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Lightning Suppression by Chaff Seeding

HEINZ W. KASEMIR

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ABSTRACT

The basic concept of lightning suppression by chaff seeding is to increase the conductivity inside a thunderstorm by a continuous release of ions liberated through corona discharge on chaff fibers which are dispersed from an airplane inside the cloud. This increased conductivity would permit the current produced by the thunderstorm to flow from the positive to the negative charge center or from the negative charge center to the ground without the generation of the high electric fields which are necessary to initiate lightning discharges.

The application of this simple concept to modify the electric field or the lightning activity of a real thunderstorm encounters a number of questions on the theoretical as well as on the practical side that are difficult to answer. For instance, (1) Will the corona discharge be quenched by its own space-charge production if a certain amount of the released charge is trapped by cloud particles in the close environment of the chaff fibers?; (2) Does the generation of a conducting chaff-seeded area in the storm produce a field concentrating effect at the boundary of the area that is apt to generate rather than suppress lightning discharges?; and (3) Can the chaff be distributed fast enough through a large enough cloud volume to discharge effectively the cloud in a reasonable time? These and other problems are discussed in detail in this report. Finally, the first results on an accelerated field decay caused by chaff seeding underneath a thunderstorm are presented.

LIGHTNING SUPPRESSION BY CHAFF SEEDING

Heinz W. Kasemir

1. PHYSICAL CONCEPT

The purpose of seeding a thunderstorm with chaff is to inhibit lightning discharges. The physical concept of chaff seeding is to increase the conductivity of the cloud through ionization of the air by corona discharge on the chaff fibers, with the result that the electric field is kept below the value necessary to ignite lightning. The principal idea of chaff seeding can be easily demonstrated by a laboratory experiment. A metallic sphere of about 0.5-m diameter is placed over a grounded plate with an air gap of 10 to 20 cm between sphere and ground. If the sphere is charged to several 100 kV by use, for instance, of a Van de Graff generator, sparks will flash over between the sphere and the grounded plate. If we now bring into the air one chaff fiber of about 5-cm length, the sparkover will stop immediately. The chaff fiber is attached to the end of a long thin Teflon rod, that is, it is well insulated and does not touch either the sphere or the plate. If we remove the chaff fiber from the air gap, the sparks will flash over again. In this experiment, the charged sphere represents the thunderstorm, the plate is the earth surface, and the sparks are cloud-to-ground lightning. The chaff fiber shows the effect of chaff seeding, an effect that can readily be explained. Corona discharge at the two ends of the fiber produce a large number of ions which flow in a wide stream from the upper end of the fiber to the sphere and from the lower end to the plate. This ion flow increases the conductivity of the air between sphere and plate and the resulting current is such a load on the Van de Graff generator that the voltage at the sphere drops below the flashover voltage.

This experiment shows us that three important conditions must be fulfilled if chaff seeding of a thunderstorm is to be as effective in suppressing lightning discharges as the presence of one chaff needle is in suppressing spark discharges during the laboratory experiment. These conditions are: (1) that the volume of air in a storm or between the storm and ground can be made conductive by the corona discharge on the chaff fibers; (2) that the electric field necessary to produce lightning is higher than that to produce corona discharge; and (3) that the current induced by corona discharge will load down the thunderstorm generator so that the electric field remains below the value required to ignite lightning.

The last point may be clarified by a reference to a technical circuit diagram of the current flow of the thunderstorm generator (fig. 1). On the left side of figure 1, the generator symbols G_1 and G_2 represent the positive and negative charge generation in the top and the base of a storm. The unmarked resistor symbols (rectangular small boxes) at the hot terminals of the generators indicate that we are dealing with current generators. This means that the charge is produced at a given rate whether it

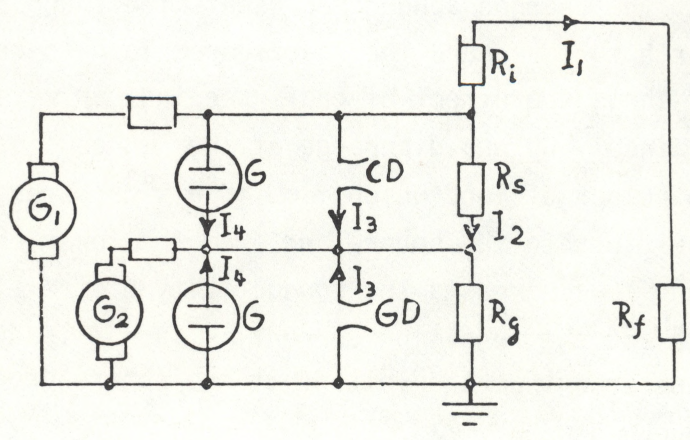

Figure 1. Circuit diagram of a thunderstorm generator.

can dissipate or not. Three different means are provided in the circuit diagram for the dissipation of charge. These are (from left to right in fig. 1) the two glow lamps G, the two spark gaps CD and GD, and the ohmic resistors R_s and the series R_i, R_f, and R_g. The current flow through the ohmic resistors represents the conduction current of a thunderstorm. R_s is the shunt resistor between the hot terminals of the two generators; it is determined by the conductivity of the column of air between the upper positive and the lower negative charge inside the storm. R_g is the resistance of the air column between the base of the cloud and the ground, and R_i is the resistance of the air column between the top of the storm and the ionosphere. The current flow in this branch of the circuit is closed by R_f which represents the resistance between the ionosphere and the earth in the fair weather areas. With the exception of R_f, the resistors have comparatively high values (of the order of hundreds of MΩ) so that the charge produced by the generators cannot leak away rapidly. As a consequence, the voltage at the terminals builds up to high values until a spark is ignited through the spark gaps CD or GD. These spark gaps picture the lightning discharges in a real thunderstorm, with CD representing the cloud discharge and GD the ground discharge. The glow lamps of the circuit diagram have no natural equivalent in the thunderstorm. They represent the artificially introduced corona discharge of the chaff fibers. If the voltage across the glow lamps reaches their breakdown value, the lamps will ignite and keep the voltage at this value very effectively. Any further increase in the current output of the generators will be shunted through the glow lamps. If the glow lamps have a lower ignition voltage than the spark gaps, no flashover at the spark gaps will occur.

It is generally assumed that the average thunderstorm produces a current output of about 3 A, which is equally divided between the three load circuits. 1 A flows as conduction current between the two main charge centers inside the storm through the shunt resistor R_s. From a technical point of view, this current may be considered as a leakage current across faulty insulation between the poles of the generator. It is the purpose of chaff seeding to increase this conduction current by increasing the conductivity between the generator poles to a higher level so that the voltage between the poles is reduced below the ignition voltage for lightning. The next section will include a discussion in detail on how conductivity is increased by the corona discharge on the chaff fibers.

Another part of the current output flows from the positive pole in the top of the storm to the ionosphere through the resistor R_i, spreads out in the ionosphere over the whole globe, flows down to earth through the resistor R_f, and returns to the negative pole of the thunderstorm generator through the resistor R_g. This current output is the contribution of the storm to the atmospheric fair-weather electric field. The current flow in this branch, called the global circuit, is assumed to be of the order of 1 A.

The last part of the thunderstorm charge production is dissipated in lightning discharges. If we assume that the average thunderstorm produces one lightning discharge every 30 s and that 30 C are discharged by each lightning, 1 A continuous-supply current is required to feed the lightning activity. More severe storms may generate lightning discharges every 5 or 10 s. With the same amount of coulomb discharged, the lightning supply current would be of the order of 3 to 6 A. As it has been mentioned above, the thunderstorm--in a technical sense--is a current generator with a given current output. Therefore, if lightning activity is to be suppressed, the lightning supply current of 1 to 6 A has to be channeled through another circuit which, in our case, is the shunt resistor R_s or the ground resistor R_g. To absorb this current without an increase in the terminal voltage, this resistor R_s or R_g has to be decreased by one-half to one-fifth of its natural value by chaff seeding. In the circuit diagram, figure 1, this decrease of the resistor is represented by the glow lamp G which will ignite if a certain generator voltage is reached. For proper operation of the circuit, the ignition voltage of the glow lamp should be less than the flashover voltage of the spark gap, and the glow lamp should be capable of absorbing the spark-gap supply current without a substantial increase in the generator voltage.

As applied to the thunderstorm problem, this means that the field to start corona discharge on the chaff fibers should be significantly lower than the igniting field of lightning and that the conductivity of the chaff-seeded volume should be increased to such an extent so that the lightning supply current can be absorbed without a significant increase of the field. The first condition is easily met because the onset field of the corona discharge on a chaff fiber 10- to 100-μm thick and 5- to 10-cm long is of the order of 30 kV/m, whereas the igniting field of the lightning discharge is about 500 kV/m. The fulfillment of the second condition is not so easily asserted and will be discussed in section 2 that follows.

2. EFFECT OF CORONA DISCHARGE ON CHAFF FIBERS UPON THE CONDUCTIVITY OF THE CLOUD

The conductivity of the air stems from the ionization of air molecules by cosmic rays and from radioactive emanation of the ground. The ion production is given by the ionization constant q, which is of the order of 5 to 20 x 10^6 ion pairs per second per cubic meter. One single chaff fiber with a corona current of 1 μA will produce 6 x 10^{12} ion pairs per second, that is, it would be equivalent to the natural ion production of a volume of 3 x $10^5 m^3$ of a cube of 68-m length, width, and height. If we require that the ion production in the cube should be increased three times, then the chaff fiber with a corona current of 1 μA would provide the required number of ion pairs for a cube with a side length of about 46 m. A cloud volume of 4 x 4 x 4 km^3 = 64 x $10^9 m^3$ contains 65 x 10^4 of such cubes. This means that about one-half million chaff fibers would be enough to increase the ion production in the cloud by a factor of three. Implicit in this estimate is the assumption that a field of about 70 kV/m exists to produce the corona current of 1 μA and that the chaff fibers are evenly distributed throughout the volume.

In estimating the increase of conductivity by an increase of ion production, we have to take into account the loss by recombination and attachment. As the negative ion stream released by the chaff fiber moves upward and the positive ion stream moves downward, ions of opposite polarity do not meet. Consequently, there is no ion loss by recombination of small ions. Only if the upward-moving negative ion stream meets the downward-moving positive ion stream produced by another chaff fiber floating at a higher level will there be recombination of small ions. This recombination of intermixing, however, will be beneficial for a continuous current flow, as will be discussed later.

A heavy loss of small ions will occur in the first few seconds by attachment to the cloud droplets until the droplets are charged to capacity and will reject further attachment of ions of the same sign. An area of negative space charge will form above the chaff fiber and one of positive space charge below it. This will have two effects. First, the presence of a negative space charge in the negative ion stream will deflect the ions to both sides until the uncharged cloud droplets at the sides also become negatively charged. This will result in a kind of trumpet-shaped space charge as depicted in figure 2. Second, these negative and positive space charges forming above and below the single chaff fiber will generate an electric field, opposed to the existing field, which produces the corona discharge. If the space charges can accumulate unchecked of if their opposing field is not cancelled by other means, then the corona discharge will be quenched by its own space-charge generation.

This result, however, is applicable only to a single chaff fiber or to the uppermost or lowermost layer of the seeded area. If we have two layers of chaff fibers, as in figure 2, the fields of the inner positive and negative space-charge layers will approximately cancel at the locus of the chaff fiber. The extrapolation to more than two layers of chaff fibers is evident. Such a volume filled with positive and negative space-charge pockets resembles very strongly that of a dielectric material polarized by an external field. The local fields of the internal

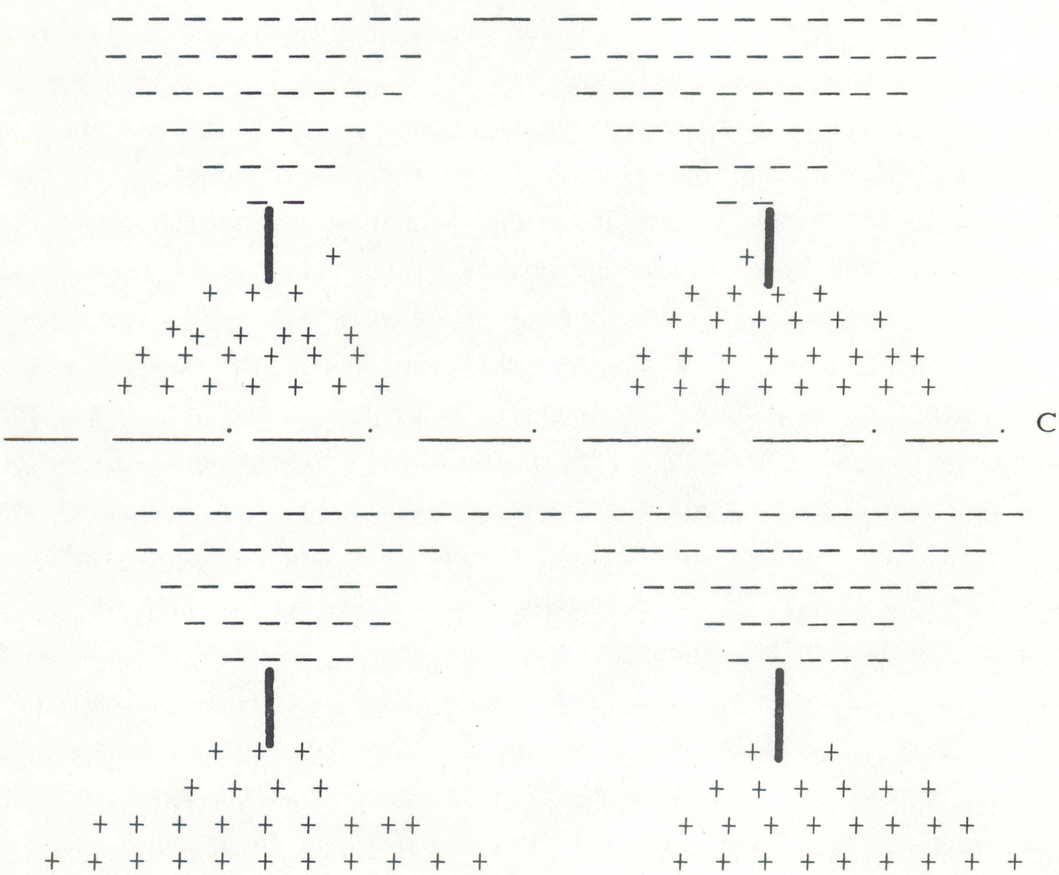

Figure 2. Positive (+) and negative (-) space-charge distribution of an array of chaff fibers.

dipoles cancel each other by the sheer number of dipoles, and the reduction of the primary field inside the dielectric can be interpreted as the effect of the surface charge at the boundary of the dielectric material.

In the case of chaff seeding for the purpose of lightning suppression, we require, in addition to the field-reducing effect, that an enhanced current flow be carried through the seeded area. This would necessitate that at the contact area (marked by a dashed line C in fig. 2) between the positive space charge of the upper chaff fiber and the negative space charge of the lower chaff fiber a strong recombination takes place between the opposite-charged cloud droplets or that this contact area is penetrated by a sufficient number of positive small ions coming down from the upper chaff fiber and of negative small ions coming up from the lower chaff fiber. Even if the small ions recombine rapidly with cloud droplets or small ions of opposite polarity, they reduce the space-charge pockets and stimulate a continuous corona discharge. For a continuous current flow through the seeded area, it is only necessary that each chaff fiber carries the current through its own region of influence.

A numerical analysis to determine the size of the region of influence is extremely difficult. Probably the best way to solve this problem is to carry out measurements in a large cloud chamber equipped with a plate condenser that is capable of generating fields of the order of 100 kV/m. However, three effects shall be mentioned, each of which tends to reduce the little pockets of space charge (thereby helping to prevent the quenching of the corona discharge) and to support the current flow. These effects are: recombination of positive- and negative-charged cloud droplets, turbulent mixing, and washout by precipitation. The enhanced coagulation of oppositely charged cloud droplets may even lead to precipitation enhancement. This coagulation or recombination would apply also to raindrops falling through the seeded area. The raindrop will pick up a number of highly charged cloud droplets passing through, for instance, the upper negative space-charge pocket, becoming itself negatively charged. As the raindrop enters the positive space-charge pocket below, it will now coagulate with the positive-charged cloud droplets, lose its negative charge, and become positively charged. This process will continue alternately until the raindrop leaves the seeded area. Besides reducing the space-charge pockets, this process will also increase the growth rate of the raindrop.

With regard to the purpose of the following calculation, we will assume that an enhanced current flow can be carried through the seeded area. Given a sufficient overlapping of the region of influence of the chaff fibers, the large number of small ions liberated by corona discharge, the recombination of charged cloud droplets, the effect of turbulent mixing, and the washout of space-charge pockets by precipitation are lumped together in one material parameter --namely, the conductivity inside the seeded area--with the resulting effect that the conductivity inside the seeded area is increased by corona discharge. If one accepts the assumption that the conductivity inside the seeded area is increased by chaff seeding, the problem of the field concentration at the surface of a conductive body in an electric field becomes apparent immediately. If we also generate by chaff-seeding regions of field concentration, this method of lightning suppression may inadvertently become a method of lightning triggering. It is therefore quite important to have quantitative answers to the following three questions: (1) How does the field concentration at the boundary depend on the inside-to-outside conductivity ratio of the seeded area?; (2) How does the field concentration depend on the geometrical shape of the seeded area?; and (3) How much is the field concentration factor changed if we are dealing with the inhomogeneous field generated by space charges instead of the general assumption of a homogegeous field?

The solution of the third question is more difficult and will be discussed in section 3.2. The solution of questions 1 and 2 is given in section 3.1 that follows.

3. FIELD CONCENTRATION AT THE BOUNDARY OF THE CHAFF-SEEDED AREA

3.1 In a Homogeneous Cloud Field

The calculation is carried out for the following problem: A body of a given shape, with the constant conductivity λ_2, is embedded into an environment of the constant conductivity λ_1. The whole system is exposed to a homogeneous electric field F_1 in the direction of the z-axis of a Cartesian coordinate system x, y, z. Find the field F_2 inside the body and the maximum field F_m at the boundary of the body. The body shall be represented either by an infinitely long elliptical cylinder or by a spheroid. The solution shall be given in the case of the cylinder for:

ac, the small axis of the elliptical cross section is in the z-direction;

bc, both axes are equal, in which case the elliptical cylinder becomes a circular cylinder;

cc, the large axis of the elliptical cross section is in the z-direction;

and, in the case of the spheroid, for:

as, a flat disc, with the short axis in the z-direction;

bs, a sphere;

cs, a prolonged spheroid, with the long axis in the z-direction.

The cases ac to bc may be encountered if the chaff is dispersed continuously from an airplane, and the cases as to cs may be encountered if the chaff is dispersed discontinuously in little packages from an airplane, dropsonde, or rocket.

The derivation of the potential function is not given here because the solution to the problems ac to cc can be obtained from the textbook, Static and Dynamic Electricity, by Smythe (1950) if the dielectric problem is transformed into a current flow problem by substituting the conductivities λ_1 and λ_2 for the two dielectric constants ε_1 and ε_2. The solution to problem as to cs is given by Kasemir (1952).

A very simple equation has been obtained for the maximum field concentration F_m at the boundary of the seeded area as well as one for the attentuated field F_2 inside the seeded area. These equations are valid for all of the above stated problems and are as follows:

$$\frac{F_2}{F_1} = \frac{\lambda_1/\lambda_2}{\lambda_1/\lambda_2 + (1-\lambda_1/\lambda_2)\rho} \tag{1}$$

and

$$\frac{F_m}{F_1} = \frac{1}{\lambda_1/\lambda_2 + (1-\lambda_1/\lambda_2)\rho} \tag{2}$$

From equations (1) and (2), it also follows that

$$F_2 = \frac{\lambda_1}{\lambda_2} F_m \tag{3}$$

where

F_1 = original field outside the seeded area,

F_2 = field inside the seeded area,

F_m = maximum field at the boundary,

λ_1 = conductivity outside the seeded area,

λ_2 = conductivity inside the seeded area, and

ρ = form factor, which depends only on the geometrical shape of the seeded area (fig. 3).

With the horizontal half-axis a and the vertical half-axis b of either the elliptical cylinder or the spheroid, ρ is given for the elliptical cylinder by

$$\rho_c = \frac{a}{a + b} \tag{4}$$

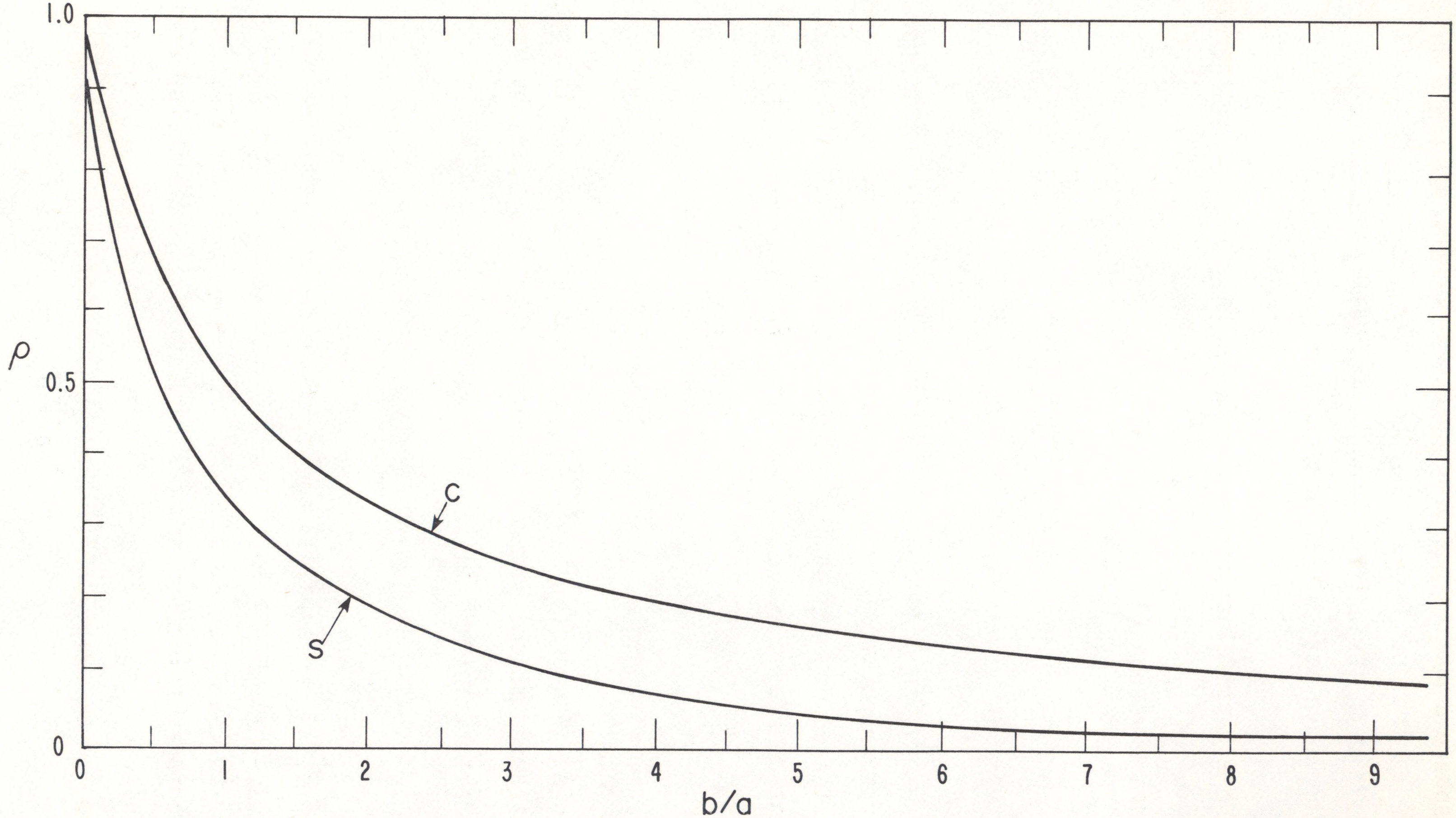

Figure 3. Form factor for ρ as a function of the ratio b/a (vertical axis b to horizontal axis a of the ellipse). C is the elliptical cylinder and S is the spheroid.

and for the spheroid by

$$\rho_s = \frac{a^2}{a^2-b^2}\left(1 - \frac{b}{\sqrt{a^2 - b^2}} \tan^{-1} \frac{\sqrt{a^2 - b^2}}{b}\right) \quad . \tag{5}$$

For a → ∞, the elliptical cylinder as well as the spheroid degenerates into a horizontal infinite layer. Note that ρ_c and ρ_s approach 1. For $\rho = 1$, it follows from equation (1) that

$$\frac{F_2}{F_1} = \frac{\lambda_1}{\lambda_2} \quad . \tag{6}$$

As F_1 and λ_1 are given parameters, the field F_2-- according to equation (6)--is inverse proportional to λ_2. This is a well-known result and follows from the assumption of a continuous current flow. If $i_1 (=\lambda_1 F_1)$ is the current density outside and if $i_2 (=\lambda_2 F_2)$ is the current inside the seeded area, we then obtain from equation (6)

$$i_2 = i_1 \quad . \tag{7}$$

If we bring a conductor into a homogeneous field, there is usually a field concentration at the boundary. However, in this case, by inserting $\rho = 1$ into equation (2), we obtain

$$F_m = F_1 \quad . \tag{8}$$

The maximum field F_m is equal to the original field F_1 outside of the seeded area, that is, there is no field augmentation at the boundary.

If we go to the other extreme and let b → ∞, then the ellipitical cylinder deteriorates into a vertical infinite layer and the spheroid into an infinitely long circular cylinder. In this case, ρ_s and ρ_c approach zero. From equations (1) and (2), we obtain

$$F_2 = F_1 \tag{9}$$

and

$$\frac{F_m}{F_1} = \frac{\lambda_2}{\lambda_1} \tag{10}$$

These are somewhat unexpected results. Equation (9) says that the field inside the seeded area is the same as outside the seeded area no matter how much we increase the conductivity inside the seeded area. This means that continuous seeding from a dropsonde, which may generate a body of seeded area like a prolonged spheroid, would have almost no field-reducing effect. Further, we learn from equation (10) that the field concentration on the ends of the prolonged spheroid is proportional to the inside-to-outside conductivity ratio of the seeded area. Both effects are favorable to the generation of lightning and are adverse to its suppression. Therefore, the manner in which a cloud is seeded will have some effect on the outcome, that is, whether lightning discharges are suppressed or prematurely triggered.

The field augmentation given by equation (10) has to be considered as a maximum value which will never be obtained. To give an estimation of how close we may come to the maximum value with reasonable shapes for the seeded area, figure 4 shows the field augmentation F_m/F_1 as a function of the ratio b/a which represents the ratio of the vertical to the horizontal dimension of the seeded area. The curves of figure 4 are calculated with the assumption that $\lambda_2 = 2\lambda_1$, that is, the conductivity inside the seeded area is twice as much as the conductivity outside. The maximum field augmentation is then 2. For an axial ratio of b/a = 10/1, the field augmentation is 1.96; and for b/a = 5/1, it is 1.92. This means that for even moderately slim spheroids, the field augmentation at the ends of the spheroid is close to its maximum value.

If we reduce the axial ratio further to b/a = 1, the spheroid takes on the shape of a sphere. Here we have the maximum field concentration factor of 1.5 and the weakening factor of 0.75 for the field inside the sphere. If we assume that a field F_1 of 70 kV/m is necessary to produce corona current strong enough to consume that part of the thunderstorm current output which would otherwise dissipate in lightning discharges,

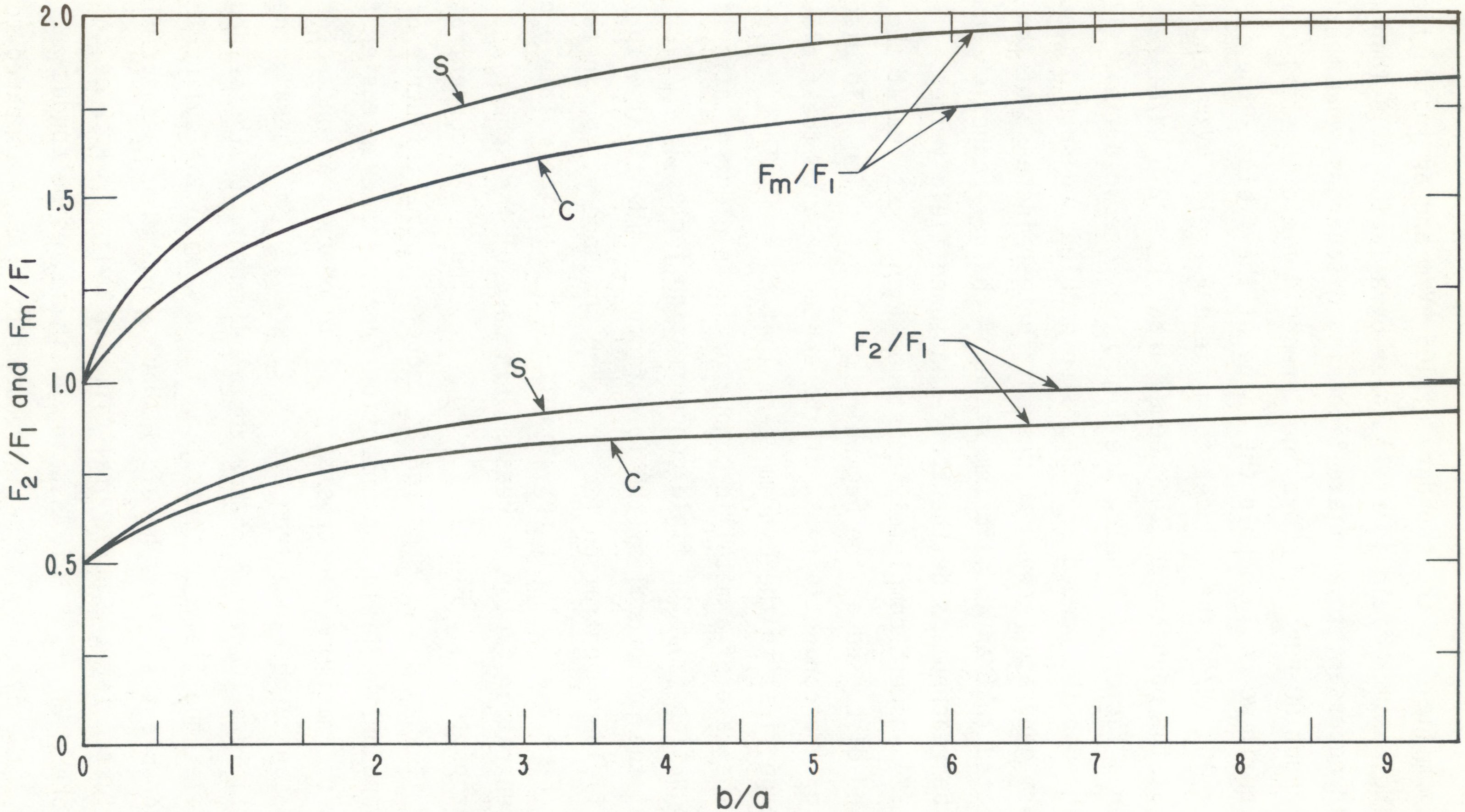

Figure 4. *Field concentration F_m/F_1 at the boundary of the seeded area; field attenuation F_2/F_1 inside the seeded area. S refers to the spheroid and C to the cylinder.*

we have a maximum field at the boundary of 105 kV/m and an inside field of 52 kV/m. The maximum field is still lower by a factor of 5 than the threshold field necessary to initiate lightning discharges, and the inside field is about 80 percent above the threshold field to start corona discharge. Even if we could double the value of the fields --the inside field F_2 = 104 kV/m, the thunderstorm field F_1 = 140 kV/m, and the maximum field at the boundary of the seeded area F_m = 210 kV/m --we are still more than a factor of 2 below the lightning threshold field. The current flow through the seeded area has also doubled and should load down the thunderstorm generator enough to prevent further increase of the field. It may be expected that an equilibrium state of charge production and dissipation will be reached inside the above-mentioned field values.

Equation (2) answers completely questions 1 and 2 stated at the end of section 2 and discussed at the beginning of this section. To discuss the influence of the conductivity λ_2 of the seeded area on the field concentration, we go first to the extreme case that $\lambda_2 = \infty$. This would be equivalent to the case of a metallic conductor in an electrostatic field. According to equation (2), the field concentration factor is $F_m/F_1 = 1/\rho$. This means that the reciprocal of the form factor is identical with the electrostatic field concentration factor. For the sphere, for instance, $\rho = 1/3$ and $F_m/F_1 = 3$. If λ_2 is not infinite but a finite multiple of λ_1, the field concentration factor decreases. In case of the sphere and for $\lambda_2 = 2\lambda_1$, it drops to 1.5. Finally for $\lambda_2 = \lambda_1$, the field concentration factor is 1 as it should be. Question 2, concerning the influence of the geometrical shape on the field concentration factor, is even easier to answer because the maximum "electrostatic" field concentration factor for all shapes can be obtained from $1/\rho$ in figure 3. In general, the smaller the ratio b/a (vertical to horizontal dimension of the seeded area), the smaller the field concentration factor, with the cylindrical shape more favorable than the spheroidal shape. The electrostatic field concentration factor for the horizontal circular cylinder is 2 as compared to the sphere which is 3. Assuming again an inside conductivity $\lambda_2 = 2\lambda_1$, the cylinder value is reduced to 1.33 as compared to the sphere value of 1.5. This means that line seeding from an airplane flying horizontally through or below the cloud will produce the most desirable shape of the seeded area.

The maximum field value given by equation (2) is an upper limit. This value will be reduced because the surface charge at the boundary is not restricted to a very thin layer, but spreads out over a volume of 100-or-more-meter thickness. It will also be reduced because the primary thunderstorm field F_1 is not constant, but goes through zero and changes polarity at the poles of the generator. This is a general feature of a field generated by space charges. The calculation for such a cloud field is given in section 3.2 for a seeded area in the form of a sphere. It would be more tedious than difficult to perform the same calculation for all the different shapes of seeded areas used here. The results will be principally the same; therefore, the example of the sphere is sufficient to demonstrate the reducing effect which an inhomogeneous cloud field has on the field concentration at the boundary of the seeded area.

3.2 In An Inhomogeneous Cloud Field

The calculation is carried out for the field concentration at the top of the sphere which is exposed to an inhomogeneous field distribution. The conductivity inside the sphere is λ_2 and outside the sphere is λ_1.

As emphasized before, the thunderstorm has to be considered as a current generator; that is, its primary characteristic is the current source density ω, not the space charge. The relation between the current source density ω and the space charge density q is

$$\frac{\varepsilon}{\lambda}\omega = \cancel{\frac{\varepsilon}{\lambda}}\; q \; ; \tag{11}$$

that is, the space charge density q depends on λ if the current source density is given (Kasemir, 1959). This will be the first of three conditions to impose on the potential function which solves our problem; that is, with a given current source density, the space charge density inside the seeded area shall be reduced in proportion to the increase in conductivity as given by equation (11). The second and third conditions, respectively, are that the potential functions Φ_1 outside and Φ_2 inside the sphere are identical at the sphere surface and that the radial current flow through the sphere surface is continuous.

We divide the thunderstorm into four layers of equal thickness "a", numbered I, II, III, and IV from top to bottom (fig. 5), and place the zero point of the Cartesian coordinate system x, y, z as well as that of the spherical coordinate system r, θ, φ, used later, in the middle of the storm. In the highest layer I, the current source density ω increases from zero at the top of the layer to its maximum value ω_o at the bottom of this layer. We have then

$$\omega = \omega_o \frac{2a - z}{a} \; ; \; a \leq z \leq 2a; \text{ Layer I} . \tag{12}$$

In layers II and III, the current source density decreases linearly with z, goes through zero in the middle of the storm, and reaches its maximum negative value at the bottom of layer III. We have then

$$\omega = \omega_o \frac{z}{a} \; ; \; -a \leq z \leq + a; \text{ Layers II and III} . \tag{13}$$

In layer IV, the current source density drops from its negative maximum value at the top to zero at the bottom of the layer. We have then

$$\omega = \omega_o \frac{2a + z}{a} \; ; \; -2a \leq z \leq -a; \text{ Layer IV} . \tag{14}$$

Such a current source distribution would result if we assume that precipitation particles become, for instance, negatively charged in the upper part of the thunderstorm, leaving the positive charge behind as they fall into the lower layers. Here a polarity change in the charging mechanism occurs, and the precipitation particles acquire positive charge, leaving the lower part of the storm negatively charged as they fall from the cloud (Kasemir, 1965).

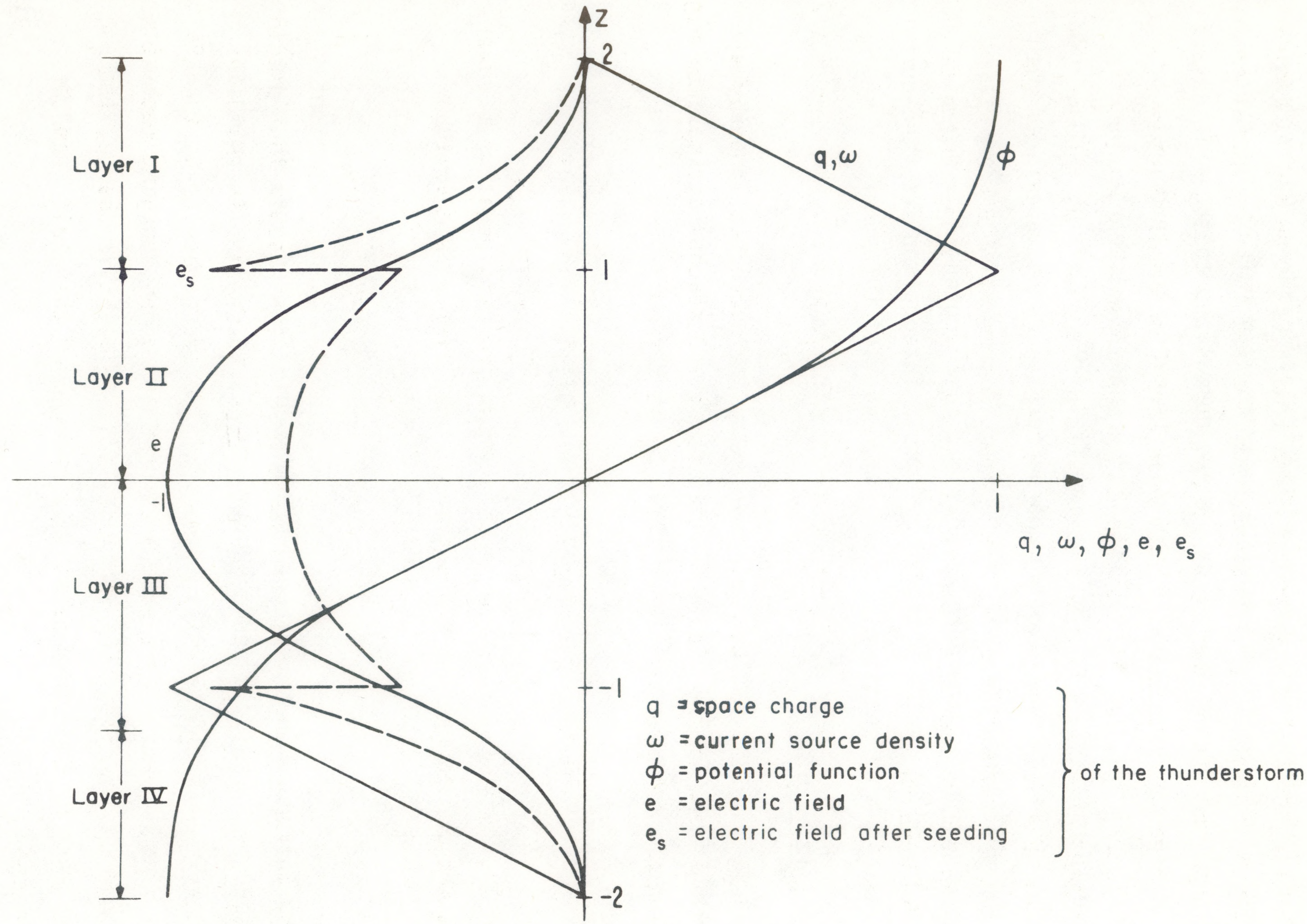

Figure 5. Field distribution of a chaff-seeded area in the inhomogeneous field of a thunderstorm.

Figure 5 shows the resulting charge, field, and potential configuration of the given current source distribution. Field, current source, and charge density are normalized to their maximum value. The distance z and the radius R of the seeded sphere are normalized to the thickness a of the layers. The positive and negative poles of the thunderstorm generator, that is, the highest positive and negative charge concentrations are then at $z = \pm 1$. The maximum field $e = -1$ occurs in the middle between the positive and negative charge for $z = 0$ and tapers off with increasing positive or negative z.

The equations of the normalized field e and potential ϕ for our thunderstorm model can be obtained by simple integration from the current source distribution equations (12), (13), and (14). They are as follows:

$$\left.\begin{aligned} e &= \frac{(z-2)^2}{2} \\ \phi &= \frac{(z-2)^3}{6} + 1 \end{aligned}\right\} \text{Layer I; } 1 \le z \le 2 \,. \tag{15}$$

$$\left.\begin{aligned} e &= \frac{z^2}{2} - 1 \\ \phi &= -\frac{z^3}{6} + z \end{aligned}\right\} \text{Layers II and III; } -1 \le z \le +1 \,. \tag{16}$$

$$\left.\begin{aligned} e &= -\frac{(z+2)^2}{2} \\ \phi &= \frac{(z+2)^3}{6} - 1 \end{aligned}\right\} \text{Layer IV; } 2 \le z \le -1 \,. \tag{17}$$

If we now introduce in this thunderstorm model a seeded area in the shape of a sphere with radius R and conductivity λ_2, we obtain the potential function ϕ_1 outside the sphere,

$$\begin{aligned} \phi_1 = &\left[r - \frac{r^3}{10} + \frac{1-\alpha}{2+\alpha} \left(1 - \frac{R^2}{10}\right) \right] P_1 \\ &- \left(\frac{1-\alpha}{3\alpha+4} \frac{3R^7}{r^4} + r^3\right) \frac{P_3}{15} \,, \end{aligned} \tag{18}$$

and the potential function ϕ_2 inside the sphere,

$$\phi_2 = \frac{1}{\alpha}\left[r - \frac{r^3}{10} + \frac{2(\alpha - 1)}{2 + \alpha}(1 - \frac{R^2}{10})r\right] P_1$$
$$- \left[\frac{3(1 - \alpha)}{3\alpha + 4} + 1\right] \frac{r^3 P_3}{15} \quad . \tag{19}$$

In equations (18) and (19),

$\alpha = \frac{\lambda_2}{\lambda_1}$ = ratio of conductivities from inside to outside of the sphere,

$r; \theta$ = polar coordinates, and

$P_1; P_3$ = Legendre's polynomials which are functions of $\cos\theta$.

The potential functions ϕ_1 and ϕ_2 fulfill all the boundary conditions outlined above and are, therefore, the unique solutions to our problem. Differentiation in respect to r yields the r-component e_{1r} and e_{2r} outside and inside the sphere, respectively. Thus, we have

$$e_{1r} = - \left[1 - \frac{3r^2}{10} + \frac{2(\alpha - 1)}{2 + \alpha} \frac{R^3}{r^3}(1 - \frac{R^2}{10})\right] P_1$$
$$- (\frac{1 - \sigma}{3\alpha + 4} \frac{4R^7}{r^7} - 1) \frac{r^2 P_3}{5} \tag{20}$$

and

$$e_{2r} = - \frac{1}{\alpha}\left[1 - \frac{3r^2}{10} + \frac{2(\alpha - 1)}{2 + \alpha}(1 - \frac{R^2}{10})\right] P_1$$
$$+ \frac{7}{3\alpha + 4} \frac{r^2 P_3}{5} \quad . \tag{21}$$

At the surface of the sphere $r = R$, we obtain from equations (20) and (21) the r-component of the field e_{1R} and e_{2R}. Thus, we have

$$e_{1R} = - (\frac{3\alpha}{2 + \alpha} - \frac{R^2}{10} \frac{5\alpha + 4}{2 + \alpha}) P_1 + \frac{7\alpha}{3\alpha + 4} \frac{R^2 P_3}{5} \tag{22}$$

and

$$e_{2R} = -\frac{1}{\alpha}\left(\frac{3\alpha}{2+\alpha} - \frac{R^2}{10}\,\frac{5\alpha+4}{2+\alpha}\right)P_1 + \frac{7}{3\alpha+4}\,\frac{R^2P_3}{5} \quad . \qquad (23)$$

From equations (22) and (23), it is easy to see that

$$e_{1R} = \alpha e_{2R} \text{ or } \lambda_1\, e_{1R} = \lambda_2\, e_{2R}$$

which is the condition for the continuous current flow through the surface of the sphere.

If we differentiate e_{1R} with respect to θ and set this equation equal to zero, we obtain from equation (22) the point of the sphere surface where the maximum field occurs. With P_1'; P_3' being the differentials of the Legendre's polynomials, we obtain from equation (22)

$$0 = \left[\left(\frac{3\alpha}{2+\alpha} - \frac{R^2}{10}\,\frac{5\alpha+4}{2+\alpha}\right)P_1' - \frac{7\alpha}{3\alpha+4}\,\frac{R^2P_3'}{5}\right]\sin\theta \ .$$

Because the expression in the brackets is not, in general, zero, it follows that $\sin\theta = 0$ and

$$\theta = 0 \text{ or } 180° \ ;$$

that is, the field maxima occur at the upper and lower points of the sphere. At these points, P_1 and P_3 are ± 1, and we obtain the maximum field e_{1R} max from equation (22)

$$\pm\, e_{1R\ max} = -\frac{3\alpha}{2+\alpha} + \frac{R^2}{10}\left(\frac{5\alpha+4}{2+\alpha} + \frac{14\alpha}{3\alpha+4}\right) \ . \qquad (24)$$

To compare this result with that obtained above for the homogeneous field, we set $\lambda_2 = 2\lambda_1$; $\alpha = 2$ which reduces equation (24) to

$$\pm\, e_{1R} \max = -\,1.5 + 0.58\ R^2 \ . \qquad (25)$$

For R<<1, the field concentration at the top of the sphere is 1.5 which was also the case for the homogeneous field. This result is to be expected because if the radius of the sphere is small compared to a, the sphere is surrounded by a practically homogeneous field. If the radius of the sphere grows to a, the field concentration at the top decreases to about 1.

The dashed line in figure 5 shows the field curve e_s as a function of z if a sphere of radius R = 1 and $\lambda_2 = 2\lambda_1$ is brought into the thunderstorm model. The external field rises with the approach of the upper and lower points of the sphere to about 0.9, which is not quite twice the value 0.5 of the thunderstorm field at these points. Nevertheless, even a field concentration of 0.9 is still less than the maximum field 1.0 of the storm center for z = 0 without seeding.

Inside the sphere, the field is reduced to 0.44 at the top and bottom and increases to about 0.73 in the center of the sphere.

With respect to a real thunderstorm, we have the following situation. If the maximum field of the storm has grown to 100 kV/m and the storm is seeded, we have a maximum field concentration of 150 kV/m at the boundary of the seeded area and of 75 kV/m inside, provided the sphere-shaped area is small compared to the thunderstorm dimensions. As the area grows, the maximum field at the boundary drops to about 90 kV/m and the inside field varies between 44 and 73 kV/m. The maximum fields are below igniting values for lightning by a factor 2 to 3, and the minimum fields are still above the corona onset field. Therefore, there is not much danger that lightning will be generated instead of being suppressed by chaff seeding. At the same time, the fields are not reduced to values that are too small to maintain corona discharge.

The real thunderstorm does not consist of infinite layers of space charge, as in our model, but is rather limited in the horizontal compared to the vertical extension. However, if we cut away the sides and limit the space charge layers to the inside of a cylindrical box, the thunderstorm field will drop off even more rapidly from its maximum value as shown in figure 5. In consequence, the field concentration at the upper and lower points of the seeded area will drop off faster with the growth of the area, so that the overall field-leveling effect will occur earlier and will be more pronounced.

In summary, we can answer question 3 first raised in section 2--How much is the field concentration factor changed if we are dealing with the inhomogeneous field generated by space charges instead of the general assumption of a homogeneous field?--as follows. The seeded area has an equalizing effect on the field distribution of a thunderstorm. Chaff seeding will decrease the maximum field value between the two main charge centers and will increase the outside field at the upper and lower boundaries of the seeded area, analogous to the maximum field concentration in a homogeneous field. However, this maximum field value would be lower than in the case of the homogeneous field; and, if the seeded area is large enough to reach to the poles of the thunderstorm generator, it would even be lower than the maximum field of the storm not seeded.

4. FIELD TESTS WITH CHAFF SEEDING

For the field test, a C-47 airplane was equipped with the following instruments:

(a) Two field mills capable of measuring the three components of the electric field;

(b) Two chaff dispensers;

(c) One corona discharge indicator; and

(d) Sensors for different meteorological and airplane parameters, including a strip chart and tape recorders.

Each field mill records two components of the atmospheric electric field and automatically eliminates the influence of the airplane charge on the measurement (Kasemir, 1972).

The chaff dispenser contains the chaff, not as needles cut to a preset length and pressed into little packages containing a million pieces, but as a long strand of conductive fibers wound upon 10 reels. The reels constitute one dispenser unit, housed in one wing tank. During the operation, 10 strands are forced out through 10 guide holes at great speed; before leaving the tank completely, the strands are chopped by a helical chopper into needles of a preset length. This design has three features which are crucial for lightning suppression. First, the chaff is emitted continuously. Bird nesting, that is, bunching together of needles in clumps of several hundred or thousand, is completely eliminated. Second, the chaff is distributed more evenly behind the airplane because a continuous stream of needles, not individual packages, emerges from the airplane. Third, it is possible to experiment with different lengths of needles; the needle length depends on the speed of the choppers which is easily adjustable.

The corona discharge indicator measures the electromagnetic emission of the chaff fibers as soon as they emerge from the chaff dispenser. This emission range should be limited to 50 to 100 m and the indication be selective as to corona discharge on the chaff only; that is, corona discharge on the airplane itself should not be measured. The last point is difficult to establish and needs more detailed study. Otherwise, the instrument seems to work properly. One essential point has already been confirmed; namely, corona discharge occurs on the chaff needles whenever the electric field in the atmosphere surpasses a threshold value of about 30 kV/m, thus substantiating laboratory tests.

The following flight procedure has been developed. The airplane flies below developing thunderstorms or shower clouds and hunts for areas with electric fields of about 60 kV/m or more. If such an area is found and the field pattern has been established by several passes through this area, chaff will be ejected on two to four seeding runs. The electromagnetic emission of the corona discharge and the electric field are then recorded during consequent passes back and forth through the seeded area until either the corona discharge or the strong electric field disappears. Figures 6 and 7 are typical examples of such flight records.

Figure 6 shows the corona discharge on the upper trace and the vertical field component on the lower trace. Seeding occurrences have been marked on the record by shading. Eleven passes were made below the storm. Chaff was dispensed during the second, third, and fifth passes. On the second and fourth passes, the trace of corona discharge emission appears small and irregular. During the third pass, the plane missed the previous seeded area completely; no corona discharge was recorded. Yet

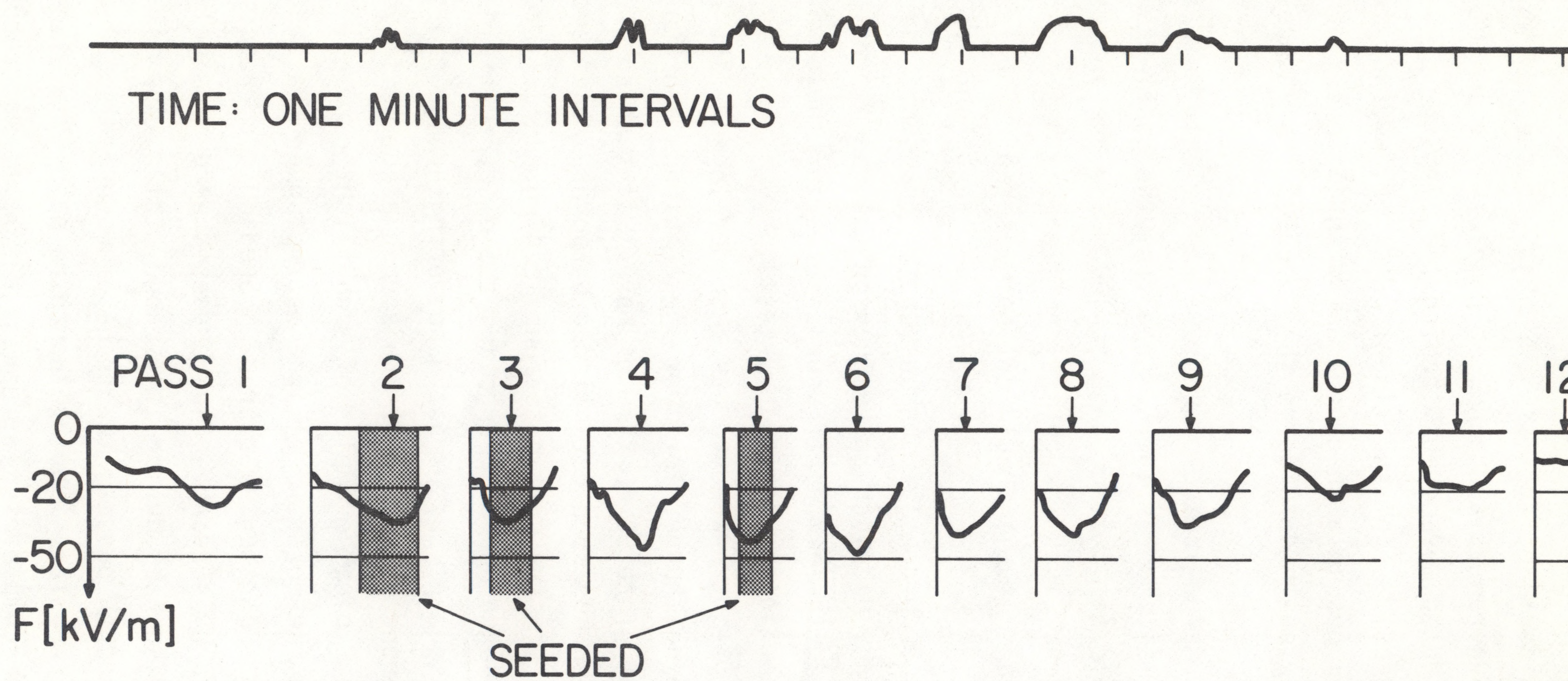

Figure 6. Corona discharge generated by chaff seeding, August 2, 1966.

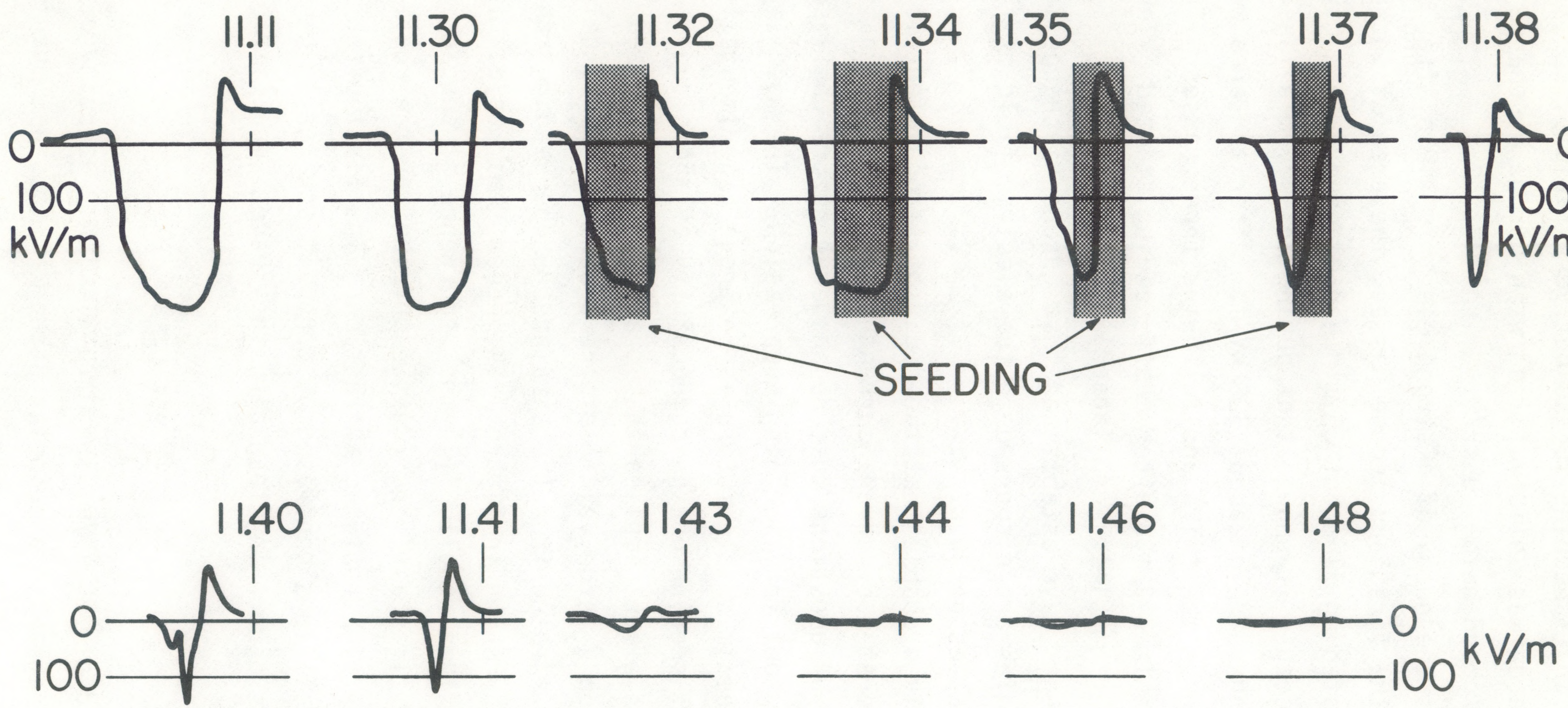

Figure 7. Field decay after chaff seeding, August 1, 1966.

it seemed that the chaff needles spread out very rapidly, and, after 5 to 10 min, the whole area was solidly filled with corona discharge emission until the fields dropped below 20 kV/m.

Figure 7 shows the decay of a strong electric field after chaff seeding. Between the first and second passes, the area of interest was lost and not relocated until about 20 min had elapsed. This circumstance proved fortunate because it showed that during this 20-min lapse the field remained at its high value of about 300 kV/m. After the area was relocated, chaff seeding began on the third and following three passes. The decay of the field was recognized 3 min after chaff seeding started. Ten min thereafter, the field had completely collapsed.

These experiments have established that corona discharge is generated whenever chaff needles are dispersed in the electric field of thunderstorms exceeding values of 30 kV/m.

It seems highly probable that the decay of strong electric fields is caused or accelerated by corona current produced by the chaff needles.

Yet, a number of questions must be answered before chaff seeding becomes an effective tool for lightning suppression. The most important research task in the immediate future is to prove experimentally that the effect of chaff seeding on the conductivity of the cloud is as stated in section 2. This effect implies that chaff can be dispensed in a reasonable time through a large volume of the cloud. If we visualize the thin line of chaff ejected from the airplane on one seeding run, then the fast field decay shown in figure 7 is indeed remarkable. Two facts may have helped in this result: (1) the occurrence of seeding underneath the cloud in clean air, and (2) the movement of the chaff fibers toward the cloud by electrostatic attraction. The first effect involves the movement of small ions generated by corona discharge in clean air. If movement of ions occurs in clean air, they have a mobility b of about

$$b = 10^{-4} \frac{m}{s} / \frac{V}{m} ,$$

that is, in a field of 300 kV/m, ions travel with a velocity of 30 m/s. As we are dealing here with a unipolar stream of ions without ion loss by recombination, the ions are capable of filling 1 km^3 in 30 s. This movement of ions could indeed account for a fast and widespread effect on the field.

The second effect, which is favorable to dispersion of the chaff fibers themselves, is the electrostatic attraction of the fiber by the negative space-charge center in the cloud. It is a well-known fact that the negative corona discharge starts at a lower electric field than the positive corona discharge. This means that the chaff fiber loses its negative charge at the beginning and consequently acquires a positive charge. This charge will assist the positive and repress the negative corona discharge until a current balance is reached where positive and negative corona currents are equal. The end effect is that in steady-state conditions, the chaff fiber is positively charged and is lifted against gravity into the cloud by coulomb forces.

It is not safe to assume that the same favorable conditions also exist inside the cloud. For instance, cloud droplets may collect on the chaff fiber and add so much weight that gravity overcomes electrostatic lift. Furthermore, it is a sound assumption that the movement of small ions is greatly reduced by their attachment to the immobile cloud droplets, as discussed in section 2. The advantage that the fields inside the cloud are much stronger than those outside is partly offset by the fact that the regions of high electric fields are not reasonably well know theoretically and are much more difficult to determine experimentally because field measurements are seriously hampered by the static precipitation charge. These are areas in which future research must be concentrated.

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