NASA TECHNICAL NOTE

NASA TN D-2892

NASA TN D-2892

N65-27813

(ACCESSION NUMBER) (THRU)

12 (PAGES) 1 (CODE)

(NASA CR OR TMX OR AD NUMBER) 25 (CATEGORY)

FACILITY FORM 602

D

GPO PRICE $

~~OTS~~ CFSTI PRICE(S) $ 1.00

Hard copy (HC)

Microfiche (MF) .50

DETERMINATION OF PLASMA TEMPERATURE AND ELECTRON DENSITY DISTRIBUTIONS USING MILLIMETER WAVES

by William F. Leonard

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JULY 1965

DETERMINATION OF PLASMA TEMPERATURE AND

ELECTRON DENSITY DISTRIBUTIONS

USING MILLIMETER WAVES*

By William F. Leonard
Langley Research Center

SUMMARY

27813

A method for obtaining good spatial resolution in the measurement of electron density and temperature variations in a thermal plasma of cylindrical cross section using millimeter waves is described. The technique, which is an application of the Abel inversion technique, involves the division of a plasma into concentric zones and evaluation of the attenuation constant in each zone from measured attenuation losses. Results of measurements made on a cyanogen oxygen flame at 61.2 Gc are given, and correlation of the peak temperature (4470° K) at the center of the flame with spectroscopic measurements is shown.

INTRODUCTION

As a result of high-temperature plasma research, various techniques have been developed to measure the electromagnetic properties of an ionized gas. These methods fall into the following categories: metallic current probes, electron beam probes, optical measurements of emission line broadening and of emission spectra, and schemes employing microwave interactions with the medium. Probe techniques are often not applicable due to a lack of suitable theories for interpreting the data they supply, and optical measurements may be limited because of low spectral line intensity. Therefore, efforts have been extended toward the use of microwave diagnostics (refs. 1, 2, and 3) to measure the electromagnetic properties of a plasma (refs. 4, 5, and 6). Of particular interest is the determination of plasma temperature and electron density. Some previous studies of plasma temperature and electron density (refs. 7 and 8) had, in general, low spatial resolution and resulted in average values for the electron density and temperature.

The purpose of this report is to describe a high-resolution millimeter-wave survey technique for studying electron density and temperature distributions in nonreflecting stratified cylindrical plasmas. This is done by first

---

*Presented at the Millimeter and Submillimeter Conference, Orlando, Florida, January 7-10, 1963, sponsored by The Institute of Electrical and Electronics Engineers.

describing the conditions necessary for a plasma to be nonreflecting, then applying a survey method based on the Abel inversion technique to an assumed cylindrical model for a plasma. Experimental results obtained on a cyanogen oxygen flame are then presented and compared with spectroscopic measurements of the peak temperature at the center of the flame.

SYMBOLS

$A_{k,j}$	area coefficient
B	degeneracy factor in Saha's equation
K	equilibrium constant for dissociation or ionization
l	path length, cm
N_e	electron density, cm^{-3}
r_k	radius vector
T	absolute temperature, $^{\circ}K$
V_i	ionization potential, eV
x_j	component of radius vector perpendicular to transmission path
α	attenuation constant, dB/cm
β	phase constant, rad/cm
Γ_p	power reflection coefficient
γ	propagation constant
δ	attenuation, dB
λ	wavelength, mm
ν	collision frequency, sec^{-1}

Subscripts:

i	summation index
j,k	zone indices for area coefficients
n	summation

o free space

p plasma

SURVEY METHOD

The propagation of electromagnetic EM waves in a plasma is described in terms of a complex propagation constant $\gamma = \alpha + j\beta$ which is a function of the electron density N_e, temperature and collision frequency ν of the plasma. (See ref. 4.) In general, to determine the electron density, temperature, and collision frequency of a plasma both the attenuation constant α and the phase constant β must be known. However, under certain conditions (figs. 10 and 15 of ref. 5), if either $\frac{\nu}{\text{EM frequency}} \geqq 10^{10}$ and $\frac{N_e^{1/2}}{\text{EM frequency}} \leqq 10^{3}$ or $\frac{N_e^{1/2}}{\text{EM frequency}} \leqq 3.16 \times 10^{-2}$ then the phase shift in the plasma is equal to that of free space and the power reflection coefficient Γ_p is less than 10^{-4}. Thus, for a "nonreflecting" plasma the experimental quantity of interest is the attenuation constant. An obvious means to insure these above criteria is to increase the EM frequency; this has the added benefit of obtaining good spatial resolution in addition to simplifying the experimental measurements. That is, for systems operating at EM frequencies greater than 60 Gc, the physical dimensions of the horn antennas are less than 0.3 inch, and Buser and Buser (ref. 9) have experimentally shown that the beam is well collimated and is approximately equal to the width of the horns. Thus, if the ratio of plasma diameter (assuming a cylindrical plasma) to the width of the antenna receiving aperture is large, good spatial resolution can be obtained.

The effect of temperature on the EM properties of a plasma is determined through the use of known gas equilibrium constants and Saha's equation. Saha's equation relates the electron density to the temperature in an ionized gas for a given ionization potential V_i and total gas pressure. Saha's equation is

$$\log K_p = -\frac{23070\ V_i}{4.573\ T} + 2.5 \log T + \log B - 6.491 \tag{1}$$

where K_p is the equilibrium constant for dissociation or ionization of the various constituents of the plasma and B is the degeneracy factor. (See ref. 8.) If the known equilibrium constants and those calculated from equation (1) are used, a composition calculation for neutral particles and electrons can be made.

If it is assumed that $\Gamma_p = 0$ (or $\beta = \beta_o$), one further requirement becomes necessary to determine N_e and T from attenuation measurements; that is, the value of the collision frequency must be known. This is necessary because the slope of the curve relating phase shift to electron density (fig. 10 of ref. 5) is zero regardless of the value of the collision frequency. However, for many plasmas the collision frequency may be computed from kinetic-theory relations. (See eq. (4) of ref. 8.) Thus, with a measured attenuation constant, a calculated collision frequency, and a knowledge of gas constituents, the electron density and temperature can be determined.

In order to arrive at a reasonable survey method based on these criteria, the following plasma conditions are assumed:

1. The plasma is nonreflecting at the EM frequency used.

2. The plasma is cylindrical, having radial variations only.

3. The ratio of plasma diameter to width of antenna receiving aperture is large.

4. The ionization potential, total gas pressure, and collision frequency of the plasma are known.

Once these plasma conditions are assumed, the electron density and temperature variations in a plasma can be determined by measuring the insertion loss experienced as the test plasma traverses between two microwave horns normal to the direction of propagation.

Since theory is based on attenuation per unit path length, a model for evaluating effective path lengths will be helpful in converting from measured attenuation in dB to attenuation per unit path length in dB/cm. Figure 1, which represents the model used to evaluate laboratory tests, shows a cylindrical plasma divided into five concentric zones of constant attenuation per unit path length with a width equal to that of the receiving horn aperture. The number of zones depends on the ratio of the plasma diameter to the width of antenna receiving aperture. The effective path

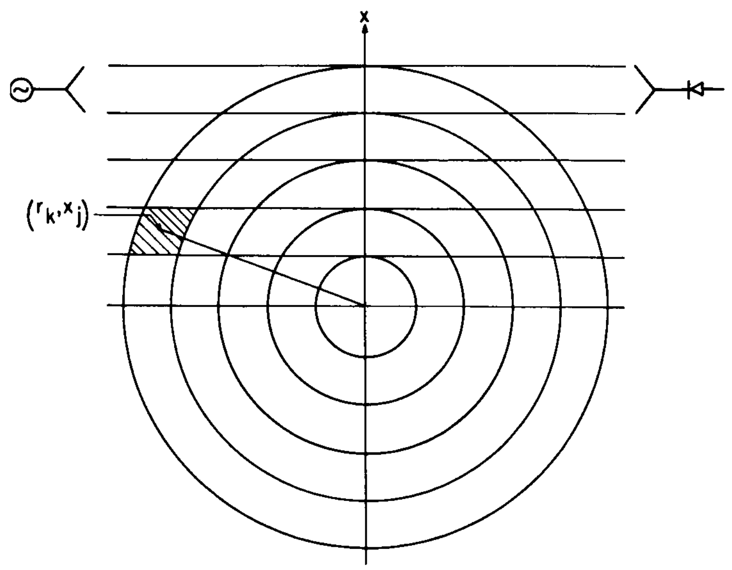


Figure 1.- Assumed model of a cylindrical plasma.

length in a zone is found by dividing the area of the strips in that zone by the width. The area of a strip in a particular zone is obtained from a table of area coefficients $A_{k,j}$ for given values of r_k and x_j (ref. 10).

Once the effective path lengths and measured attenuation losses are known for each strip, the attenuation constant for each zone can be determined from the following expression:

$$\alpha_n = \frac{\sum_{k=1}^{n} \delta_k - \sum_{i=0}^{n-1} \alpha_i l_i}{l_n} \tag{2}$$

where the subscript n designates the zone starting with $n = 1$ for the outer zone and δ_k is the attenuation in decibels in a zone for a particular strip. If the attenuation constants thus obtained are used, the electron density and temperature in each zone are found from theoretical plots of attenuation per unit length versus electron density and electron density versus temperature for the plasma being surveyed.

TEST APPARATUS

The test plasma used to evaluate the survey technique was a stoichiometric cyanogen oxygen flame which forms a 3-inch-diameter subsonic jet at atmospheric pressure. The calculated collision frequency for this flame is 6×10^{10} sec^{-1} (ref. 8), and computation of the equilibrium plasma characteristics for a stoichiometric equilibrium combustion of cyanogen and oxygen gives a plot of temperature versus electron density as shown in figure 2.

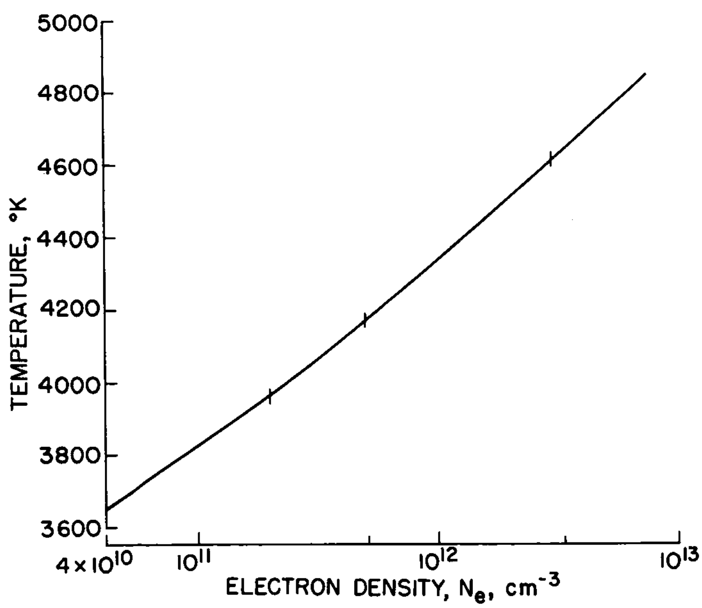


Figure 2.- Variation of electron density with temperature for the cyanogen oxygen flame.

Examination of the electromagnetic properties of a plasma at a frequency of 61.2 Gc (frequency used in tests) and for a collision frequency of 6×10^{10} sec^{-1} yields the following:

(1) The cyanogen oxygen flame is nonreflecting for electron densities less than 10^{13} cm^{-3}. (See fig. 10 of ref. 5.)

(2) A plot of attenuation constant versus electron density is as shown in figure 3.

By combining figures 2 and 3, a useful plot of temperature versus attenuation constant can be made and is shown in figure 4.

Therefore, the cyanogen oxygen flame meets the necessary requirements outlined and a temperature distribution can be made by measuring transmission loss as a function of flame diameter.

Figure 5 is a block diagram of the millimeter-wave apparatus. The signal source is a 60 to 70 Gc backward wave oscillator which feeds into a 3-dB coupler for

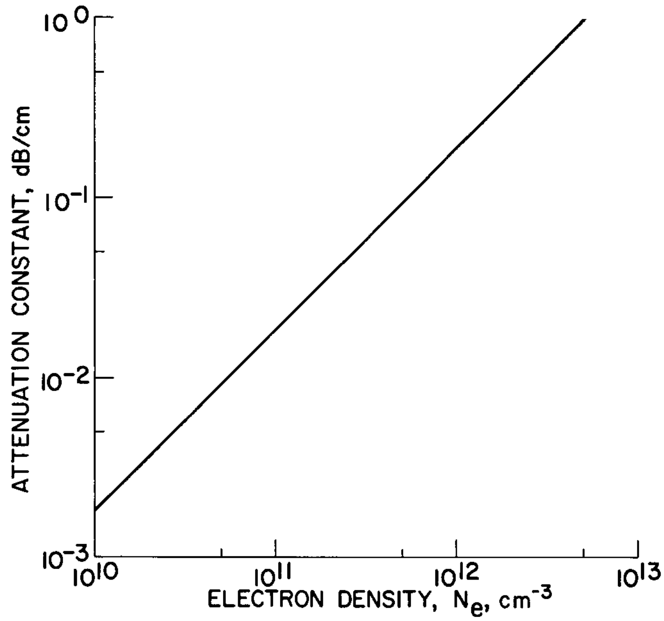


Figure 3.- Dependence of attenuation constant on electron density. $\nu = 6 \times 10^{10}$ sec^{-1}; $\lambda = 4.9$ mm.

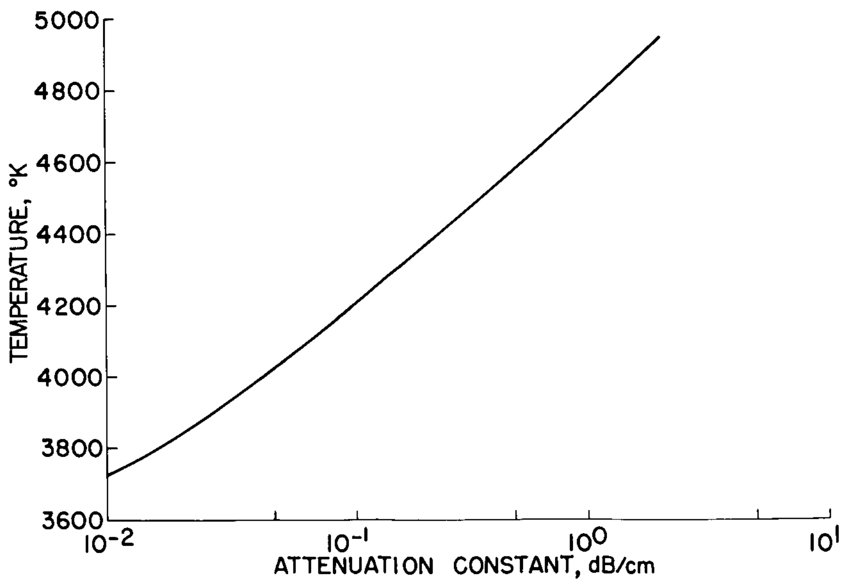


Figure 4.- Dependence of attenuation constant on temperature. $\nu = 6 \times 10^{10}$ sec^{-1}; $\lambda = 4.9$ mm.

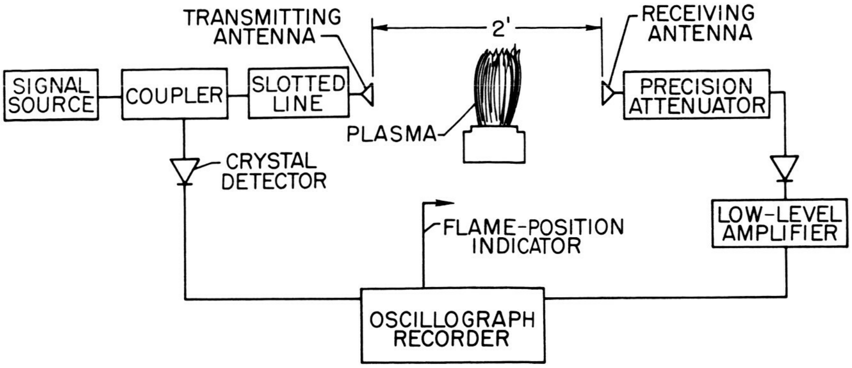
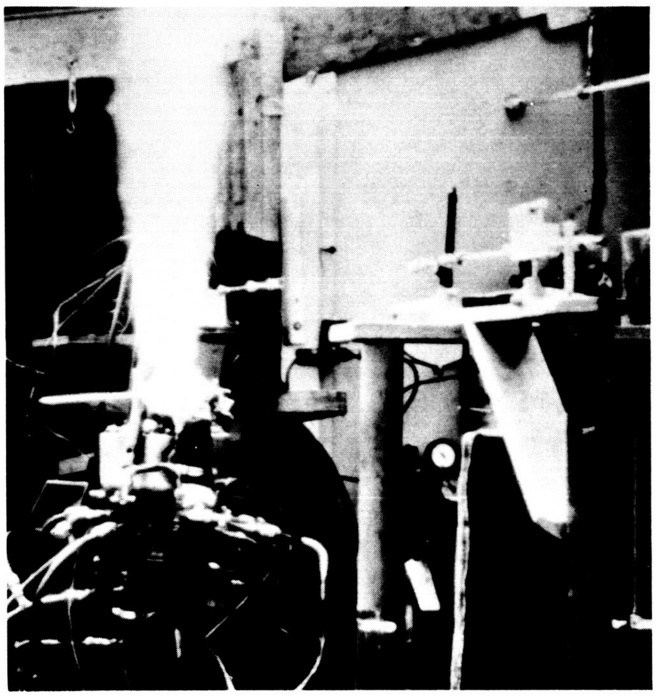


Figure 5.- Schematic diagram of test apparatus.

monitoring power output levels. Frequency of operation is checked by measuring the wavelength with a slotted line. The antennas are 15-dB nominal gain horns with an aperture width of 0.3 inch. An oscillograph recorder is used to record the power monitor signal, flame position, and transmitted signal. Figure 6 is a photograph of the test facility.



L-65-16
Figure 6.- Photograph of test facility.

RESULTS

Attenuation measurements were made on a stoichiometric cyanogen oxygen flame at a frequency of 61.2 Gc. The ratio of flame diameter to width of receiving horn antenna was 10:1; thus, the flame was divided into five concentric zones each having a width of 0.3 inch (the width of the receiving horn aperture).

The measured attenuation experienced as the flame traversed between the horns is shown in figure 7. Application of these data to the assumed plasma model yields the attenuation constant for each zone. The resulting electron density and temperature distributions, from figures 3 and 4 and values obtained for the attenuation constants, for the cyanogen oxygen flame are shown in figure 8.

Although some fluctuations were present in the flame, the survey technique gave a distribution which follows a bell-shaped curve with a maximum temperature

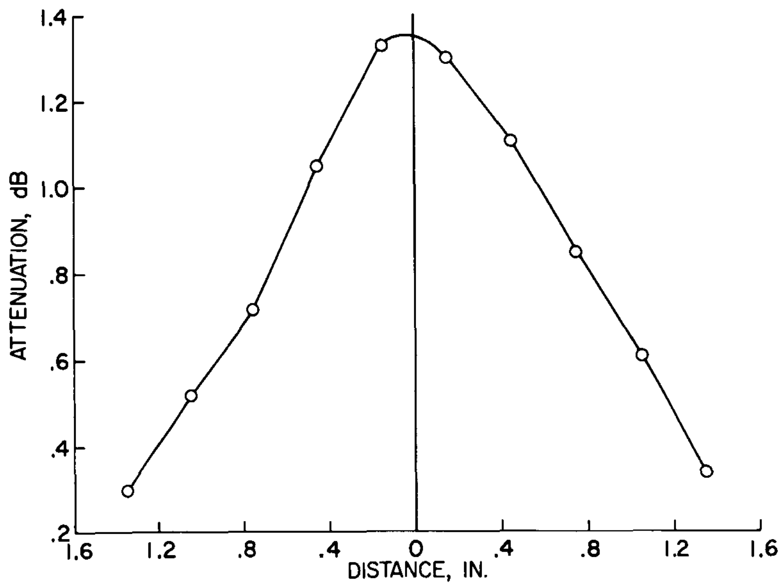


Figure 7.- Transverse survey of cyanogen oxygen flame at 61.2 Gc.

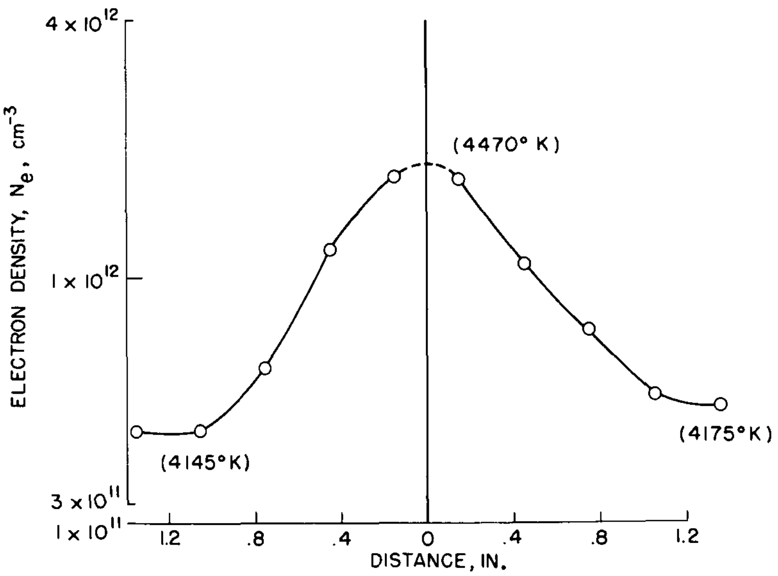


Figure 8.- Electron density and temperature distributions in a cyanogen oxygen flame.

at the center of 4470° K and a minimum of 4145° K at the edge. The peak temperature at the center of the flame has been correlated with unpublished spectrographic data, obtained at the Langley Research Center, based on the rotational structure of the vibrational rotational CN band. (See ref. 11 for a description of this technique.) The spectrographic measurements gave a peak value of 4500° K at the center of the flame which is within 1 percent of the millimeter wave value.

The flare of the electron density and temperature distributions in figure 8 results from the assumption that the attenuation coefficient α is a constant in each zone. This effect becomes negligible in the calculation of α (eq. (2)) toward the center of the flame because the total attenuation contributed by the outer zone is small.

An advantage of this method for studying the temperature variations in the cyanogen oxygen flame is that the results are not very sensitive to the accuracy of the calculated collision frequency. This can be shown by comparing a plot of α versus $N_e^{1/2}$ for various values of ν (fig. 1 of ref. 5) and figure 2 for T versus N_e. If the collision frequency is in error by an order of magnitude, the error in the temperature values determined from attenuation measurements at 61.2 Gc will be less than 12 percent. The shape of the temperature distribution curve does not change with collision frequency.

CONCLUDING REMARKS

Electron density and temperature distribution of a nonreflecting cyanogen oxygen flame have been determined by using a millimeter-wave survey scheme. The distributions follow the expected bell-shaped curve and the peak temperature at the center of the flame agrees within 1 percent of spectroscopic measurements.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 21, 1965.

REFERENCES

1. Drummond, James E.: Plasma Physics. McGraw Hill Book Co., Inc., 1961.

2. Wharton, Charles B.: Microwave Diagnostics for High-Temperature Plasmas. UCRL-4836 (Contract No. W-7405-eng-48), Univ. of California, Mar. 1957.

3. Bunn, Harlin L.: Microwave Diagnostic Systems and Techniques for Use in Controlled Fusion Research. IRE, Trans. Instr., vol. I-11, no. 1, June 1962, pp. 3-10.

4. Bachynski, M. P.; Johnston, T. W.; and Shkarofsky, I. P.: Electromagnetic Properties of High-Temperature Air. Proc. IRE, vol. 48, no. 3, Mar. 1960, pp. 347-356.

5. Balwanz, W. W.: Interaction Between Electromagnetic Waves and Flames. Pt. 6 - Theoretical Plots of Absorption, Phase Shift, and Reflection. NRL Rept. 5388, U.S. Naval Res. Lab., Sept. 23, 1959.

6. Buchsbaum, S.: On the Interaction of Microwave Radiations With a Plasma. Semi-Annual Progress Report. ZPH-013 (Contract AF 33(616)-3283), Convair-San Diego, Apr. 1, 1958, pp. 77-89.

7. Rudlin, Leonard: Preliminary Results of a Determination of Temperatures of Flames by Means of K-Band Microwave Attenuation. NACA RM E51G20, 1951.

8. Huber, Paul W.; and Gooderum, Paul B. (With appendix A by Theo E. Sims and Duncan E. McIver, Jr., and appendix B by Joseph Burlock and William L. Grantham): Experiments With Plasmas Produced by Potassium-Seeded Cyanogen Oxygen Flames for Study of Radio Transmission at Simulated Reentry Vehicle Plasma Conditions. NASA TN D-627, 1961.

9. Buser, R.; and Buser, W.: Determination of Plasma Properties by Free-Space Microwave Techniques. J. Appl. Phys., vol. 33, no. 7, July 1962, pp. 2275-2282.

10. Pearce, William J.: Calculation of the Radial Distribution of Photon Emitters in Symmetric Sources. Conference on Extremely High Temperatures, Heinz Fischer and Lawrence C. Mansur, eds., John Wiley & Sons, Inc., c.1958, pp. 123-134.

11. Greenshields, David H.: Spectrometric Measurements of Gas Temperatures in Arc-Heated Jets and Tunnels. NASA TN D-1960, 1963.

NASA-Langley, 1965 L-4276