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ELECTRON TEMPERATURE AND CONCENTRATION IN A THERMAL ATOMIC OXYGEN SOURCE

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I. Introduction

The lower earth orbit environment erodes materials primarily due to the presence of atomic oxygen at concentrations on the order of $10^9 cm^{-3}$.[1] Corresponding electron concentrations are on the order of $10^5 cm^{-3}$ with an electron temperature on the order of 0.15 eV. [2] A thermal atomic oxygen source for materials screening has been built for NASA by Boeing Aerospace.[3] This device is shown in Figure 1. Plasma is created by 13.56 MHz rf power applied to oxygen flowing in a 7.6 cm ID glass tube. Charged and neutral particles from the plasma flow downstream to the "T" region where the small glass tube connects to a 15.2 cm ID glass tube. Materials are typically exposed near the aluminum flange located at x=24.1 cm with power, pressure, and flow set to 100W, 100mtorr, and 6.7 sccm, respectively. The objective of the work described here was to use a microwave interferometer and Langmuir probes to characterize the electron concentration in this thermal atomic oxygen source.

II. Apparatus

Two flat (0.5mm thick) 304 stainless steel Langmuir probes were used; one was a round disk with exposed area $2.04 \times 10^{-4} m^2$ and the other was a square with area $1.16 \times 10^{-2} m^2$. The small disk probe was used at x=0 and 10 cm while the large square probe was used at x=10, 16.5, and 25cm. The 9cm x 60cm 304 stainless steel ground plate shown in Figure 1 was found to be essential for stable Langmuir probe measurements. Bias voltage was supplied by batteries attached to an integrated circuit voltage regulator. Bias voltage was measured with a Fluke 8020B Multimeter and probe current was measured with a Phillips PM3365 100MHz oscilloscope in conjunction with viewing resistors with values 10.3kΩ, 95.8kΩ, and 1MΩ (oscilloscope input resistance). To minimize rf noise, all electrical connections were made with coaxial cables. Langmuir probes have been summarized in several texts [4,5,6] and the circuit used for these measurements was described previously.[7]

The microwave interferometer passed 9.2 GHz microwaves through the walls of the glass tube and through the plasma via transmitting and receiving horn antennas. Microwave interferometers for plasma diagnostics have been described in the literature.[8,9] The interferometer used in this work is very similar to that shown in Figure 6.7 on p. 201 of Reference 8. Basically, power from the microwave source was split into a plasma path and a reference path. Microwaves from these two paths were then added and detected. The electron concentration in the plasma changed the phase of the plasma path microwaves resulting in a detector output voltage that was proportional to electron concentration.

III. Results

Typical operating conditions in the thermal atomic oxygen source were found to produce electron concentrations at the center of the "T" in Figure 1 that were well below the detection threshold of the interferometer ($10^8 cm^{-3}$). Hence, we calibrated (with the interferometer) the circular Langmuir probe at an artificially high plasma density and then

used the circular and the square Langmuir probes to measure the low electron concentrations that exist during materials exposure tests.

To create this high density plasma, argon gas was used at a pressure of 350 mtorr, a flow rate of 19.5 sccm and an output power of 200W with 72W reflected back to the rf power supply. These conditions filled both the vertical and horizontal tubes with a very bright dense plasma. Using standard Langmuir probe techniques, the electron temperature of this plasma was measured to be 4.71±0.82 eV. Figure 2 shows calibration of the Langmuir probe with the interferometer. For this data, the horns of the interferometer and the circular probe were located at x=0. The probe was oriented in a horizontal position that minimized reflected microwave power. The probe was biased to -42V to insure that it was collecting saturation ion current. As shown in Figure 2, the rf source was pulsed on and off for times on the order of 5 seconds. The interferometer and Langmuir probe measured electron concentrations of 4.03×10^9 and $3.39 \times 10^9 cm^{-3}$, respectively. This gives a ratio of 1.2, which is excellent agreement between the two techniques.

The atomic oxygen source was then set to more realistic operating conditions: power in the range 50 to 200W with zero reflected power, oxygen pressure 100 mtorr, and flow rate 6.7 sccm. Figure 3 shows typical Langmuir probe volt-ampere characteristics for the square probe located at x=25cm with power settings of 50, 100, 150, and 200W. Electron temperature was obtained from a semilogarithmic plot of the logarithm of electron current versus probe voltage. Electron current was obtained by subtracting saturation ion current from the probe current. In Figure 3 the electron temperatures for 50, 100, 150, and 200W were 0.56±0.11, 0.63±0.05, 0.55±0.04, and 0.69±0.04 eV, respectively. That is, for these conditions the electron temperature was nearly independent of power setting, an observation that is consistent with others.[10,11]

Electron concentration was found by assuming singly charged ions, invoking the plasma condition $n_i=n_e$, and using the expression

$$n_e=n_i=\frac{I_{SI}\sqrt{\frac{m_i}{kT_e}}}{0.607Ae} \qquad (1)$$

where I_{SI}, m_i, and A are the saturation ion current, the ion mass, and the probe area, respectively. This is from Equation (3.2.20) on page 60 of Reference 5. For this analysis, we assumed that the dominant positive ion was 0_2^+ which is consistent with the work of others.[12] In Figure 3 the electron concentration for 50, 100, 150, and 200W were $1.33 \pm .45 \times 10^4$, $6.87 \pm .94 \times 10^4$, $1.40 \pm .12 \times 10^5$, and $2.97 \pm .33 \times 10^5 cm^{-3}$, respectively.

Similar measurements at x=0, 10, and 16.5 cm showed that the electron concentration could be expressed as a function of power and position by the expression

$$n_e = 973P^2 \exp\left(\frac{-x}{5.21}\right) \tag{2}$$

where n_e is electron concentration in cm^{-3}, P is power in W, and x is distance in cm. Plug flow analysis[13] of ambipolar diffusion [14] predicts that dependence in the x direction would be

$$n_e \propto \exp\left(\frac{-x}{\lambda}\right) \tag{3}$$

with

$$\lambda = \frac{0.174R^2 u_x}{D_a} \tag{4}$$

where R, u_x, and D_a are the tube radius, the flow velocity and the ambipolar diffusion coefficient, respectively. Figure 4 compares all measured data points with this analytical expression. Figure 5 shows contours of constant electron concentration in the x-P plane.

While electron temperature was nearly constant with power at each location, it was found to be a function of x. For example, at a power setting of 100W, the electron temperature at x=0, 10, 16.5, and 25 cm was 2.51±0.17, 1.22±0.05, 0.80±0.06, and 0.63±0.05eV, respectively.

IV. Conclusions

Electron concentration was measured as a function of power and position. The electrons were lost to the walls through ambipolar diffusion and their concentration was accurately described by Eq. 2. That is, electron concentration was proportional to power squared and decayed exponentially with distance.

V. Recommendations

Data similar to Figure 5 should be generated for erosion rate and for atomic oxygen concentration as measured with a catalytic thermocouple probe.[15] Additional plug flow analysis should be used to develop an analytical model for concentrations of all species of interest. Laser-induced fluorescence (LIF) should be investigated for measuring atomic

oxygen concentration and to identify reactant species emitted from the surface of materials exposed to atomic oxygen.

VI. References

1. M. F. Rose, IEEE Transactions on Electrical Insulation, *EI-22*, pp. 555-571, 1987.

2. R. L. F. Boyd, *Space Research by Rocket and Satellite*, New York:Harper & Brothers, 1960, Chapter 1.

3. NASA Contract NAS8-36586, 1986-1989.

4. R. H. Huddlestone and S. L. Leonard, editors, *Plasma Diagnostic Techniques*, New York: Academic Press, 1965, Chapter 4.

5. I. H. Hutchinson, *Principles of Plasma Diagnostics*, New York: Cambridge University Press, 1987, Chapter 3.

6. O. Auciello and D. L. Flamm, editors, *Plasma Diagnostics*, Volume 1, New York: Academic Press, 1989, Chapter 3.

7. P. D. Pedrow and A. M. Nasiruddin, IEEE Transactions on Plasma Science, *17*, pp 17-23, 1989.

8. M. A. Heald and C. B. Wharton, *Plasma Diagnostics With Microwaves*, New York: Robert E. Krieger Publishing Co., 1978.

9. Hotston and M. Seidl, J. Sci. Instrum., *42*, pp 225-230, 1965.

10. J. E. Heidenreich, III, et al., J. Vac. Sci. Technol. B, *5*, pp 347-354, 1987.

11. J. Felts and E. Lopata, J. Vac. Sci. Technol. A, *5*, pp 2273-2275, 1987.

12. T. H. Lin, et al., IEEE Transactions on Plasma Science, *16*, pp 631-637, 1988.

13. I. Stakgold, *Green's Functions and Boundary Value Problems*, New York: John Wiley, 1979, pp 11-13.

14. F. F. Chen, *Introduction to Plasma Physics and Controlled Fusion*, Vol. 1, New York: Plemum Press, 1984, pp 159-169.

15. M. R. Carruth, et al., Rev. Sci. Instrum., *61*, pp 1211-1216, 1990.

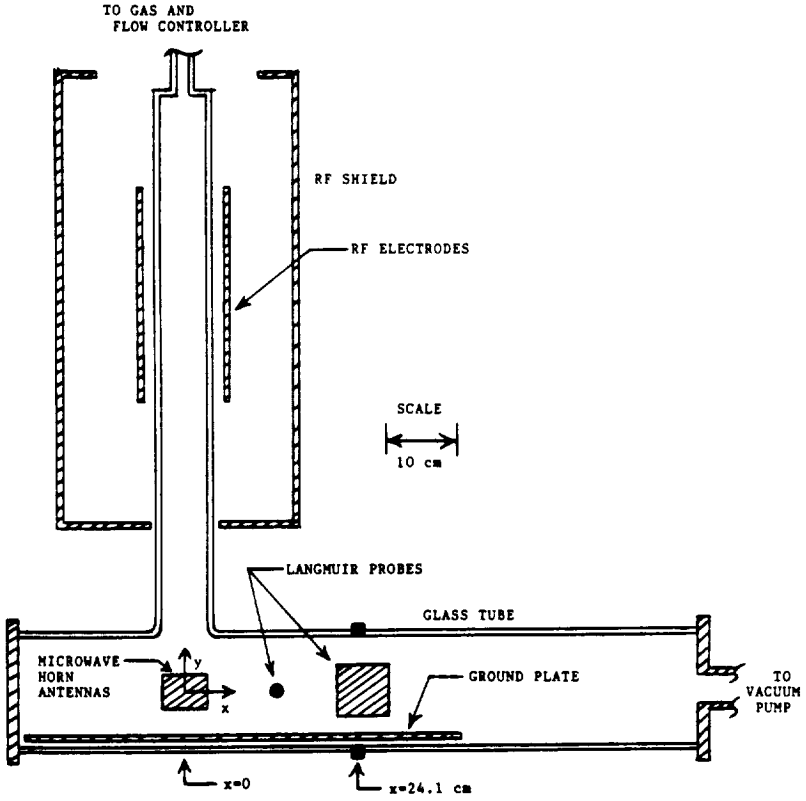

Figure 1. Thermal atomic oxygen source.

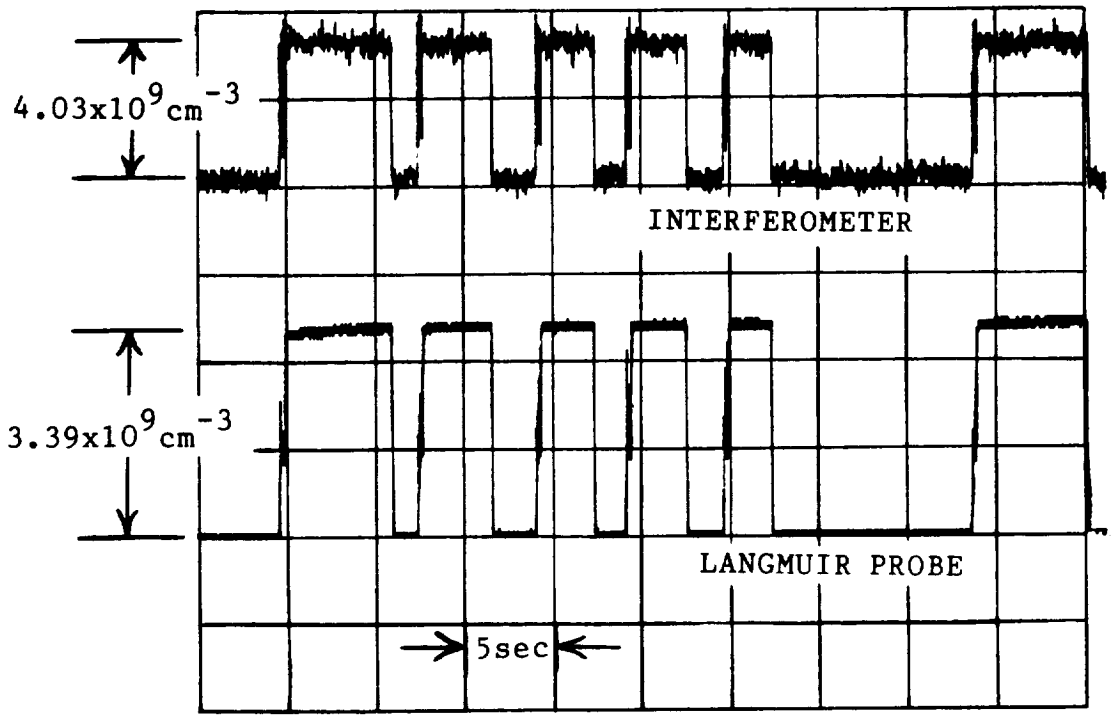

Figure 2. Calibration of Langmuir probe with microwave interferometer.

LANGMUIR PROBE IN OXYGEN

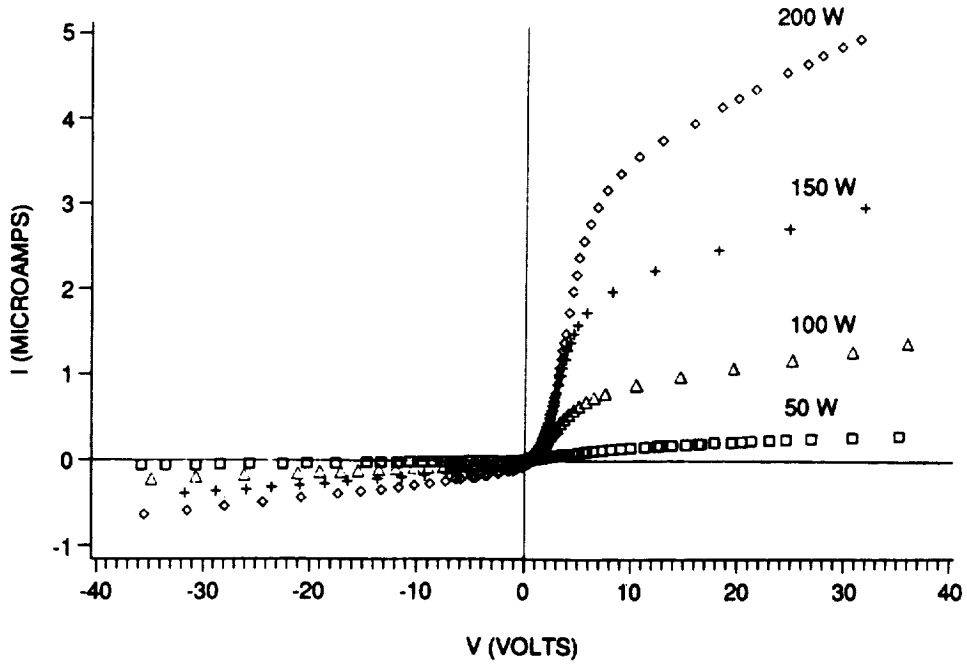

Figure 3. Square Langmuir probe at x=25cm with 100mtorr oxygen.

MEASURED VERSUS ANALYTICAL

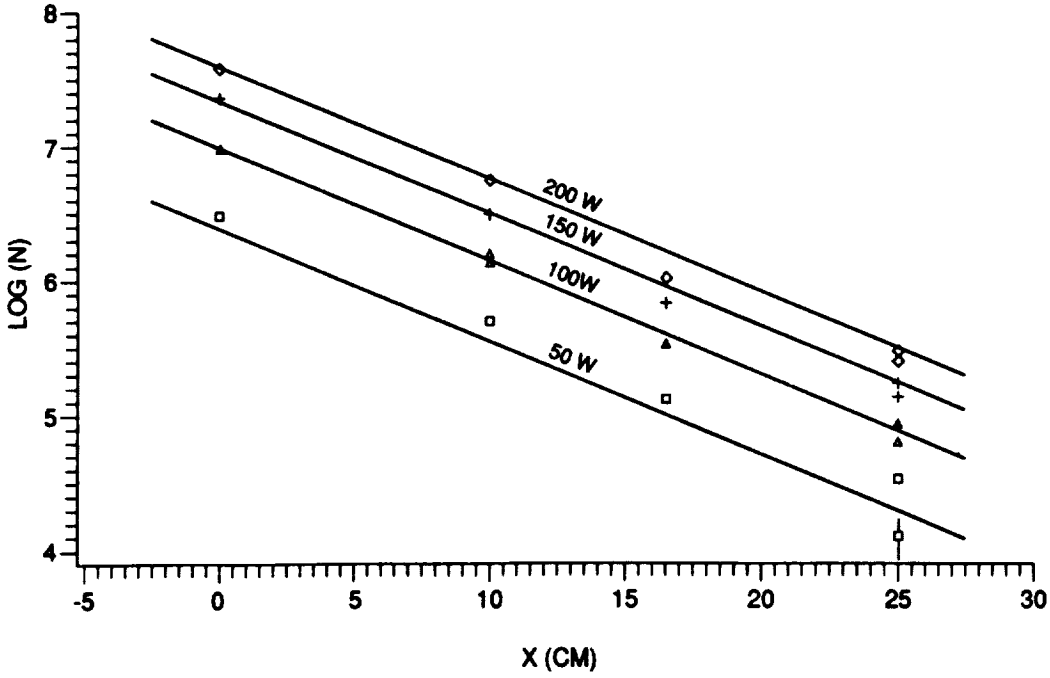

Figure 4. Analytic expression (solid lines) compared to measured data (symbols).

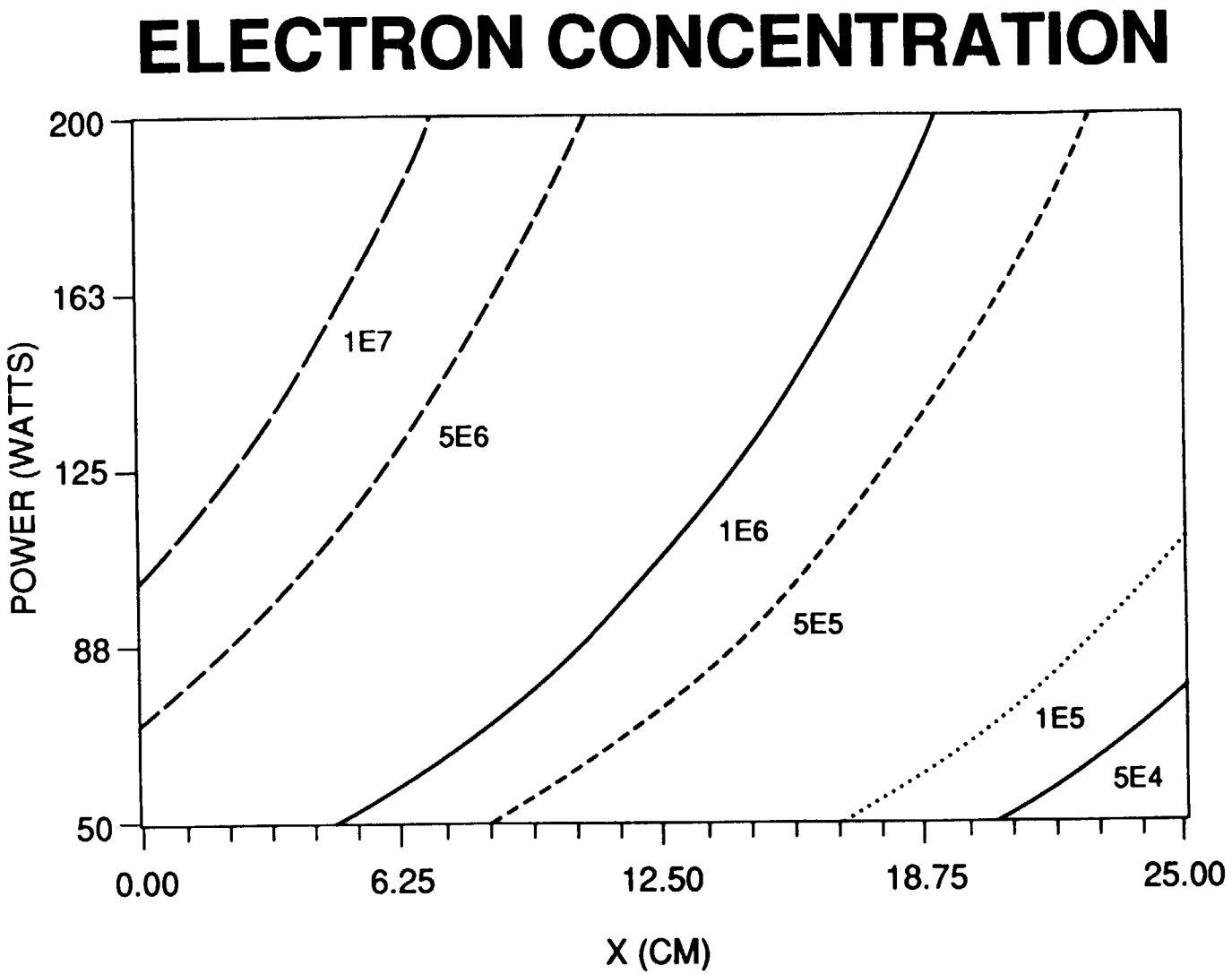

Figure 5. Contours of constant electron concentration in units of cm-3. Oxygen at 100mtorr and 6.7sccm. From Eq. 2.