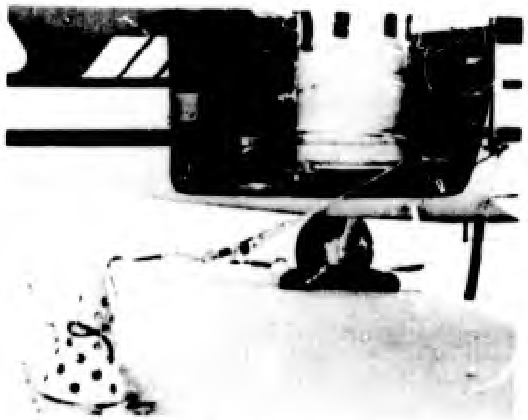

Figure 10. Task Equipment Arrangement

As an emergency safety precaution an electrically operated line cutter was installed should an inadvertent ground hangup be encountered[ref 7].

(2) Test Procedure: The entire 3,600 feet of line was deployed from the barrels in flight, and the ammeter readings were recorded for several flight parameters of altitude and airspeed during straight and level and pylon turn maneuvers. In addition, peak data was to be recorded for any ground contacts that might occur. The steady-state conditions included: straight and level at several altitudes up to approximately 3,000 feet AGL; pylon turn without ground contact and; pylon turn with ground contact.

(3) Test Data: The flight was flown on 30 September 1970 at Clinton County Air Force Base, Ohio, elevation 1,072 feet.

(a) Weather—Clear and cool, visibility more than 15 miles, scattered layer of clouds at about 4,000 feet, AGL.

(b) Winds—210 degrees at 4 knots surface winds and 300 degrees at 35 knots at 3,000 feet AGL.

(4) Results: The results of this test showed no requirement for further investigation of steady-state shock hazards. Extremely small currents were encountered with and without ground contact. A maximum current of 9 microamperes occurred at ground contact with a maximum altitude separation of 1,800 feet. Currents up to even 10^3 times this amount are unlikely to cause any hazard to aircraft, personnel or equipment[ref 13].

The data, however, reinforces our analysis of the phenomena as described in section II(B). Of particular interest is the constant current characteristic as reflected in table I. Line 1 in table I, for instance, exhibited a 0.2 to 0.3 μA current with an altitude separation of 50 feet. The maximum potential voltage difference for this separation is estimated from equation 5, section II(B) to be about 1,500 volts. With the range of resistances used, the voltaged difference between the end of the line and the airplane was changed from 0.4 volt to 40 volts.

Thus the field distortion at the end of the line varied from 1,460–1,500 volts toward the potential of the aircraft.

The field distortion caused by the aircraft-line system was about 50,000 volts during one orbit just prior to and just after ground contact. For example, the resistance was 2–200 megohms, and altitude separation was 1,800 feet (table I, line 5). Using equation 5, section II(B), the undisturbed potential was estimated to be about 50,000 volts. The difference in the voltage between the aircraft and the end of the line ranged from 3.0–300 volts, depending on the resistance selected, due again to the constant current characteristic. The field distortion is in this case about 50,000 volts again in the direction of the aircraft.

After ground contact (bottom line, table I), the following data were affirmed: 9 μA, resistance 2 megohms, altitude separation 1,800 feet. The estimated undisturbed potential difference was again 50,000 volts. The voltage difference between line end and aircraft was 12 volts, which represents a field distortion of about 50,000 volts, but this time in the direction of the ground.

TABLE I
DATA

CURRENT μA*	RESISTANCE (Megohms)	AIRCRAFT ALTITUDE (Feet AGL)	END-OF-LINE ALTITUDE (Feet AGL)	MANEUVER
0.2–0.3	2–200	3,000	2,950	TRAIL
0.3	2–200	3,300	2,000	PYLON TURN
0.4	2–200	2,500	1,800	" "
0.7	2	2,200	1,000	" "
1.5	2–200	2,000	200	" "
3.0–4.2	2–200	1,400	0	" "
6.0	2	1,600	0	" "
8.0	2	1,700	0	" "
9.0	2	1,800	0	" "

*Peaks were recorded from 42 μA to 92 μA at ground contact with resistance at 2 megohms. Because of the damping in the ammeter, these peaks have little significance.

4. Transient Hazards

a. Discharge Energy Levels:

The steady state hazards are considered very small. The major hazards during fair-weather conditions lie in the transients, particularly during the ground impact. Figures 3 and 6 indicate that for an altitude separation of 1,800 feet, the system's voltage must almost instantaneously change by 50,000 volts. The system can be analyzed as shown in figure 11. The energy of the discharge can be approximated by:

$$E_D = \tfrac{1}{2} CV^2 \tag{6}$$

where: E_D = Energy level in joules
C = Capacitance in farads
V = Voltage Differential

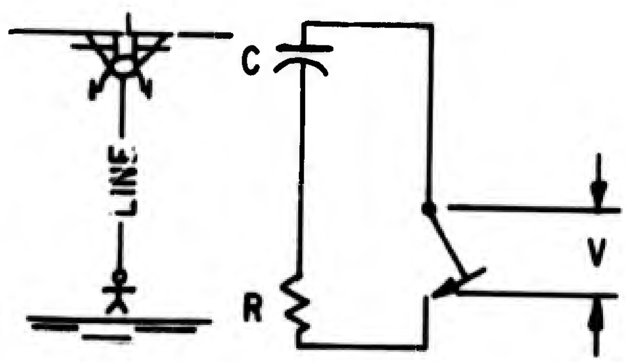

Figure 11. R C Circuit

A representative figure for the capacitance of a light aircraft of the Cessna 206 class is from 1,000 to 1,500 pf [illegible], thus, the energy of the discharge is:

$$E_{D_{1800}} = \tfrac{1}{2} C\ (V_{1800})^2$$
$$= 1.4 \text{ joules}$$

The discharge energy with altitude can be estimated using equations 5 and 6 as follows:

$$E_{D_h} = \tfrac{1}{2} C \left[\int_0^h E\, e^{[illegible]}\, dz \right]^2 \quad \text{(Joules)}$$

where h is the altitude in meters. (7)

A plot of this equation is shown in figure 12.

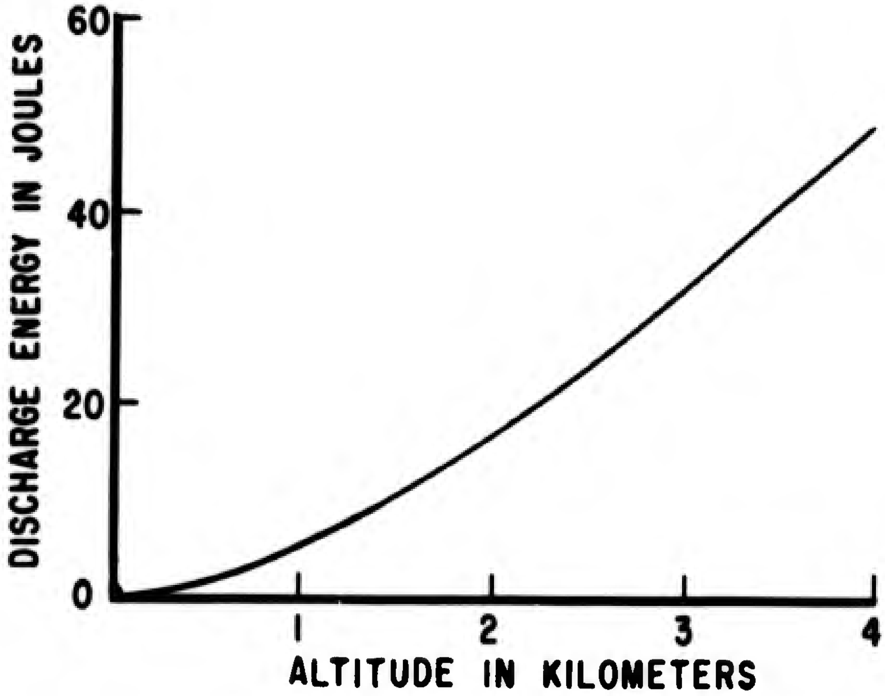

Figure 12. Energy Level vs Altitude for an Ideal Fair-Weather Day

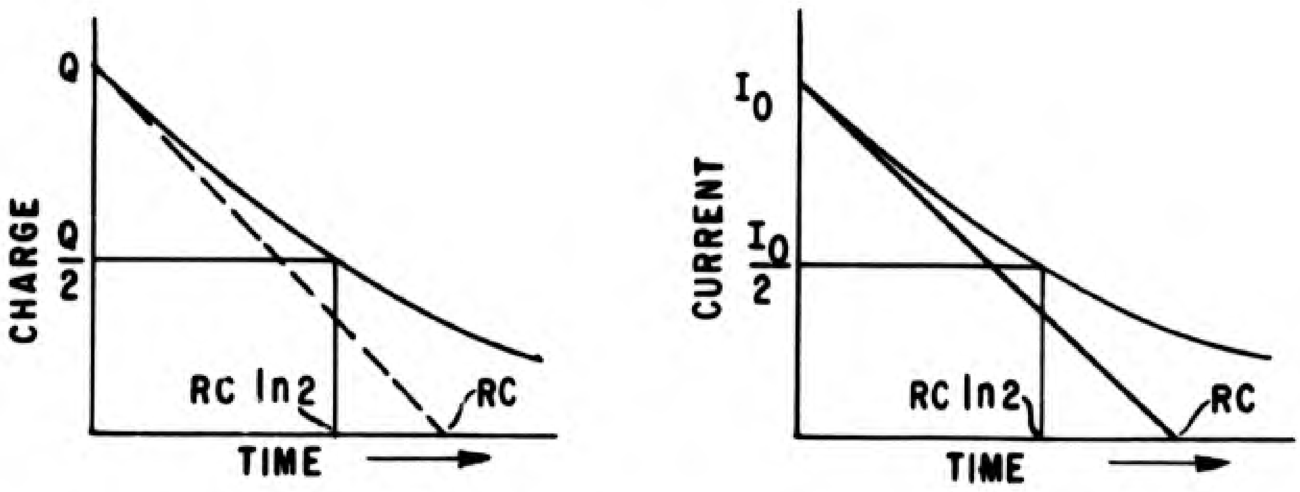

Figure 13. R C Circuit Characteristics

b. Surge Current Magnitudes:

The magnitude of a discharge in terms of joules is rather vague, thus it might be well to analyze the system as a normal RC circuit as shown in figure 13. Assume an aircraft altitude of 3,000 feet altitude and man as the resistance.

The amount of charge Q, a capacitor is capable of storing is the voltage, V, times the capacitance, C, or

$$Q = VC \tag{8}$$

The initial discharge current, I, is equal to the charge, Q, divided by the resistance, R, times the capacitance, C, or

$$I = Q/(RC) \tag{9}$$

Assuming:

V = 100,000 Volts (approximate atmospheric potential at 3,000 feet).
C = 1,000 pf (capacitance of a small aircraft).
R = Vary from 10 to 1,000 ohms. Average low voltage body resistance is about 25,000 ohms; however, at voltages above 1,000 to 2,000 volts, resistance is considerably less; 10 ohms is not unusual above these voltages. At the same time, arcing is likely to occur across the edges of the soles of shoes, rendering them negligible resistance[ref 13].

Using these:

$Q = CV = 10^{[illegible]}$ coulombs.
$I = Q/(RC) = 10^{[illegible]}$ to $10^{[illegible]}$ amperes.

Thus a peak surge of the discharge of 100,000 volts at $10^{[illegible]}$ amperes might be possible. Assuming the same C and aircraft attitude, peak surge current is plotted against body resistance in figure 14 with the hazard areas indicated.

5. Weather Hazards

The atmospheric potential can greatly change by the weather conditions. All analyses in this report were based on fair-weather conditions. If there is any electrical activity within 10 miles, the atmospheric potential is likely to increase significantly, and any hazards that were present in the fair-weather case are greatly magnified. In addition, the stresses imposed on the atmosphere by the presence of the line under certain conditions might draw a lightning strike. Because of the presence of corona discharge, a protective saturated charge blanket forms around the immediate area of the system, making it unlikely that any lightning strikes would incur as long as the system is in a steady-state mode.

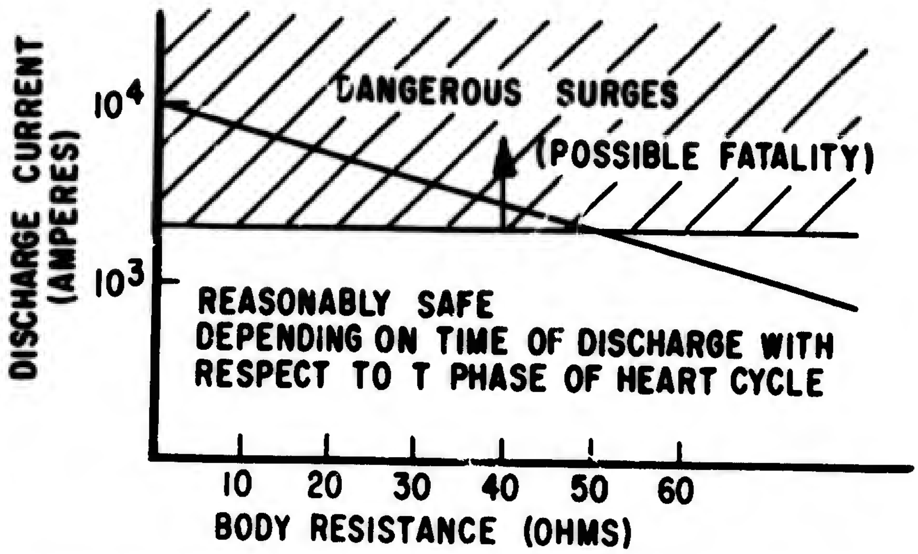

Figure 14. Surge Current vs Body Resistance for Aircraft at 3,000 Feet Under Ideal Fair-Weather Conditions

SECTION III

RECOMMENDED PROTECTION PROCEDURES

The following protection procedures are recommended when using an electrically conductive line. (When using a non-electrically conductive line, the safety procedure is to allow the line to contact the ground before handling.)

A. WEATHER CONSIDERATIONS

1. Operations where line will come in contact with the ground should not be flown within 10 miles of weather conditions which are, or could become, potentially electrical.

2. Operations where line will not come in contact with the ground should not be flown within 5 miles of weather conditions other than fair.

B. PERSONNEL CLOTHING

1. Aircrew: Any aircrew member who is likely to be the only electrical connection between line and aircraft should wear conductive gloves which are in some way grounded to the aircraft.

C. LINE CONFIGURATIONS

All line configurations should be examined for their inherent hazards. No line, for example, should be a conductor down to within several hundred feet of the ground and then have a conventional insulated portion of the line for the remaining link to ground. At high voltages, conventional insulators breakdown and arcing along the insulated section of the line, rendering it almost zero resistance, is possible.

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