VIII-6. MICROWAVE BREAKDOWN TECHNIQUE FOR MEASURING IONIZATION RATE OF HIGH TEMPERATURE GASES IN A SHOCK TUBE

J. B. Chown, W. C. Taylor, and T. Morita

Stanford Research Institute, Menlo Park, California

Introduction. In the design of antennas for use on hypersonic re-entry vehicles, the effect of high-temperature ionized gas surrounding the vehicle must be considered. Interaction of the fields of the antenna with adjacent ionized medium requires examination of parameters that are not involved in the usual RF plasma interaction. In the nonlinear case where the RF field is strong enough to produce additional ionization in the gas, breakdown occurs and proceeds catastrophically until the electron density is high enough that the plasma limits the strength of the field penetrating the plasma. The power-handling capability of the antenna depends upon the RF fields created and the electron production and loss rates in the flowing medium.

A solution to the problem of predicting threshold power levels for breakdown due to RF ionization of room temperature air can be obtained by the use of empirical data in connection with the electron continuity equation.[1-4] The solution of this equation gives the ionization rate required to initiate breakdown by overcoming the various electron loss rates.

One fundamental parameter needed for estimating breakdown levels is the ionization rate of the gas as a function of the applied field. Unfortunately, this data has been available only for room temperature air.[5] The purpose of the work reported here was to measure the ionization rates for air at the elevated temperatures that are encountered in hypersonic flight.

Determination of Ionization Rate. Solving the electron continuity equation under the assumption that diffusion is the principal loss mechanism gives the breakdown criterion

$$\frac{\nu_i}{P} = \frac{DP}{(P\Lambda)^2} + \frac{\ln \frac{n_T}{n_0}}{P\tau} \qquad (1)$$

where ν_i is the RF ionization rate, D is the appropriate diffusion coefficient, and Λ is the effective diffusion length, which depends on the field configuration. The pressure P is included as a measure of gas density. The last term in the equation represents the additional increment of ν_i required for breakdown to occur during a pulse length τ, where n_0 is the ambient electron density and n_T is the density at breakdown. The first two terms on the right side of the equation represent loss by attachment and diffusion, respectively.

*This paper was made possible through support extended by Air Force Cambridge Research Laboratories under Contract AF 19 (628) - 4800.

The technique used to determine the ionization rate in elevated temperature gases was to measure the breakdown characteristics of an X-band slot antenna in the uniform slug of high temperature air created in an arc-driven shock tube. This facility was used because the gas dynamic properties of the shock-heated air can be reliably predicted by shock tube theory. By comparing these results with breakdown data obtained with the antenna in room temperature air at the same density, the hot air ionization rate was obtained.

Figure 1 shows the X-band slot antenna installed in the 12-inch diameter shock tube used to perform the experiment. The antenna is mounted in a flat plate with a sharp leading edge to obtain a very thin boundary layer. Ion probes placed in the free stream and flush with the plate, shown in Fig. 1, were used to determine the initial electron density n_o. Other similar probes were employed to trigger the pulse when the normally shocked air was over the antenna.

The gas density in the ionized flow was varied from $\rho/\rho_0 = 4 \times 10^{-4}$ to 5×10^{-2}, and the gas temperature was $3200^o \pm 200^o$ K. Initial electron densities in the flow varied from 2×10^9 to 5×10^{10} electrons/cc. The n_o is such that ambipolar diffusion may be assumed. The final density, n_T, was taken to be n_{crit} ($\sim 10^{12}$ el/cc) for the frequency used in the test.

The tests were performed by providing a 5-microsecond pulse of constant peak power to the antenna when the test slug was over the antenna. The time required for breakdown to occur, τ, was obtained from the oscilloscope photographs. Pulse lengths before breakdown as low as 0.02 microseconds were recorded. The gas density was determined from the shock speed and initial pressure in the tube.

The ionization rate data for the 3200^o K air and 300^o K air[5] as a function of E_e/P* is presented in Figure 2. It is seen that the hot air rate is greater than an order of magnitude higher than that for cold air. The significance of this higher ionization rate is evident in the example shown in Figure 3, which compares the calculated CW breakdown power level assuming ambipolar diffusion, using the two rates. This predicts, on the basis of the new data, an additional 3-dB decrease in minimum power-handling capability for the X-band slot antenna used in the test.

References:

1. S. C. Brown, "High Frequency Gas Discharge Breakdown", Proc, IRE 39, No. 12, pp 1493-1501, December 1961.
2. L. Gould, and L. W. Roberts, "Breakdown of Air at Microwave Frequencies", J. App. Phys. 27, No. 10, pp 1162-1170, Oct. 1956.
3. J. B. Chown, W. E. Scharfman, and T. Morita, "Effect of Ambient Plasma on Antenna Breakdown", 6th Symposium on Bistatic Missile and Aerospace Technology, pp 51-68, Academic Press, New York, 1961.

* $E_e = E_{rms}[1 + (\omega/\nu)^2]^{-\frac{1}{2}}$, where ν is the collision frequency.

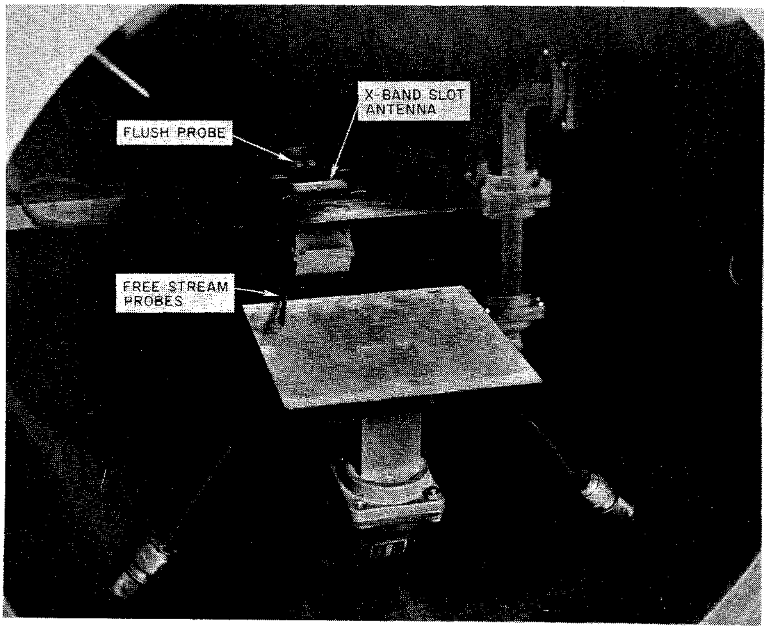

Figure 1. X-Band Antenna Installation on Shock Tube

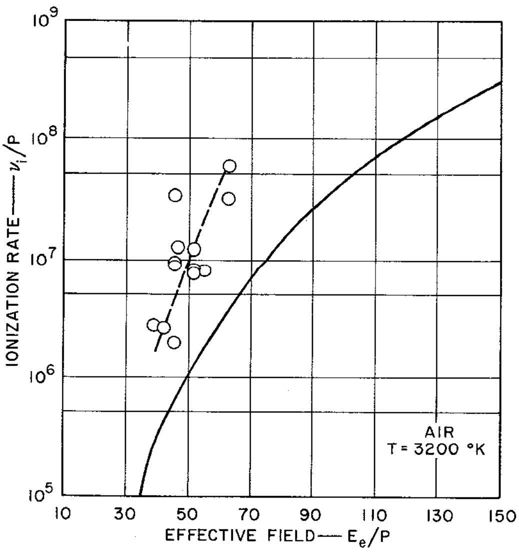

Figure 2. Measured Ionization Rates for 3200° K Air Compared with Cold Air

4. J. B. Chown, W. C. Taylor, E. F. Vance, J. E. Nanevicz, and T. Morita, "Effects of Re-entry and Space Environments on Antenna Breakdown", presented at 3rd Symposium on the Plasma Sheath, Sept. 21-23, 1965, Boston, Mass (AFCRL).
5. W. E. Scharfman and T. Morita, "Focused Microwave Technique for Measurement of the Ionization Rate and Collision Frequency", J. App. Phys. 35, No. 7, pp 2016-2020, July 1964.

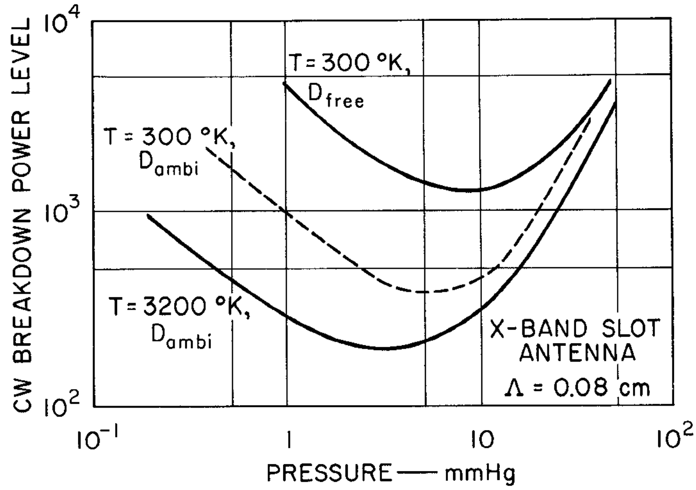

Figure 3. Predicted CW Breakdown Power Level for X-Band Slot Using New Ionization-Rate Data Compared with Cold Air Results