EFFECT OF AMBIENT PLASMA ON ANTENNA BREAKDOWN

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Abstract

A crucial factor in radiating from missiles and hypersonic vehicles during some portions of their flight regime is the modification of breakdown of air by high ambient ionization. The work reported here is the result of experimental investigations of the power-handling capability of antennas operating in the presence of plasmas produced by dc and RF discharges as well as thermally generated plasmas.

The experimental results of the effect of initial ionization on antenna breakdown indicate that even when the plasma density is low enough that the attenuation is negligible, the breakdown level may be significantly reduced.

Introduction

Most studies of voltage breakdown phenomena in gases have been performed with negligible amounts of plasma present before the voltage is applied. In a number of the experiments, some means--such as a radioactive source--is provided to ensure that a sufficient number of electrons are available to start the breakdown process. The electron density is intentionally kept at a very low level, however, so that the breakdown is not influenced by the plasma.

During the flight of a missile, several situations may occur for which the initial plasma density may be so large that the breakdown power levels will be appreciably lower than when only the small number of electrons necessary to start the process are present. Situations in which these high plasma densities may be encountered vary from the ionosphere, where electron densities on the order of 10^6 electrons/cc may be experienced, to electron densities of 10^{10} electrons/cc which may occur when the missile is enveloped by rocket exhaust gases (during staging), and as high as 10^{15} electrons/cc produced in air by the aerodynamic heating experienced at re-entry velocities.

Recent work at Stanford Research Institute on the power-handling characteristics of antennas at low pressures indicates that, in the presence of existing ionization where the plasma frequency is about one-half of the RF frequency, an antenna will break down with RF power densities of about one order of magnitude less than that without the ionization.[1]

Flight test data on actual missiles indicating plasma-induced breakdown are available on many missile systems.[2] A drop in the transmission of the beacon signal when the missile antenna was bathed in flame, as well as a drop in the telemetry signal at staging, has been reported for various missiles. Since the drop was not aspect-sensitive, it may be attributed to breakdown rather than flame attenuation. Voltage breakdown, as well as attenuation, has also been reported during re-entry. These results definitely show that plasma-induced voltage breakdown must be considered in the design of any transmission system to be used during re-entry.

The experimental data reported here are the result of several separate experiments involving antenna and cavity breakdown measurements employing different methods of producing the initial ionization in the breakdown field. The experimental data indicates that a decrease in the breakdown power levels when antennas are subjected to high ambient electron densities may be as high as 10 db.

Breakdown Mechanism

The breakdown of antennas at low pressure has been studied in the past by various investigators[3,4,5] and it has been shown that the primary source of ionization is electron motion. The equation which describes this mechanism is

$$\frac{\partial n}{\partial t} = (\nu_i - \nu_a)n + \nabla^2 (Dn) + S \qquad (1)$$

where n is the electron density, ν_i is the frequency of ionization per electron, ν_a is the frequency of attachment per electron, D is the diffusion coefficient, and S is the rate of production of electrons by an external source. For breakdown to occur, the rate of change of electron density with time, $\partial n/\partial t$ must be slightly greater than zero. Under these conditions the electron density will increase exponentially with time at a rate determined by $\partial n/\partial t$, which is the value of the difference between electron production and loss rates.

Equation (1) can be integrated over a time period of the pulse, t to obtain the final density, n, as follows:

$$\ln \frac{n}{n_o} \quad \int_0^t \left[(\nu_i - \nu_a) + \frac{\nabla^2 (Dn)}{n} \right] dt \tag{2}$$

where the initial source S has been neglected except in that it establishes the initial density, n_o. The CW solutions of Eq. (1) give results of the form

$$\frac{\nabla^2 (Dn)}{n} = - \frac{D}{\Lambda^2} \tag{3}$$

where

$$\frac{1}{\Lambda^2} = \frac{\nu_i - \nu_a}{D}$$

Here Λ has the dimensions of length and is the characteristic diffusion length for the particular geometry and conditions considered; ν_i will be taken as the value of electron production rate per electron required to produce breakdown. If it is assumed that throughout the pulse the electron distribution is essentially constant in time up to breakdown, then the results of Eq. (3) can be substituted into Eq. (2), giving

$$\ln \left(\frac{n_t}{n_o} \right) = (\nu_i - \nu_a) t - \frac{Dt}{\Lambda^2} \tag{4}$$

Equation (4) can be normalized with respect to pressure, p, and rewritten to give the pulsed breakdown condition:

$$\frac{\nu_i}{p} = \frac{\nu_a}{p} + \frac{Dp}{(p\Lambda)^2} + \frac{\ln \frac{n_t}{n_o}}{pt} \tag{5}$$

The last term in Eq. (5) represents the additional increment of ν_i required for breakdown during the pulse length t. The value of n_t is assumed to be approximately equal to the electron density associated with the plasma frequency, $f_p = 9 \times 10^3 \, n^{1/2}$, where f_p is the frequency of the applied electric field; n_o is the initial electron density.

The presence of an initial electron density in the vicinity of an antenna can affect the breakdown power required by reducing loss rate of electrons. This is evident in Eq. (5) where increasing the value of n_0 will decrease the additional increment of ν_i necessary for breakdown during the pulse length t. Also affected by the initial density is the diffusion coefficient, D. In the breakdown process in an un-ionized gas, the free diffusion coefficient is used to determine the breakdown field strength. When an antenna is immersed in a plasma, however, the diffusion process may be ambipolar. Under this condition the electrons remain in the region of high electric fields for longer periods of time than under free-diffusion conditions. Thus, their probability of gaining ionizing energy is increased and the breakdown field strength is reduced.

CW Breakdown

The equation describing breakdown under CW conditions is the same as Eq. (5), with the exception that, for CW, $t \to \infty$ and $(\ln n_t/n_0)/pt \to 0$. Thus Eq. (5) becomes

$$\frac{\nu_i}{p} = \frac{\nu_a}{p} + \frac{Dp}{(p\Lambda)^2}$$

With the elimination of the time dependent term, $(\ln n_t/n_0)/pt$, the CW breakdown of the antenna is not dependent on the ambient electron density except to the extent that it determines whether free or ambipolar diffusion is obtained.

Experimental Results

A series of experiments have been performed at Stanford Research Institute in which the reduction in the breakdown power level has been determined in the presence of various types of plasmas.

Plasma with High Electron Temperature*[6]

The first series of tests were made using a plasma created in air by dc and RF discharges positioned over the surface of slot antennas. In plasmas of this type created by a discharge, the electron temperature reaches several electron volts (1 ev ≈ 11,200°K) while the gas temperature remains close to ambient.

*This work was done for the Electronics Research Directorate of the Air Force Research Division, ARDC, Contract AF 19(604)-3458.

Figure 1 illustrates an experimental set-up in which a dc discharge was used to create a plasma over the aperture of a 0.53λ slot antenna (17-inch slot at 370 Mc). The slot antenna is mounted in a conducting ground plane with a dielectric cover. The cathode is formed by an aluminum block elevated over the insulated ground plane, while the anode is formed by a section of ground plane formed by removing the dielectric cover. The dc glow discharge was placed so that the negative glow area of the discharge was located over the aperture. The electron density was estimated by measuring the change in reflection coefficient when the plasma was present.

When the dc discharge was adjusted so that the plasma density was on the order of 4×10^8 electrons/cc ($\omega_p/\omega < 0.5$) and 270 Mc CW power applied, the presence of the plasma decreased the power-handling capability at low pressures (0.2 mm Hg) by about 10 db. Under this condition the electron temperature was about 4 ev (40,000°K).

Similar experiments have been made on an X-band slot (formed by the waveguide cross-section) operating with a 0.5-μsec pulse width at 200 pulses per second. Without the plasma the slot broke down at 2 kw peak power, while in the presence of plasma created by a dc discharge the slot broke down at about 1 kw.

Cool Plasma*

The second series of breakdown tests were made in a air-filled coaxial cavity containing a plasma in which the electron and gas were in thermal equilibrium at ~ 300°K. This was accomplished by making breakdown measurements in the afterglow of an RF discharge.

The electric field distribution for a half-wavelength resonant cavity, shown in Fig. 2, is known to be a simple cosine function of length. The radial field is inversely proportional to the distance from the cavity axis. By inserting polyfoam into the cavity, as shown in Fig. 2, the region over which the discharge could occur was limited to a region where the electric field along the cavity was known to be relatively constant. The technique used to form the electron density within the cavity is to start a discharge with a 10-μsec pulse at the cold (i.e., no plasma in the cavity) resonant frequency. While the discharge pulse is on,

*This work was done for the Air Force, Wright Air Development Division, under Contract AF 33(616)-5584.

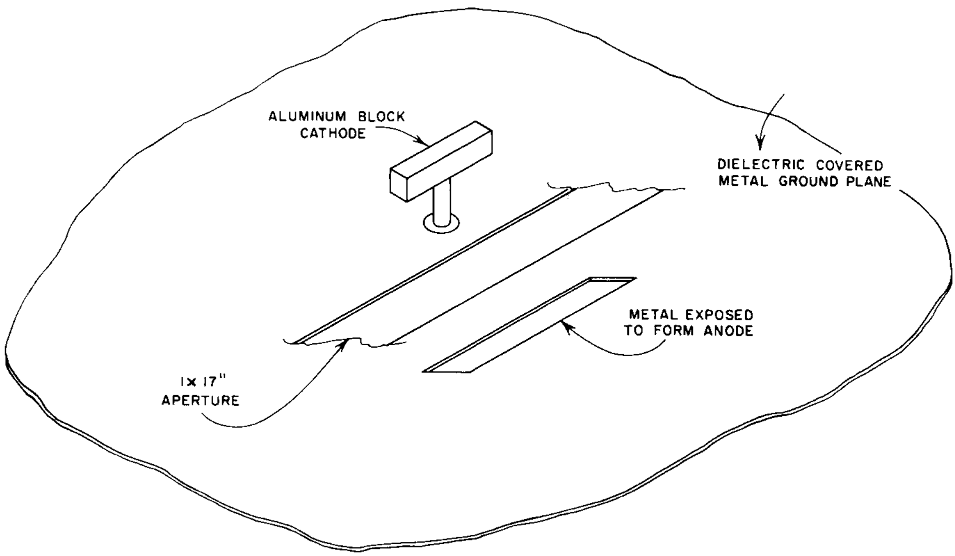

Fig. 1. Configuration Used in Producing a DC Plasma Over Surface of Slot Antenna.

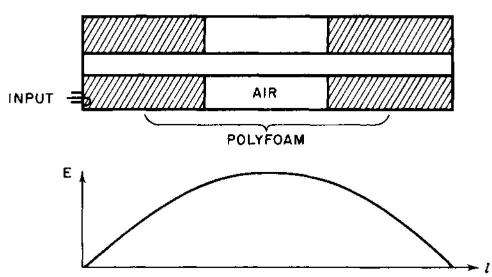

Fig. 2. Drawing of Coaxial Cavity Used in Afterglow Experiments and the Fundamental-Mode Electric Field Distribution Along the Length of the Cavity.

the electrons in the plasma are heated to an average energy of several electron volts while the gas molecules remain at a temperature close to ambient. When the pulse is turned off the electrons lose their energy very rapidly. The electron density also decays with time, but at a much slower rate. This difference in decay rates for energy and for density allows measurements to be made in a relatively dense, cool plasma (~ 300°K) of the afterglow period. The electron density at different times in the afterglow was measured by determining the change in the resonant frequency of the cavity from the no-plasma condition. Breakdown measurements were made by applying a pulse of RF energy at a time after the discharge pulse when the desired plasma density was reached. The frequency of the test pulse was adjusted to be equal to the resonant frequency of the cavity at the time of its application in order to couple sufficient energy into the cavity to produce breakdown.

The breakdown data, taken over a range of electron densities are plotted in Fig. 3. The relative breakdown power is given as a function of pressure for constant values of ω_p/ω, where ω_p is the plasma angular frequency, and $\omega_p = 8.9 \times 10^3 \sqrt{n}\, 2\pi$. The value $\omega_p/\omega = 0$ corresponds to the no-plasma condition. As the pressure is decreased, the effect of the plasma becomes more pronounced. This is the behavior that one would expect if the breakdown were diffusion-controlled. The presence of the plasma changes the diffusion coefficient from free diffusion towards ambipolar diffusion. As the electron density and ω_p/ω increase, the diffusion coefficient and power required for breakdown decrease.

Thermal Plasma*[7]

The third and last set of breakdown measurements to be considered were made in the presence of a hot plasma. The plasma temperature in this case was on the order of 2500°K, and was produced in the hot gases of an ethylene and oxygen flame burning at low pressure.

The flame equipment consists of a 200-cfm rotary ballast pump, an 18-inch-diameter Pyrex test section in which the 6-inch-diameter burner is located, gas flow controls, and a mixing chamber. The test section, flow controls and RF system are shown in Fig. 4.

*This work was done for the Aero-Space Division of Boeing Airplane Company, P.O. No. 2-009203-8652 under Air Force Contract AF 33(600)-41517.

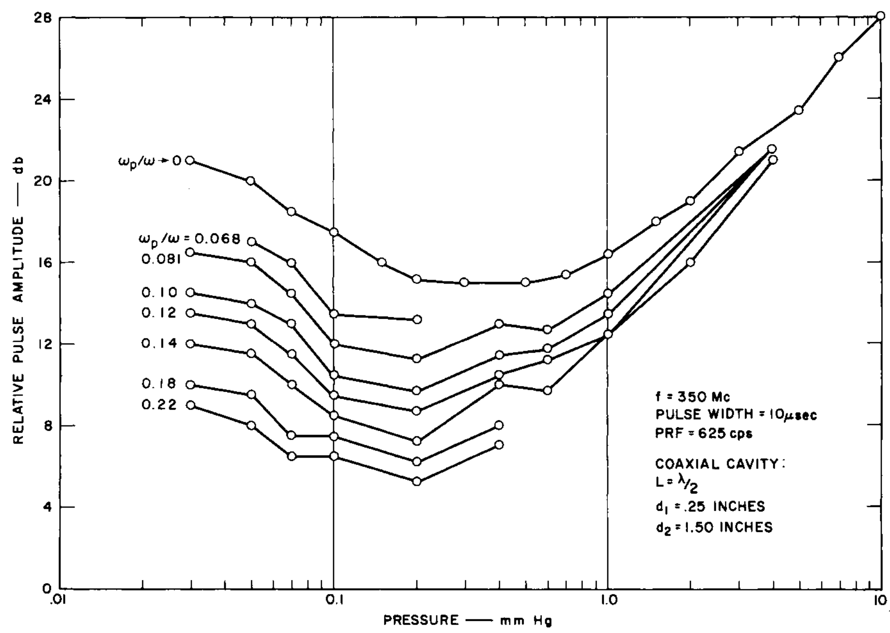

Fig. 3. Effect of a Plasma, Occurring in the Afterglow of an RF Discharge, on the Breakdown of Air in a Coaxial Cavity.

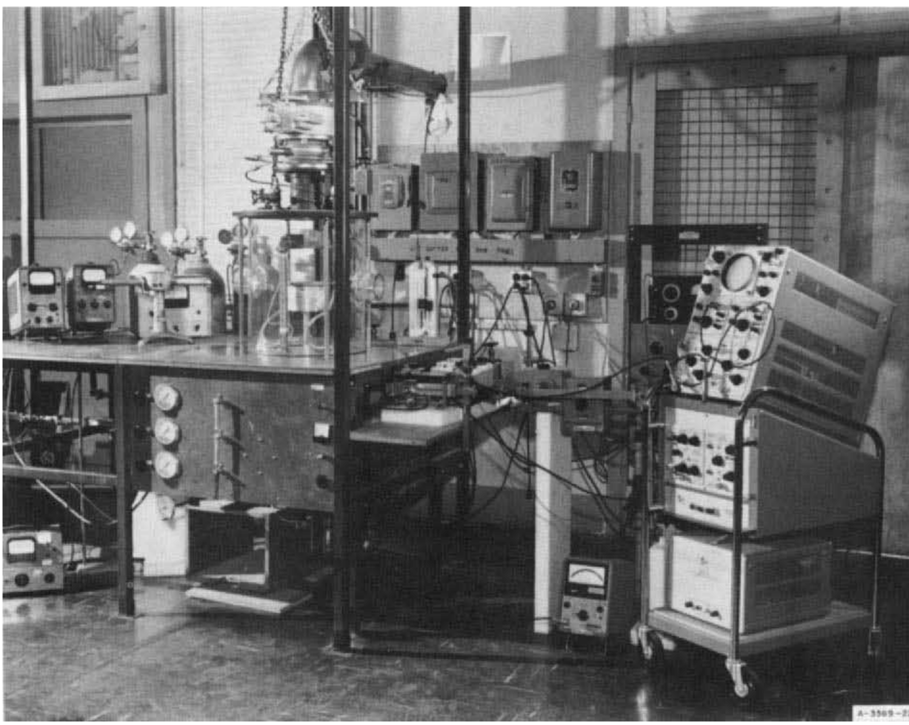

Fig. 4. Low Pressure Flame Experimental Set-up.

Three gases are used in the flame. The ethylene and oxygen (C_2H_4 and O_2) are burned and produce a flame with a maximum temperature on the order of 2500°K. The third gas used is nitrogen, N_2, which is employed as a diluent, and which provides some measure of control of flow rate, as well as flame speed, and thus of flame position relative to the burner. Figure 5 shows a flame at 8 mm Hg pressure in the test section.

The antenna selected for the tests is a simple slot antenna. The slot is formed by terminating a standard 0.4- by 0.9-inch waveguide in a 3- by 5-inch ground plane. The waveguide is sealed at the aperture with a boron nitride window which allows the guide to be maintained at atmospheric pressure. The antenna is located above the edge of the burner; it is shown in Fig. 5.

The plasma conditions were determined by measuring the phase shift and attenuation of an X-band signal transmitted through the plasma. These tests made it possible to calculate the electron density and collision frequency. The plasma temperature was determined using the sodium line reversal technique.

The results of the pulse breakdown tests are presented in Fig. 6. Three conditions of the gases over the surface of the antenna are shown. The frequency throughout the tests was 9.4 kMc. The pulse width was maintained at 2.2 μsec with a 200 cps repetition frequency. The top curve in Fig. 6 is the power required to initiate breakdown on the slot antenna in air with no flame. Only the initiate data are presented for the pulse breakdown case, since the maintain value of power is a maximum of 0.1 to 0.2 db below the initiate in all cases. A polonium source was employed to provide the necessary electrons to initiate the discharge.

The second curve in Fig. 6 indicates the effect of the combustion products of the ethylene-oxygen flame on the breakdown power level. The ω_p/ω in this instance is approximately 0.07 at a pressure of 10 mm, which corresponds to an electron density of about 5×10^9 electrons per cc. At other pressures, ω_p/ω varies directly with pressure.

The bottom set of curves in Fig. 6 shows the effect of the gases above the ethylene-oxygen flame on breakdown, where the electron density is such that the ω_p/ω ratios vary from 0.25 to 0.65. The increase in the electron density indicated by the higher ω_p/ω ratios was provided by the addition of sodium to the flame and by varying the flame temperature. The ω_p/ω values used were derived from the RF propagation measurement.

On the basis of the experimental data presented in Fig. 6, the power-handling capability of the slot antenna under

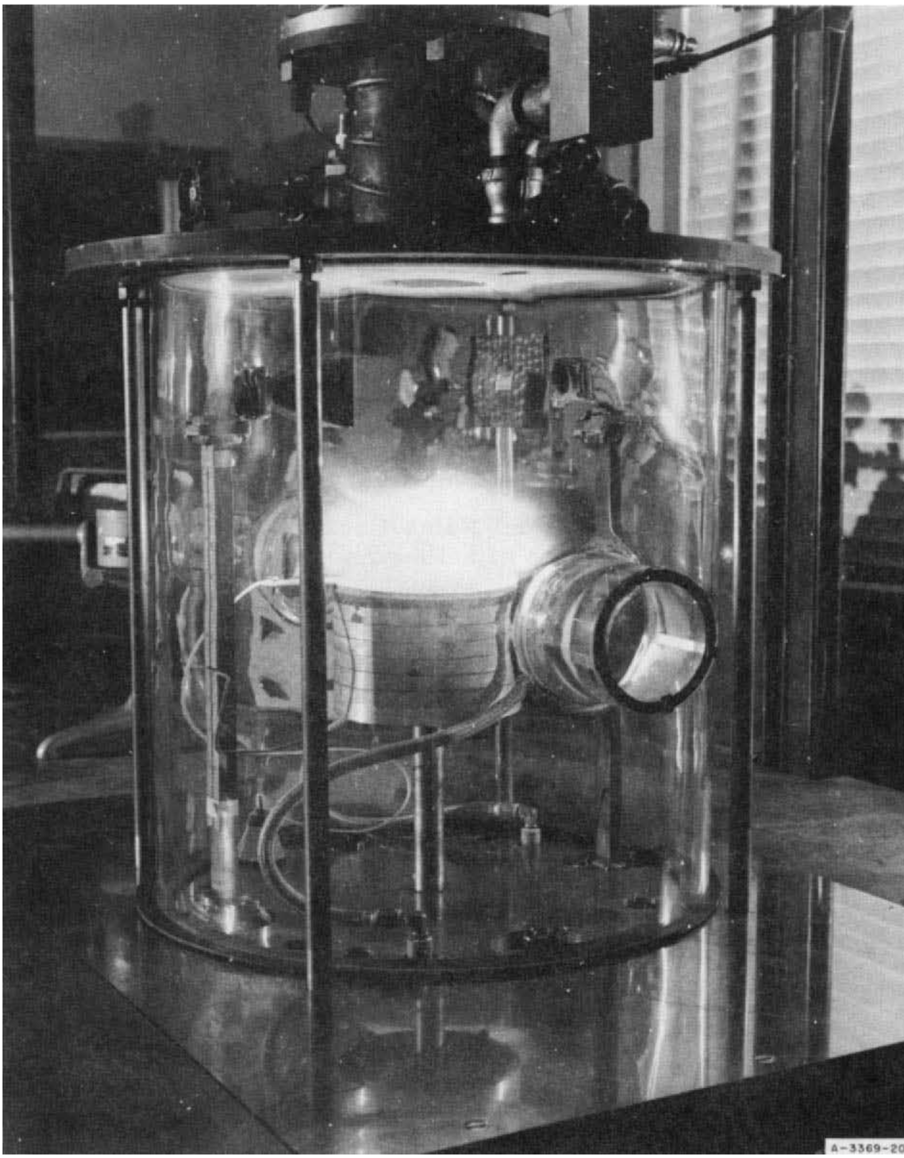

Fig. 5. Ethylene-Oxygen Flame Burning at 8 mm Hg Pressure.

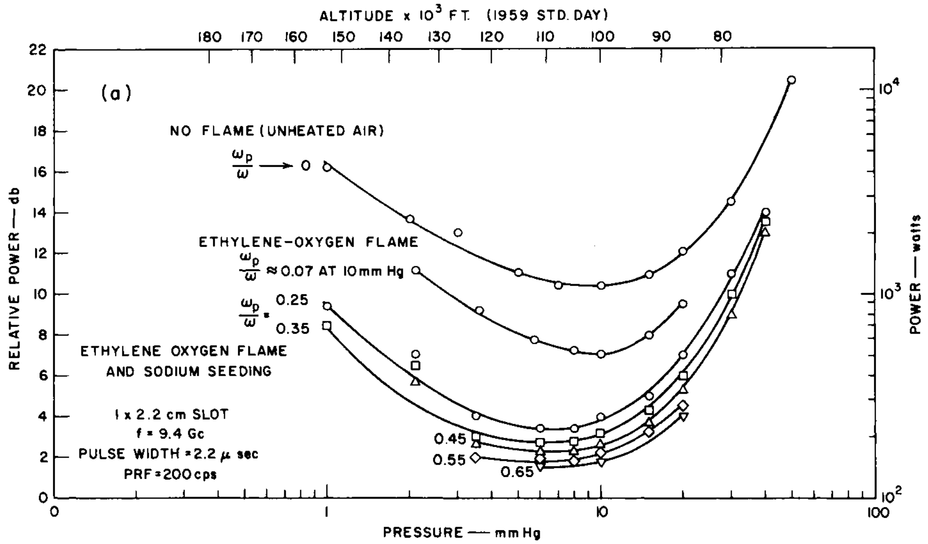

Fig. 6. Measured X-Band Pulse Breakdown Power Levels in the Presence of a Plasma.

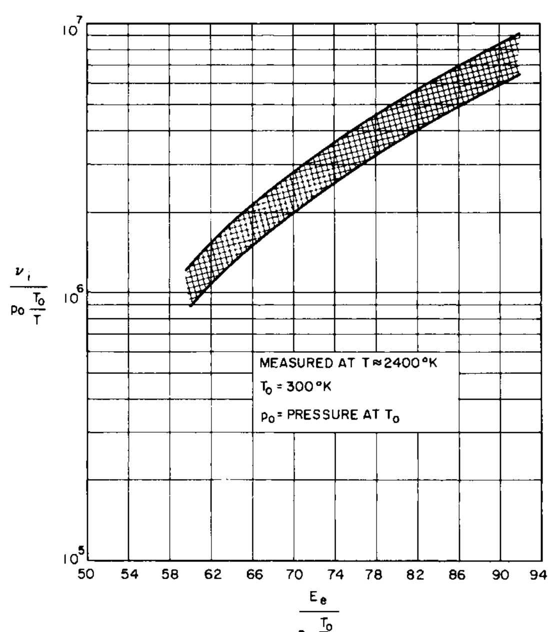

Fig. 7. ν_i/p as a Function of E_e/p for Ethylene-Oxygen Flame.

consideration is reduced by as much as 9 db when subject to ambient electron densities such that $\omega_p \rightarrow \omega$ for this particular flame.

By making measurements in ethylene-oxygen flame the validity of the theoretical formulation of breakdown in hot gases has been verified. A knowledge of the ionization rate and collision frequency as a function of electric field in the flame is required to compute the breakdown fields. These parameters have been determined by the method outlined below. Unfortunately, the determination of these relationships for the seeded flame is not yet complete.* The measurements of the breakdown of a slot antenna placed in an ethylene-oxygen sodium-seeded flame were presented in Fig. 6. After the theoretical formulation was checked, calculations for hot air were made using 300°K air data in lieu of any data on air at elevated temperatures. A method that is being used to determine this parameter for the seeded ethylene-oxygen flame is described below.

The technique developed for measuring the ionization rate involves the use of a focused microwave system to obtain breakdown in the plasma under consideration. This consists of an 18-inch-diameter parabolic reflector which is fed by an open-ended waveguide placed so that the energy is focused into a spot with a 3-db diameter of 4.8 cm. The reflector is placed outside the Pyrex cylinder and focused so that the maximum power density occurs over the burner centerline. By the use of standard-gain horns, the power density at the burner centerline has been found in terms of the input power. Thus, the electric field strength for breakdown in the flame can be expressed in terms of the power fed to the reflector.

Utilizing the breakdown relation of Eq. (5)

$$\nu_i = \nu_a + \frac{D}{\Lambda^2} + \frac{\ln \frac{n_t}{n_0}}{t}$$

it may be shown that the attachment rate, ν_a, is made negligible by the proper choice of operating pressure. The diffusion loss, D/Λ^2 in a focused system is small compared to the last term, $(\ln n_t/n_0)/t$. Thus by measuring the initial electron density in the ionized medium, and noting

*This measurement is to be made in the near future under Contract AF (604)-7367, which is sponsored by Air Force Cambridge Research Laboratories.

the pulse width used for the breakdown, the ionization rate for a given breakdown voltage can be expressed as

$$\nu_i = \frac{\ln \frac{n_t}{n_0}}{t} \quad .$$

Figure 7 shows the relationship between ν_i and E_e for the unseeded ethylene-oxygen flame and was obtained by utilizing this technique. The normalizing function p T_o/T accounts for the change in gas density.

Similar measurements have been made in O_2, N_2 and air at 300°K. The results agree reasonably well with other published data on these gases. The collision frequency at breakdown (which may also be obtained by making measurement at two different pressures and pulse widths such that pressure times the pulse width is a constant) obtained from these measurements is also in agreement with published values. Differences between values measured by the above technique and published values are of the order of 20 percent. It should be stressed that we are still in the process of refining this technique and that our measured values are preliminary.

Using the data shown in Fig. 7 for an unseeded ethylene-oxygen flame, agreement between measured and computed breakdown fields is within about 2 db.

The calculated breakdown data presented in Fig. 8 are for partially ionized air. They were determined by estimating the electron loss terms on the right side of Eq. (5), and calculating the ionization rate required for breakdown. In order to find the required electric fields to produce this ionization rate a relationship between ν_i and E_e was determined from CW data in 300°K air on parallel plate structures. Although the data are not strictly correct for higher-temperature air, these values have been used in the absence of other data. E_e is the effective field which would produce the same energy transfer to the electrons as a dc field, and is given by

$$E_e = \frac{E\nu_c}{(\nu_c^2 + \omega^2)^{1/2}}$$

where E is the rms field and ν_c is the collision frequency.

The top curve for ambient air in Fig. 8 can be compared directly to the top curve of Fig. 6 for the no-flame condition. The agreement between the theoretical curve and the experimental curve is within 1 db up to pressures of 30 mm.

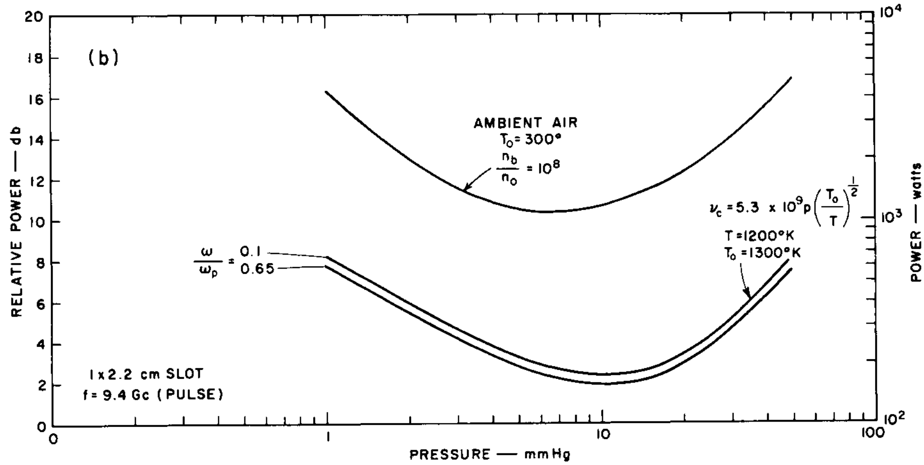

Fig. 8. Calculated X-Band Pulse Breakdown Power Levels in the Presence of a Plasma.

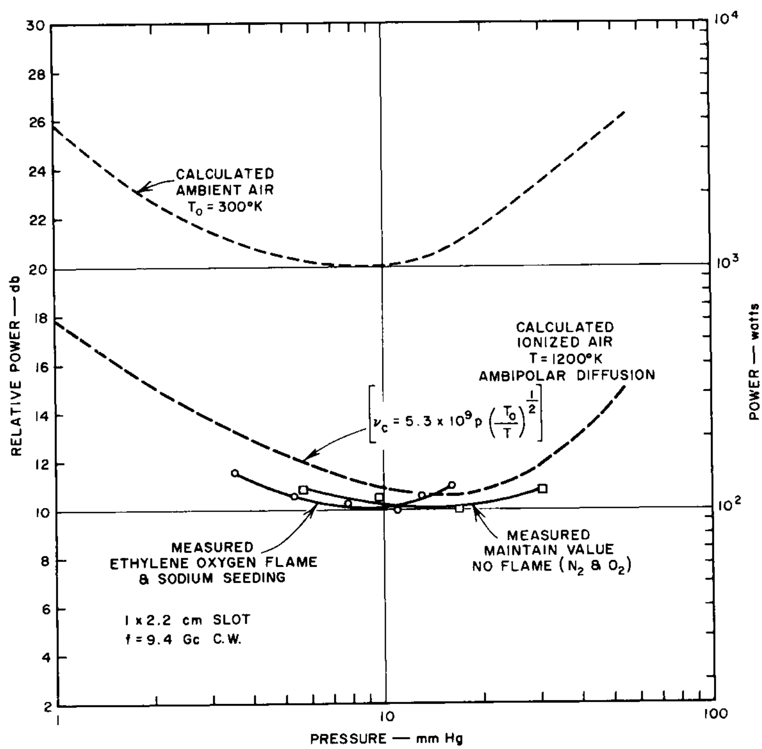

Fig. 9. Measured and Calculated X-Band CW Breakdown Power Levels in the Presence of a Plasma.

At high pressures, the curve deviates more, since the effective diffusion length for the slot is valid only in the diffusion-controlled region of breakdown. Assuming that a $(T/T_o)^{1/2}$ temperature dependence is chosen for the collision frequency at a given density, the power-handling capability is lowered from 8 db to 10 db in the vicinity of the minimum. The calculated results show that once ambipolar diffusion is obtained, there is very little difference in the breakdown level. This is to be compared with the measured result, which shows several db difference in going from ω_p/ω of 0.1 to 0.65. Since the degree of ionization was varied by adjusting the temperature of the salt, and hence of the flame, part of the difference in the curves of the measured data may be due to temperature effect on the ionization rate, diffusion loss, and the collision frequency.

A value of 1200°K was assumed for the gas temperature, even though the average temperatures in the flame were determined to be on the order of 2000°K, to account for the cooling effect of the ground plane on the hot gases adjacent to the slot antenna.

The available X-band CW power source was not sufficient to break down the 1.0- by 2.3-cm slot without the presence of the flame. Thus, the CW breakdown power levels as a function of p for the no-flame condition given in Fig. 9 are calculated values. The value of breakdown level for the case when weakly ionized air surrounds the antenna was also calculated, and is shown in Fig. 9 as well. For the CW breakdown case, the time-dependent term $(\ln n_t/n_0)p\tau$, which depends upon the initial value of the electron density, has been eliminated. Thus, CW breakdown is independent of the electron density except as it determines whether the diffusion is free or ambipolar.

The measured values of breakdown power levels with the sodium-seeded flame present are shown in Fig. 9. As stated earlier, direct comparison of the results cannot be made. The calculated values of breakdown in air with ambipolar diffusion assumed with $\nu_c = 5.3 \times 10^9 p(T_o/T)^{1/2}$ indicate that the power-handling capability would be reduced by about 9 to 10 db in the vicinity of the minimum.

The measured breakdown data show that a 10-db decrease is experienced with the flame on--about the same decrease in power handling experienced in the pulse case.

Shown also in Fig. 9 is the power level required to maintain the discharge without the flame and in an N_2 and O_2 gas mixture. The flame was turned on momentarily to ignite the discharge. It is interesting to note that the power required to initiate breakdown in the presence of the plasma produced by the flame is the same as the extinguish level with no external source of electrons. Actually, one might expect the extinguish power level to be the limiting condition for reduction in power handling for CW operating antennas.

From the breakdown standpoint, CW systems are less desirable than the pulse systems, because when breakdown occurs--which may be due only to a momentary disturbance--it will not extinguish until the electron density in the vicinity of the antenna is altered to the point where the maintaining potential exceeds the transmitter power. In the pulse case, however, once the high electron density is removed, the antenna will no longer break down.

Conclusions

The tests of the effect of initial plasmas on breakdown indicate that even when the plasma density is so low that there is negligible absorption and reflection from a plasma, the breakdown level may be significantly lowered. These measurements and calculated results indicate that for antennas mounted on re-entry bodies or boost-glide vehicles, ionization produced by aerodynamic heating may lower the power required for breakdown by as much as an order of magnitude. Thus, special consideration must be given to the antenna and system design to ensure that voltage breakdown with all its attendant difficulties will not occur during critical periods. The results do not include the effects of flow, which would tend to raise the breakdown power. This aspect of the breakdown problem is presently being considered.

If, during re-entry for example, the plasma frequency in the ionized gas reaches as high as a few tenths of the RF frequency, the antenna should be operated with power levels at least 10 db below the breakdown level found in a non-ionized case. Under this condition no breakdown will occur. Then the signal will be attenuated only by the plasma formed by the vehicle. In a regime of this density, the attenuation would be from several db to 20 db. If more power than this were applied to the antenna, breakdown would occur with all additional power going into the plasma formed by the breakdown, and with increased attenuation occurring due to the transmission through the plasma. Changes in VSWR, pulse shape (for the pulse case), and radiation patterns would be incurred. On the other hand, if the plasma frequency were approximately equal to or higher than the RF frequency, the plasma attenuation would be so large that the presence of voltage breakdown would make no difference.

References

1. W. E. Scharfman and T. Morita, "Power Handling Capability of Antennas at High Altitudes," presented at Plasma Sheath Symposium, Boston, Massachusetts (7-9 December 1959) (to be published in Electromagnetic Radiation in Hypersonic Environment, Pergamon Press, Summer 1960).

2. W. H. Drake and F. S. Howell, "Radio Frequency Propagation to and from ICBM's and IRBM's," presented at 1959 National Symposium on Space Electronics and Telemetry, San Francisco, California (28-30 September 1959).

3. J. Gould and L. W. Robert, "Breakdown of Air at Microwave Frequencies," J. Appl. Phys., Vol. 27, No. 10, pp. 1162-1170 (October 1956).

4. A. D. MacDonald, "High-Frequency Breakdown of Air at High Altitudes," Proc. IRE, Vol. 27, No. 3, p. 436 (March 1959).

5. S. C. Brown, "High Frequency Gas Discharge Breakdown," Proc. IRE, Vol. 39, No. 12, pp. 1493-1501 (December 1951).

6. W. E. Scharfman and T. Morita, "Voltage Breakdown of Antennas at High Altitudes," Tech. Report 69, SRI Project 2494, Contract AF 19(604)-3458, Stanford Research Institute, Menlo Park, California (April 1960).

7. J. B. Chown, "Study of Plasma-Induced Voltage Breakdown at Low Pressure," Final Report, SRI Project 3369, Contract AF 33(600)-41517, Stanford Research Institute, Menlo Park, California (July 1961).