7. High-Voltage Insulation

More than any other factor, what separates high-power design from low-power is insulating for high voltage. Thermal management, on the other hand, is just as important for low-power systems as for high-power ones. Poor attention to thermal design can make a low-power system just as hot as a high-power system that suffers from a comparable lack of attention. The physical attributes are also proportional, in general. What is it, then, that separates a low-power system from a high-power one in terms of insulating for high-voltage?

Figure 7-1 gives us a point of departure. It is Paschen's curve for electrical breakdown in air, the most commonly used insulating medium. It plots the voltage between electrodes that will cause electrical breakdown, or ionization of the air between them, as a function of the product of the barometric pressure and electrode spacing. The most immediately recognizable piece of information from the curve is the absolute voltage minimum, approximately 340 V, below which it is not possible to produce breakdown in air regardless of spacing or pressure. But what about electrical systems of less than 340 V where arcing has been seen? For instance, what about the arc discharges that we have all observed coming from the terminals of a car's 12-V storage battery when we need to jump-start it? The arcing does not come about when we connect the battery to an external circuit. No matter how slowly we move the circuit lead to the battery terminal, we cannot generate an arc. Once the circuit is complete, however, current and self-inductance are established in the circuit. Now any attempt to break the circuit will almost always produce an arc—but not because of the original 12 V. The voltage across an inductor, expressed quantitatively as $-L\ di/dt$, is qualitatively whatever voltage is required to maintain whatever current is flowing in the inductance. And the source of the voltage is the energy stored in its magnetic field, $1/2\ LI^2$. This circuit-sustaining voltage can and will be more than enough to ionize air. (Indeed, this is how arc-welding machines work.)

Therefore, designers of systems whose operating voltages are less than 340 V do not have to worry about electrical insulation but only about preventing conductors or electrodes from coming into contact with each other. These systems, then, are most properly in the low-power domain. Given that most high-power systems will operate at voltages above 340 V (except for a precious few highly modular solid-state systems), Paschen's curve can also tell us just how good an electrical insulating medium air is for higher voltages. For instance, note the data point at the upper-right-hand corner of the curve. It shows that breakdown for electrodes spaced by one centimeter at one atmosphere of barometric pressure (and 25°C ambient temperature) will occur at 30,000 V. (At one-inch spacing under similar conditions, breakdown occurs at 79,000 V.) Those who have had any practical experience with high-voltage design will recognize that these are hardly the design criteria most commonly used. (The far more common guideline is one inch of separation for every 10,000 V.) Does the curve lie? No it does not. But it is based on conditions that are almost never realized in practice: that the conductors are an infinite plane, parallel, and perfectly smooth. When these

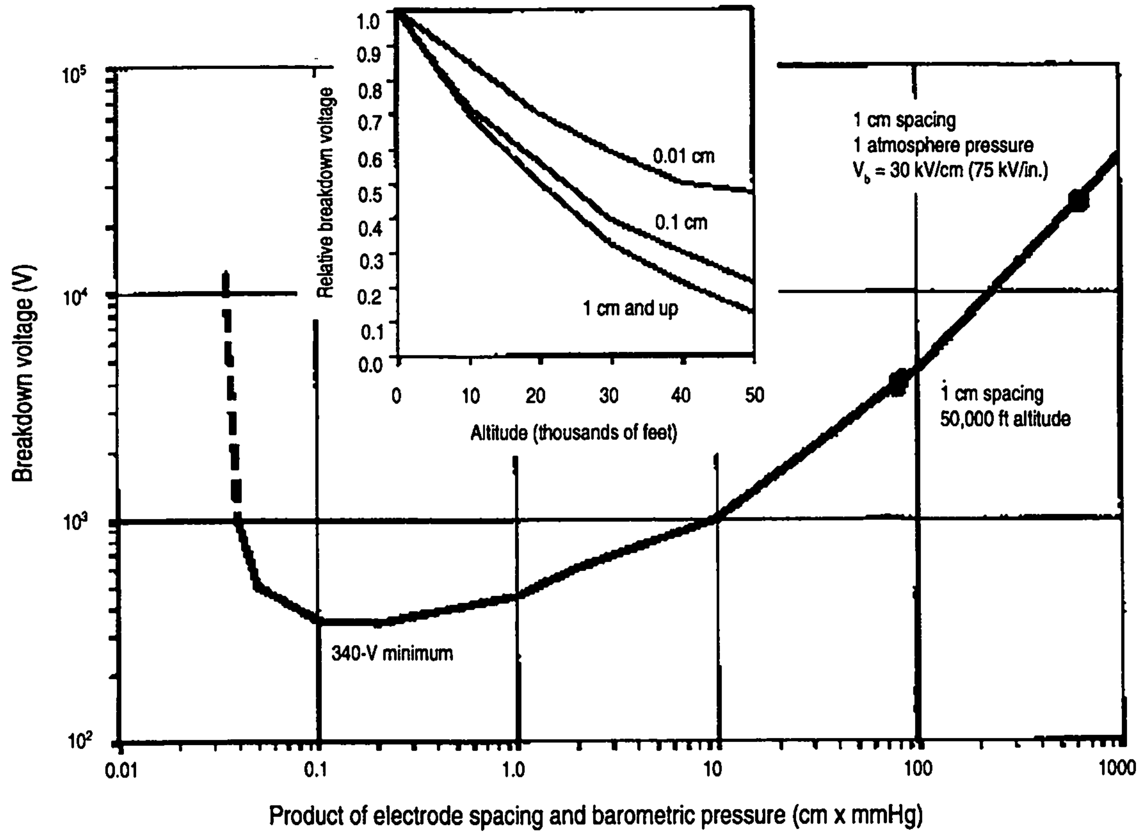

Figure 7-1. Paschen's curve for electrical breakdown of air.

electrode conditions are approached, air will perform as advertised.

Breakdown voltage is also influenced by atmospheric pressure. For two parallel-plane electrodes whose spacing is uniform, breakdown voltage decreases as barometric pressure decreases until the 340-V minimum value is reached. This phenomenon is due to the fact that as the molecular density of the air is reduced, there is greater likelihood that a free ion can traverse the space between electrodes without running into something. However, as pressure is reduced even further, the required voltage for breakdown increases once again. This is because a more limited number of air molecules make ionization more difficult. Note in the inset graph in Fig. 7-1 that as altitude increases up to 50,000 ft, where atmospheric pressure is 87 mm of mercury, voltage hold-off performance steadily deteriorates, and the deterioration is more severe for large spacings than for small.

Far more common than parallel-plane electrodes, which resemble the interior of a smooth-sided box, are combinations with different geometries, where some electrodes resemble spheres or points (or spherical or pointed ends of cylindrically shaped electrodes), and others resemble infinite planes. Figure 7-2 illustrates what happens to electric-field intensity in such geometries. Between parallel planes, the electric fields are uniform everywhere in the space between them and are normal to the surfaces. Equipotential lines (in the two-dimensional representation) or planes (in the three-dimensional representation) are equally

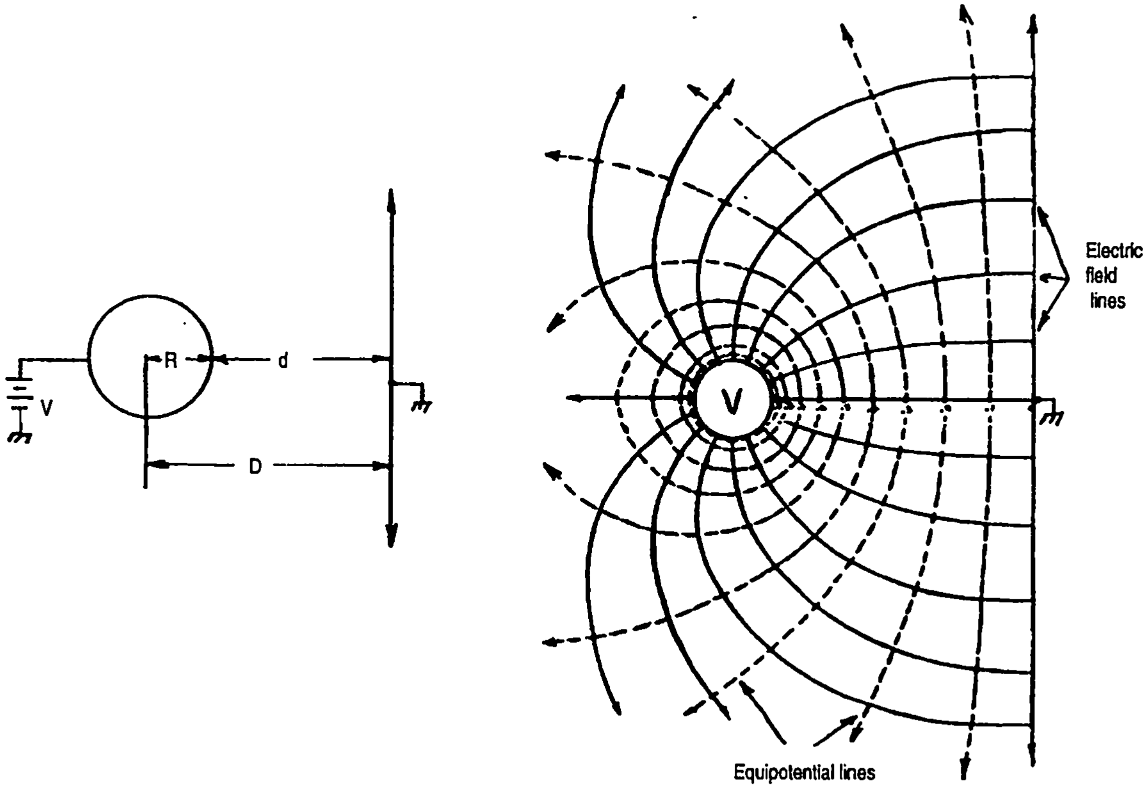

Figure 7-2. Determination of maximum voltage gradient between spherical and planar electrodes.

spaced and are normal to the electric-field lines, which means they are parallel to the electrodes.

However, when one of the electrodes is spherical in shape (circular in the two-dimensional representation), note that the equipotential lines on the right-hand side of the figure come closer together the nearer they are to the surface of the sphere. The voltage difference between any two equipotential lines is the same, which means that the electric-field gradient or strength increases as one nears the surface of the sphere or point and can be many times as great as the field strength at the surface of the planar electrode. The exact expression for peak voltage gradient electric field of this configuration can be stated as

Table 7-1. Voltage gradients between spherical and planar electrodes.

R = constant		D = constant		
d	Peak electric field	R	d = D-R	Peak electric field
0.01R	1.007 V/d	0.01D	0.99D	100 V/D = V/R
0.1R	1.07 V/d	0.1D	0.9D	10.6 V/D
0.5R	1.37 V/d	0.1D	0.9D	10.6 V/D
R	1.78 V/d	0.3D	0.7D	4.3 V/D
2R	2.7 V/d	0.4D	0.6D	3.7 V/D
5R	5.6 V/d = 1.1 V/R	0.5D	0.5D	3.6 V/D
10R	1.5 V/R	0.6D	0.4D	3.75 V/D
20R	1.03 V/R	0.7D	0.3D	4.4 V/D
100R	1.005 V/R	0.8D	0.2D	5.9 V/D
Inf.	V/R	0.9D	0.1D	10.8 V/D

$$Gradient = \frac{\left\{\frac{2d}{R}+1+\left[\left(\frac{2d}{R}+1\right)^2+8\right]^{1/2}\right\}V}{4d},$$

where d is the distance between electrodes, R is the radius of the spherical electrode, and V is voltage (see Fig. 7-2). As d/R approaches infinity,

$$Gradient \Rightarrow \frac{\left(\frac{2d}{R}+\frac{2d}{R}\right)}{4d}V = \frac{4d}{4dR}V = \frac{V}{R}.$$

The approximate expression for peak voltage gradient is

$$Gradient = 0.9V\frac{R+d}{Rd}.$$

Table 7-1 shows how the electric-field intensity at the surface of the sphere varies as the spacing between the sphere and the plane is varied. When the sphere is close enough to the plane so that the spacing is small compared to the radius of curvature, both electrodes appear to be relatively planar (much as the surface of the Earth appears flat to those of us standing on it, even though many of us believe the Earth to be spherical). When this is the case, the electric-field intensity is very near to V/d, where d is the spacing.

However, as the spacing is increased, the roundness of the sphere becomes increasingly apparent. When the spacing is large with respect to the radius of curvature, the gradient at the surface of the sphere approaches V/R, where R is the radius of curvature, and has nothing to do with the spacing. Thus, if V/R for a given conductor exceeds 79 kV/in. (or 30 kV/cm), the air at its surface will ionize, producing what is called a corona, or partial discharge. If the spherical electrode is already a long way from the planelike conductor, moving it farther away will not increase the corona-inception voltage. In most cases, the corona is self-limiting because the ionized air is an electrical conductor that, in effect, increases the radius of curvature of the electrode to the point where the electric-field gradient at its outer surface is no longer high enough to ionize any more air.

Figure 7-3 shows the same information in a slightly different way. It shows that the electric-field gradient, or strength, normalized either to V/d or V/R. The gradient reaches a maximum of 1.78 when the spacing and radius are the same and asymptotically approaches V/d and V/R as the normalized dimensions R/d and d/R increase from unity. What is interesting is how rapidly the asymptotes are approached. When either normalized dimension is greater than 5, it is almost all the way there.

Situations are occasionally encountered when electrode geometry is better described as sphere-opposing-sphere, or cylinder-opposing-cylinder (such as parallel-wire transmission line), as shown in Fig. 7-4. When the two electrodes are close together, they behave as though they were both planar, with the electric-field gradient approaching V/d as shown before. When they are separated by an

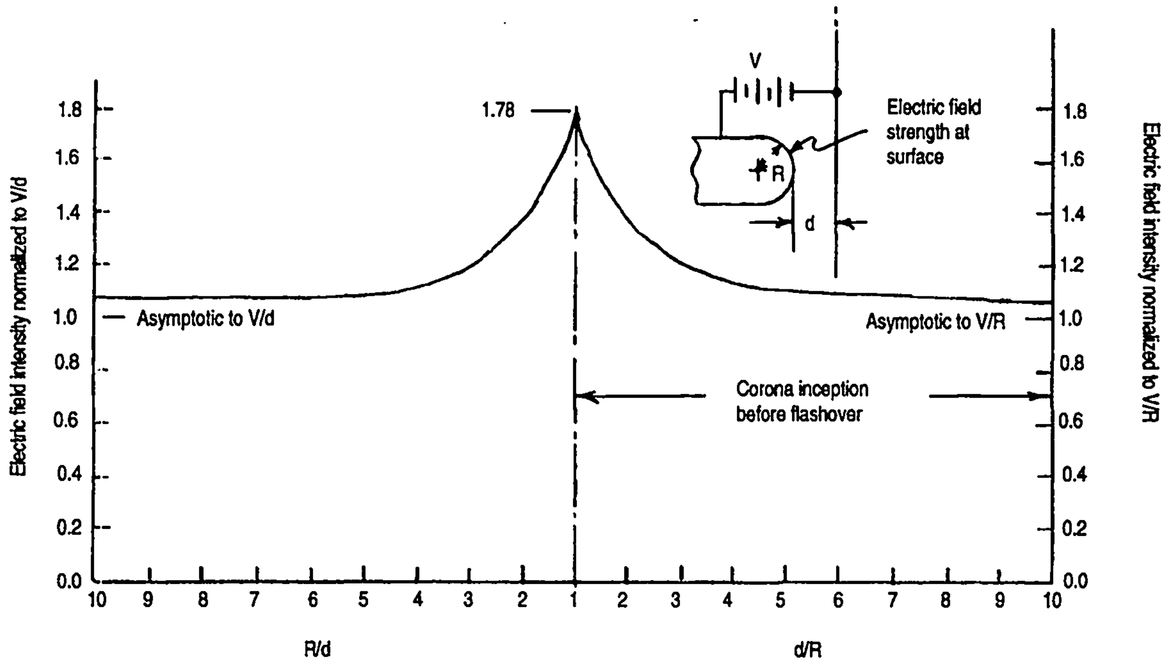

Figure 7-3. Electric-field intensity at surface of spherical conductor opposing plane.

amount that is large with respect to the radii of curvatures, electric-field strength increases at the surface of both conductors. What is surprising to many is the fact that the voltage between conductors required for surface corona is twice as great for sphere-to-sphere as for sphere-to-plane geometry because the aggravated condition at the spherical surfaces is now, in effect, divided in half. (The corona will actually start first at the surface of the conductor that is negative with respect to the other.) Notice the symmetry and the shape of the equipotential lines. At the mid-point between conductors a conducting plane could be inserted without affecting the situation at all. For electrodes in this configuration, the exact expression for peak voltage gradient can be stated as

$$Gradient = \frac{\left\{\frac{d}{R}+1+\left[\left(\frac{d}{R}+1\right)^2+8\right]^{1/2}\right\}V}{4d}.$$

As d/R approaches infinity,

$$Gradient \Rightarrow \frac{\left(\frac{d}{R}+\frac{d}{R}\right)}{4d}V = \frac{2d}{4dR}V = \frac{V}{2R}.$$

The approximate expression for peak voltage gradient for two spherical electrodes is

$$Gradient = 0.9V\frac{R+\frac{d}{2}}{Rd}.$$

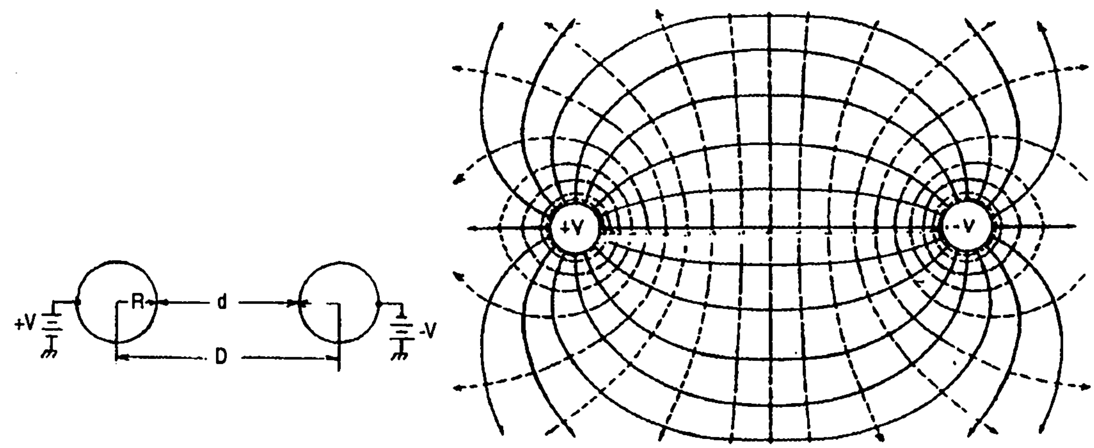

Figure 7-4. Determination of maximum voltage gradient between two spherical electrodes.

Table 7-2 shows how the electric-field intensity at the surface of the spheres varies as the spacing between the spheres changes.

Figure 7-5 shows plots of actual breakdown performance of spherical electrodes whose diameters increase from 6.25 to 25 cm and whose spacing increases from 0 to 40 cm. Notice that they all behave similarly when they are 1 cm apart; they all break down at about 22 kV. In other words, their average-voltage gradient is 22 kV/cm (which isn't 30 kV/cm, but it's close). All electrodes, including even the 2-cm-diameter ones, behave almost as if they were infinite planes. However, as the electrodes are separated by increasing distance, the average-voltage gradient at which breakdown occurs diminishes as the curves tilt toward the horizontal, or *V*/2*R*-asymptote, direction.

Figure 7-6 shows the improvement gained by replacing air with transformer oil. (Sometimes dielectric gases like nitrous oxide and sulfur hexafluoride are used, but in applications where weight and mobility are not important, oil is usually preferred.) The trends related to electrode geometry are similar for oil and air, except that for oil, the *V*/*d* asymptote is at 200 kV/cm instead of 22 kV/cm for air—almost 10 times the dielectric strength. As the spacing-to-radius ratio is increased, the tilting to the horizontal is, if anything, more abrupt than it is for air. Note the effect of a needle-pointed gap. Because the radius of curvature is so

Table 7-2. Voltage gradients between two spherical electrodes.

R = constant		D = constant		
d	Peak electric field	R	d = D-R	Peak electric field
0.01R	1.003 V/d	0.1D	0.8D	5.8 V/D
0.1R	1.073V/d	0.15D	0.7D	4.3 V/D
0.5R	1.2 V/d	0.2D	0.6D	3.7 V/D
R	1.4 V/d	025D	0.5D	3.6 V/D
2R	1.8 V/d	0.3D	0.4D	3.75 V/D
5R	3.2 V/d	0.4D	0.2D	5.9 V/D
10R	5.6 V/d = 0.56 V/R			
20R	10.5 V/d = 0.53 V/R			
100R	50.5 V/d = 0.505 V/R			
Inf.	0.5 V/R			

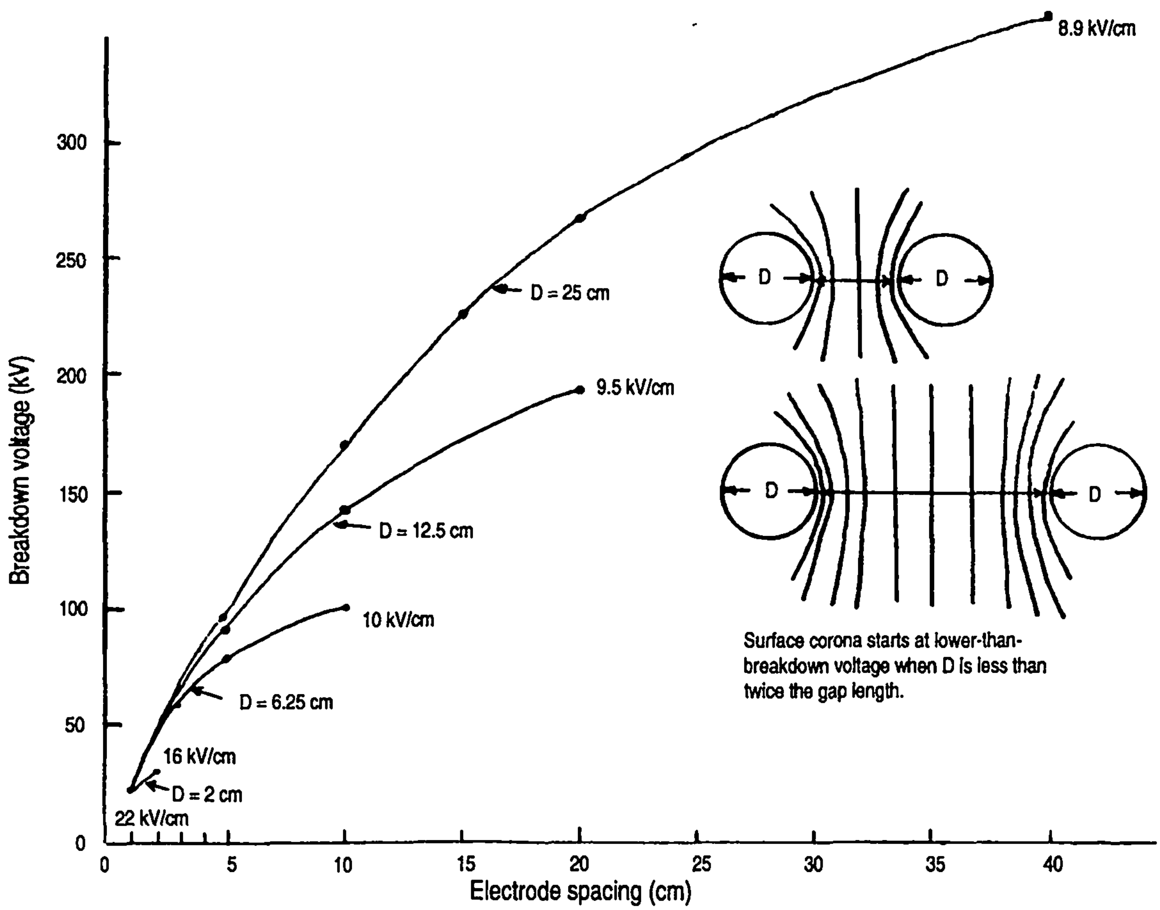

Figure 7-5. Breakdown performance of spherical electrodes in air ($t = 25°C$, $p = 1$ atm)

small to begin with, the characteristic has no *V/d* component to speak of. Therefore, it is horizontal-leaning over the entire range of gap spacings. The needle-gap geometry is almost the least desirable of all. (The absolute least desirable is the geometry where the needle opposes the plane. Unfortunately, this geometry is the one approximated by unrelieved screw bodies and many forms of electrical terminals. In such cases, the screws must either be smoothed off or recessed.)

In order for it to be an effective insulator, transformer oil must be dry, which means low in water content. A standard test for oil dryness is the American Society for Testing and Materials (ASTM) voltage-breakdown test, which is illustrated in the upper left of Fig. 7-6. The test apparatus uses cylindrical, flat-faced electrodes spaced 0.1 in. apart. For oil dryness to be minimally acceptable, breakdown must not occur with 30 kVac (60 Hz) applied between electrodes. This is the so-called 30-kV oil figure of merit.

Oil, like most gases and vacuum, has higher dielectric strength for short pulses than for dc or 60-Hz ac. When tested with a standard lightninglike short-duration waveform (1.5-µs rise from zero to peak, 40-µs fall from peak to half-amplitude), oil will withstand 2 to 3 times the dc or 60-Hz ac breakdown voltage. This time-dependency has been ascribed to the inertia of conducting dipoles within the oil. They must be aligned end-to-end before the equivalent of ionization occurs.

Solid dielectrics are used in many insulating applications, especially where they also play a mechanical role as well. Such dielectrics are the ceramic or glass insulators used to separate high-power vacuum-tube electrodes that have large potential differences. In these cases, the insulator also functions as an extension of the vacuum-tight envelope of the tube. High-voltage transmission cables use plastic dielectrics such as polyethylene or Teflon.

When dealing with solid dielectrics, special care must be taken to assure that there is no trapped air between the metallic conductors and the solid insulation. Semiconducting layers are often used in such applications to act as a transition between conductor and insulator in an effort to short-circuit any trapped air. The terminations at either end of such cables are especially prone to the problems of trapped air. Often their castings are made of an epoxy resin that has been embedded with metallic shapes that linearize the electric-field gradient along the surface of the insulator. However, unless these castings are made under the best of conditions—usually in a vacuum—they too can have trapped air bubbles.

Figure 7-7 illustrates the plight of an air-filled void within a solid dielectric. The problem is double-barreled. First, the solid dielectric has a higher relative permittivity (dielectric constant) than air, ranging from 2 to 3 for most plastics and up to 9 for high-alumina ceramic. Therefore, an air-filled void in such material will function as a capacitive voltage divider. As such, the voltage stress

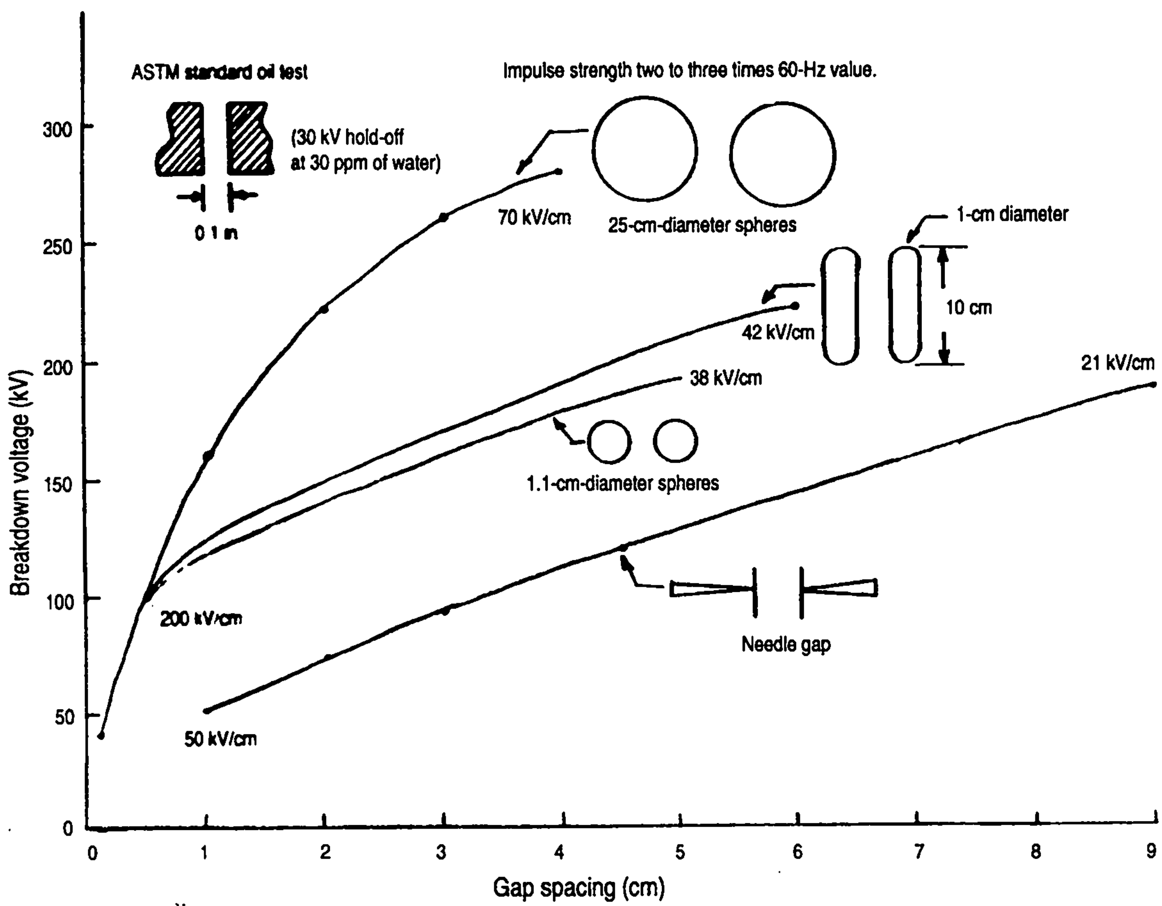

Figure 7-6. Insulation performance of dry transformer oil at t = 25°C.

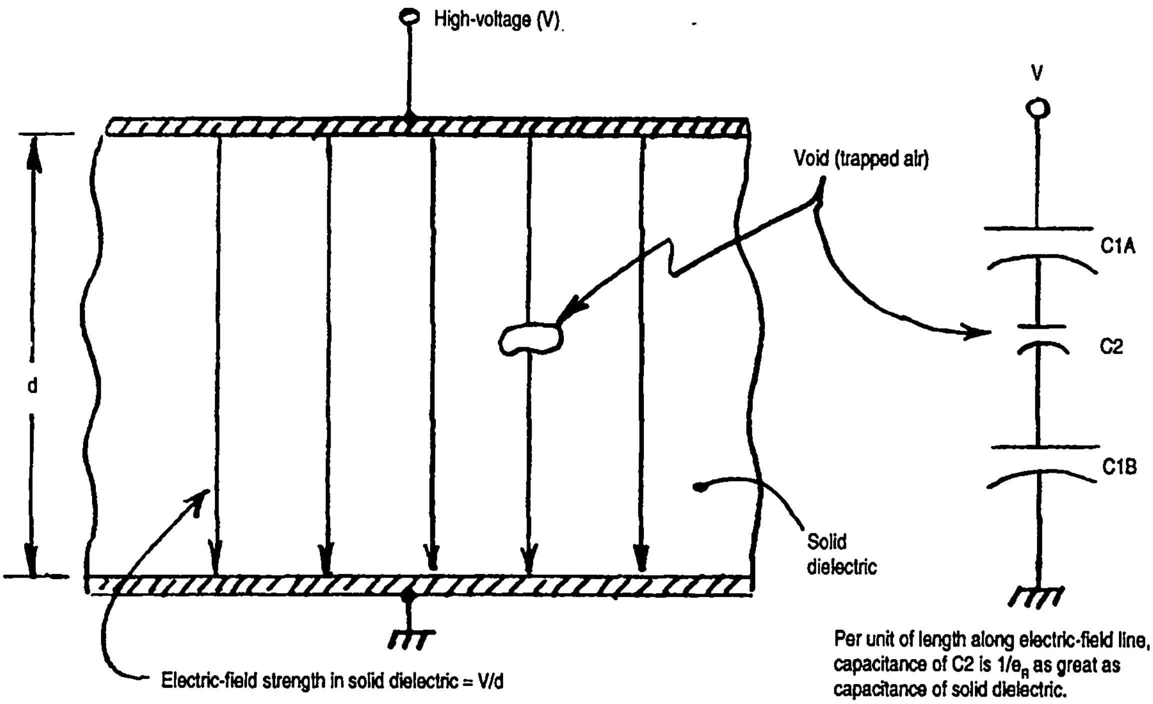

Figure 7-7. Effect of trapped-air void in solid dieletric insulator.

across the void, per unit of length, will be the product of the solid dielectric electric-field strength (V/d) and its relative permittivity (e_R). This is bad enough, but the second problem is the electric field. It will be higher in the solid dielectric to begin with because of its greater dielectric strength (which was one of the reasons for using it in the first place). It is not unreasonable to expect that the air in the void will be ionized at the intended working voltage. The ionized air will be superheated and will wish to expand, a desire that it usually satisfies by blowing the casting apart.

In general, designing for low corona at high voltages requires that electric fields be made as uniform as possible, which means a designer needs to approach the condition of parallel-plate geometry as closely as possible. When this is physically impractical, it is mandatory to remember the criterion that the operating voltage, V, divided by the radius of curvature of the smallest-diameter electrode in a system, R, must be less than the breakdown-voltage gradient of air (79 kV/in., or 30 kV/cm, at sea level and room temperature). And this is for electrodes spaced by many times the radius of curvature. As spacings are decreased, the operating voltage must also be decreased by a factor that reaches a maximum of 1.78 when spacing is equal to radius of curvature. For spacings smaller than this, the parallel-plate criterion of V/d becomes increasingly dominant and flashover occurs at the same voltage at which corona would begin.

One of the more difficult problems in high-voltage engineering is the termination of a high-voltage coaxial cable, as shown in Fig. 7-8. The problem is not how to terminate the cable inner conductor but how to terminate the shield. High-performance, high-voltage coaxial cables use highly flexible rubberlike dielectrics with carbon-filled, semiconducting layers that are located between the outer surface of the copper inner conductor and the inner diameter of the dielectric and between the outer diameter of the dielectric and the outer shield. This is done to make sure that there is no trapped air in these interfaces.

Why such concern? Consider a typical high-voltage cable that has a 1-in. shield diameter and whose inner conductor has a diameter of about 0.2 in. The spacing, d, between inner and outer conductors is 0.4 in., and the radius of the inner conductor, r, is 0.1 in. The cable is rated for over 100 kV. If the conductors were parallel plates, the electric-field intensity in the dielectric would be 100 kV/ 0.4 in., or 250 kV/in., just for reference. In coaxial geometry, however, the electric field is not constant in the radial direction. Its strength is inversely proportional to the radial distance measured from the center line. The total voltage across the cable is given as

$$V = \int_{R=r}^{R=r+d} \frac{k}{R} dR,$$

where k is a constant. The integration yields

$$V = k \ln(r+d) - \ln(r) = k \ln\left[\frac{(r+d)}{r}\right] = k \ln\left(1 + \frac{d}{r}\right).$$

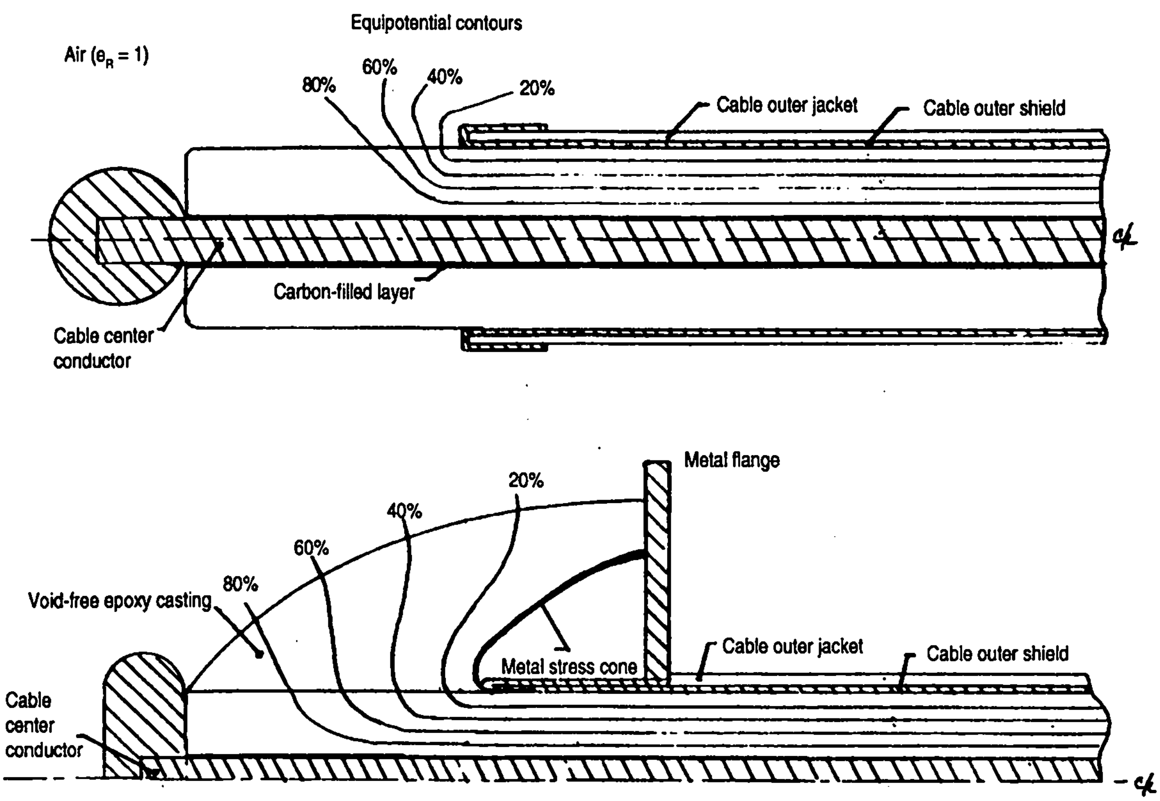

Figure 7-8. The problem of terminating a high-voltage coaxial cable.

The value for the constant k can be derived as follows:

$$k = \frac{V}{\ln\left(1+\frac{d}{r}\right)} = \frac{100\ kV}{\ln\left(1+\frac{0.4}{0.1}\right)} = \frac{100\ kV}{\ln(5)} = 62\ kV.$$

At the surface of the inner conductor, the electric-field intensity is k/r = 62 kV/0.1 in., or 620 kV/in. At the outer diameter of the dielectric, the electric-field intensity is $k/(r + d)$ = 62 kV/0.5 in., or 124 kV/in. But this is the field strength in the solid dielectric, which has a dielectric constant of about 3. A pocket of air trapped between dielectric and shield would see a field strength of 3 x 124 kV/in., or 372 kV/in., and air will break down when the field strength exceeds 79 kV/in.

When terminating the shield as shown in the top half of Fig. 7-8, the equivalent of an air pocket is created right at the point where the shield stops but the solid dielectric continues. For the cable discussed above, the air in the immediate vicinity will ionize, producing localized corona that may or may not lead to breakdown to the terminated center conductor. In any case, it will do the dielectric no good and will eventually lead to cable failure at the circumferential stress point.

Successful coaxial cable terminations more closely resemble the cross-section shown in the lower half of Fig. 7-8. In this case, a metal stress cone is slipped under the outer braid. The cone flares back to a disclike flange, which becomes the outer-conductor connection. This connection will not work in air because of the mismatch of dielectric constants and dielectric strengths. If, however, the cable end can be potted by means of a void-free epoxy casting or room-temperature-vulcanizing (RTV) silicone that more closely matches the cable dielectric in permittivity and strength, the transition can be made with uniform electric-field strength along the outer surface of the casting. In such a configuration, the field strength is safely below the breakdown strength of air. (This type of transition can also work if immersed in transformer oil or if the casting is hollow and filled with oil.)