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Electrostatic Charging of the CH-53E Helicopter

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We have measured the effects of electrostatic charging on the CH-53E helicopter. Measurements were made over a clean runway and over sandy terrain in basically desert conditions where electrostatic charging is known to be a problem. While the measured charging current (up to ~ 75 μA) and open circuit voltages (up to ~ 140 kV) cannot be claimed as maximum values attainable by the CH-53E, they show that the CH-53E is affected by electrostatic charging in much the same way as all other helicopters. Furthermore the range of data recorded in these tests has allowed us to formulate a model for the electrostatic charging of a hovering helicopter in both "clean air" and "sandy air" situations. This model is consistent with our own data and recorded prior experience with electrostatic charging of helicopters. The model confirms that electrostatic charging depends on many parameters none of which can be controlled under normal operating conditions, thus the quantitative effects of electrostatic charging — the short circuit current and the open circuit voltage — are very variable. It also predicts that the CH-53E can readily attain short circuit currents of ~ 300 μA and open circuit voltages of ~ 400 kV.

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CONTENTS

ELECTROSTATIC CHARGING OF THE CH-53E HELICOPTER

INTRODUCTION

All aircraft suffer electrostatic charging as they fly through the air. There are a variety of reasons for this charging: impact with charged snow, water, or dust particles; emission of charged exhaust particles; frictional charge transfer from neutral particles that strike the aircraft; induction charging from atmospheric electric fields; and direct conduction of charge to the aircraft by a lightning discharge. Electrostatic charging is not noticed in most aircraft because it is always dissipated on landing before anyone contacts the aircraft and ground simultaneously. In the case of a helicopter, however, the aircraft is loaded and unloaded while it is hovering, and the ground personnel, in some cases the air crew also, are subject to severe electric shocks. The voltage of a large hovering helicopter can reach well above 100,000 volts and its electrical stored energy approaches a lethal level.

This is not a newly discovered phenomenon: Enough reports to fill a bookshelf have been written on the subject going back at least to the mid 1940s.[1] However, the subject has taken on a new urgency with the deployment of the CH-53E, which, because of its size, routinely produces near lethal shocks. The reports in the literature tend to fall into two categories: those reporting measurements of helicopter potentials, and those concerned with techniques intended to eliminate the hazard of electrostatic charging. Most of the latter reports describe passive[1,2] and active[3,4] discharge systems, devices intended to reduce the aircraft voltage by inducing corona. Also most of the effort seems to have been spent on complex active discharge systems[5], because they offer "cockpit control". However such systems have met with little success and it has been suggested that active discharge systems cannot work over the required range of atmospheric conditions.[2,6,7]

In this report we describe first a series of measurements that were made to check whether electrostatic charging affects the CH-53E helicopter in the same way that it affects other helicopters. Measurements were made over a clean runway and over sandy terrain in basically desert conditions where electrostatic charging is known to be a problem. While the voltages and

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currents measured were well within the anticipated range and indicate that the CH-53E is not substantially different from other helicopters, certain aspects of our measurements were unexpected and very different from any previously reported. These aspects of the results have led us to propose a specific model for the process of electrostatic charging of helicopters in both the "clean air" situation and over "sandy terrain". The model is described and compared with the data. Finally various implications are drawn from the model: how the electrostatic charging hazard varies with such parameters as the helicopter thrust and body size, and how the electrostatic charging hazard can be minimized if not eliminated.

DESCRIPTION OF EXPERIMENT

After testing of our measuring apparatus at the Naval Air Test Center, Patuxent River, MD, we made a series of measurements at the Twentynine Palms Marine Corp Base, Twentynine Palms, CA. Measurents were made of the voltage and the current generated by CH-53E helicopters at two different times of day and over two different kinds of terrain. Two ostensibly identical helicopters were alternated into use for the measurements. Measurements were made early in the morning when the air was cool and relatively humid, and in the hot dry afternoons of August 7, 8, and 9, 1984. Measurements were made with the helicopters hovering over a clean aluminum runway surface and over the desert sand. The measurements were made in four sessions, starting in the afternoon over clean terrain and ending in the morning, two days later, over sandy terrain.

In each session, the current generated by the helicopter was measured while the helicopter voltage was held at ground potential by the current measuring circuit (see Figure 1). This is the "short circuit current" delivered by the helicopter. In all of these measurements, the electrical measuring circuit is connected to the helicopter through the hook and cable of the auxiliary hoist. The current measurements were made at hovering heights between 20 and 100 feet. The purpose of the current measurement, aside from the importance of the helicopter charging rate, was to establish a current level that could be drawn by a voltmeter connected to the helicopter without changing its voltage appreciably, i.e. to permit measurement of the "open circuit voltage". As will be seen later, this effort was not entirely successful because of the unexpected current/voltage characteristic of the helicopter.

The time of day, and the helicopter altitude were recorded for each measurement. The altitude information was taken from the helicopter instruments. Temperature and humidity as functions of time of day were obtained from the base control tower. These quantities were, of course, measured at the tower, several miles from the experiment site. In some cases, due to very local showers at the experiment site, the humidity was presumably much higher than recorded.

The current measurements, Figure 1, were made by shorting the helicopter to ground through a 1000 Ω resistor located on the ground directly under the hovering aircraft and measuring the voltage across the resistor with a sensitive voltmeter and a chart recorder located in a motor home/measurement van located about three hundred feet away. The resistor and the voltmeter were connected by a length of RG/223 shielded cable, 500 feet long.

For the voltage measurements the circuit shown in Figure 2 was used. The shunt resistor was a two watt carbon composition resistor with a value of 100 kΩ or 1 MΩ. The dividing resistor consisted of a string of ten American Products, Inc., type HBV carbon film resistors contained in a heavy walled plastic tube, twenty feet long. The rated maximum voltage for each resistor was 30 kV and the voltage coefficient was negative 1.3×10^{-6} per volt. Values of the dividing resistors between 4 and 200 GΩ were used. The voltmeter was a Keithley Instrument Co. Model 550, and the chart recorder was a Hewlett Packard Model 680.

The voltage measurement scheme was designed to minimize two sources of error: reduction of the aircraft voltage by drawing too much current with the measuring apparatus, and reduction by increasing the corona current due to the presence of the measuring apparatus. Figure 2 is a schematic diagram of the voltage measuring scheme. The dividing resistor, R_d, is connected on one end to the hook of the auxiliary hoist and on the other to the shunt resistor, R_s, contained in a shielded box on the ground. The value of R_d was chosen to draw less than one tenth of the short circuit current generated by the helicopter with the intent of reducing the helicopter voltage by no more than this amount. As discussed later, for the sandy terrain case, even this small current probably reduced the helicopter voltage by ~ 30%, for which the "open circuit voltage" must be corrected. The resistor, R_s, was chosen to produce a voltage of about one volt, a convenient size to measure. In order

to avoid increasing corona current, R_d was distributed over a length of 20 ft., equal to the helicopter hover altitude. This choice made a minimum change in the electric field produced by the helicopter, at the expense of permitting voltage measurements only at an altitude of twenty feet. Figure 3 shows the effect of different schemes on the helicopter electric field.

The simplest circuit that can be envisaged for the helicopter as an electric generator is that of a voltage source in series with a resistor called the source resistance. The voltage of the voltage source is the "open circuit voltage". The value of the source resistance is the ratio of the "open circuit voltage" to the "short circuit current" that was measured above. However for a complex system such as the electrostatically charged helicopter there is no reason to assume that the source resistance is constant. To determine the variation of the source resistance, several voltage measurements were made using a value of R_d that was comparable to the source resistance.

RESULTS

The data from the four sessions of measurements, and the aircraft and weather conditions are shown in Table I. The measurement sessions are described below, one by one.

The first session was an afternoon session and measurements were made with the helicopter hovering over the clean aluminum runway. (This runway must be the closest thing in the world to an ideal ground plane.) The session started at 1?:0 hours with a measurement of the helicopter current using aircraft #17. At an altitude of 20 feet, the aircraft generated an average charging current of one microampere (μA). The direction of the current was positive, that is, electrons flowed from the ground to the helicopter. This was a lower current than had been expected from this large aircraft. At an altitude of 100 feet, the average charging current increased to a positive ½ μA. The frequency response of the current measuring circuit is relatively high and is limited by the voltmeter and the chart recorder. As a result corona spiking shows very clearly in the current measurement chart records and amounts to peak-to-peak variations on the order of the average current.

Table 1

NUMBER	DATA BOOK NUMBER	TIME	TEMP °F REL.HUM.%	CH53E A/C#	A/C WT. (1000 lb)	DIVIDING RESISTOR R_D	SHUNT RESISTOR R_S	A/C ALTITUDE (FEET)	A/C CHARGING CURRENT	A/C VOLTAGE	COMMENTS ON CHART RECORD
AFTERNOON TEST OVER CLEAN ALUMINUM RUNWAY - 7 AUG 1984											
1	1	1310	108/12	#17	47	0	1KΩ	20	+1 μA	-	
2	1A	1319		"		0	"	100	+4 μA		
3	2-1	1335		"		20000	1MΩ	20		+100 kV	Erratic.
4	2-2			"		"	"	20		+60 kV	Rather Steady
5	2-3	1345	105/30	"		"	"	100		+40 KV	Starts at 80 kV, settles at 40 kV.
6	2-4	1500	105/11	"		"	"	20		+40 kV	Steady over hover-climb - hover sequence.
7	"	"		"		"	"	100		+40 kV	
8	2-5			"		"	"	20		+24 kV	(Steady) Reconnection results in transient and hover voltage.
9	2-6	1540		"		"	"	"		+60 kV	Fly around - starts at 120 kV settles to 60 kV.
10	2-7	1545	109/7	"	42.5	"	"	"		+50 kV	Fly around - starts at 80 kV settles to 60 kV
MORNING TEST OVER CLEAN ALUMINUM RUNWAY - 8 AUG 1984											
11	1-1	0555	81/20	#15	45.5 (Both A/C)	0	1KΩ	20	-3.5 to -6.5 μA	-	Erratic.
12	1-2			"		"	"	100	-8 μA	-	Steady.
13	1-3			"		"	"	20	-5 to -6 μA	-	No chart record.
14	1-4			"		"	"	100	-12 to -10 μA	-	
15	1-5	0607		"		"	"	20	-6 μA	-	Steady.
16	2-1	0618		#15		20000	1MΩ	20	-	-90 KV	Steady over a 30 second interval.
17	2-2			"		"	"	100	-	60 kV	Noisy but steady average.
18	2-3			"		"	"	20	-	-80 kV	No chart record.

Table 1 (Cont'd)

19	2-4			"		"	"	20	-	-100 kV	No chart record - Fly around, come come in at 100 ft., desc. and conn.
20	2-5	0629		"		"	"	20	-	-90 kV	Steady - Fly around come in at 100 ft., desc. and conn.
21	3-1	0636		"		0	1kΩ	20	-10 µA	-	Steady - Measure current on #15 again.
22	3-2			"		"	"	100	-15 µA	-	Very short record.
23	4-1	0649		#17		"	"	20	+2 to +1 µA	-	Erratic.
24	4-2			"		"	"	100	+1.5 to +1 µA	-	
25	4-3			"		"	"	20	+ 1µA	-	Very small erratic signal.
26	5-1	0658	82/18	#15		"	"	20	-6 to -8 µA	-	Erratic.
27	5-2			"		"	"	100	-10 to -12 µA	-	Steady.
28	6-1	0717		"		20GΩ	100KΩ	20		-100 kV	Very Steady
29	6-2			"		"	"	100		-80 kV	Steady High current drawn during measurement.
30	6-3	0720		"	41.5	"	"	20	-	-100 kV	Very Steady
AFTERNOON TEST OVER SAND TERRAIN 8 AUG 84											
31	1-1	1350	111/9	#15	46.5	0	1KΩ	20	+150 µA	-	Initial transient.
32	1-1			"		"	"	20	+70 to +25 µA		Very erratic.
33	1-2			"		"	"	20-100	+30 to +60 µA		On climb from 20-100 ft.
34	2-1	1411		"		40GΩ	100KΩ	20	+3.5 to +1.8 µA	+140 to +70 kV	Erratic.
35	2-2			"		"	"	100	+2.2 to +2 µA	+90 to +80 kV	Steady.
36	2-3			"		"	"	20	+2 µA	+80 kV	Very Steady.

Table 1 (Cont'd)

37	3-1	1442		"		8GΩ	100KΩ	20	10 to 7.5 μA	+40 to +30 kV	
38	3-2			"		"	"	100	5 μA	-+20 kV	Chart record strange. Meter reading was 20 kV.
39	3-3	1446	112/12 @1500	"	43.5	"	"	20	5 μA	-+20 kV	Very erratic chart record. Use meter reading.
MORNING TEST OVER SAND TERRAIN - 9 AUG 84											
40	1-1	0628	82/52 @0600	#17	47.0	0	1KΩ	20	+60 to +30 μA		
41	1-2			"		"	"	100	+10 to +15 μA		Very erratic.
42	1-3			"		"	"	20	+30 μA		
43	2-1			#15		"	"	20	+30 to +10 μA		Erratic.
44	2-2			"		"	"	100	+7 μA		Somewhat erratic.
45	2-3	0636		"		"	"	20	+7 μA		Steady.
46	3-1	0650		"		200GΩ	100KΩ	20		+30 to +60 KV	#17 blowing sand on #15, Peak at extra sand.
47	3-2	0653		#17		"	"	20		+80 to +100 kV	#15 blowing sand on #17, Extra dust makes little difference.
48	3-3	0658	82/42	"	45.5	"	"	20		+80 to +100 kV	No chart record. #15 blowing much sand on #17.

Because the average charging current was so low, the largest dividing resistor, 200 GΩ was used for the voltage measurements. This value was only marginally large enough, as the voltage measurements drew from 0.12 to 0.6 μA of the 1.0 μA charging current. Fortunately, subsequent measurements showed that drawing this large percentage of the charging current affects the aircraft voltage to a very small extent, under these conditions.

Two voltage measurements were made with the aircraft hovering at 20 feet. The aircraft was initially at 100 kV and dropped to about 60 kV. Between the measurements the dividing resistor was disconnected and reconnected to the shunt resistor. To resolve this difference, the aircraft ascended to 100 feet and returned to 20 feet for another measurement. On the descent, at about 1345 hours, the resistor broke. At 1500 hours the measurements resumed. The aircraft voltage was measured at 20 feet, 40 f .t, and at 100 feet, and then the divider resistor was disconnected when the aircraft returned to 20 feet. The aircraft then ascended to 100 feet and returned to 20 feet; the resistor was reconnected, and the connection transient voltage and the steady average were measured. The transient voltage, which is very fast, is due to the capacitive discharging of the end of the resistor. The average voltage was 24 kV.

Next to achieve a more realistic situation, the aircraft circled for five minutes, returned to the measurement site at an altitude of 100 feet, descended to 20 feet, and the resistor was connected. After the initial connection transient, the average aircraft voltage decreased from 90 kV to about 60 kV in about two minutes. A second identical test gave similar results.

The second session started at 0555 hours the next day. Measurements began using aircraft #15. The choice was the pilots', as the two aircraft were identical. The terrain was the aluminum runway as in the previous test. The aircraft current was measured as the hover altitude was cycled from 20 to 100 to 20 to 100 to 20 feet. The result was a consistent negative 5 to 6 μA at 20 feet and 8-9 and 10-12 μA at 100 feet. The aircraft voltage was then measured using again the 200 GΩ resistor. The results were a very consistent 80 to 100 kV at 20 feet over four measurement periods: two as the aircraft was cycled from 20 to 100 to 20 feet, and two after the aircraft circled a few minutes and then descended from 100 feet to hover at 20 feet. These voltages were

negative. At 0635 hours, after completing the voltage measurements, the current measurement on the aircraft was repeated. The second result was 10-12 μA at 20 feet and 15 μA at 100 feet; again negative.

To try to resolve the overnight change in polarity of the aircraft, the aircraft was changed and at 0649 hours the current generated by aircraft #17 was measured. The result was 1 to 2 μA positive, at 20 feet and 1 to 2 μA negative at 100 feet. At 0658 hours the aircraft was changed again and the current generated by #15 was measured. Aircraft #15 was still negative, producing 6-8 μA at 20 feet and 10-12 μA at 100 feet, consistent with the measurements at 0555 hours.

The final measurement of this session was to measure the voltage of #15 while the measuring circuit was drawing a current comparable to its charging current. A 20 GΩ dividing resistor and a 100 kΩ shunt resistor were used in the measuring circuit. An initial measurement was made at 20 feet and another after the aircraft had been cycled to 100 feet and back. The result was 80-100kV, negative, the same voltage as measured with the 200 GΩ resistor. [A caveat is that although the humidity never reached a high value, there was very local precipitation in the test area at the time of the last test, and generally some weather activity in the larger area.]

At 1350 hours on the second afternoon the sandy terrain measurements began. The instrument van remained in the same place but the shunt resistor, connected to the van by a coaxial cable, was moved from the edge of the aluminum runway to the desert sand. Electrical ground remained the aluminum runway to avoid a large loop of earth current that arose when a wet electrical ground was established at the shunt resistor and the van remained connected to the runway.

In the swirling sand at 20 feet the charging current of aircraft #15 varied considerably, from 60-70 μA to 25-30 μA in a thirty second interval. On ascending to 100 feet the current settled to 40-60 μA. The current was positive, indicating a positive aircraft voltage. The voltage was measured, using a 40 GΩ dividing resistor and a 100 kΩ shunt, at 20 feet and again after a cycle to 100 feet and back. During the first measurement the voltage started at 120 kV and decayed to about 60 kV in 45 second interval. After the ascent and return to 20 feet the voltage settled to a constant 80 kV.

The last measurement of this session was a voltage measurement using a low value of dividing resistor, as before, to measure the effect of a large current drain on the aircraft voltage. In this case a 4 GΩ dividing resistor and a 100 kΩ shunt were used. Again measurements were made at an aircraft hover height of 20 feet, before and after an ascent to 100 feet. The first voltage was a fairly steady 30-40 kV while the second voltage varied from 28-8 kV in less than a 30 second interval. This third session ended at about 1446 hours.

In the last session measurements were made over sandy terrain on both aircraft #15 and #17. Again measurements were made at 20, 100, and 20 feet. For both aircraft, the initial currents at 20 feet were erratic as were the currents at 100 feet. However, when the aircraft returned to 20 feet their currents stabilized: #15 at 7 μA and #17 at 30 μA both positive. These measurements started at 0628 hours and ended at 0636 hours. The next set of measurements was made with one helicopter blowing sand on the other to try to increase the effect of the sand particles on the voltage generation of the aircraft. These measurements use the 200 GΩ dividing resistor and were again made at 20 feet. The voltage of aircraft #15 was measured during a five minute interval while #17 was blowing sand on it. The result was that the voltage of #15 stayed between 20 and 40kV, rising to 60kV when the dust was particularly dense. When the voltage of #17 was measured, the result was between 80 and 100kV, peaking as high as 120kV for an instant, and not affected by the extra dust blown on it by #15. The measurements were over at 0658 hours.

DISCUSSION

The purpose of these tests was to check whether electrostatic charging affected the CH-53E helicopter in approximately the same way that it has been observed to affect previous helicopters. The highest voltage measured was 140 kV and it was measured while drawing 3.5 μA during the afternoon test over the sandy terrain. The highest current drawn from the CH-53E was 70 μA, again over the sandy terrain. These values are in keeping with earlier measurements on other helicopters, but cannot be interpreted as the maximum values attainable by the CH-53E. Rather, the results show that electrostatic charging of the CH-53E is not fundamentally different from that of other

helicopters. The CH-53E is just larger, with larger engines, a larger downdraft, and inevitably a larger capacity for electrical generation.

The tests also show, as has been known for a long time, that the charging of helicopters is a complex phenomenon, or at least a phenomenon in which some important variables cannot be controlled. When hovering over sandy terrain, the measured voltage fluctuates, seemingly with the turbulent dust cloud generated by the aircraft. And even over the clean runway, when there is no sand cloud, two nominally identical helicopters charge to similar potentials but with opposite polarity.

Although the two helicopters are essentially identical, #17 always generated more current, in an algebraic sense, than #15. Where aircraft #17 generated +1 μA in the clean environment (Lines 1 and 23 on the data table, Table I.), aircraft #15 generated about -6 μA (Lines 11, 13 and 15.). Where #17 generated 30 μA in the sand environment (Line 42.) #15 generated 7 μA (Line 45). In the sandy environment, where the electrical processes seem to be dominated by the particles both aircraft generated positive currents, and their behaviors were similar. When the large contribution of the particles was not present the two aircraft generated currents of opposite polarity, resulting in a range of voltages from +100kV to -100kV during the tests over the clean runway. Current measurements over the clean runway were made consecutively on #15, #17, and then #15, during the shortest possible period, 22 minutes. The fact that #15 produced a negative current both before and after #17 produced a positive current leads to the conclusion that the difference is not caused by environmental changes but is in the helicopters themselves. Most probably the difference is in the exhaust materials of the two helicopters.

Figure 4 is a schematic diagram of the simplest equivalent circuit for the electrically active helicopter. The voltage, V, is the open circuit voltage of the aircraft as measured through the high resistance dividing resistors. The resistor, R, is the ratio of this open circuit voltage and the short circuit current generated by the aircraft as measured through the 1000 ohm resistor. The capacitance, C, is the capacitance between the hovering aircraft and ground. Table II gives the values of quantities as measured in the various tests. The values of capacitance are calculated assuming that the aircraft is a cylinder 74 feet long and 9 feet in diameter. At an altitude of

Table 2

TEST	CH-53E A/C#	ALTITUDE	VOLTAGE	CURRENT	EQUIVALENT SOURCE RESISTANCE	CAPACITANCE	TIME CONSTANT
Afternoon/clean	#17	20	+50 kV	+ 1 μA	50 GΩ	526 pF	26 sec
Morning/clean	#15	20	-90 kV	- 6 μA	15 GΩ	526 pF	7.9 sec
Afternoon/sand	#15	20	+80 kV	+ 50 μA	1.6 GΩ	526 pF	.86 sec
Morning/sand	#15	20	+45 kV	+ 7 μA	6.4 GΩ	526 pF	3.2 sec
Morning/sand	#17	20	+90 kV	+ 30 μA	3.6 GΩ	526 pF	1.6 sec

ten feet the capacitance between the aircraft and ground is 684 picofarads. At 20 feet, the altitude at which most measurements were made, the capacitance dropped to 526 picofarads. The last column is the circuit time constant, the product of R and C.

It is useful to compare the electrical behavior of the helicopter with the simple circuit of ideal components in Figure 4. During the second set of clean terrain measurements, when #15 was charging negatively to a value of about -100kV, the voltage and current measurements determined a value of 15 GΩ for R. If a voltmeter with an input resistance of 20 GΩ were used to measure the voltage of the corresponding equivalent circuit, the result would be a value of -57 kV. When a 20 GΩ resistor was actually used to measure the voltage of #15, the result was still a value very near -100kV, indicating a much lower "open circuit" source resistance. Clearly in the "clean air" situation, the aircraft voltage is stabilized against changes in the current to ground until the current to ground becomes equal to the short circuit current. Such behavior leads immediately to a model for the electrostatic charging of the helicopter in the clean air situation. In this case, the helicopter is emitting charge into the atmosphere, most likely in the form of charged soot particles in the exhaust, which is blown away in the downdraft leaving the helicopter charged with the opposite sign. This charging continues until the potential of the helicopter with respect to the surrounding air has risen to a high enough level that corona occurs off the sharp points on the helicopter, most likely the rotor blades. Thus the potential of the helicopter is stabilized at the corona limit, and will indeed be insensitive to the current to ground as observed. Also, consistent with observation, small changes in the tune of the engines or perhaps in the materials used in the exhaust duct, may cause changes in the particulate material ejected in the exhaust and in the sign of the charge carried away. It is not surprising that the aircraft voltage is stabilized by its corona current. This stabilization mechanism was the basis of corona discharge voltage regulator tubes that were used in vacuum tube electronic circuits as reference voltage sources. Apparently, for aircraft #15, positively charged particles are carried away from the aircraft in the exhaust, leaving the aircraft negatively charged. This current, equal to the measured short circuit current, but of opposite sign, i.e. ranging from 3 to 15 μA for #15, is just balanced by corona discharge from the fuselage and rotors at a

potential of -100 kV. It is the nature of the corona discharge that once it is established it will accomodate large changes in current with only relatively small changes in voltage. When a resistor to ground draws half of the charging current, the corona current is reduced by a half, with only a small change in the aircraft's voltage.

When the equivalent circuit for the aircraft hovering over sandy terrain was tested by measuring the aircraft's voltage with a relatively low resistance voltmeter, the result was quite different. The actual source resistance of the aircraft was much higher than the source resistance estimated from the measured open circuit voltage and short circuit current, 1.6 GΩ for the afternoon/sandy terrain measurement. The expected result of the voltage measurement using a 4 GΩ dividing resistor was about 60 kV. While the actual result was 20 kV, indicating an effective source impedance of 12 GΩ. In fact, over a relatively short period of time, using aircraft #15, the set of data shown on lines 31 through 39 in Table 1, had a characteristic behavior of: short circuit current ~ 50 μA, intermediate current of 5 μA at potential 20 kV, and low current of 2 μA at potential 80 kV. Thus the mechanism by which the helicopter collects charge from its surroundings provides only a very small current while the aircraft is at a high voltage, and this current increases as the aircraft voltage decreases toward ground potential.

These variations of helicopter current and voltage are shown in Figure 5.

A MODEL FOR ELECTROSTATIC CHARGING

We envisage the situation depicted in Figures 1 and 2 in which a hovering helicopter is connected to ground by a measuring system that does not disturb the electric field distribution. The current flowing through the measuring system is I_H and the potential of the helicopter with respect to ground is ϕ_H. In the clean air case, the only currents flowing from the helicopter are the current I_H; the charging current of the engines, I_E; and the corona discharge current, I_C. Thus by continuity

$$I_H + I_E + I_C = 0 \ . \qquad (1)$$

We can represent the charging current as

$$I_E = n' q' v A , \qquad (2)$$

where n' is the density of soot particles near the helicopter, q' is the charge on each particle, v is the down-draft velocity, and A is the area over which the particles are spread. (This functional dependence of I_E is not important but it is convenient to define the quantities n' and q', as will be seen later.) Also, we can represent the corona current as

$$I_C = \frac{G\phi_H''}{\phi_C}\left(1 - \frac{\phi_C}{|\phi_H''|}\right) \quad \text{for } |\phi_H''| > \phi_C ,$$

and (3)

$$I_C = 0 \quad \text{for } |\phi_H''| < \phi_C ,$$

where

$$\phi_C = 100 \text{ kV} ,$$

G is a current of magnitude ~ 1 ampere, and ϕ_H'' is the potential of the helicopter with respect to the air mass around it, i.e. with respect to the local space potential. In this case, we hypothesize that the charged soot particles come to ground in the down-draft where they are discharged and play no further role, i.e. no substantial cloud of soot particles is built up around the helicopter. The potential of the helicopter with respect to ground is

$$\phi_H = \phi_L + \phi_H'' , \qquad (4)$$

where ϕ_L is the local space potential, i.e., the potential of the air mass around the helicopter with respect to ground, and this depends on the charges distributed around the helicopter. In the clean air case, the only charges not actually on the helicopter are the charges q' in the down-draft below the helicopter, so that ϕ_L is given by

$$\phi_L = F' n' q' . \qquad (5)$$

Here F' is equal to $y^2F_2/4\varepsilon_o$, where y is the altitude of the helicopter, ε_o is the permittivity of free space, and the quantity F_2, is calculated in Appendix I. Thus the open circuit voltage of the helicopter is

$$\phi_H(1) = F' \frac{I_E}{vA} + \phi_C \left(\frac{\phi_H''}{|\phi_H''|} - \frac{I_E}{G}\right) , \qquad (6)$$

and the short circuit current is just

$$I_H(2) = -I_E . \qquad (7)$$

The arguments of the left hand quantities in Eqs. (6) and (7) refer to locations on the curve in Figure 5a.

Comparing Eqs. (6) and (7) with the data for aircraft #15, i.e. lines 11 through 22, and 26 through 30 in Table 1, we see that I_E is typically - 5 μA and $\phi_H(1)$ is typically -100 kV. Thus ϕ_L is positive and between 1.7 and 3.4 kV, and $\phi_H'' \geq$ -100 kV.

When a helicopter hovers at low altitude over sandy terrain, it is enveloped in a large sand cloud, which is often so dense that one cannot see the helicopter from a distance. For the CH-53E, the diameter of the circle defined by the rotor is 24.3 m (79 feet), typically, measurements were made with the helicopter at an altitude of - 6 m (20 feet), and the sand cloud had diameter - 61 m (- 200 feet) and extended to an altitude of - 30 m (- 100 feet). As can be seen in Appendix I, none of these numbers is critical, but it is important that the sand cloud is large compared to the helicopter altitude and the rotor diameter. Clearly the sand cloud represents a dynamic equilibrium. The sand particle density starts at some low value when the helicopter first flies in, and builds up to its equilibrium value apparently within a minute or two. We assume that the electrical data obtained in our experiments relates to the sand cloud in its equilibrium condition and believe that this is born out by the fact steady state values of current and voltage were achieved. This is not to claim that the sand particle density is a constant of nature but only that over the period of a few minutes within which any given measurement was made the sand density did not change appreciably.

Our model for the electrostatic charging of a helicopter in the sandy terrain case is simply that sand particles in the sand cloud are charged because of the triboelectric effect at the ground. Then the potential of the hovering helicopter is caused primarily by the helicopter being immersed in the cloud of charged sand particles. If the average charge on sand particles striking the ground is q_1, the average charge on the sand particles leaving the ground is q_2, and

$$q_2 = q_1 + q_o (1 - q_1/q_s) , \tag{8}$$

where q_o is the average charge acquired by an initially uncharged particle in one pass across the ground and q_s is the value at which the average charge saturates after a large number of passes across the ground. Then we define the ratio

$$Q = q_o/q_s . \tag{9}$$

If the area of the circle defined by the rotors is A1, the thrust of the helicopter, W, is given by

$$W = \rho_o A1 v^2 , \tag{10}$$

where ρ_o is the air density, and v is again the down-draft velocity. The flow of air in the sand cloud is such that all the air passes down through the area A1 of the rotor, but not all of the charged sand particles within this area make contact with the helicopter. Only those sand particles within the area A, where

$$A/A1 = A_R < 1 , \tag{11}$$

make contact with the helicopter. Now we assume that in the sand cloud

$$|\phi_H^n| < \phi_C ,$$

so that the current at the helicopter becomes

$$I_H = -I_E + n v A(q_u - q_\ell) , \tag{12}$$

where q_u is the average charge on the sand particles before they contact the helicopter, and q_ℓ is the average charge after they have touched the helicopter. Note we assume that the charging current I_E is emitted from the helicopter independently of the sand. We believe this is a reasonable assumption because the sand particle density n is small. In fact the optical extinction length, L, in the sand cloud is ~ 10 m and the typical radius of a sand particle < ~ 0.1 mm, therefore the sand density is

$$n \sim 3\times10^{6}\ m^{-3}\ ,$$

and the average distance between particles is > 20 particle diameters. The sand particles move with the air velocity but they move only slowly through the air, therefore there are few collisions between sand particles and we assume that none occur on the journey from the helicopter to the ground. Conversely, we assume that all particles hit the ground on their way down, and we further assume that there is a turbulent layer of air in contact with the ground within which the sand particles that have touched the helicopter and those that have not, are thoroughly mixed. We also assume that the density, n', of soot particles is much less than the density, n, of sand particles, which is why the soot particles do not constitute a significant particulate cloud in the clean air case. The average charge of sand particles striking the ground in the down-draft is therefore

$$q_1 = q_u\,(1-A_R) + q_\ell A_R\ , \qquad (13)$$

and as before the soot particles are discharged at the ground and play no further role.

Before proceeding further, we must look closer at the interaction of charged sand particles with the ground. As described in Eq. (8), initially uncharged sand particles accumulate charge through the triboelectric effect at the ground up to a value q_s, but the sign of the charge has not been specified. In practice the sand particles are charged positively, so that positively charged sand particles passing across the ground in the down-draft, on the average, become slightly more positively charged up to the value q_s.

But what happens to negatively charged sand particles? Since the triboelectric effect is, in this case, positive, we must assume that negatively charged sand particles behave normally and are always discharged when they contact the ground, the same as the soot particles. Therefore Eq. (13) applies only when

$$q_\ell > 0 ,$$

and Eq. (14),

$$q_1 = q_u (1-A_R) , \qquad (14)$$

applies when

$$q_\ell < 0 .$$

To complete the picture, we allow for one further physical effect, namely, the wind. This we do by allowing a volume loss of B m^3/s from the top of the sand cloud, i.e. a current loss of

$$I_{loss} = Bnq_u ,$$

and an influx of uncharged, but sand laden, air into the turbulent layer at the ground. Thus the average charge on the sand particles in the upper cloud is

$$q_u = q_2/(1+B1) , \qquad (15)$$

where B1 is the ratio

$$B1 = B/(v\ A1) . \qquad (16)$$

When a sand particle makes contact with the helicopter, the charge on the sand particle and the charge on the helicopter are shared such that the surface charge density on the sand particle σ_S is $\sim 1.5\times\sigma_H$, where σ_H is the surface charge density on the helicopter.[8] Since we can write the potential of the helicopter with respect to the local space potential as

$$\phi_H'' = \frac{\sigma_H r_H}{\varepsilon_o} , \tag{17}$$

where r_H ($\sim$ 1.5 m) is the effective radius of the body of the helicopter, we can also write

$$\phi_H'' = F'' n q_\ell , \tag{18}$$

where

$$F'' = \frac{L r_H}{1.5} \cdot \frac{1}{4\varepsilon_o} \tag{19}$$

In Eq. (19), L, the optical extinction length, has replaced $(n\pi r_p^2)$, where r_p is the average sand particle radius. Finally, we can write the potential of the helicopter as

$$\phi_H = \phi_u + \phi_\ell + \phi_E + \phi_H'' \tag{20}$$

where

$$\phi_u = F\, n q_u \tag{21}$$

is the potential caused by the sand particles with charge q_u;

$$\phi_\ell = F'\, n q_\ell \tag{22}$$

is the potential caused by the sand particles with charge q_ℓ;

and $$\phi_E = F' \frac{I_E}{vA} \tag{23}$$

is the potential caused by the engine exhaust particles. Here the parameters F and F' are given by

$$F = \frac{F_1 y^2}{4\varepsilon_o}$$

and

$$F' = \frac{F_2 y^2}{4\varepsilon_o} ,$$

and the quantities F_1 and F_2 are computed in Appendix I. They are dimensionless geometric factors relating the potential at the helicopter to the charge density in the sand cloud. The sand cloud is broken into two regions, the upper cloud where the particle charge is q_u, and the cylinder of base area A immediately under the helicopter where the particle charge is q_ℓ. As long as the size of the sand cloud is large compared to the altitude of the helicopter, F and F' are nearly constant and the functional dependence of the potentials on the altitude is approximately correct as given. F_1 and F_2 do depend on the area A as shown in Figure I-2 in Appendix I.

Given the above model for electrostatic charging over sandy terrain, we can recognize that there is a transition point in the current/voltage characteristic at the condition

$$q_\ell = 0 .$$

If we define this point as $\{I_H(3), \phi_H(3)\}$, (refer to Figure 5b) then for

$$q_\ell < 0,$$

$$I_H = \frac{I_H(3)\ \{F+F'+F''\} + I_E\{F+F'\} - vA\phi_H}{F' + F''} \qquad (24)$$

and for

$$q_\ell > 0 \ ,$$

$$I_H = K\{I_H(3)+I_E\} - I_E-(K-1)\,\frac{vA\phi_H+K\{(F'+F'')\ (I_H(3)+I_E)\ -F'\ I_E\}}{F + K\{F'+F''\}} \qquad (25)$$

where

$$K = 1 + \frac{B1+Q}{A_R(1-Q)} \ . \qquad (26)$$

In comparing the model with the data for aircraft #15 as depicted in Figure 5, it is clear that

$$I_H(3) \sim 5\ \mu A \ .$$

It is also clear that since both Eqs. (24) and (25) are linear in I_H and ϕ_H, the current/voltage characteristic consists of two straight lines that intersect at $I_H(3)$, $\phi_H(3)$. Then for

$$I_E = 5\ \mu A \ ,$$

Eq. (24) gives

$$\phi_H(3) = 22.5\ kV$$

if A_R is chosen as

$$A_R = 0.5 \ .$$

The short circuit current, i.e. Eq. (24) with $\phi_H = 0$, is then

$$I_H(4) = 84\ \mu A \ ,$$

and the open circuit voltage, i.e. Eq. (25) with $I_H = 0$, is

$$\phi_H(5) = 119 \text{ kV} .$$

The values of B1 and Q are related as

$$B1 \cdot Q = A_R(K-1) = .05$$

so that values of

$$B1 = 0.025$$

and

$$Q = 0.025$$

are acceptable.

For

$$I_E = 0 \ \mu A ,$$

Eq. (24) gives

$$\phi_H(3) = 22 \text{ kV}$$

if A_R is chosen as

$$A_R = 0.25.$$

The short circuit current, i.e. Eq. (24) with $\phi_H = 0$, is then

$$I(4) = 53.0 \ \mu A .$$

and the open circuit voltage, i.e. Eq. (25) with $I_H = 0$, is

$$\phi_H(5) = 120 \text{ kV}.$$

Values of B1 and Q are not affected.

For a cloud 200 feet in radius and 100 feet high, with

$$I_E = 5\ \mu A$$

Eq. (24) gives

$$\phi_H(3) = 22.4\ kV$$

if A_R is chosen as

$$A_R = 1.0.$$

The short circuit current is now

$$I_H(4) = 136.7\ \mu A,$$

the open circuit voltage is

$$\phi_H(5) = 120\ kV,$$

and the values of B1 and Q are ~ 0.05. This last example shows how the size of the cloud can affect the helicopter current.

Thus we see that our model accomodates both the "clean air" and the "sandy air" situations, and gives numerical predictions that are close to the measured values for $\phi_H(3)$ and $I_H(4)$, while values of $\phi_H(5)$ are well within the range of voltages reported in previous measurements. The model is also self consistent. In the "sandy air" case,

$$\phi_H'' < 6\ kV$$

and the charge on the sand particles is always much less than the maximum set by corona discharge

$$q_s \sim q_{max} \times 10^{-2} .$$

The model is also consistent with the general understanding of electrostatic charging that has come from previous measurements in that we can write the short circuit current in the "sandy air" case as

$$I_H(4) \sim v\, A1\, n\, q_o \left(1 + \frac{F}{F'+F''}\right) - I_E \left(\frac{F''}{F'+F''}\right) \qquad (27)$$

in which the dominant term is

$$v\, A1\, n\, q_o \frac{F}{F'+F''} .$$

The ratio F/F' is approximately the volume ratio of the sand cloud around the helicopter to that underneath, and since most helicopter loading and unloading is done at the same hover altitude (~ 20 feet), this ratio probably increases slowly with the thrust. Thus overall the model predicts that $I_H(4)$ increases approximately linearly with the thrust, W. Similarly, the open circuit voltage in the "sandy air" case can be written as

$$\phi_H(5) \sim \frac{1}{B1+Q} \{F+K(F'+F'')\} \{Knq_o - I_E/vA1\} \qquad (28)$$

where K ~ 1. The dominant term, for K = 1, is (F + F'), which is approximately a measure of the volume of the sand cloud and as such is probably directly proportional to the thrust of the helicopter. Thus the open circuit voltage, $\phi_H(5)$, also varies approximately as the thrust, W.

Our model for the electrostatic charging of a hovering helicopter agrees then not only with the data presented above for the CH-53E but also with the much larger body of data accumulated over the years. There is, however, one term omitted in the above formulation because it appeared to play only a small role in our measurements; that term is the space potential caused by atmospheric electric fields. Voltage measurements were made for both aircraft at altitudes of ~ 30 m (100 feet), but no consistent variation with altitude

was observed. We would expect atmospheric electric fields to be superimposed as an additional term, ϕ_A, in Eq. (6) for the "clean air" case; and to be less important in the "sandy air" case because the distribution of the charge around the edges of the sand cloud will always tend to cancel the atmospheric fields.

We can now examine the model to see what can be done to minimize the hazard of electrostatic charging. First, the hazard represented by a charged helicopter is that the potential of the helicopter, with respect to the ground on which the man is usually standing, is always in the dangerous range, i.e. greater than a few kilovolts, and for a large aircraft like the CH-53E the stored energy ($0.5\ C\ \phi_H^2$) is large enough to provide a lethal shock. The only specific property ascribed to the helicopter is its ability to generate the current I_E. We have suggested that this current is due to the aircraft's engines because such an effect is easy to imagine, but I_E really represents any charging current generated by the aircraft. Clearly the effects caused by I_E can be eliminated by modifying the aircraft so that I_E goes to zero. Thus the electrostatic charging in "clean air" could be eliminated by removing I_E. However, removing I_E would have minimal effect on the open circuit voltage over sandy terrain! Furthermore, reduction of I_E does not reduce the open circuit voltage even over clean terrain and it is doubtful that any system can be found that can really eliminate I_E.

In the clean air situation, the corona limit is set by the potential difference, ϕ_H'', at which "points" on the helicopter emit a corona current equal to the charging current, I_E, i.e. the aircraft is acting as its own "wick". By putting more, sharper points on the aircraft the necessary potential difference can be reduced, and since the potential of the helicopter with respect to the ground is primarily due to ϕ_H'', this brings the helicopter potential appreciably closer to ground potential, as has been demonstrated in the studies of passive discharge systems. However, when hovering over sandy terrain, passive wicks can only reduce ϕ_H'' to zero, i.e. hold the aircraft at the local space potential, and this represents only a small decrease in ϕ_H. On the other hand, an active discharge system, that is also able to "sense" ground potential, could in principle reduce the potential of the aircraft with respect to ground to ϕ_H, if it can supply the current I_H given in Eqs. (24) and (25). While this may seem an attractive approach, it must be

remembered that to reduce ϕ_H below - 20 kV requires discharge currents in excess of - 10 μA which is the most current that the CH-53E's three engines produced during our tests at Twentynine Palms. One must also control the sign of the discharge current in order to accomodate both positive and negative triboelectric effects. [Discharge currents of several hundred μA have been generated in demonstration active discharge systems.[9]]

CONCLUSIONS

We have reported a series of measurements on the electrostatic charging of the CH-53E helicopter. Measurements were made over a clean runway and over sandy terrain at the Marine Corps Base at Twentynine Palms, CA during the month of August when near desert conditions exist. These are the first measurements on the CH-53E and are some of the only measurements in which current and voltage were measured simultaneously. First, the measurements confirm that the CH-53E is affected by electrostatic charging in much the same way as other helicopters. In addition, details of these measurements, particularly the direct comparison of two nominally identical aircraft and of "clean air" and "sandy air" situations, have led us to formulate a detailed model of the electrostatic charging process.

This model of electrostatic charging has been shown to be consistent with the general understanding developed from previous measurements, as well as with the present measurements. Thus the model agrees that over sandy terrain, Eqs. (27) and (28), both the short circuit current and the open circuit voltage will increase roughly as the thrust of the aircraft. But the model also shows that the short circuit current and the open circuit voltage are directly proportional to the sand particle density, n, and the triboelectric charge, q_o, both of which can vary with the terrain and with such parameters as atmospheric humidity. Furthermore, the average charge on the sand particles, even in the open circuit condition, is only about one thousandth of the maximum charge that those particles could carry. Thus not only can the density of particles vary, but the charge per particle could increase several fold. Then the open circuit voltage is also dependent on the "wind" through B1 as well as the charge ratio, Q. With all these uncontrolled variables, it is not surprising that the phenomenon of electrostatic charging shows great variability; indeed such variability must be expected.

In the "clean air" situation, the model emphasizes the fact that any net charging current, I_E, results in the helicopter reaching the corona limited open circuit voltage, and that reducing the net charging current does not reduce the open circuit voltage. Here it must be remembered that even with an active discharge system it will be very hard to ensure that the net charging current is exactly zero, and a likely outcome is that the helicopter potential will be driven successively positive then negative as the system hunts for a balance in the ever changing natural environment.

We can examine the model to determine what might be the maximum values of the short circuit current and the open circuit voltage for the CH-53E. There is no doubt that without strong atmospheric electric fields the worst conditions will exist in situations where there is a large particulate concentration in the atmosphere. Therefore considering the "sandy air" case, since during these tests the aircraft were carrying a full load of fuel but no cargo, their thrust was reduced to approximately half that of maximum load and currents and voltages of twice the measured values must be expected with full load under the same operating conditions. Further factors of two can easily be envisaged in terms of a decrease in the wind factor (B1 goes to zero), the triboelectric charge, q_o, may double, and the charge ratio, Q, could be halved. Indeed there is no reason to believe that our measurements represent an extreme case for any of these parameters. Collecting these factors, we can easily envisage values of the short circuit current in excess of 300 μA (~ 75x2x2), and values of the open circuit voltage in excess of 800 kV (~ 100x2x2x2), without allowing any variation in the sand particle density. In fact, while short circuit currents near 300 μA have been recorded, no open circuit voltages even close to 800 kV have been measured in the past and we suspect that some natural constraint forbids all three factors from combining in this way. Thus we suspect that the open circuit voltage is limited to values in the range of 400 kV (~ 100x2x2), which would be in keeping with previous measurements.

The fine-weather electric field intensity at the ground[10] is of the order of 100 volts/m. But under large cumulo-nimbus clouds during storm activity fields of 20 kV/m are common and fields up to ~ 100 kV/m are possible particularly at sea. Thus even in the "clean air" situation open circuit potentials in excess of 200 kV are easily attained.

Finally, the only sure way to make a hovering helicopter safe against electrostatic charging during loading and unloading operations is to reduce the helicopter voltage to ground voltage. Since it is not operationally acceptable to use a separate grounding line from aircraft to ground, the connection between aircraft and ground must be made through the pendant assembly and the support crewman on the ground. This can be accomplished perfectly safely with appropriate resistors incorporated in the lifting pendants and in the auxiliary hoist cable. The electric shock hazard posed by the helicopter must be considered both for the continuous short circuit current generated by the helicopter and for the pulsed charging or discharging of the capacitance of the helicopter. The average ground crewman should not be perturbed by continuous currents up to ~ 1000 μA flowing through his body to ground or by pulses containing less than ~ 250 mJ of energy.[11,12] Thus if the lifting pendants and the auxiliary hoist cable are made to contain a series resistance of approximately 10 MΩ the ground personnel are protected even for helicopter capacitances up to 1000 pF and open circuit potentials of 400 kV. In fact, this is another old idea that has failed to reach the proper decision-makers in helicopter design.[6,2,7]

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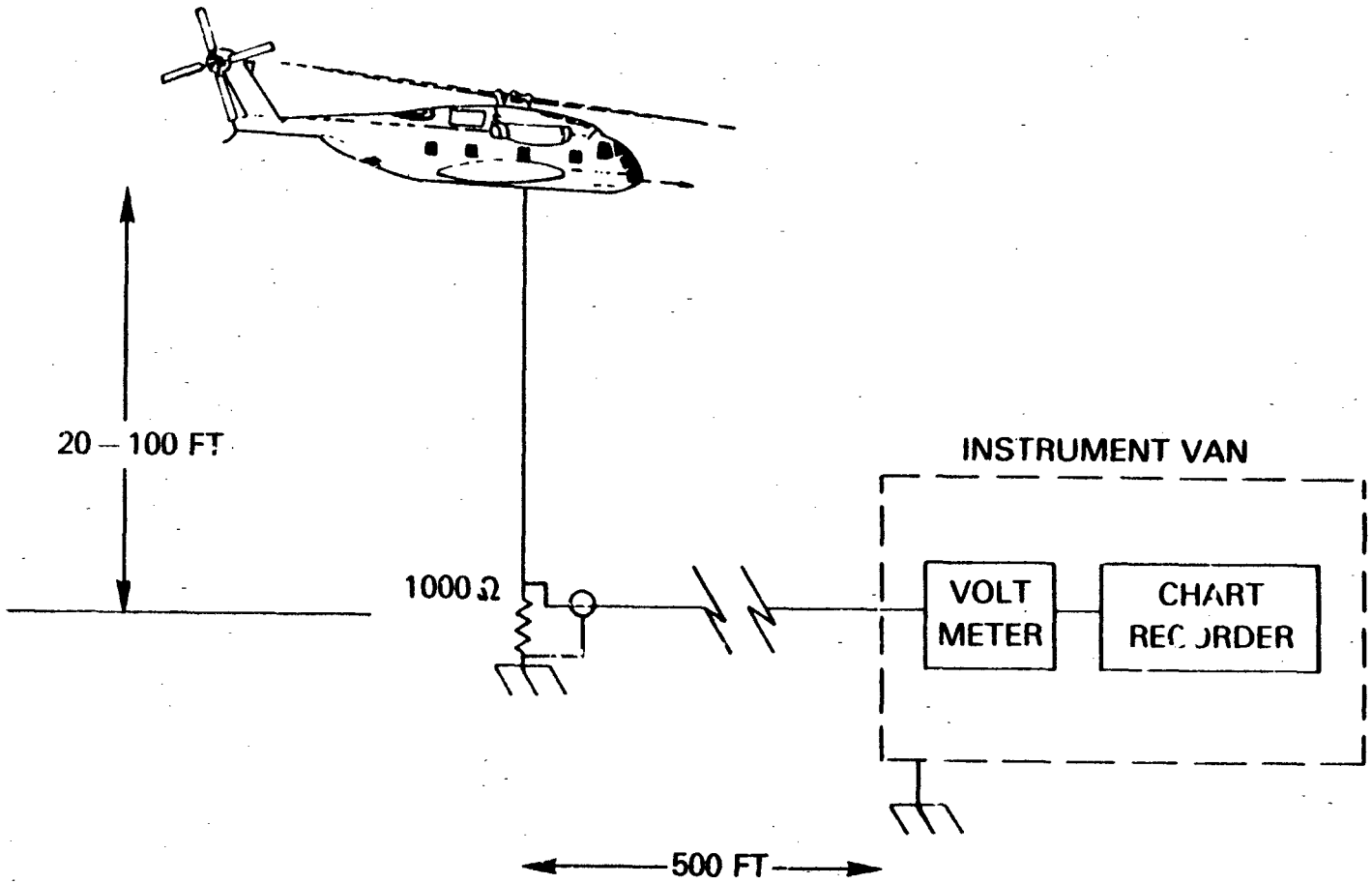

Fig. 1 — Schematic diagram of the system used to measure the current generated by the hovering helicopter while it is held at ground potential. The measured current is referred to as the "short circuit current."

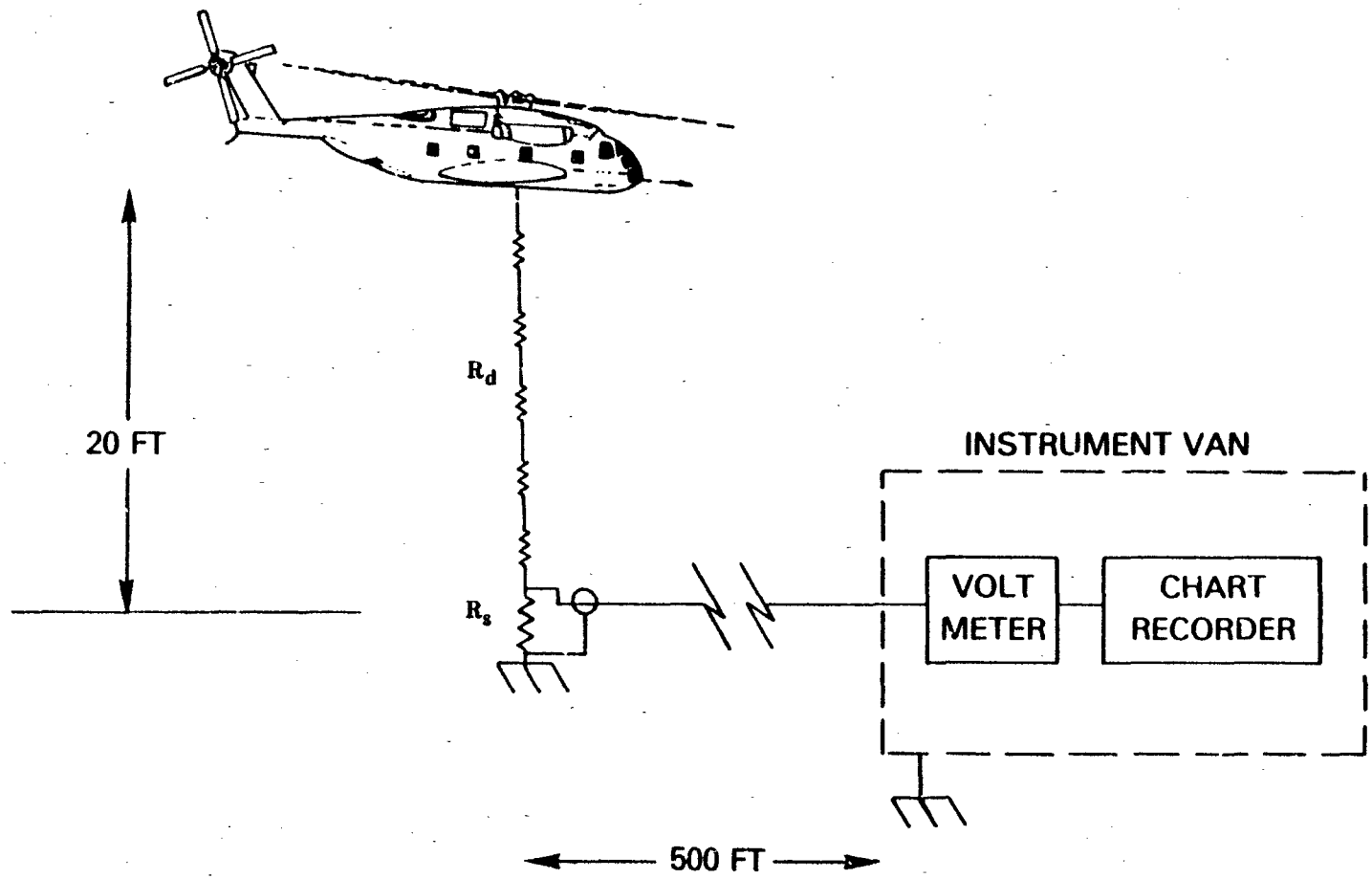

Fig. 2 — Schematic diagram of the system used to measure the voltage of the hovering helicopter while making a minimum change in its electric field configuration. The measured voltage is referred to as the "open circuit voltage."

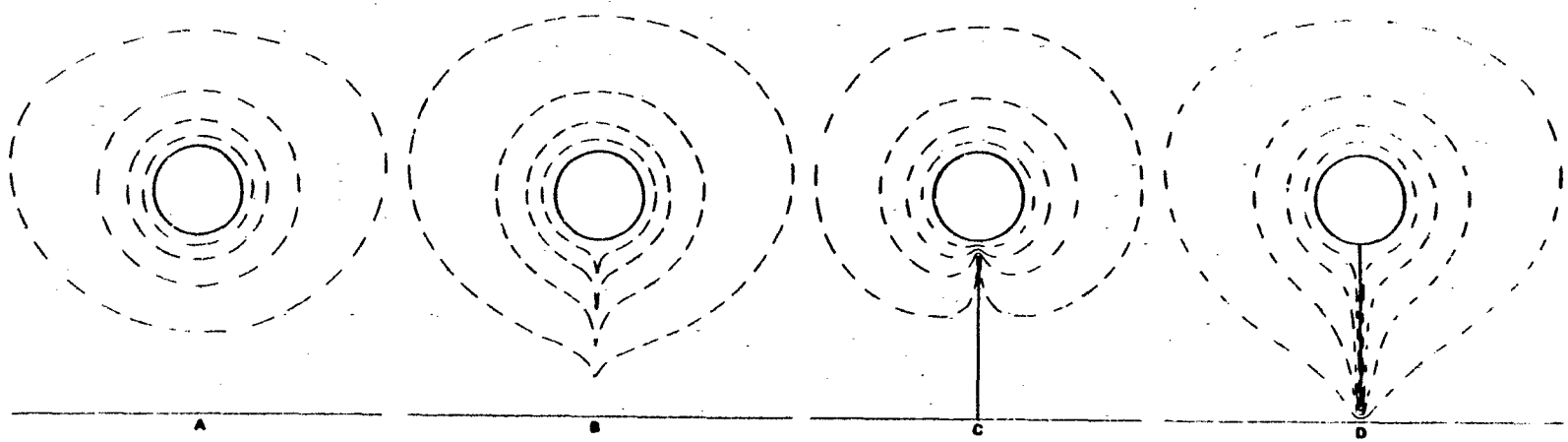

Fig. 3 — Schematic diagram that illustrates the contours of constant voltage for various configurations of dividing resistors. a) Contours without a dividing resistor. b) Contours with the uniformly graded dividing resistors used in this experiment. c) Contours with dividing resistor located in helicopter, i.e., the entire voltage drop occurs inside the aircraft. d) Contours with the dividing resistor located near the ground. The point of the figure is that configurations c) and d) can make large changes in the corona current of the aircraft.

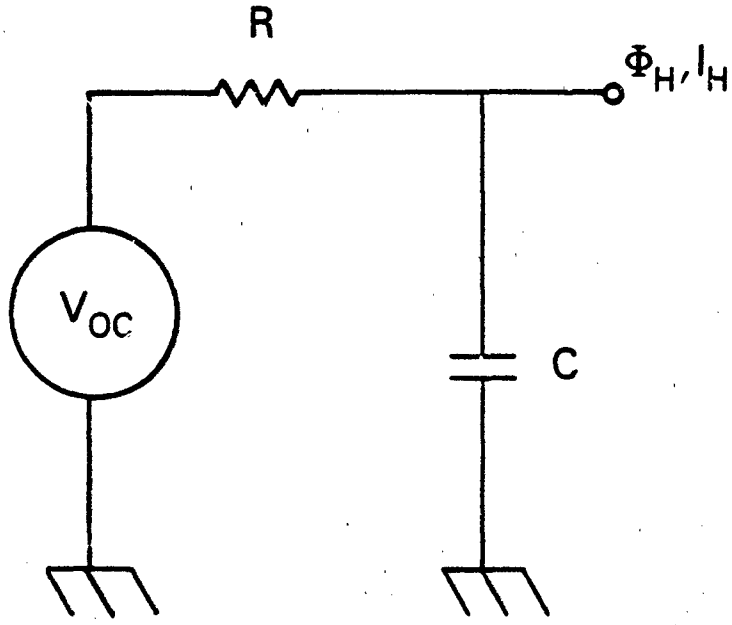

Fig. 4 — The simplest equivalent circuit f. r a hovering helicopter. V_{oc} is the measured open voltage of the helicopter, R is the ratio of this voltage to the short circuit current and C is the capacitance of the helicopter to ground.

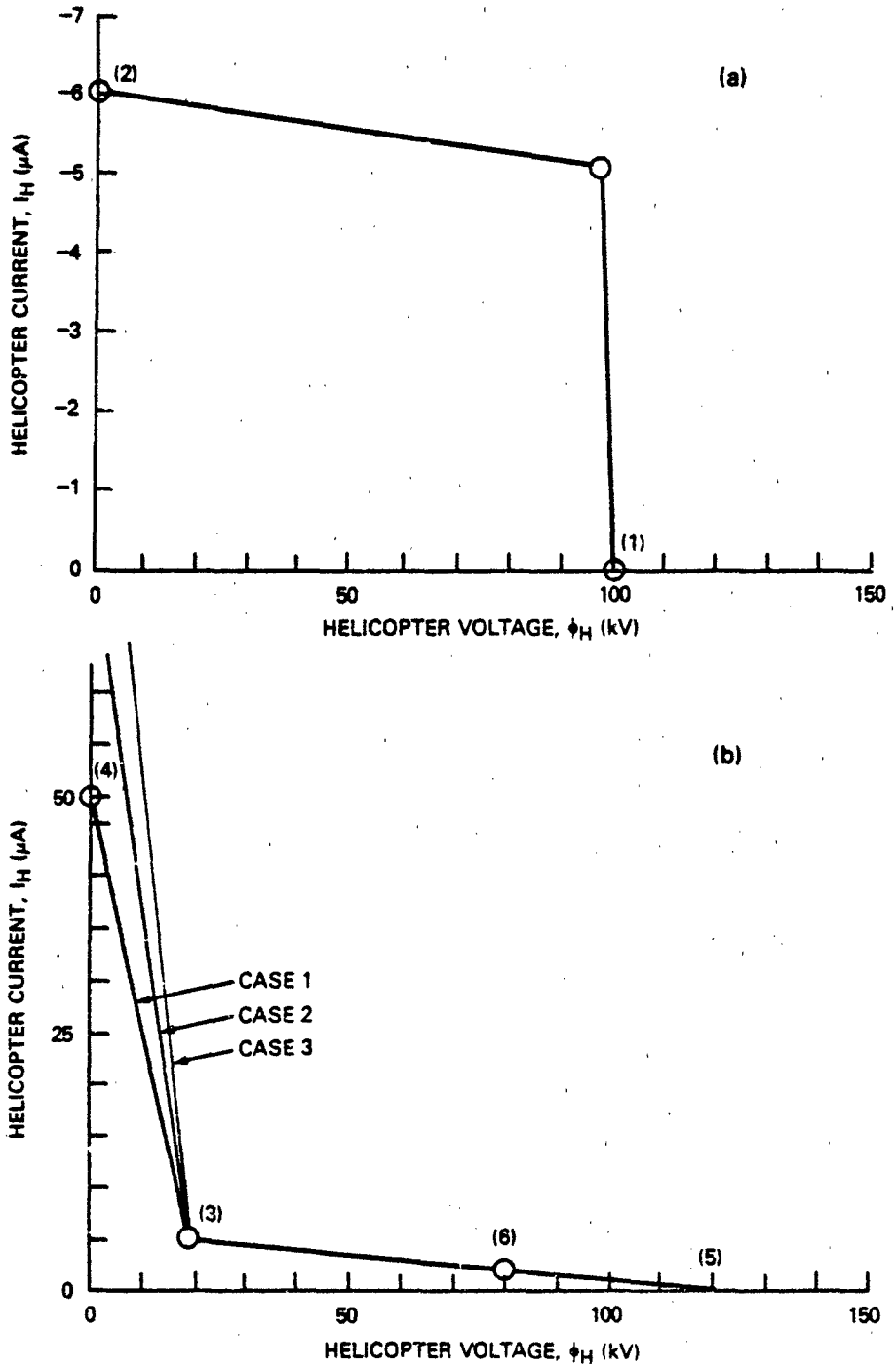

Fig. 5 — Typical CH-53E current/voltage characteristics: a) over clean runway and, b) over the sandy terrain. The points, O, represent consistent average measurements and the solid lines are the model equations (3), (24), and (25).

REFERENCES

1. R. Gunn, W. C. Hall, and G. D. Kinser, "The Precipitation Static Interference Problem and Methods for its Investigation." Proc. IRE, 34, 156-161 (1946).

2. D. G. Douglas and J. E. Nanevicz, Stanford Research Institute, and B. J. Solak, Boeing Company, Vertol Division, "Passive Potential Equalization Between the Cargo Handler and a Hovering Helicopter", (~1975).

3. "Helicopter Static Electricity Conference Notes." Sikorsky Aircraft Division, United Aircraft Corp., August 1958.

4. J. F. Clark, "Method and Apparatus for Discharging an Electric Charge." U. S. Patent No. 3035208, May 1962.

5. O. Tranbarger, B. M. Duff, T. E. Owen, "Helicopter Model Studies for On-board Electrostatic Sensors", USAAVRADCOM-TR-81-D-26, Fort Eustis,VA, September 1981. **ADA105511**

6. G.J. Born, W.F. Burke, and E.J. Durbin, "A Fundamental Study of Static Electric Phenomena (Applied to Helicopters)", Research and Development Technical Report ECOM-02412-10, United States Army Electronics Command, Fort Monmouth, NJ, March 1972.

7. R. V. Anderson, "Electrostatic Theory Applied to Helicopter Charging." Lightning Technology Round-up, DOT/FAA/CT-83-25, pages 60-1 through -8, June 1983. **ADP002209** **ADA135100**

8. C. D. Hendricks, in "Electrostatics and its Applications" Edtd. by A. D. Moore, John Wiley, New York, 1973, Chapter 4.

9. J. E. Nanevicz, and D. G. Douglas, "Electrostatic Discharge Systems", Final Report, Contract P. O. CH700377, SRI Project 1657, SRI, Menlo Park, CA, November 1972. AD912 403L

10. M. A. Uman, Lightning, McGraw Hill Book Company, New York, 1969, Chapter 3.

11. C. F. Dalziel, "A Study of the Hazards of Impulse Currents", Proc. AIEE 1037-43, (1953).

12. C. F. Dalziel and W. R. Lee, "Lethal Electric Currents", IEEE Spectrum 44-50, February 1969.

APPENDIX I - CALCULATION OF THE POTENTIAL DUE TO THE SPACE CHARGE OF THE SAND CLOUD

The sand cloud is assumed to be a cylinder of radius, R_L, and height, y_L. The potential is computed for a position located on the cloud axis that is a distance, y, above the ground. Two calculations are required: the first is for a position that is immersed in the sand cloud; the second is for a position that is at the top of a sand cloud. These calculations yield potentials that correspond to the potential due to the entire cloud and to the potential due to the charged sand in a cylinder immediately under the aircraft. Since potentials add linearly, the difference between these two calculated potentials corresponds to the potential due to the entire cloud less a cylinder directly underneath. This difference leads to the value of the constant, F_1 used in the text. The potential due to the charged cylinder itself leads to the value of the constant, F_2.

The potentials are calculated by using Coulomb's Law for the potential due to a distributed charge, and the appropriate boundary conditions. In this case the appropriate boundary condition is that the ground is a conducting plane at zero potential. and it is satisfied by assuming that an image cloud, of opposite charge to the real cloud, exists under the ground plain.

Equation I-1 is the expression for the potential at an arbitrary

$$\phi(y) = \int_{-y_L}^{+y_L} \int_{0}^{R_L} \frac{nq}{4\pi\varepsilon_o} \frac{2\pi R' dR' dy'}{\sqrt{(y-y')^2+(R')^2}} \qquad (I-1)$$

axial position, y, above ground, due to a charged cylindrical cloud, y_L high and R_L in radius, above a ground plane. The cloud charge density, nq, is uniform, but of opposite sign for positive and negative values of y'. Equation II-2 is the result after

$$\phi(y) = \int_{-y_L}^{+y_L} \frac{qndy'}{2\varepsilon_o} \left(\sqrt{(y-y')^2+R_L^2} - \sqrt{(y-y')^2}\right) \qquad (I-2)$$

integrating over R'. Figure I-1 is a plot of the integrand of Equation I-2. The crosshatched areas in the figure cancel in the integral, with the result that the potential is due to the charge between ground and 2y, less the potential due to another strip 2y wide located at the far end of the image

cloud. Splitting the integral of Equation I-2 into parts above and below the ground plain, and changing signs appropriately to account for the opposite sign of the image charge, permits nq to be a taken as a constant, as shown in Equation I-3. This integral

$$\phi(y) = \frac{nq}{2\varepsilon_o}\left[\int_{o}^{y_L} dy' - \int_{-y_L}^{o} dy'\right]\left[\sqrt{(y-y')^2+R_L'} - \sqrt{(y-y')^2}\right] \quad \text{(I-3)}$$

is evaluated by first changing variables and then using a standard integral table. These steps are shown in Equations I-4 and I-5.

$$\phi(y) = \frac{nq}{2\varepsilon_o}\left[-\int_{y}^{y-y_L} + \int_{y+y_L}^{y}\right]\left(\sqrt{x^2+R_L^2} - \sqrt{x^2}\right) dx \quad \text{(I-4)}$$

$$\phi(y) = \frac{nq}{4\varepsilon_o}\left[x\left(\sqrt{x^2+R_L^2} - \sqrt{x^2}\right)+R_L^2 \ln\left|x+\sqrt{x^2+R_L^2}\right|\right]\left[-\Big|_{y}^{y-y_L} + \Big|_{y+y_L}^{y}\right] \quad \text{(I-5)}$$

(The notation of Eq. (I-5) means that the first quantity in brackets is evaluated between the limits $y-y_L$ and y, then between y and $y+y_L$, and then the first quantity subtracted from the second.)

Finally, dividing and multiplying this expression by y^2 and changing the limits appropriately results in the following expression for the potential as a function of y and of the ratios of cloud height and radius to y. This result is shown in Equation I-6.

$$\phi(y)=\frac{nqy^2}{4\varepsilon_o}\left[\frac{x}{y}\left(\sqrt{\left(\frac{x}{y}\right)^2+\left(\frac{R_L}{y}\right)^2}-\sqrt{\left(\frac{x}{y}\right)^2}\right)+\left(\frac{R_L}{y}\right)^2 \ln\left|\frac{x}{y}+\sqrt{\left(\frac{x}{y}\right)^2+\left(\frac{R_L}{y}\right)^2}\right|\right]\left[+\Big|_{y-y_L}^{y} - \Big|_{y}^{y-y_L}\right] \quad \text{(I-6a)}$$

$$\phi(y) = \frac{nqy^2}{4\varepsilon_o}\left[2G\left(1,\frac{R_L}{y}\right)-G\left(1-\frac{y_L}{y},\frac{R_L}{y}\right)-G\left(1+\frac{y_L}{y},\frac{R_L}{y}\right)\right] \quad \text{(I-6b)}$$

$$G\left(z,\frac{R_L}{y}\right) = z\left(\sqrt{z^2+(R_L/y)^2} - \sqrt{z^2}\right) + (R_L/y)^2 \ln\left|z + \sqrt{z^2+(R_L/y)^2}\right| \quad \text{(I-6c)}$$

It now remains to calculate ϕ_u and ϕ_ℓ or at least F_1 and F_2 in Equations 21 and 22 of the text. The first potential is due to the charge in the entire cloud (R_L=100 ft., y_L=100 ft.) less the charge in a cylinder (R_L=35.64 ft.,

y_L=20 ft.) directly under the position of the aircraft, y. The result is shown in Equation I-7, and corresponds to $A_R = 1$.

$$\phi_{\ell} = \frac{nq_u y^2}{4\epsilon_o}[2G(1,5)-G(-4,5)-G(6,5)-(2G(1,1.8)-G(0,1.8)-G(2,1.8))] \quad (I-7)$$

Substituting Equation I-6 into I-7 yields the expression for F_1.

$$F_1 = [2G(1,5)-G(-4,5)-G(6,5)-(2G(1,1.8)-G(0,1.8)-G(2,1.8))] = 8.66 \quad (I-8)$$

The second potential, ϕ_ℓ, and F_2 were found in the previous computation. The value of F_2 is given by Equation I-9.

$$F_2 = (2G(1,1.8)-G(0,1.8)-G(2,1.8)) = 1.14 \quad (I-9)$$

Values of F_1 and F_2 expressed as functions of cylinder base area i.e., A_R, are given in the curves of Figure I-2.

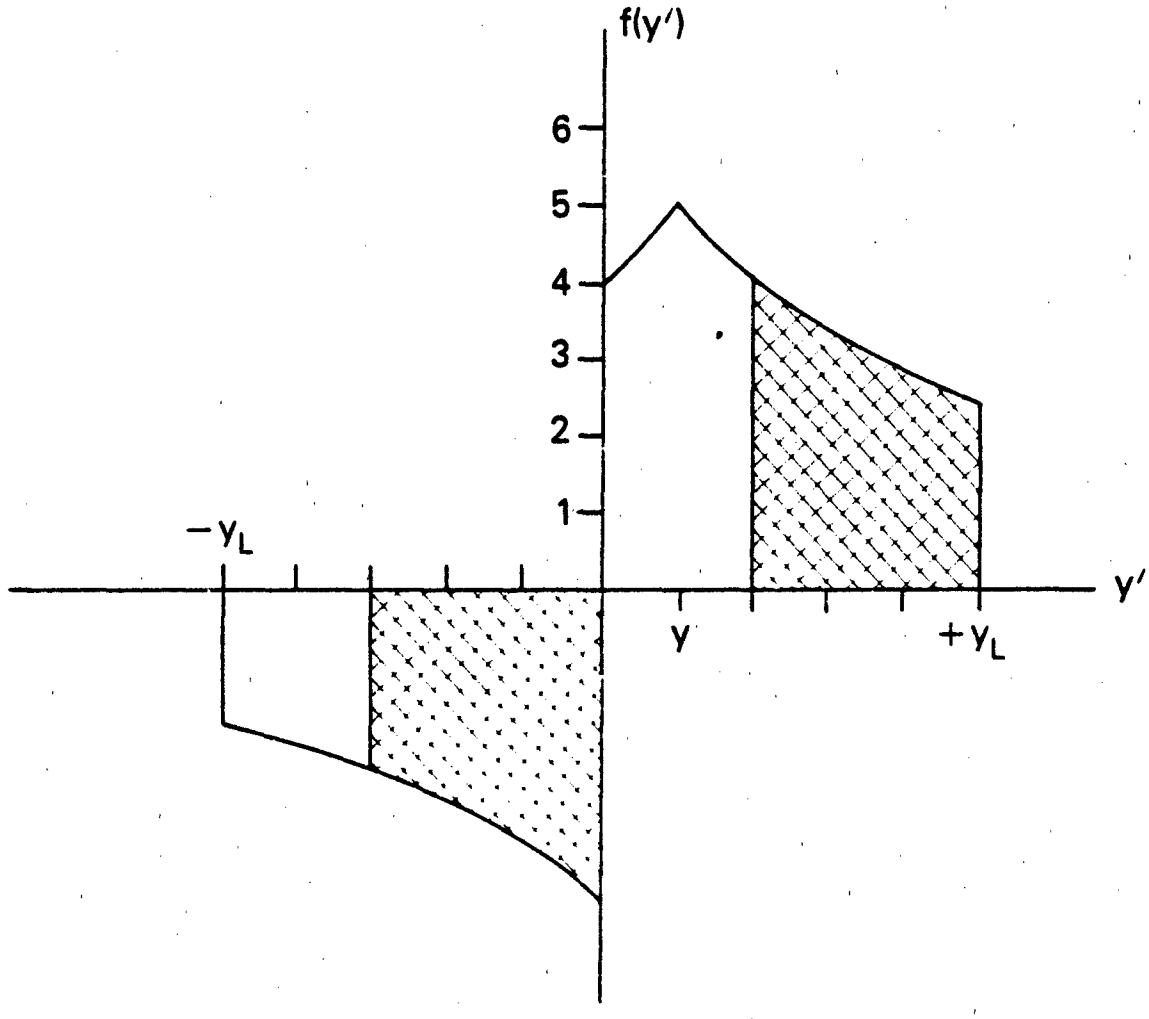

Fig. I-1 — Plot of the integrand of EQ. (I-4). The cross hatched areas cancel, showing that the only contribution to the potential comes from the charged particles between ground and twice the aircraft altitude diminished by a slab of equal thickness at the edge of this image charge.

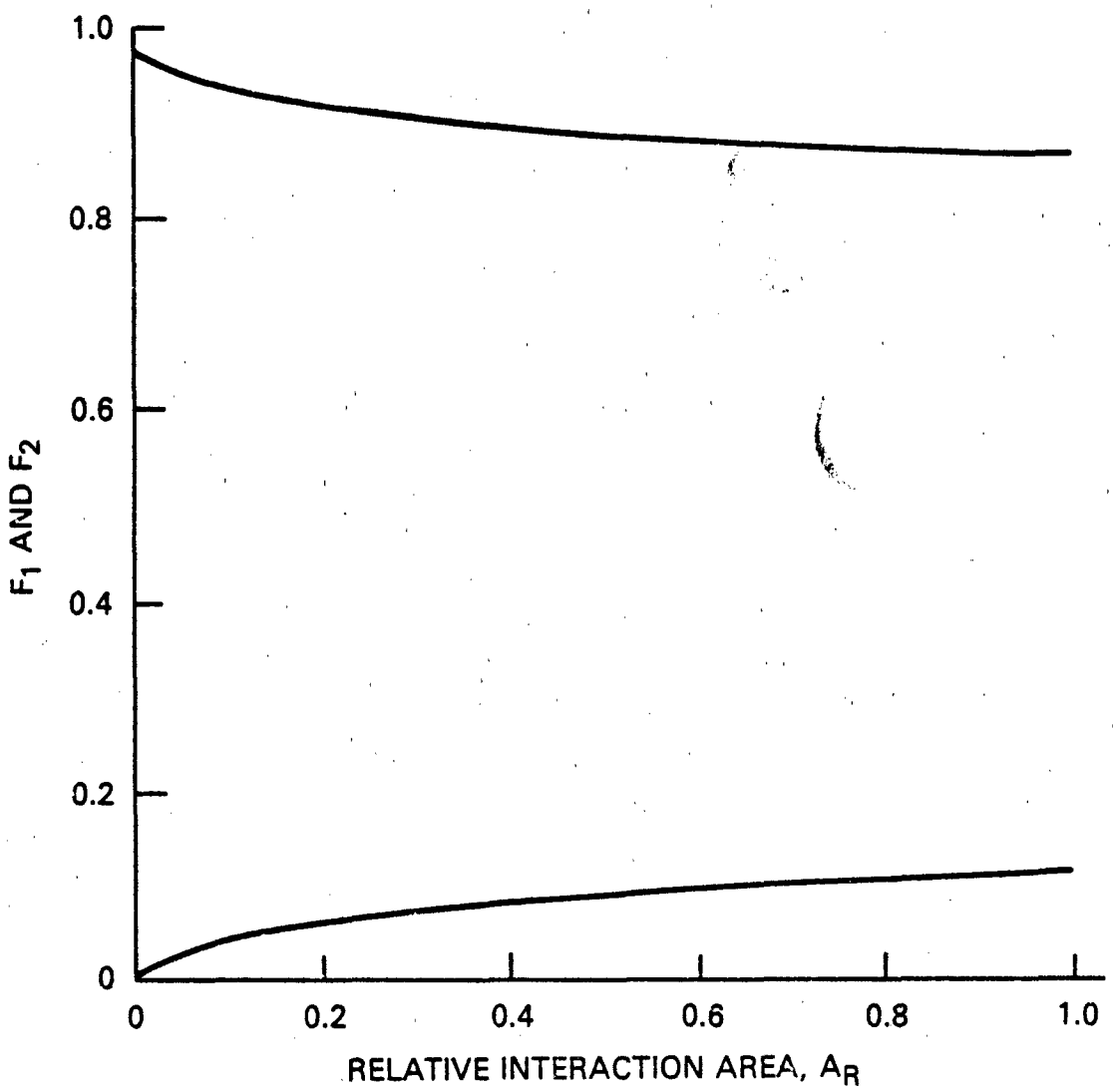

Fig. I-2 — Plots of F_1 and F_2 as a function A_R, the ratio of the area of the helicopter/cloud interaction region to the area swept by the CH-53E rotor. F_1 is always $\sim$ 0.9 and F_2 is always $\sim$ 0.1.

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