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Arc Energy Estimations: Applications in Lightning-Induced Concrete Spall

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ARC ENERGY ESTIMATIONS:
APPLICATIONS IN LIGHTNING-INDUCED CONCRETE SPALL

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After lightning contacts a building, the possibility of a physical break in its conductive path to ground may exist. Given such a break, an electric field may develop across the gap until it exceeds the breakdown strength of the non-conducting, or dielectric, material. Breakdown subsequently occurs and energy is dissipated during the development of an arc channel. If the dielectric is concrete, a concern exists that the energy available for arc formation may be capable of launching pieces of spall into sensitive equipment. This paper discusses the mechanisms of energy dissipation in arc formation and quantifies the energy available for concrete spall.

BACKGROUND

In the global atmospheric circuit, thunderstorms act as generators as the rest of the world acts as an RC circuit [1]. Intracloud lightning represents short circuits in the generator due to large electric field gradients. A cloud-to-ground electron channel results from breakdowns due to small pockets of positive charge in the air. Lightning provides a mechanism of lowering charge to earth when the localized electric field exceeds the breakdown strength of air.

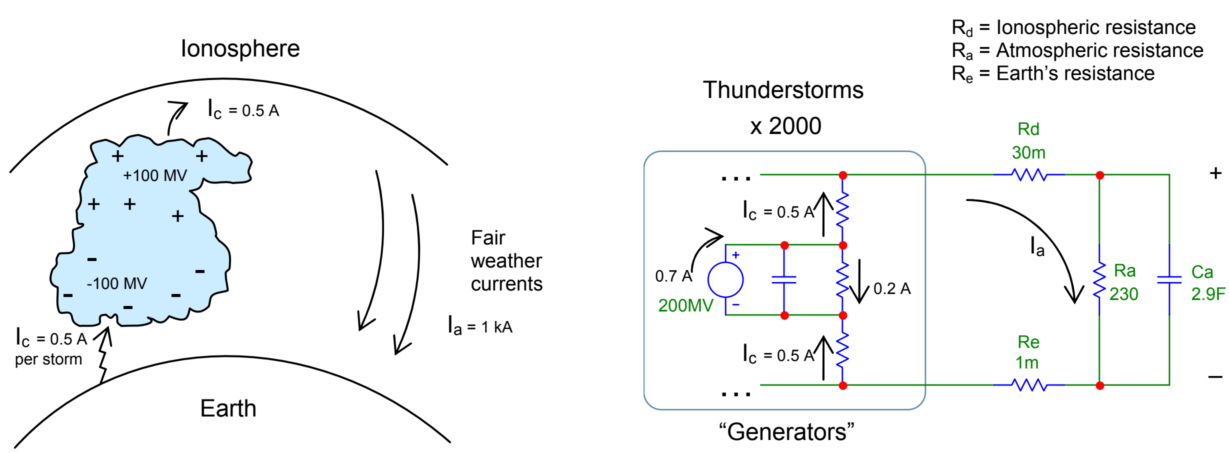


Figure 1. Global atmospheric circuit [1].

If lightning contacts a building with a physical gap in its conductive path to ground, an arc will form when the local electric field is greater than the breakdown strength of the material in the gap. A concern exists that the gap may contain rapidly expanding gas with the kinetic energy to potentially launch spall. Bounding the kinetic energy in the gap is possible by calculating the total energy dissipated. The energy dissipated by the discharge is highly dependent on the resistance of the path. If resistance is constant, Equation 1 can be used to calculate the energy dissipated in the channel where the integral of the current squared is equal to the action integral known to be 3×10^6 A^2s for a 1% probability strike and 5×10^4 A^2s for a 50% probability strike [2].

$$E = \int_0^t I^2 R\, dt = R \int_0^t I^2 dt \qquad (1)$$

Although the resistance of the arc channel in actuality is not constant and the simplified calculation can not be directly used to determine the energy dissipated in the breakdown, the relationship provides insight to the solution. With the appropriate time-varying arc resistance and current, the total energy input to the channel can be calculated.

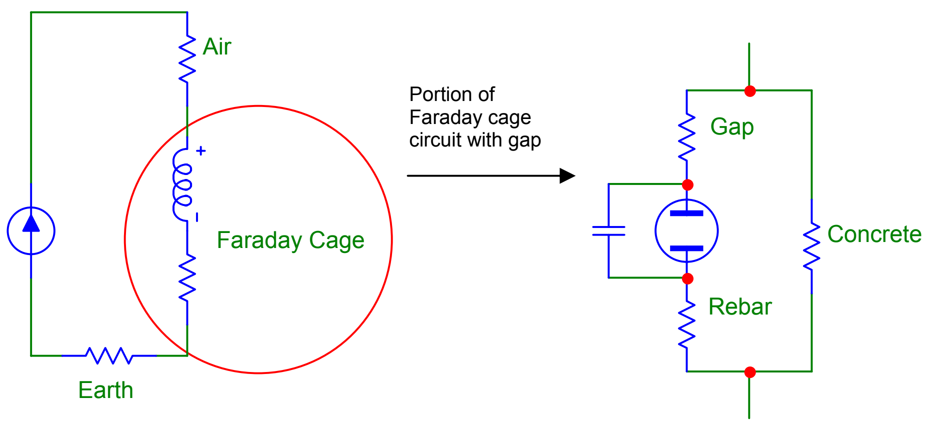


Figure 2. A lightning strike to a building, or Faraday cage, will present a more complicated circuit with a closing switch if a gap exits.

THEORY

Arc energy dissipation is frequently addressed in high voltage switch optimization. Many theoretical and empirical relationships have been developed to characterize the performance of gas, liquid, and solid dielectric switches. Early work by Drabkina describing rapid spark channel development with the excitation of a shock wave was expanded by Braginskii to account for electrical and thermal conductivity of the ionized gas [3-4]. T.H. Martin later applied the model to common pulsed power switch dielectrics by modifying the conductivity [5]. Concurrent and subsequent experimental work by a number of authors suggests the Braginskii model is appropriate for modeling high voltage spark gaps [5-10]. Others have specifically applied the Braginskii model to lightning channels [11].

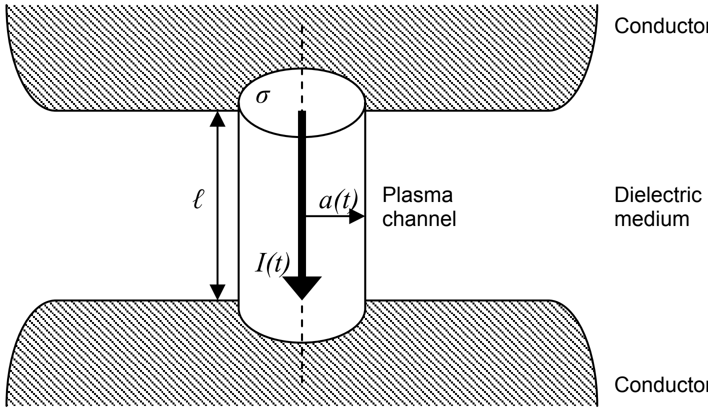


Figure 3. Plasma channel in a dielectric medium between two conductors

In an air gap, Braginskii describes the process beginning with the formation of a narrow current-carrying channel in the gas with high temperature and ionization. Joule heat released in this channel leads to increased pressure and thickening of the channel. The thickened channel drives a strong cylindrical shock wave into the undisturbed gas. Hydrodynamic cooling (associated with expansion) and radiative cooling sufficiently keep the temperature of the conducting channel, therefore its electrical conductivity, constant.

The arc channel is approximated by the energy balance equations

$$\frac{dW}{dt} + p\frac{d\pi a^2}{dt} = Q_J \tag{2}$$

$$\left(\varepsilon + \frac{p}{\rho}\right)\frac{dM}{dt} = Q_T + Q_R \tag{3}$$

where W is the internal energy, M is the mass, p is the pressure, a is the radius, and $(\varepsilon + p/\rho)$ is the enthalpy of the channel (ε is the internal energy per unit mass of the gas and ρ is the density). Joule heating is expressed by Q_J, while Q_T and Q_R represent thermal conduction and heat loss by radiation, respectively.

$$Q_J = \frac{I^2}{\pi a^2 \sigma} \tag{4}$$

Equations 2 and 3 can be used to obtain

$$Q_T + Q_R = \eta Q_J \tag{5}$$

For a weak shock, η is approximated as 1. For a strong shock, η has a more complicated notation, but allows us to compute the channel radius. Considering a channel in air, the conductivity as a function of temperature changes comparatively slowly and may be assumed constant. The resistance of the channel is therefore

$$R(t) = \frac{\ell}{\pi a^2(t)\sigma} \tag{6}$$

The channel radius is given by (as presented by Martin [5])

$$a^2(t) = \left(\frac{4}{\pi^2 \rho_0 \xi \sigma}\right)^{1/3} \int_0^t I^{2/3}(\tau) d\tau \tag{7}$$

The gas dependent constant ζ is assigned 4.5 for hydrogen and can be applied to all gases. Given a linearly increasing arc channel current

$$I(t) = I_{peak} \frac{t}{\tau} \tag{8}$$

The channel radius takes the form

$$a^2(t) = \frac{3}{5}\left(\frac{4 I_{peak}^2 t^5}{\tau^2 \pi^2 \rho_0 \xi \sigma}\right)^{1/3} \tag{9}$$

The energy input to the channel, or joule heating, per unit length is then

$$\frac{E(t)}{\ell} = \int_0^t \frac{I^2(t)}{\pi a^2(t)\sigma} dt \tag{10}$$

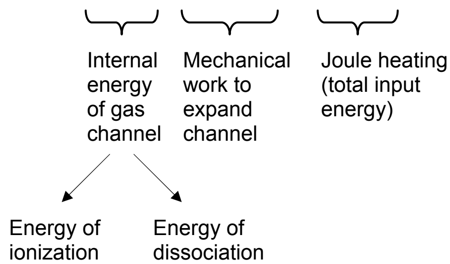
The conductivity and density constants for common pulsed power switching dielectrics are given in Table 1.

Table 1. Conductivity and density constants [5]

Material	Conductivity (S/m)	Density at 14.7 psia (kg/m^3)
Water	6×10^4	1.0×10^3
Oil	6×10^4	0.9×10^3
SF_6	1.6×10^4	6.16
Air	2×10^4	1.293
Helium	1.4×10^4	0.178
Hydrogen	3×10^4	8.990×10^{-2}

As joule heating is the sum of the internal energy of the channel and the mechanical work done to expand the channel, it represents the total energy available to the arc. The internal energy of the gas in the channel, W, is composed of the total energy of ionization plus the energy of dissociation. This term dominates the energy balance Equation 8, limiting the energy available for mechanical motion thus limiting the energy available for spall [12].

$$\frac{dW}{dt} + p\frac{d\pi a^2}{dt} = \frac{I^2}{\pi a^2 \sigma} \tag{8}$$



Arc formation has been investigated as a means for material fragmentation, including concrete destruction. Bluhm calculates the fragmentation efficiency of an arc, η_f, where t_y is the yield strength (3 to 300 × 10^6 N/m), G is the shear modulus (1 to 4 × 10^{10} N/m^2), ω is the specific free surface energy, and S is the area of the newly created surface. Applying the assumption that most of the energy is expended for plastic deformation of the solid, E_{pl}, he obtains η_f = (0.013 to 0.047) η_t [12].

$$E_{pl} = 9\omega S \ln\left(\frac{G}{\pi\tau_y}\right) \tag{9}$$

$$\eta_f = \left(\frac{\omega S}{A}\right)\eta_t \tag{10}$$

Slight modifications to Bluhm's published total efficiency, η_t, calculation should be made for lightning-induced fragmentation. For example, pulser efficiences can be neglected if lightning can be approximated as a perfect current source. Assuming the total efficiency of a lightning current source to be 100%, a lightning-adjusted fragmentation efficiency is therefore 1.3 to 4.7%. Conservatively restated, 5% of the input energy (joule heating) is available for fragmentation, or spall. As the input energy can be computed with the Braginskii channel radius equation, the next section will quantitatively describe the energy available in the gap.

APPLICATION TO LIGHTNING

Utilizing the channel radius equation for a linearly increasing 200 kA peak (1% probability) pulse at 3 μs (50% probability) [2], the total energy input into the spark channel in air is 154 J/cm at peak current. Most lightning return stroke energy estimates are approximately 30 J/cm based on a peak current of 20 kA [13]. The Braginskii model is presumed to be applicable in the early stages of the discharge and agrees well with the Plooster model at peak current giving approximately 7 J/cm [11]. Energy at peak current and total energy scale linearly at lower peak current pulses. Extrapolating to approximate total input energy based on a peak current of 200 kA results in 660 J/cm.

Acknowledging the water content of concrete and recalculating our previous result with the stated conductivity of water gives a total energy input to the spark channel of 677 J/cm at 3 μs with a linearly increasing 200 kA peak pulse. Scaling energy at peak to total energy as done with air, results in 2901 J/cm.

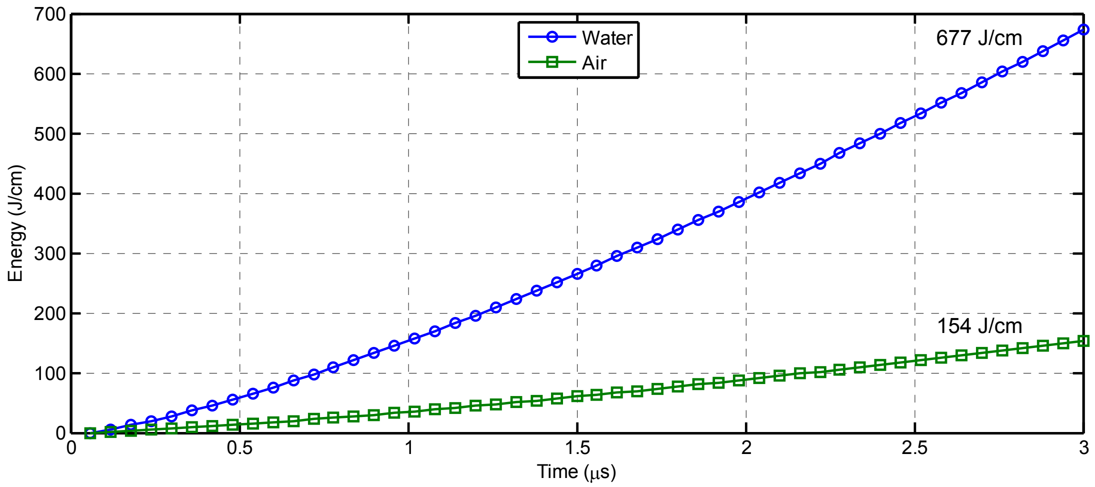


Figure 4. Energy input to arc channel (joule heating) in water and air given a linearly increasing 200 kA peak pulse at 3 μs.

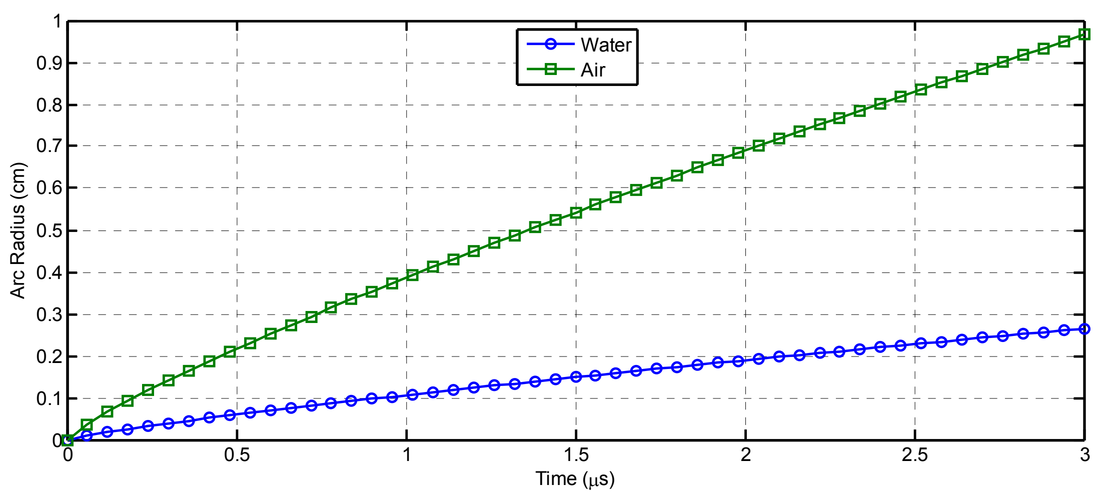


Figure 5. Differences in the arc radius in the two dielectric materials account for the differences in energy dissipation.

Table 2. Results for 200 kA peak lightning pulse

Material	Energy per unit length at peak current (J/cm)	Energy per unit length scaled for entire pulse (J/cm)	Energy per unit length available for spall for entire pulse (J/cm)
Air	154	660	33
Water	677	2901	145

Application of the lightning-adjusted spall fragmentation efficiency provides the listed values in Table 2. In this example, the energy per unit length available for spall during the entire duration of the pulse is approximately 21% of the energy per unit length at peak current. This leads to the conservative general relationship in Equation 11 given an input of Equation 8.

$$E_{spall}(t) \approx \frac{\ell}{4}\int_0^t \frac{I^2(t)}{\pi a^2(t)\sigma}\,dt \qquad (11)$$

CONCLUSIONS

While a steel-reinforced concrete building may be considered a Faraday cage for lightning protection, there exists an important requirement that all rebar must be sufficiently electrically connected to avoid arc formation. In the case of insufficient electrical connections, theoretical and experimental work in the development of spark channels allows for quantification of energy available for spall due to lightning. It appears reasonable to assume a total energy input to the channel on the order of 10^2 to 10^3 J/cm. Correspondingly, the energy available to create new surfaces is on the order of 10^1 to 10^2 J/cm. Elimination and minimization, at the very least, of gaps is directly proportional to elimination and reduction of arc energy available for concrete spall.

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