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Corona Discharge from Antenna Wire: A First Partial Report

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Corona Discharge from Antenna Wire

By

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ARL MEMORANDUM REPORT NO. 167

TITLE: Corona Discharge from Antenna Wire
A First Partial Report

TO: Director, Aircraft Radio Laboratory

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31 May 1944

This report consists of 7 pages and an appendix of xi pages.

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SUBJECT: Corona Discharge from Antenna Wire
A First Partial Report

A. DIRECTIVE: Verbal Directive from Branch Chief.

B. PURPOSE:

1. To examine the conditions for corona at the surface of a wire.

C. DESCRIPTION:

1. This report is a theoretical discussion. No test apparatus was used.

D. PROCEDURE:

1. This report is a theoretical discussion. No test procedure was used.

E. RESULTS:

1. An analysis of the case of an insulated wire placed at the axis of a conducting cylinder yields the following equation (Appendix 1):

Equation 1
$$E = GR_2 \log \frac{R_3}{R_2} + \frac{GR_2K_2}{K_1} \log \frac{R_2}{R_1}$$

where

E = potential difference between the wire and cylinder

G = potential gradient in the air at the outer surface of the insulation.

R_1 = outer radius of wire (single strand)

R_2 = outer radius of insulation

R_3 = inner radius of cylinder

K_1 = dielectric constant of insulation

K_2 = dielectric constant of air.

2. For a bare wire of radius R_2 (that is, for a wire in which the thickness of the insulation is zero, $R_1 = R_2$) equation 1 reduces to:

Equation 2 $$E = GR_2 \log \frac{R_3}{R_2}$$

where G is now the potential gradient in the air at the surface of the wire.

3. An analysis of the case of an insulated wire parallel to, and at a distance H above a conducting plane, yields the following equation (Appendix 2):

Equation 3 $$E = GR_2 \log \frac{2H}{R_2} + \frac{GR_2K_2}{K_1} \log \frac{R_2}{R_1}$$

where E = potential difference between the wire and the plane.

H = distance between the wire and the plane

R_1, R_2, K_1, K_2, and G = are defined as in par. E-1.

4. For a bare wire of radius R_2 (that is, for a wire in which the thickness of insulation is zero or $R_1 = R_2$) equation 3 reduces to:

Equation 4 $$E = GR_2 \log \frac{2H}{R_2}$$

5. It has been found empirically (F. W. Peek, Dielectric Phenomena in High Voltage Engineering) that the potential gradient required to produce corona in the air about a wire depends upon the radius of the wire, the density of the air, and the surface condition of the wire. Humidity has no appreciable effect on the starting point of visual corona, provided the conductor surface is dry. Change of the initial ionization of the air, even to a considerable extent, has no appreciable effect on the starting point of corona. Initial ionization has been found to reduce the time lag of breakdown, however, and to introduce a steadying effect on the values of the rupturing voltage. The visual corona gradient about a wire has been found independent of the material of the wire, provided that the surface condition remains the same. The

presence of water on the surface of a conductor greatly lowers the gradient required for onset of corona. The presence of oil on the surface of a conductor also lowers the gradient required to produce breakdown in the air at the surface of a conductor, but to a much smaller extent than water. Dirt on the surface of a conductor, or other surface irregularity, causes corona to start at a lower apparent gradient by increasing local gradients, causing local corona discharges.

6. The empirical equations given by Peek (loc. cit.) relating the gradient required for corona in air at the surface of bare wire to the radius of the wire and to the temperature and pressure of the air are:

Equation 5 $$G = 30\,md \left(1 + \frac{0.301}{\sqrt{dr}}\right) \text{ Kilovolts per cm.}$$

Equation 6 $$d = \frac{3.92b}{273 + t}$$

where G = gradient required to produce visual corona in air at the surface of a wire of radius r.

d = air density factor

r = radius of wire, in cms.

b = barometric pressure, in centimeters of mecury

t = temperature, in degrees Centigrade

m = irregularity factor (m = 1 for smooth, polished wire. For stranded cable m varies from .70 to .87 depending on the number of strands and the cable construction. For cabled wire r is taken as half the outer diameter of the cable).

7. The potential gradient required at the surface of bare wire for corona may be computed from equations 5 and 6, and the potential difference required to achieve this gradient may be calculated for a bare wire at the axis of a conducting cylinder, or for a bare wire above a plane by means of equations 2 and 4, respectively.

8. The calculation of the conditions for corona about an insulated wire is complicated by considerations of small air

gaps at the boundary between the wire and the insulation, by the collection of surface charge on the insulation from the ionized air in its vicinity, by the magnitude of the electric currents conducted through the insulation, and by the dielectric strength of the insulating material. The resistance of insulating materials is generally not linear. An increment in potential difference is accompanied by a greater increment in current at large potential differences than at small potential differences. No computations or measurements have been made at ARL to date to predict or determine the effect of insulating coatings on the corona characteristics of wire.

9. An analysis of some typical corona data was attempted for bare .040" diameter copperweld wire, and bare .162" diameter copper wire obtained on the B-17 airplane at Kansas City (Appendix 3). Data were submitted giving the potential gradients (measured at the top generating voltmeter on the B-17 airplane) at which antennas of the two wire sizes went into corona, at specific altitudes and outside air temperatures. Based on these data the gradients at the surface of the .040" diameter wire required to produce corona were computed from equations 5 and 6. On the assumption that the charge on a bare wire was, for practical purposes, independent of the wire size, and proportional to the field intensity measured on the generating voltmeter, the field intensity at the generating voltmeter at which the large diameter wire might be expected to go into corona was computed. The predicted value was 886 volts per cm., while the average measured value was 789 volts per cm. Much more data must be obtained and analyzed before any definite conclusions can be drawn regarding the validity of the above assumptions. Computations and data are contained in Appendix 3.

F. CONCLUSIONS:

1. Calculation of the gradient at the surface of the fixed-wire liaison antenna (bare copperweld, .040" diameter) on the B-17 airplane indicates that it is of the order of 200 times the gradient measured at the top generating voltmeter.

2. Further work will be done by the Special Devices Branch in an attempt to determine the conditions under which insulated wire goes into corona.

G. RECOMMENDATIONS:

1. None

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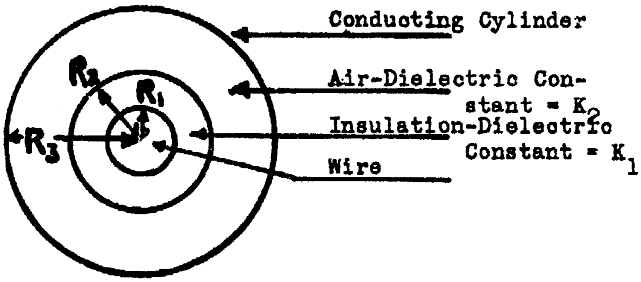
APPENDIX I

DERIVATION OF THE EQUATION RELATING THE POTENTIAL DIFFERENCE BETWEEN AN INSULATED WIRE AND A CONCENTRIC CONDUCTING CYLINDER TO THE GRADIENT AT THE SURFACE OF THE WIRE (NEGLECTING END EFFECTS).



If q is the charge per cm. of length, the dielectric flux density at radius r is $D = \frac{2q}{r}$ lines/cm^2, and the electric field strength in the medium is $F = \frac{2q}{Kr}$ dynes, where K has different values in different media. The electric field strength in the air layer, F_2, is given by $F_2 = \frac{2q}{K_2 r}$. The electric field strength in the insulating layer, F_1, is given by $F_1 = \frac{2q}{K_1 r}$.

The drop of potential across the air layer, E_2, is given by

$$E_2 = \int_{R_2}^{R_3} \frac{2q}{K_2 r}\, dr = \frac{2q}{K_2} \log \frac{R_3}{R_2}$$

The drop of potential across the insulating layer, E_1, is given by

$$E_1 = \int_{R_1}^{R_2} \frac{2q}{K_1 r}\, dr = \frac{2q}{K_1} \log \frac{R_2}{R_1}$$

The potential drop between the inner and outer conductor, E, is given by

$$E = E_1 + E_2 = \frac{2q}{K_1} \log \frac{R_2}{R_1} + \frac{2q}{K_2} \log \frac{R_3}{R_2}$$

The maximum potential gradient in the air layer (at R_2), G, is equal to

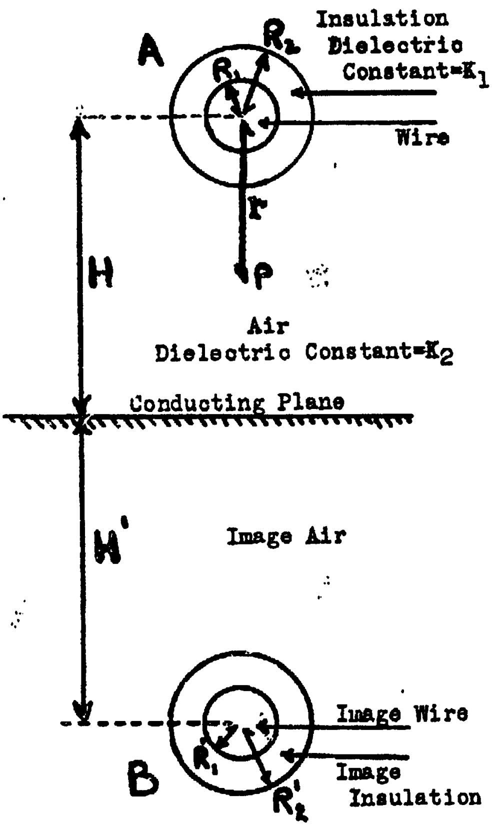
$$G = \frac{2q}{K_2 R_2}$$

Substitution in the previous equation gives

$$E = \frac{G K_2 R_2}{K_1} \log \frac{R_2}{R_1} + G\, R_2 \log \frac{R_3}{R_2}$$

APPENDIX II

DERIVATION OF THE EQUATION RELATING THE POTENTIAL DIFFERENCE BETWEEN A CONDUCTING PLANE AND A PARALLEL INSULATED WIRE TO THE POTENTIAL GRADIENT AT THE SURFACE OF THE WIRE (NEGLECTING END EFFECTS).



An insulated wire at A is suspended a distance H above and parallel to a plane. The charge on the wire per cm. of length is q. In accordance with the method of images, a wire placed beneath the plane at B, directly beneath the wire at A, and a distance H' = H below the plane, with a charge -q per cm. of length, will not distort the field.

The flux density at a point a distance r cm. from the center of a wire is given by

$$D = \frac{2q}{r}$$

The electric field strength at a point P, on the line connecting the wire centers, due to the charge on the wire at A will be

$$F_A = \frac{2q}{Kr}$$

and that due to the image wire at B will be

$$F_B = \frac{2q}{K(2H-r)}$$

The total field strength at P will be

$$F = F_A + F_B = \frac{2q}{K}\left(\frac{1}{r} + \frac{1}{(2H-r)}\right)$$

Now

$$E = \int F\,dr = \int \frac{2q}{K} \left(\frac{1}{r} + \frac{1}{2H-r} \right) dr$$

$$= \frac{2q}{K} \left\{ \log r - \log (2H - r) \right\}$$

$$= \frac{2q}{K} \log \frac{r}{2H - r}$$

Hence, the potential difference between the wires will be

$$E' = E_1' + E_2' + E_3'$$

where

$$E_1' = \int_{R_1}^{R_2} F\,dr$$

$$= \frac{2q}{K_1} \left(\log \frac{R_2}{2H-R_2} - \log \frac{R_1}{2H-R_1} \right)$$

$$= \frac{2q}{K_1} \log \frac{R_2\,(2H-R_1)}{R_1\,(2H-R_2)}$$

$$E_2' = \int_{R_2}^{2H-R_2} F\,dr = \frac{2q}{K_2} \left(\log \frac{2H-R_2}{R_2} - \log \frac{R_2}{2H-R_2} \right)$$

$$= \frac{4q}{K_2} \log \frac{2H-R_2}{R_2}$$

$$E_3' = \int_{2H-R_2}^{2H-R_1} F\,dr$$

$$= \frac{2q}{K_1} \left(\log \frac{2H-R_1}{R_1} - \log \frac{2H-R_2}{R_2} \right)$$

$$= \frac{4q}{K_1} \log \frac{R_2 \, (2H-R_1)}{R_1 \, (2H-R_2)}$$

$$E' = E_1' + E_2' + E_3' = \frac{4q}{K_1} \log \frac{R2 \, (2H-R1)}{R_1 \, (2H-R_2)} + \frac{4q}{K_2} \log \frac{2H-R_2}{R_2}$$

The electric field strength or the potential gradient at the surface of the insulation (at R_2) will be, from the original equation for F,

$$G = \frac{2q}{K_2} \left(\frac{1}{R_2} + \frac{1}{2H-R_2} \right).$$

Eliminating q between the above equations

$$E' = \frac{2GK_2}{K_1} \frac{1}{\left(\frac{1}{R_2} - \frac{1}{2H-R_2}\right)} \log \frac{R_2 \, (2H-R_1)}{R_2 \, (2H-R_2)} + \frac{2G \log \frac{2H-R_2}{R_2}}{\left(\frac{1}{R_2} - \frac{1}{2H-R_2}\right)}$$

where E' is the potential difference between the wire and its image and G is the potential gradient at the surface of the insulation of the wire. The potential difference between the wire and the plane (E) will be equal to:

$$E = \frac{E'}{2}$$

$$E = \frac{G \, K_2}{K_1} \frac{1}{\left(\frac{1}{R_2} - \frac{1}{2H-R_2}\right)} \log \frac{R_2 \, (2H-R_1)}{R_1 \, (2H-R_2)}$$

$$+ \frac{G \log \left(\frac{2H-R_2}{R_2}\right)}{\left(\frac{1}{R_2} \quad \frac{1}{2H-R_2}\right)}$$

and, when H is much greater than either R_1 or R_2,

$$E = \frac{GR_2K_2}{K_1} \log \frac{R_2}{R_1} + G \, R_2 \log \frac{2H}{R_2}$$

APPENDIX III

Analysis of Flight Data:

1. The following summary of data, giving relative corona onset fields for two sizes of wire used for the fixed-wire liaison antenna on B-17G, #42-31294, was submitted by the TWA-GE-ARL precipitation static research group at Kansas City. Measurements pertinent to the small wire (bare .040" diameter copperweld) were made under straight charging conditions. Measurements pertinent to the large wire (bare .162" diameter copper) were made under cross-field conditions, since straight charging conditions severe enough to cause corona from the large diameter wire were not encountered. The difference in these conditions of measurement may account for the larger variation in values for the large wire (see Table 3, below). Under cross-field conditions the reading on the top generating voltmeter (on the B-17 airplane) is not as good a reference as it would be under straight charging conditions, since wide variations in the ratios of gradients measured at different parts of the airplane are encountered. The reported values are indicated in Tables 1, 2, and 3.

2. Based on the average values of altitude and temperature, the wire diameter, and equations 5 and 6 (in the body of this report), the gradients at the surface of the two wires at which these might be expected to go into "visual corona" were computed. These computed values and the ratio of the computed field intensities at the surface of the wire to the average measured field intensities at the top GVM are indicated in Table 4.

3. An attempt was made to calculate the gradient indicated by the top GVM for which the large diameter wire would go into "visual corona" under the conditions of Table 3. The required gradient for corona at the surface of the wire was calculated to be 45,000 volts/cm. As a first approximation several simplifying assumptions were made; these were: 1) the irregularity factor m (of equation 5) was unity (the results are not altered as long as m is the same for both wires); 2) the charge distribution on the airplane is constant, so that the gradient measured at the top GVM is directly proportional to the charge on, and to the gradient at the surface of the antenna wire; 3) the linear charge density on the antenna wire is independent of the size of the wire (within the limits of the accuracy of measurement) for the two sizes considered; and 4) Peek's equations 5 and 6 are valid. The relation between the gradient at the surface of a wire, its radius and the linear charge density on its surface in a medium of dielectric

constant equal to unity (air) is:

$$G = \frac{2Q}{R}$$ where

G is the gradient at the surface of a wire

Q is the linear charge density on a wire

R is the radius of a wire.

If we let:

R_1 = radius of the small wire (.020" = .0508 cm.)

R_2 = radius of the large wire (.081" = .205 cm.)

G_1 = computed gradient for "visual corona" at the surface of the small wire (under the average conditions of Tables 1 and 2, G_1 = 62,100 volts/cm.)

G_2 = computed gradient for "visual corona" at the surface of the large wire (under the conditions of Table 3, G_2 = 45,000 volts/cm.)

X_1 = average measured gradient at the top GVM for corona onset from the small wire liaison antenna (303 volts/cm.)

X_2 = gradient at the top GVM for corona onset from the large wire liaison antenna (to be computed)

Q_1 = linear charge density on the surface of the small wire (at the region of the liaison antenna of highest charge density) for corona onset.

Q_2 = linear charge density on the surface of the large wire (at the region of the liaison antenna of highest charge density) for corona onset.

Then:

$$Q_1 = \frac{G_1 R_1}{2}$$

$$Q_2 = \frac{G_2 R_2}{2}$$

Assuming that:

$$\frac{Q_1}{X_1} = \frac{Q_2}{X_2} = \text{constant}$$

We obtain:

$$X_2 = \frac{Q_2}{Q_1} X_1$$

$$X_2 = \frac{G_2 R_2}{G_1 R_1} X_1$$

Hence:

$$X_2 = 886 \text{ volts/cm.}$$

The average measured gradient at the top GVM for corona onset from the large diameter wire was 789 volts/cm.

APPENDIX III

TABLE I

Corona Data Obtained for the Fixed-Wire Liaison Antenna (.040" Diam. Bare Copperweld Wire) on B-17G, #42-31294, on 10 March 1944.

	ALTITUDE	TEMPERATURE (DEGREES CENTIGRADE)	POTENTIAL GRADIENT AT TOP GENERATING VOLT-METER AT WHICH LIAISON ANTENNA WENT INTO CORONA (Volts per Centimeter)
	7300	-10	280
	7300	-10	240
	7200	-10	280
	7000	-10	280
Average	7200	-10	270

TABLE II

Corona Data Obtained for the Fixed-Wire Liaison Antenna (.040" Diam. Bare Copperweld Wire) on B-17G, #42-31294, on 11 March 1944.

	ALTITUDE (Feet)	TEMPERATURE (DEGREES CENTIGRADE)	POTENTIAL GRADIENT AT TOP GENERATING VOLT-METER AT WHICH LIAISON ANTENNA WENT INTO CORONA (Volts per Centimeter)
	9100	-16	320
	9100	-16	360
	9800	-19	360
	9800	-20	320
	9600	-19	320
Average	9480	-18	336

APPENDIX III

TABLE III

Corona Data Obtained for the Fixed-Wire Liaison Antenna (.162" Diam. Bare Copper Wire) on B-17G, #42-31294, on 16 March 1944.

	ALTITUDE (Feet)	TEMPERATURE (DEGREES CENTIGRADE) (Estimated)	POTENTIAL GRADIENT AT TOP GENERATING VOLT-METER AT WHICH LIAISON ANTENNA WENT INTO CORONA (Volts per Centimeter)
	6500	-3	480
	6400	-3	440
	6400	-3	640
	6400	-3	640
	5900	-3	1040
	5900	-3	1040
	6000	-3	1240
Average	6200	-3	789

APPENDIX III

TABLE IV

Calculated and Measured Conditions for Corona from the Liaison Antenna on B-17G, #42-31294. All calculations are based on the average values indicated in Tables I, II, and III.

	Table I	Table II	Table III
Wire diameter.	.040"	.040"	.162"
Average measured field intensity at top GVM for onset of corona from wire of the diameter indicated.	270 volts/cm	336 volts/cm	789 volts/cm
Calculated field intensity at top GVM for onset of corona from wire of the diameter indicated.	----------	----------	886 volts/cm
Calculated field intensity at the surface of the wires for "visual corona" in air.	63,300 volts/cm	60,900 volts/cm	45,000 volts/cm
Ratio of calculated field intensity at surface of wire to average measured field intensity at top GVM.	234	181	57

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SUMMARY

It has been determined by the Army-Navy Precipitation Static Project at Minneapolis, and by the TWA-GE-ARL precipitation static research group at Kansas City, that the primary source of radio interference of precipitation static origin is corona discharge from the antennas themselves. A larger diameter bare wire or a suitably insulated wire substituted for W-106 wire (bare copperweld, .040" diameter) was found to reduce the tendency for corona to occur from the fixed-wire antennas. In the attempt to understand better the mechanism of corona discharge from wires an analysis of the potential gradients at the surfaces of bare and insulated wire has been made for two postulated conditions: first, the wire at the axis of a conducting cylinder, and, second, the wire parallel to a conducting plane. In both cases end effects have been neglected, and in the latter case a simplifying assumption has been made that the radius of the wire is small in comparison with the separation between the wire and plane.

A working approximation, to simplify the considerations governing the selection of a corona-resistant antenna wire which must be substituted for the present W-106 wire, is proposed. This approximation - that the amount and distribution of static charge along the fixed wire antennas on the airplane is independent of the size of the wire and that the magnitude of the charge on the antenna wire is proportional to the electric field measured at some point on the airplane - is checked against the small amount of flight data available for a bare wire antenna.

Calculations indicate that the electric field intensity at the surface of the present fixed wire liaison antenna (W-106 wire) is about 200 times as great as the field measured on the top generating voltmeter on the B-17G airplane, serial no. 42-31294.

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