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**TEMPERATURE MEASUREMENTS IN
NITROGEN AND NITROGEN-OXYGEN PLASMAS**

H. N. Olsen, G. Bedjai, and F. L. Kelly

Plasma Sciences Laboratories, Inc.

October 1970

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FOREWORD

The research reported herein was sponsored by the Arnold Engineering Development Center (AEDC) Air Force Systems Command (AFSC), under Program Element 65701F, Project 4344, Task 434412.

The results of the research were obtained by Plasma Sciences Laboratories, Inc., Tarzana, California, under contract F40600-69-C-0007. The research was performed during the period June 15, 1969 to June 15, 1970, and the manuscript was submitted for publication on July 15, 1970.

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The investigation was conducted under the direction of Dr. H. N. Olsen, serving as Principal Investigator. Mr. G. Bedjai and Mr. F. L. Kelly assisted by performing the experimental work and processing the data as well as with the preparation of the report. The authors wish to acknowledge the help of Mr. D. G. Olsen with the tabulation of data for processing and in the preparation of illustrations for the manuscript.

This technical report has been reviewed and is approved.

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ABSTRACT

Using as a source a dc subsonic plasma jet operating in nitrogen and in nitrogen-oxygen mixtures at atmospheric pressure, emission coefficients of the $N_2(2+)(0,0)$ λ 3371 neutral molecule band, $N_2^+(1-)(0,0)$ λ 3914 ionized molecular band, λ 7468 NI atomic line, and the electron continuum have been measured over the temperature range of 3800 to 10000°K. The emission coefficients of the discrete radiation, calibrated on an absolute scale, were used to calibrate the simultaneously measured electron continuum over the temperature range. Approximate analytical treatments were used to extrapolate the calibrated continuum curves to lower temperatures where discrete radiations can not be observed. The experimental results show considerably higher continuum emission coefficients at low temperature than can be accounted for by any existing theoretical treatments.

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NOMENCLATURE

A_n^m	Transition probabilities - sec^{-1}
B_v	Rotational energy constant - cm^{-1}
c	Velocity of light - cm-sec^{-1}
E_e	Electronic state energy - cm^{-1}
E_r^i	Rotational state energy - cm^{-1}
E_v	Vibrational state energy - cm^{-1}
E	Ionization energy - cm^{-1}
$\bar{g}$	Gaunt factor
g_m, g_-	Statistical weight
J'	Upper state quantum number
K'	Upper state quantum number
K_i	Calibration constant
LS	Large spectrograph
k	Boltzmann's constant - erg-deg^{-1}
m	Mass of electron - gm
N_0	Number density of neutral nitrogen atoms - cm^{-3}
N_2	Number density of neutral nitrogen molecules - cm^{-3}
N_2^+	Number density of ion nitrogen molecules - cm^{-3}
N_e	Number density of electrons - cm^{-3}
N_-	Number density of negative nitrogen ions - cm^{-3}
O_-	Number density of negative oxygen ions - cm^{-3}
P	Rotational P branch components
Q	Rotational Q branch components

Q_a	Absorption cross-section - cm^5
Q_{1D}	Negative ion absorption cross-section - cm^5
q_{vv}	Franck-Condon factor
R_e	Electronic moment $\text{watt}^{\frac{1}{2}}\text{-sec}^{\frac{1}{2}}\text{-cm}^{3/2}$
R	Rotational R branch components
$S_{J'}^i$	Line strength for rotational components
SS	Small spectrograph
T	Temperature - $^{\circ}\text{K}$
U_0	Nitrogen atom partition function
U_2	Nitrogen molecule partition function
U_2^+	Nitrogen molecular ion partition function
x, y, z	Coordinates - cm or inches
Z	Effective nuclear charge
$\alpha_{K'}$	
$\beta_{K'}$	Alternation factors for even and odd K'
γ	Doubling constant - rotational state
ϵ	Emission coefficient - $\text{watt-cm}^{-3}\text{-sr}^{-1}\text{-sec}$
λ	Wavelength - cm

I. INTRODUCTION

The objective of the investigation described in this report was to develop spectral diagnostic methods for pure nitrogen plasmas in the temperature range of 3000°K to 5000°K. This represents a first step in the development of practical tools for rapid spectral diagnostics of supersonic plasma streams such as are employed in Air Force material testing and reentry simulation facilities. Extensions of the methods for applications to air plasmas were initiated toward the end of this program with applications to nitrogen-oxygen mixtures.

In an earlier investigation¹ it was shown that the continuous radiation in seeded nitrogen and air plasmas could be used with the Kramers-Unsold theory for determination of equilibrium temperatures but the same was not found to be true for the unseeded pure gases. The relative simplicity of detectors for spectrally resolved continua and their potential applications in future rapid scanning diagnostic systems emphasized the need for this investigation of the theoretical and experimental relationship between radiation and temperature in equilibrium plasmas.

The general plan of this investigation was to experimentally establish the relationship between the radiation of four different species of particles, i.e. neutral and ionized molecules, atoms and free electrons, in high temperature, atmospheric pressure, pure nitrogen plasmas where absolute calibrations can be made against analytical treatments based on an equilibrium composition of the gas. The calibrated discrete spectra of the atomic and molecular species can then be used to experimentally calibrate the electron continuum against temperature as the level of temperature in the plasma is successively reduced. At lower temperatures, where the discrete radiations blend into the background continuum, the calibration can proceed only by means of an extrapolation based on an analytical description of the temperature

dependence of the continuum established at the higher temperatures through proper combinations of theory and experiment.

The analytical and experimental methods first established on nitrogen plasmas are then applied to nitrogen-oxygen mixtures used to simulate air plasmas. Here the problems of gas mixing and rate processes involving the NO molecule and the NO^+ molecular ion enter the picture requiring more extensive experimentation on pure air plasmas for more complete descriptions.

The apparatus used for producing the controlled laboratory plasmas and for detecting and calibrating the several species of radiation are described in Section II. Section III treats the analytical computations of the normalized emission coefficient for each of the species of radiation considered. In this section the wavelength increments of the molecular band systems are defined as used throughout and corrections of some errors made in an earlier treatment² of these systems have been included. The detailed experimental procedures and results are given in Section IV. In Section V the experimental and theoretical significance of the results are discussed with conclusions and recommendations given in Section VI.

II. APPARATUS

Three different sources were used to produce the nitrogen, nitrogen-oxygen and air plasmas used in this investigation, i.e., a dc plasma jet, a dc free-burning arc and an rf induction torch. The general arrangement of these three sources with respect to the radiation detection and calibration systems is shown schematically in Fig. 1. Detailed descriptions of the apparatus and experimental methods are given in the following sub-sections.

A. PLASMA JET

The plasma jet, developed in an earlier phase of this long range diagnostics program and which is described in detail in Ref. 3, was designed to permit changes in its internal configuration. Two configurations, i.e., high (I) and low (III) temperature, were used in this program to produce temperatures ranging from 3000 to 6000°K and 5000 to 10000°K respectively. The jet head was designed to operate with or without an observation section and quench chamber. In cases where the quench was used the exit gas was first cooled by means of a nested tube heat exchanger before being vented. No attempt was made to determine the quantity of heat transferred to the quench chamber or that which remained in the vented gases. Only the losses in the jet head were determined calorimetrically.

Because of the tungsten cathode only nonreacting gases such as argon or pure nitrogen can be used as the primary gas. A range of temperatures in the plasma can be obtained by controlling the current, gas flow, and position of observation. A very sizeable reduction in the jet temperature can be effected by adding down stream cooling gas through an opening provided in the lower constrictor section. By means of the configuration changes and down stream gas injection, temperatures ranging from 3000°K to 10000°K could be established in 1 atm pressure plasmas in pure nitrogen and nitrogen-oxygen mixtures.

The latter could be obtained by adding oxygen as the down stream gas to a nitrogen plasma. Because of the tungsten cathode pure air could not be run with this jet.

B. FREE-BURNING ARC

The arc burned freely in pure nitrogen at 1.1 atmosphere pressure between a 1/8 inch dia, 1% thoriated tungsten cathode and a plane copper anode in a vacuum tight water cooled chamber. The electrodes were also water cooled and separated by 1/4 inch and the current was adjusted to 210 amp with an operating potential of 29.1 volts. Again, because of the tungsten cathode, only pure nitrogen could be used.

C. RF INDUCTION TORCH

An rf induction torch similar to that described by Olsen, Eckert and Kelly² has been used here to produce equilibrium plasmas in nitrogen and air. The plasma was electromagnetically induced in a swirling stream of gas flowing at a rate of 30 scfh within a 4 inch dia air cooled transparent quartz tube. Typical operation with nitrogen was 60kw plate power at 30 scfh; with air the plate power was 50kw at 25 scfh. The specially designed 100kw power source developed at PSL was used for generating these plasmas.

D. SPECTROGRAPHS

Two plane grating spectrographs have been used throughout this program either individually or in combination as shown in Fig. 1. For high resolution work involving separate quartet or sextet groupings of the nitrogen band systems the 1 meter reflection optics instrument (LS) having a first order dispersion of $8.3 \frac{\text{\AA}}{\text{mm}}$ was used. This instrument was equipped for either photoelectric or photographic readout. Typical photographed spectra are shown in Fig. 2.

To permit simultaneous measurements of two species of radiation the 1/4 meter grating spectrograph (SS) developed as part of the spectral

probe system for seeded plasma diagnostics and described in Ref. 1 was placed in the same optical path as the large instrument by means of a half-silvered mirror as shown in Fig. 1. With a dispersion of $55\text{\AA}/\text{mm}$ only the continuum, well separated spectral lines, or broad increments of the band systems can be recorded with photoelectric readout on this instrument. The optical speed is $f/10.5$ as compared with $f/9$ for the 1 meter spectrograph. The glass optics posed no problem since all radiation detected with the small spectrograph was at wavelengths $\lambda > 3800\text{\AA}$.

Interchangeable entrance and exit slits, and photomultiplier housings were provided for both spectrographs. Blue sensitive 1P28 photomultipliers were used throughout the investigations. Widths of $50\text{ }\mu$ and $500\text{ }\mu$ were used interchangeably as entrance and exit slits. In the exit position the broad slit represents a $28\text{\AA}$ increment of the dispersed spectrum of the small spectrograph at $\lambda 3920\text{\AA}$ and a $3.9\text{\AA}$ increment for the large instrument at the same wavelength.

E. DUAL-SIGNAL RECORDING SYSTEM

In order to eliminate the question of changes in source conditions during the time required to record a full radial profile, the data recording system was designed to permit simultaneous recording of two radial profiles. With this system the radiation from any one of the three sources or from the calibration carbon arc was directed by means of a plane mirror through an aperture and focusing lens and onto a half-silvered mirror which separated the beam into two parts of nearly equal intensity. These two beams were directed to the entrance slits of the two spectrographs as shown on the schematic diagram of Fig. 1.

The amplitude (intensity) signals taken from each of the photomultipliers were fed to separate impedance matching operational amplifiers and then into a chopper circuit. The chopper consisted of a sealed relay driven by a solid state timing circuit with variable on-off time periods. This chopper alternately connected the two intensity signals (y_1 or y_2) to the y input of the x-y recorder while the radial

position signal from the transport table served as the x-axis signal of the recorder. To permit simultaneous recording of signals with large differences in amplitude, the photomultiplier voltages must be independently adjusted. This was accomplished by using a common regulated high voltage supply and separate voltage divider networks as shown in Fig. 3.

The simultaneous recording of two species of radiation from a plasma with two spectrographs and detectors requires that the separate optical systems be in precise alignment. To achieve this an auto-collimating method was used on each of the two spectrographs in common with the half-silvered mirror, the focusing lens, and right-angle mirror. The photomultiplier on each spectrograph was replaced by a tungsten lamp so that an image of the entrance slit, illuminated in monochromatic light, was formed at the point where the source would normally be located. The images of the two spectrograph slits, formed in this manner at different wavelengths in the visible spectrum, were observed with a small instrument telescope and were made to coincide on the cross-hair by rotating, tilting and translating the half-silvered mirror (beam splitter). When optical coincidence was accomplished, the system was in proper alignment as indicated by identical recorded shapes of a common intensity profile. The progressive reduction of slit widths and lengths increased the alignment precision.

The shapes of the continuum and atomic line profiles of the conically shaped, free-burning, argon arc were observed as simultaneous pairs on the x-y recorder by means of the chopping method to demonstrate proper alignment. Figures 4 and 5 show experimental profiles recorded in this manner. The separation of the carbon arc traces corresponds to the difference in spectrograph slit widths. When the peak amplitudes of the two signals are made to be the same by adjusting photomultiplier voltages, and the spectrographs are set at the same wavelengths with equivalent slit widths the result is a single trace of y vs x under chopping conditions as shown for example in Fig. 4. When the two curves have different amplitudes or shapes, the two traces are defined

by the tops and bottoms of the chopping pulses generated by the alternating amplitudes as shown in Fig. 5.

F. ABSOLUTE INTENSITY CALIBRATIONS

Absolute spectral intensities have been measured throughout this investigation by comparison with the positive crater of the low current carbon arc. The intensity versus wavelength for the carbon crater was determined, according to Null and Lozier⁴, for a temperature of 3800°K and emissivity of 98%. The transport table shown in Fig. 1 was designed so that the carbon calibration arc could replace the experimental plasma at the focal position of the same optical system so that on-the-spot calibrations could be made with each measurement.

1952
280 NCC
-98 NBS
1957

o

III. ANALYTICAL METHODS

The quantitative nature of the diagnostic methods employed requires theoretical computations of emission coefficients as a function of temperature for equilibrium nitrogen and nitrogen-oxygen plasmas. Each species of radiation is discussed separately in the sub-sections which follow. The particle number densities and partition functions used in the computations were taken from the unseeded plasma compositions given in Ref. 1 as listed in Table I.

A. $N_2 (2+)(0,0), \lambda 3371 \text{ \AA}, C \text{ } ^3\Pi_u \rightarrow B \text{ } ^3\Pi_g$

The detailed structure of this band is shown in the photographed spectrum of Fig. 2. Because of the triplet nature of the electronic state from which the system arises, there are three subbands, $^3\Pi_0 \rightarrow ^3\Pi_0$, $^3\Pi_1 \rightarrow ^3\Pi_1$, and $^3\Pi_2 \rightarrow ^3\Pi_2$ with a strong R($J' \rightarrow J'-1$), a strong P($J' \rightarrow J'+1$) and a weak Q($J' \rightarrow J'$) branch; the latter may be completely neglected. The two strong branches produce characteristic triplets in the rotational structure which are grouped in sextets as observed in the spectrum of Fig. 2. Throughout this description the J' subscript used to identify a particular sextet is taken as the rotational quantum number of the upper energy level of the R branch component of the third ($^3\Pi_2 \rightarrow ^3\Pi_2$) sublevel. Such a reference was chosen because this component denoted as $R_{J'}^2$ is located nearly in the center of the sextet and its wavelength is taken as the center wavelength, λ_0 , of the sextet. According to this identification system the individual components of the sextet reading toward longer wavelengths are designated $R_{J'+2}^0$, $R_{J'+1}^1$, $R_{J'}^2$, $P_{J'+19}^0$, $P_{J'+18}^1$, $P_{J'+17}^2$. The sextet centered about the wavelength of the $R_{J'}^2$ rotational line will generally be referred to throughout this report as the " $R_{J'}$ component" of the band.

The absolute emission coefficient for any single rotational element of a vibrational band of a given electronic transition can

be expressed as

$$\epsilon_{J'}^i = C \frac{N_2}{U_2} \exp \left[-(E_e + E_v)/kT \right] S_{J'}^i \exp \left[-E_r^i(J')/kT \right] \quad (1)$$

The subscript J' is used to identify either the individual rotational component or a particular grouping of components which are individually identified by the superscript i . The electronic, vibrational, and rotational upper state energies are given by E_e , E_v and $E_r^i(J')$ respectively. The constant is given by

$$C = \frac{16\pi^3 c}{3\lambda^4} R_e^2 q_{vv}$$

where c is the velocity of light, λ the wavelength of the transition, R_e the electronic moment, q_{vv} is the Franck-Condon factor. The $S_{J'}^i$ in Eq. (1) is the relative strength factor for the i^{th} rotational component of the sextet. The number densities N and partition functions U are taken from Table I.

For purposes of computation, the emission coefficient for each component of a sextet is denoted by $\epsilon_{J'}^i$, where $i=1, 2 \dots 6$ for the components in order of increasing wavelengths. The emission coefficient for the total sextet is then

$$\epsilon_{J'} = \sum_{i=1}^6 \epsilon_{J'}^i$$

Using the wave number tabulations of Coster, et. al.⁵ and a mercury reference spectrum, the ϵ_{27} and ϵ_{28} sextets can be easily recognized as surrounding the Hg I $\lambda 3341$ line as shown on Fig. 2 and from this the R_{38} component is identified by counting to the left (shorter wavelengths).

In order to compute the emission coefficients for all components of this band it is first necessary to express the relative line strengths in terms of the upper rotational quantum number of the $R_{J'}^2$ component. From the wave number tabulation of Ref. 5 it is found that upper level quantum numbers of $J'+2$, $J'+1$, J' , $J'+19$, $J'+18$ and $J'+17$ correspond with $i = 1, 2, \dots, 6$ respectively. With these quantum numbers the respective line strengths, according to Budo⁶, which hold for $J' > 10$, are

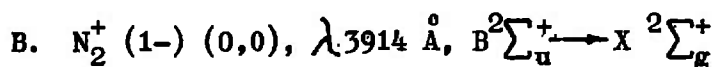
$$\begin{aligned}
 S_{J'}^1 &= \frac{J' (J'+2) (2J'+5)}{(J'+1) (2J'+3)} & S_{J'}^4 &= \frac{(J'+18) (J'+20) (2J'+41)}{(J'+19) (2J'+39)} \\
 S_{J'}^2 &= \frac{(J') (J'+2)^2}{(J'+1)^3} & S_{J'}^5 &= \frac{(J'+18)^2 (J'+20)^2}{(J'+19)^3} \\
 S_{J'}^3 &= \frac{J' (J'+2) (2J'-1)}{(J'+1) (2J'+1)} & S_{J'}^6 &= \frac{(J'+18) (J'+20) (2J'+35)}{(J'+19) (2J'+37)}
 \end{aligned} \quad (2)$$

The corresponding rotational energy levels are

$$\begin{aligned}
 E_r^1 (J') &= B_v (J'+2) (J'+3) & E_r^4 (J') &= B_v (J'+19) (J'+20) \\
 E_r^2 (J') &= B_v (J'+1) (J'+2) & E_r^5 (J') &= B_v (J'+18) (J'+19) \\
 E_r^3 (J') &= B_v (J') (J'+1) & E_r^6 (J') &= B_v (J'+17) (J'+18)
 \end{aligned} \quad (3)$$

where $B_v = B_e - \alpha_e (v + \frac{1}{2})$ with $B_e = 1.8259 \text{ cm}^{-1}$, $\alpha_e = .0197 \text{ cm}^{-1}$, $E_e = 89,147 \text{ cm}^{-1}$ and $E_{v=0} = 1017 \text{ cm}^{-1}$ for the $C^3\Pi$ state.

Since the $R_{e,vv}^2$ factor in the calibration constant for the emission coefficient is generally not known or is to be determined experimentally by comparison of computed and measured emission coefficients at the temperature of the peak value, it is only practical to compute the normalized emission coefficients, $\epsilon_{J'}^{*i}$, according to Eq. (1) with this factor set to unity. Normalized emission coefficients of each component and of the total sextet have been computed earlier (Ref. 2) using partition functions given by Drellishak, et. al.⁷ for pure nitrogen and number densities for air computed by Hilsenrath, et. al.⁸. In the original computations reported in Ref. 2 some errors were made which have been corrected here and the results are presented in Tables IIA and IIB



In the case of $\Sigma \rightarrow \Sigma$ transitions the separation of the two sub-levels with $J' = K' + \frac{1}{2}$ and $J' = K' - \frac{1}{2}$ gives rise to a quartet structure with two R and two P branch components and no Q branch. Because of the small separation of the sublevels the two subbands are not resolved in the spectrum of Fig. 2.

Following the same procedure as above for the neutral molecule band systems, the quartet components are identified by $\epsilon_{K'}^i$, where $i = 1, 2, 3, 4$, correspond with $R_{K'}^1 + \frac{1}{2}$, $R_{K'}^2 - \frac{1}{2}$, $P_{K'}^1 + 27 + \frac{1}{2}$, $P_{K'}^2 + 27 - \frac{1}{2}$. As is conventional for components of $\Sigma \rightarrow \Sigma$ transitions, the K' quantum number is used and is here defined as the upper state rotational quantum number associated with the $R_{K'}^2 - \frac{1}{2}$ component having wavelength λ_0 taken as the center value for the quartet. The emission coefficient for the total quartet is

$$\epsilon_{K'} = \sum_{i=1}^4 \epsilon_{K'}^i.$$

The $H_g \lambda 3906$ I line can be used to identify the R_6 quartet at $\lambda 3905.8 \text{ \AA}$ as shown on Fig. 2.

According to Mulliken⁹ the component line strengths can be written in terms of the K' quantum number of the upper state as

$$\begin{aligned} S_{K'}^1 &= \frac{(2K'+1)^2 - 1}{2(2K'+1)} \alpha_{K'} & S_{K'}^3 &= \frac{(2K'+53)^2 - 1}{2(2K'+53)} \beta_{K'} \\ S_{K'}^2 &= \frac{(2K'-1)^2 - 1}{2(2K'-1)} \alpha_{K'} & S_{K'}^4 &= \frac{(2K'+51)^2 - 1}{2(2K'+51)} \beta_{K'} \end{aligned} \quad (4)$$

$$\text{where } \alpha_{K'} = \begin{cases} 1 & \text{for } K' \text{ odd} \\ \frac{1}{2} & \text{for } K' \text{ even} \end{cases} \quad \beta_{K'} = \begin{cases} \frac{1}{2} & \text{for } K' \text{ odd} \\ 1 & \text{for } K' \text{ even} \end{cases}$$

are the familiar intensity alternation factors which are characteristic of this band system.

The rotational energy levels are expressed in terms of the upper level quantum number K' as

$$\left. \begin{aligned}
 E_r^1(K') &= B_0(K')(K'+1) - D_0(K')^2(K'+1)^2 + \frac{\gamma_{K'}}{2} \\
 E_r^2(K') &= B_0(K')(K'+1) - D_0(K')^2(K'+1)^2 - \frac{\gamma_{K'}}{2} \\
 E_r^3(K') &= B_0(K'+25)(K'+26) - D_0(K'+25)^2(K'+26)^2 + \frac{\gamma_{(K'+25)}}{2} \\
 E_r^4(K') &= B_0(K'+25)(K'+26) - D_0(K'+25)^2(K'+26)^2 - \frac{\gamma_{(K'+25)}}{2}
 \end{aligned} \right\} (5)$$

where $B_0 = 2.07325 \text{ cm}^{-1}$, $D_0 = 5.895 \times 10^{-6} \text{ cm}^{-1}$ and $\gamma = .002 \text{ cm}^{-1}$.

Using Eqs. (4) and (5) in Eq. (1) with $E_e = 25,462 \text{ cm}^{-1}$ and $E_{v=0} = 1204 \text{ cm}^{-1}$ the component and total emission coefficients for K' ranging from 1 to 22 were previously computed and reported in Ref. 2. As was the case of the neutral band system a number of errors were made in the original computations which have been corrected here with the results given in Tables III A and III B. The intensity alternations, which were omitted in the previous computations are clearly seen in these results. These alternations are also observed in the spectrum of Fig. 2. In order to adjust the normalized emission coefficients of Tables II and III to other composition data the required number densities and partition functions of neutral and ionized molecules are given in Table I for both nitrogen and air plasma. For completeness sake the corresponding atom, electron and negative ion number densities are also included.

An observed characteristic of this molecular ion band is the grouping of the first 26 P branch doublets ($P_{K'}^1$ and $P_{K'}^2$ for $25 \geq K' \geq 0$) in the region of the band head where there are no R branch components. This group, which is indicated by the bracketed region labeled $BH\Delta_1$ in Fig. 2 will be referred to throughout this report as the "ion band head increment". The long wavelength edge of the $3.9 \text{ \AA}$ increment ($BH\Delta_1$) is defined by the $\lambda 3914.33$ (P_{14}^1), component and the short wavelength edge falls between the $\lambda 3909.71$ (R_1) and $\lambda 3910.43$ (P_{25}^2) components. In a similar manner a $28 \text{ \AA}$ increment ($BH\Delta_2$) is defined by the P_{14}^1 and the $\lambda 3885.3$ (R_{22}) component and is also indicated in Fig. 2. The actual wavelength interval is $28.5 \text{ \AA}$ but will be referred to throughout as the $28 \text{ \AA}$ increment.

The emission coefficient for the $3.9 \overset{\circ}{\text{\AA}}$ band head increment has been computed as follows

$$\epsilon_{\text{BH}\Delta_1} = C \frac{N_2^+}{U_2^+} \exp\left(-\frac{E_e + E_v}{kT}\right) \sum_{K'=0}^{25} \left\{ \frac{2(K'+1)}{\lambda_{K'}^4} \left[1 - \frac{1}{(2K'+1)(2K'+3)} \right] \beta_{K'} \right. \\ \left. \exp\left[-B_0 K'(K'+1)/kT\right] \right\} \quad (6)$$

where all quantities are as previously defined. The component wavelengths were taken from Ref. 5. Numerical values of this emission coefficient are tabulated in Ref. 1 for air and nitrogen with $R_e^2 q_{vv} = 1.36 \times 10^{-36}$ and $E_v = 0$. These results have been corrected for the zero point energy of the $v = 0$ vibration state which is 1204 cm^{-1} rather than zero as was erroneously assumed. The corrected normalized emission coefficients for the $3.9 \overset{\circ}{\text{\AA}}$ ion band head increment are given in Table IV.

The normalized emission coefficient for the $28 \overset{\circ}{\text{\AA}}$ increment is obtained by adding the $R_{K'}$ components for $K = 1$ through 22 to the P branch components of the $3.9 \overset{\circ}{\text{\AA}}$ increment such that

$$\epsilon_{\text{BH}\Delta_2} = \epsilon_{\text{BH}\Delta_1} + \sum_{K'=1}^{22} \epsilon_{K'}^R \quad (7)$$

The normalized emission coefficients for the $28 \overset{\circ}{\text{\AA}}$ increment are also listed in Table IV. For purposes of internal consistency in this report all emission coefficients are referred to the number densities given in Table I..

C. ATOMIC LINE, $\lambda 7468 \text{ NI}$

This discrete spectral line represents transitions between the $3p \ ^4S^{\circ}$ upper and the $3s \ ^4P$ lower energy levels of the neutral nitrogen atom. Emission coefficients were computed using the number densities and partition functions of Table I and the following equation:

$$\epsilon_{7468} = C \frac{N_0}{U_0} \exp(-E_m/kT) \quad (8)$$

with

$$C = \frac{hcg_m A_n^m}{\lambda^4 \pi}$$

where h is Planck's constant, g_m the statistical weight and A_n^m the spontaneous transition probability for the line of wavelength λ and upper energy level E_m . The particle number density N_0 and partition function U_0 are for the neutral atom. The normalized emission coefficients, computed for $A_n^m = 1$, are given in Table IV. The normal temperature for the 1 atm nitrogen plasma is 15,000°K. Just as with the band systems the transition probability can be determined experimentally by comparing the measured peak value for the emission coefficient emitted by an equilibrium source with the peak of the normalized coefficient; such a determination is discussed in the next section.

D. CONTINUUM

The source of continuous radiation emitted by a diatomic gas plasma is the free electrons which are retarded by electrostatic interactions with ionized atoms, ionized molecules and screened neutral atom or molecule nuclei (free-free transitions) or which recombine with atomic or molecular ions to form neutrals and attach to neutral atoms to form negative ions (free-bound transitions). Radiative recombinations of atoms can give rise to a molecular continuous emission; however, because of the extremely low probability of such a process relative to non-radiative three body recombinations, this source of continuum may be completely neglected in the 1 atm plasmas treated here. Molecular formation by radiative two-body recombination with two atoms approaching on the potential curve of the ground state is not possible for two like molecules and can be neglected entirely here.

The analytical treatment of the electron continuum is very dependent upon the temperature range under consideration. For example, Morris, et. al.¹⁰ have shown that for nitrogen at 1 atm the free-free

and free-bound radiation of positive ions reacting with electrons can explain the entire observed continuum at temperatures above 15,000°K. At lower temperatures neutral atom-electron interactions become significant. In Ref. 10 it has been shown that for temperatures in the range 8000 to 10000°K in atmospheric pressure nitrogen the observed continuum results almost entirely from free-bound radiation of the negative nitrogen ion formed by electron attachment with neutral atoms. At temperatures below 5000°K where the number of neutral atoms and ionized molecules is low relative to the number of neutral molecules, the main contribution to the continuum is assumed to be the free-free radiation of free electrons interacting with neutral molecules.

Very little quantitative work has been reported on the continuum emitted by nitrogen or air plasmas at temperatures below 8000°K. The absence of reliable quantitative data on radiation cross-sections for the species of radiation involved makes it difficult to analytically describe the continuum at low temperatures. In the following descriptions the best approximate values available in the literature are used to compare at least the relative contributions to the total (spectrally resolved) continuum at equilibrium temperatures below 10,000°K.

In this investigation, where the aim has been to determine equilibrium temperatures from measured emission coefficients in the range of 3000°K to 10,000°K, analytical expressions for the significant sources of continua are used only as guides in extrapolating the measured continuum versus temperature curve below the lower temperature limit of the experimental calibration. In this temperature range only three sources of continua need be considered, i.e., free-free radiation of electrons retarded by positive ions and neutral molecules, free-bound radiation of electrons recombining with positive ions, and free-bound radiation of electrons attaching to neutral atoms. According to Ref. 10, free-free radiation resulting from the retardation of electrons by neutral atoms is assumed to be negligible in comparison with the free-bound radiation produced by the attachment process. With these assumptions

the relative contributions to the continuum at a given wavelength have been computed according to the following expression:

$$\epsilon_{\text{cont.}} = 5.4 \times 10^{-46} Z^2 \bar{g} N_e^2 / T^{\frac{1}{2}} + 4 \times 10^{23} \exp(-C_2/\lambda_T) / \lambda^3$$

$$\times \left[Q_{1D} N_- + \frac{Q_a N_2 N_e}{\lambda^2} \right] \text{ (watt-cm}^{-3}\text{-sr}^{-1}\text{-sec)} \quad (9)$$

where Z = effective nuclear charge

$\bar{g}$ = gaunt factor

$C_2 = 1.4388 \text{ (cm}^{-1}\text{K)}$

λ = wavelength (cm)

Q_{1D} = cross-section for recombination into $1D$ state of the negative ion, (cm^5)

N_{-1D} = number density (cm^{-3}) of negative nitrogen ions in $1D$ level

N_e = electron number density (cm^{-3})

N_2 = neutral molecule number density (cm^{-3})

Q_a = radiation absorption cross-section for neutral molecules (cm^5).

Bolt¹¹ has shown that the negative ion number densities can be computed according to the Saha and Boltzmann equations combined in the form

$$\frac{N_o N_e}{N_-} = 2 (2\pi m k T)^{3/2} \frac{U_o(T)}{g_-} \exp \left[(E_{1D} - E_\infty) / kT \right] \quad (10)$$

where $U_o(T)$ = partition function of atom

g_- = statistical weight of $1D$ state of N_- taken as 5

E_{1D} = energy of $1D$ state which is 19223 cm^{-1}

E_∞ = ionization energy which is cm^{-1}

and all other quantities have their usual meanings. In Eq. (10) the number densities of atoms and electrons can be taken from plasma compositions computed without consideration of the N_- ion

such as those given in Table I. The $N_{\text{—}}$ number densities given in Table I were determined in this manner. Using these number densities with $Z_{\text{g}}^2 = 1.0$, $Q_{1D} = 1.69 \times 10^{16}$ (Ref. 10) and $Q_a = 10^{40}$ (Ref. 12) the temperature dependence of the continuum shown in Fig. 6 was computed according to Eq. (9). In the case of air the $O_{\text{—}}$ number densities were taken from Ref. 8 and the equivalent absorption cross-section $Q_{1D} = 6.96 \times 10^{18}$ was taken from Ref. 10. Because of the exponential dependence of the continuum emission coefficient on temperature below 5000°K, errors in temperature determinations resulting from the assumption of approximately constant cross-sections should be negligible.

E. INVERSION METHODS

All experimentally measured spectral intensities were numerically inverted to emission coefficients by means of the Nestor-Olsen¹³ method for optically thin plasmas. In the case of the atomic spectral line of nitrogen measured in the high temperature range the inversion was made with absorption corrections using the iterative method recently developed for the Air Force and preliminarily reported in Ref. 14.

IV. EXPERIMENTAL PROCEDURE AND RESULTS

The general experimental procedure consisted of three phases which are described below in order of their execution. In the first phase the several forms of discrete radiation were calibrated for use in the following two phases for temperature measurement and ultimately for calibration of the continuous radiation emitted from pure nitrogen and nitrogen-oxygen plasmas respectively. Operating conditions for the two arc jet configurations are given in Table V for all reported results which are generally presented in the graphical form of radial profiles of either emission coefficients or temperature. All measured radiation intensities have been converted to emission coefficients by means of the inversion processes mentioned above. Only the inverted data are reported. Since many profiles are presented to represent original data, sometimes without specific descriptions or discussion in the text, an identifying number is placed on each illustration to correspond with the data description in Table V.

A. CALIBRATION OF DISCRETE EMISSION COEFFICIENTS

The emission coefficient for any species of radiation designated by the subscript i may be expressed in the general form

$$\epsilon_i = K_i \epsilon_i^* (N_i, U_i, T)$$

where K_i is the transition probability for the atomic spectral line or the $R_e^2 q$ factor for the band systems. The function $\epsilon_i^* (N_i, U_i, T)$ is the normalized emission coefficient described in detail in Section III for all species of discrete radiation considered. As was shown, this function passes through a unique maximum at the "normal" temperature so that the constant K_i can be determined from the ratio of the measured off-axis peak or "normal" value of the radial profile of the emission coefficient to the computed "normal" value for an LTE plasma. In the case of the electron continuum, where ϵ_i has a much more complex form which changes with temperature, this same approach

to the calibration could not be taken. The continuum calibration will be discussed separately below.

Radial profiles of the four different component groupings of the photographed spectrum of Fig. 2 are shown in Fig. 7 as measured in the high temperature nitrogen arc jet where the normal temperature was reached. In the case of the R_{16} and R_{22} components, whose normal temperatures exceed 9000°K, the on-axis values were used since there was an observed tendency for flattening of the profile with no further increase in magnitude of the axis values with increased power input or reduced gas flow rate indicating that the normal temperature was just reached on the plasma axis. For each integrated intensity measured on the large spectrograph (LS) a reference measurement was made, simultaneously, on the small spectrograph (SS) using the $3.9 \text{ \AA}$ increment at the head of the 3914 band ($\epsilon_{BH\Delta_1}$). Corresponding pairs of curves were also obtained with the $\lambda 7468 \text{ NI}$ line as reference.

The calibration constants given in the table below were obtained from the ratio of the measured to the computed "normal" values for each of the five species of radiation. Absolute calibration curves can be obtained from the data of Tables I, II and III by direct multiplication with these calibration constants.

Species (i)	λ_o^{**} ($\text{\AA}$)	Normal Temp. (°K)	ϵ_i^* $\text{cm}^{-6} \text{-sr}^{-1} \text{-sec}^{-1}$	K_i watt-sec-cm^3
BH $1-3.9 \text{ \AA}$	3912.4	8800	4.23×10^{33}	1.19×10^{36}
BH $2-28 \text{ \AA}$	3900.3	9000	7.16×10^{34}	3.0×10^{37}
R_6 Quartet	3905.8	9000	3.13×10^{33}	2.56×10
R_{16} Quartet	3894.7	9160	3.80×10^{33}	7.45×10^{37}
R_{22} Quartet	3885.8	9240	3.97×10^{33}	1.82×10^{37}
R_{38} Sextet	3322.9	8300	9.09×10^{32}	1.63×10^{37}
			$\text{watt-cm}^{-3} \text{-sr}^{-1} \text{-sec}$	sec^{-1}
Atomic Line	7468.3	15000	1.86×10^7	1.72×10^7

** Center wavelength

Because of the predominant increase in interfering band and line radiation which accompanies an increase in width of the wavelength increment of the band at high temperatures (see Fig. 2), determination of the $R_e^2 q$ factor for the $28 \text{ \AA}$ ($BH\Delta_2$) increment could not be accomplished at the normal temperature by comparing measured and computed off-axis peaks of the emission coefficient as in the case of the $3.9 \text{ \AA}$ increment. It was found more practical to use the previously calibrated $3.9 \text{ \AA}$ increment to calibrate the $28 \text{ \AA}$ increment at lower temperatures. The dual recording system was used for simultaneous recording of intensities of the two band increments in a common volume of the plasma. Using a common pair of measured radial distributions the calibrated emission coefficient of the $3.9 \text{ \AA}$ increment was used to determine the temperature of the common volume element and the absolute value of the corresponding $28 \text{ \AA}$ increment emission coefficient was then compared with its normalized value to yield the best average $R_e^2 q$ factor given in the table above. The experimental data used in this calibration are from runs 49 through 59 of Table V.

In order to obtain an independent calibration for the $\lambda 7468 \text{ NI}$ line the free-burning nitrogen arc was used since its axis temperature exceeds the normal temperature for the line. Radial profiles of the emission coefficient measured in the mid-plane with electrodes separated 0.3 inch are shown in Fig. 8 for both the absorption corrected and uncorrected case. The absorption inversion computer program described in Ref. 14 was used for the correction. The transition probabilities (calibration factor) obtained with and without absorption correction are $1.72 \times 10^7 \text{ sec}^{-1}$ and $1.39 \times 10^7 \text{ sec}^{-1}$ respectively which are to be compared with $1.61 \times 10^7 \text{ sec}^{-1}$ published by the NBS.

B. NITROGEN PLASMA JET TEMPERATURES

The photographed spectra of Fig. 2 show that, of all of the resolved quartet groups, the R_{22} component is the best choice for temperature measurements since it is free from interference at all temperatures. The same is true for the $3.9 \text{ \AA}$ band head increment which also has the advantage of a good clear portion of the continuum background (not observable in Fig. 2) immediately adjacent to it. The close spacing of the

components in the region of R_6 and the interfering spectral line near R_{16} make it difficult to obtain accurate intensity measurements of these two components with proper background corrections. The observed higher value of K_1 for the R_{16} component given in the table above clearly shows the effect of this line interference. Typical experimental results for all species under differing operating conditions are given in Figs. 9 through 13. The results of such measurements for all of the species mentioned above are shown in Figs. 14 and 15. These results show very good agreement for the $\lambda 3914$ R_6 component, $BH\Delta_1$, $\lambda 3371$ R_{38} component, and the $\lambda 7468$ atomic line. The consistently lower temperatures obtained from the R_{16} component result from the interference as is also the case for the R_{38} component at high temperatures. The erroneously high temperatures obtained from the continuum result from the application of the Kramers-Unsöld theory for ion-electron interaction only with $Z^2\bar{g} = 1$ which has been found to give theoretical values for the emission coefficient which are considerably lower than measured values; the difference increases sharply with temperature reduction.

These experimental results show that the $\lambda 3914$ $BH\Delta_1$ and $\lambda 7468$ atomic line constitute the best detectors for high temperature plasmas. To further demonstrate the consistency of this spectroscopic method for temperature measurements the R_{22} component of the $\lambda 3914$ band and the R_{38} component of the $\lambda 3371$ band have been measured in combination with the $(BH\Delta_1)$. Figures 16 and 17 show radial temperatures down to 4800°K. Similar data for the R_{38} component are given in Fig. 18. The level of temperature was changed by down stream gas dilution. Note that as the enthalpy is reduced by the dilution it is essentially the center temperature which is reduced. The dilution needed to drop the temperature level corresponding with the lower limit of the radiation detector is less for the weaker R_{38} component of the neutral band system than for the R_{22} component of the ion band system. The excellent agreement of the temperatures obtained from data of the two systems when compared with the common ion band head increment is strong evidence for local thermal equilibrium in nitrogen plasmas down to temperatures as low as 4800°K.

The measurement of temperatures has also been extended to lower levels while using the $\lambda 7468$ atom line. Comparisons of the results with those obtained from the $\lambda 3914$ $\text{BH}\Delta_1$ increment ($3.9 \text{ \AA}$) are given in Fig. 19. The fact that the atomic line consistently gives higher temperatures is an indication that either or both species were not properly calibrated. It was for this reason that the transition probability for the atomic line was checked with the free-burning arc as discussed above. The observed agreement of the measured transition probability with published values would tend to indicate that the $R_e^2 q$ factor for the band system may still be in question. Since the measurement of temperatures using the band head increment at lower levels is not very sensitive to the adjustment of the $R_e^2 q$ factor required to bring these results into agreement and, in addition, the $\lambda 7468$ line is a very poor diagnostic probe for temperatures below 6000°K , improvements in this absolute calibration were not pursued further.

Increasing the band head increment to $28 \text{ \AA}$ ($\text{BH}\Delta_2$) gave a higher signal-to-noise-ratio and thus smoother intensity traces at lower levels of temperature. Because of the discriminatory increase in background continuum with the wider slit, the lower temperature limit of applicability was not adjusted downward appreciably in comparison with that obtained with the $3.9 \text{ \AA}$ ($\text{BH}\Delta_1$) increment. Application of the broad increment was further limited by the fact that when attempting to apply it to a portion of the $\lambda 3371$ band system it was not possible to find an adjacent region of the continuum that is free from interference from other discrete radiations over a sufficiently large interval to permit proper correction for the background.

The optical system used to this point in the investigation was designed to give spatial resolution in the source by using a narrow entrance slit (50μ) and a magnifying optical system (5X). With this system some trade-off between resolution and signal to noise ratio was provided by a choice of entrance slit lengths ranging from 0.02 in. to 0.16 in.; high resolution was obtained at the expense of radiation sensitivity. Extension of measurements to lower temperatures and,

consequently, lower intensities required this trade-off between spatial resolution and light-gathering power of the total spectral detection system.

The optical system, external to the spectrograph, was modified by moving the focusing lens to its conjugate point thus producing a 4 to 1 reduced image of the source of the entrance slit. The two optical systems are identified in Table V by either a +5 or -4 magnification. The best results were obtained with a compromise solution which sacrificed resolution equally in two dimensions by using an entrance slit with identical length and width dimensions of 0.02 in. in combination with the reduced image of the source. The results of temperature measurements using this modified optical system and the $3.9 \text{ \AA}$ ($\text{BH}\Delta_1$) increment of the ion molecular band are shown for Run #81 in Fig. 22a where the lower limit for temperature measurement has been extended to 3700°K. The PSL instrumentation previously used at AEDC consisting of a small $\frac{1}{4}$ meter spectrograph in combination with an attached lens mounted on a transport table to constitute a spectral probe, was used in the same manner as the modified optical system to determine the lower temperature limitation for such a probing system. The results given in Fig. 22b show a lower temperature limit of 3825°K for this system.

The sacrifice of spatial resolution discussed above is not as serious as it might first appear. It should be noted that the plasmas investigated at PSL have diameters ranging from 0.25 in. to 0.50 in. whereas practical testing devices used by the Air Force are in the range of 1 to 2 in. dia and have considerably longer flames. The sacrifice of spatial resolution for increased sensitivity does not, therefore, appear to lead to serious limitations of these diagnostic methods in practical applications.

As has been previously reported^{1,3} the intensity level of the continuum is considerably higher than that computed on the basis of the Kramers-Unsöld theory for ions and electrons alone. While investigating nitrogen plasmas at successively lower temperatures it was found that the corresponding emission coefficients dropped much faster

for the $3.9 \text{ \AA}$ ($\text{BH}\Delta_1$) increment of the λ_{3914} band than for the background continuum. Even though attempts could be made to develop more sensitive detectors for this species of radiation, a lower limit would ultimately be reached where the desired signal would blend in with the background continuum. Beyond this level no further improvement in the detector sensitivity would be useful. Such a limit has been experimentally determined by observing the point at which the band $3.9 \text{ \AA}$ ($\text{BH}\Delta_1$) increment of the λ_{3914} band merges into the background radiation. This occurs at 3700°K for the one atmosphere nitrogen plasma.

C. EXPERIMENTAL CALIBRATION OF NITROGEN CONTINUUM

At the lower levels of temperature of a one atmosphere pure nitrogen plasma, where no discrete radiation can be detected for the band systems, there remains a very measureable continuous radiation. The earlier choice of discrete radiation for temperature measurements was made because experimental results could be compared directly with theory for calibration. This is not the case for the continuum. At best, as discussed in Section III, the theory can only be used as a guide for extrapolation, to lower temperatures, of the experimentally measured emission coefficients plotted against the temperature determined from the band head increment at higher temperatures where the two species of radiation can be simultaneously measured.

To obtain a calibrated spectral probe which can cover a wide range of temperature it was necessary to look not only at plasmas of various average temperatures but to look also at different positions in the plasmas. Average gas temperatures were determined from heat balances at the exit of the flame. Table V gives the pertinent data on the various plasmas investigated where Z represents the distance from the exit of the jet. The experimental data points of Figs. 23 and 24 were obtained with the same entrance slit width (0.02 in.) but with different slit lengths and different exit slit widths. Both figures include data obtained at two wavelengths, i.e., λ_{5600} and $\lambda_{3920} \text{ \AA}$. The observed wide spread is due mainly to the recognized fact that at longer wavelengths the continuum has a higher emission coefficient yet no

attempt has been made to compensate for this fact in these composite plots. Also a clear indication of impurity radiation in the $\lambda 5600 \text{ \AA}$ region was observed for the jet and might account for some of the spread of data. Temperatures were determined from emission coefficients of $\text{BH}\Delta_1$ or $\text{BH}\Delta_2$ measured simultaneously with the large spectrograph. The temperature profile of Fig. 22C was obtained from the emission coefficient of the $28 \text{ \AA}$ increment of the $\lambda 3920$ continuum by comparison with the extrapolated (solid) curve of Fig. 23. The source of this curve is discussed in detail in Section V.

D. EXPERIMENTAL CALIBRATION OF NITROGEN-OXYGEN CONTINUUM

This laboratory is equipped to experiment with air plasmas only in the form of nitrogen-oxygen mixtures because the arc jet in operation employs a thoriated tungsten cathode which must be protected from any oxidizing atmosphere. The oxygen was introduced downstream of the cathode region of the nitrogen plasma yet upstream of the point of arc attachment to the anode. Air plasma simulation was obtained by selecting a mixture of 20.9% oxygen by volume indicated on flowmeters at room temperature.

Table V summarizes the experimental conditions in the series of tests involved in this investigation where arc jet III was used mainly. The mixture flow rates were limited to two levels, i.e. 111 scfh and 141 scfh. The selection of different temperature profiles was achieved by probing at different distances from the jet exit (Z). The entrance slit used was 0.02 in. x 0.02 in. with either spectrograph. The exit slits were selected to adapt to the species of radiation considered. The R_{38} component of the neutral band system ($\lambda 3371$), $3.9 \text{ \AA}$ ($\text{BH}\Delta_1$) and $28 \text{ \AA}$ ($\text{BH}\Delta_2$) increments of the ionized band system ($\lambda 3914$), and the $\lambda 7468$ atomic nitrogen line were the three species used.

Profiles of the emission coefficient for the plasma flame at different distances from the jet axis for two different flow rates are shown in Figs. 25 and 26. Temperatures determined from the latter

set are shown in Fig. 27. The corresponding λ_{3914} band increment or atomic line has been used to determine the temperature profile of the jet in the range where these species emit and just above the level where the radiation disappears into the background continuum. For the band head this occurs at 4500°K and for the atomic line at 5000°K. These temperature profiles obtained with the R_{38} component of the neutral band and the $3.9 \text{ \AA}$ ($BH\Delta_1$) increment of the molecular ion band measured at the same position in the simulated air plasma are shown in Fig. 29. It is to be noted that all of the species investigated give the same temperature profile in the temperature range covered.

In a manner similar to that described above for pure nitrogen plasmas, both the $3.9 \text{ \AA}$ ($BH\Delta_1$) and $28 \text{ \AA}$ ($BH\Delta_2$) increment of the ion band system have been used to calibrate the continuum which is the only radiation detectable below 4500°K. Calibration curves for the continuum obtained by comparison with the $3.9 \text{ \AA}$ wavelength increment at $\lambda_{3920} \text{ \AA}$ for 111 scfh and 141 SCFH are shown in Figs. 30 and 31 respectively. Here, as in the case of nitrogen, the temperature was determined from the simultaneously measured $\lambda_{3914} BH\Delta_1$ emission coefficient using the large spectrograph. The temperature scale of Fig. 30 was established by referring the measured $BH\Delta_1$ emission coefficient to the temperature profile computed for the equilibrium air plasma. The temperature scale of Fig. 31 was established by reference to the temperature profile of $BH\Delta_1$ computed for a 79%-21% mixture of equilibrium nitrogen and oxygen plasmas. This is discussed further in Section V.

An rf plasma was used to investigate the air plasma in an effort to observe any possible effects of gas mixing. Stable plasmas were induced in both air and nitrogen at plate power inputs ranging from 50kw to 100 kw and in a 4 in. dia, air cooled, transparent quartz tube with swirl gas flow ranging from 30 to 50 scfh. The optical system reduced the image of the source at the spectrograph slit to one seventh of its actual size. A pre-calibrated tungsten lamp was used as a radiation standard.

Because of strong rf interference with the X-position and intensity signals, graphic recording of radial intensity profiles was

difficult. This interference was minimized by zeroing out the rf background signal. The $3.9 \text{ \AA} (\text{BH} \Delta_1)$ increment of the λ_{3914} band and the λ_{7468} atomic line measured on the large spectrograph were both used in conjunction with separate traces of their respective continua in the air and nitrogen rf plasmas. Figure 32 gives the emission coefficient (ϵ) profiles and Fig. 33 the temperature profiles for these experiments. Figure 34 shows the experimental calibration curves for ϵ versus T for the corresponding continuum, using for reference the temperatures measured with both the band head increment and the atomic line.

Considering the difficulty encountered with intensity recording in the presence of rf interference these results look satisfactory. The temperature given by the atomic line looks higher because no correction has been made for self-absorption in the large diameter plasma. This effort was not pursued further because it was obvious that the range of temperatures encountered was too high to permit any definite selections of the calibration curves for nitrogen-oxygen mixtures.

V. DISCUSSION

The forms of empirical curves that have been fit to measured temperature profiles for the electron continuum (see Fig. 23) can best be understood by referring to the type of log-log plot of Fig. 35. On such a plot any simultaneous measurement of the two emission coefficients in a given volume of plasma uniquely defines an experimental point. In this way data from any plasma at the same pressure can be compared. For example the data points indicated by (x) were obtained from the high temperature jet (I) and those by (o) from the low temperature jet (III). The analytical equilibrium characteristic curve, shown in Fig. 35 for comparison, was obtained by plotting the computed emission coefficient of the total continuum of Fig. 6 as ordinate against that of the $BH\Delta_1$ increment of the molecular ion band (taken from Table IV after correction with the experimentally determined calibration constant) as abscissa with temperature as parameter.

The data presentation of Fig. 35 vividly shows the existing discrepancy between theory and experiment for the electron continuum in nitrogen. This discrepancy can be interpreted in terms of either or both of the species of radiation. Since the ion band increment has been shown to give temperatures which are in excellent agreement with those obtained from both the neutral band and the atomic line, it is not conceivable that such a large discrepancy can be interpreted by an error in relating the analytical data to temperature determined from $BH\Delta_1$. It is, therefore, assumed that the total electron continuum calculated from nitrogen has not been properly related to temperature. As the dashed curve shows, an increase of the neutral molecule absorption cross-section by nearly six orders of magnitude would be needed to bring the data into agreement at 4000°K but would still not yield a slope which fits the experimental points. It has been found, however, that an empirical curve $\epsilon = kN_2N_e$ fits very well in the low temperature range and can be used to extrapolate the

experimental calibration curve for the continuum to lower temperature where the discrete radiation is completely masked by the continuum as a background. The horizontal and vertical dashed lines are drawn in Fig. 35 to denote the temperature level of $\sim 4000^\circ\text{K}$ below which the continuum becomes equal to or stronger than the band radiation. The solid curves of Figs. 23 and 24 show the low temperature extrapolation of this empirical 1 atm nitrogen curve.

Attempts to fit three different sources of the continuum in an air plasma to the experimental data of Fig. 30 obtained from a nitrogen-oxygen mixture were not successful as in the case of the nitrogen plasma. The observed similarity in shape of the nitrogen empirical curve (shown for comparison in Fig. 30) with the data for a nitrogen-oxygen mixture leads one to suspect that the relatively slow



reaction which accounts for the considerably higher electron density and consequently a strong O_2 continuum is not complete in the mixed plasma jet because of insufficient residence time or incomplete mixing of the added oxygen. The absence of NO was practically observed by the conspicuous lack of the characteristic odor during extended periods of operation of the nitrogen-oxygen jet without the quench chamber. Since the absence of this reaction in the nitrogen-oxygen mixture would cause the number densities of electrons and neutral molecules to be lower and the number density of ionized molecules to be higher than in an equilibrium air plasma, the experimental data points of Fig. 30 would tend to be shifted to lower temperatures and the empirical curve $\epsilon = 2.2 \times 10^{-48} \text{N}_2 \text{N}_e$ shifted to lower intensities.

To test the hypothesis that the NO reaction has not been completed in the nitrogen-oxygen plasmas investigated, the temperature dependence of the emission coefficients $\epsilon = k\text{N}_2\text{N}_e$ and $\text{BH}\Delta_1$ have been computed from number densities taken as 79% of those for an equilibrium nitrogen plasma and 21% of those for an equilibrium oxygen plasma. The particles in a given volume element resulting from the two independent plasmas are

then assumed to be thoroughly mixed. The experimental data points of Fig. 31 have been plotted against temperatures obtained from the $BH\Delta_1$ increment for this hypothetical mixture. The solid curve has also been computed for the hypothetical mixture assuming the same proportionality constant as determined for the nitrogen plasma. The observed agreement seems almost fortuitous; more experimental and theoretical work is needed to confirm this hypothesis than was possible within the scope of this investigation.

In the same manner as was done for the nitrogen plasma, the original data from which the plot of Fig. 31 was made have been compared in Fig. 36 with the equilibrium characteristic curve for air at 1 atm. These results are rather startling and, in fact, somewhat disturbing when compared with the similar comparison (Fig. 35) for nitrogen. One's first interpretation is that the contribution to the air continuum by recombination to form the O_2 ion accounts for raising the computed continuum into much better agreement with experimental results; this is in direct contradiction with the observations made above. Alternatively, it might be argued that the enhancement of the experimental continuum for the nitrogen plasma results from an impurity of oxygen. This has, however, been completely ruled out by the observed fact that the same experimental results have been obtained from the nitrogen plasma exhausting directly into room air or into a nitrogen filled quench chamber. Furthermore, the agreement of the shape of the experimental curve of Fig. 31 with the empirical curve for the hypothetical plasma and the significant disagreement with the equilibrium air curve lends strong support to the hypothesis of the mixed nitrogen and oxygen plasmas.

In order to resolve the problems raised by this investigation on "air" plasmas it would be necessary to operate on "pure" air plasmas such as are in operation in the Air Force Research and Development Laboratories. It should be noted that, despite the extensive use of air plasmas for material testing the only quantitative work on the emitted continuum has been carried out on rf plasmas or shock tubes^{15,16} at temperature above 6500°K where agreement with the theory is relatively good. Infrared measurements made by Taylor¹⁶ on shocks in

nitrogen and air at wavelengths greater than 2μ are found to be of the same order of magnitude as the results of this work in the UV. From the computed wavelength dependence of the Bremsstrahlung for both nitrogen and air¹² this should be expected. In the case of nitrogen the experimental results reported here are in agreement with Morris, et al.¹⁰ at the 9000°K point. Lower temperatures were not reported in the reference because of claimed deviations from equilibrium. Hammerling, Tear and Kivel¹⁵ have shown that in shock tubes the N_2^+ radiation overshoots its equilibrium value during relaxation due to coupled vibration dissociation. This effect can be neglected here since the relaxation time is of the order of 1μ sec and, more significantly, the effect would be to shift the calibration curves for the continuum in the opposite direction of that observed here.

VI. CONCLUSIONS AND RECOMMENDATIONS

It can be concluded from the results of this investigation that, at least in the case of nitrogen, the measured continuum below 5000°K at atmospheric pressure is proportional to the product of the number densities of neutral molecules and electrons yet considerably greater than that given by the theory for the electron continuum emitted by an equilibrium plasma. The extrapolated calibration curve given in Fig. 37 shows that for a detection limit of 10^{23} watt-cm⁻³-sr⁻¹-sec, which is estimated for the existing diagnostic facilities, the lower limit for temperature measurements in a 1 atm nitrogen plasma is 2900°K. At higher pressures, for example 50 atm, the lower temperature limit is reduced to 2400°K assuming the same calibration constant. Furthermore, changes in pressure from 10 to 50 atm at 3000°K results in only a 250°K change in temperature for a given emission coefficient as shown in Fig. 37.

Initial attempts to develop a similar calibration curve for the 1 atm air plasma by applying the same analytical and experimental methods to a mixed nitrogen-oxygen plasma jet have led to the conclusion that the jet really behaves as a 79%-21% mixture of equilibrium nitrogen and oxygen plasmas. Contrary to observations with the nitrogen plasma the continuum measured in the mixed plasma agrees relatively well with the analytical data computed for an equilibrium air plasma. The curves of Fig. 37 show that for a given measured emission coefficient the temperatures determined by the two calibration curves would differ by only 400°K at 3000°K. Assuming that the same relationship holds at elevated pressures, the same temperature limits can be hypothesized.

It is recommended that the diagnostic methods and apparatus developed under this contract be used to establish the lowest level

of temperatures encountered in a practical Air Force testing facility. A more extensive follow-on research and development program should then be undertaken to investigate the air plasma with the same thoroughness as reported here for the nitrogen plasma. With a proper calibration of the low temperature air continuum a rapidly scanning diagnostic system can be designed for the monitor and control of practical material testing facilities.

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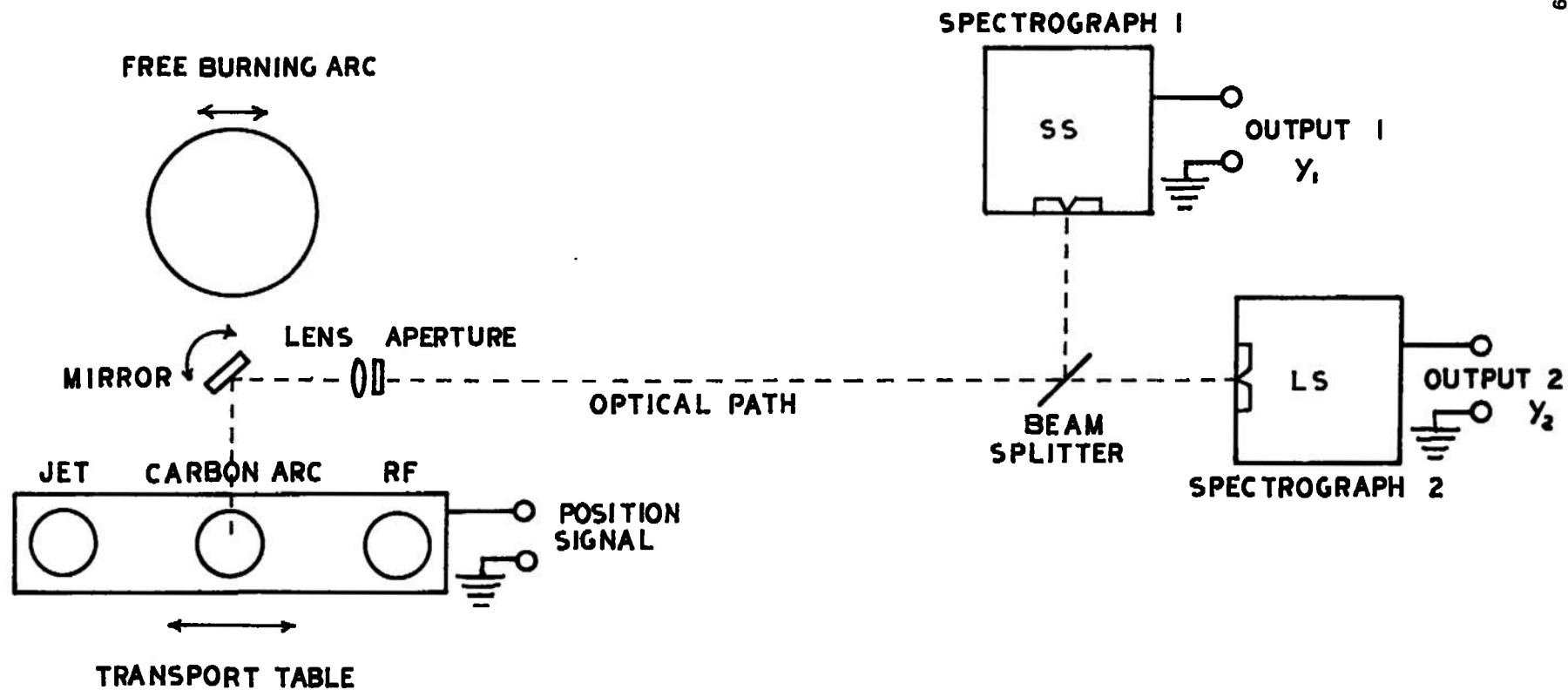


Fig. 1. Schematic diagram of experimental apparatus.

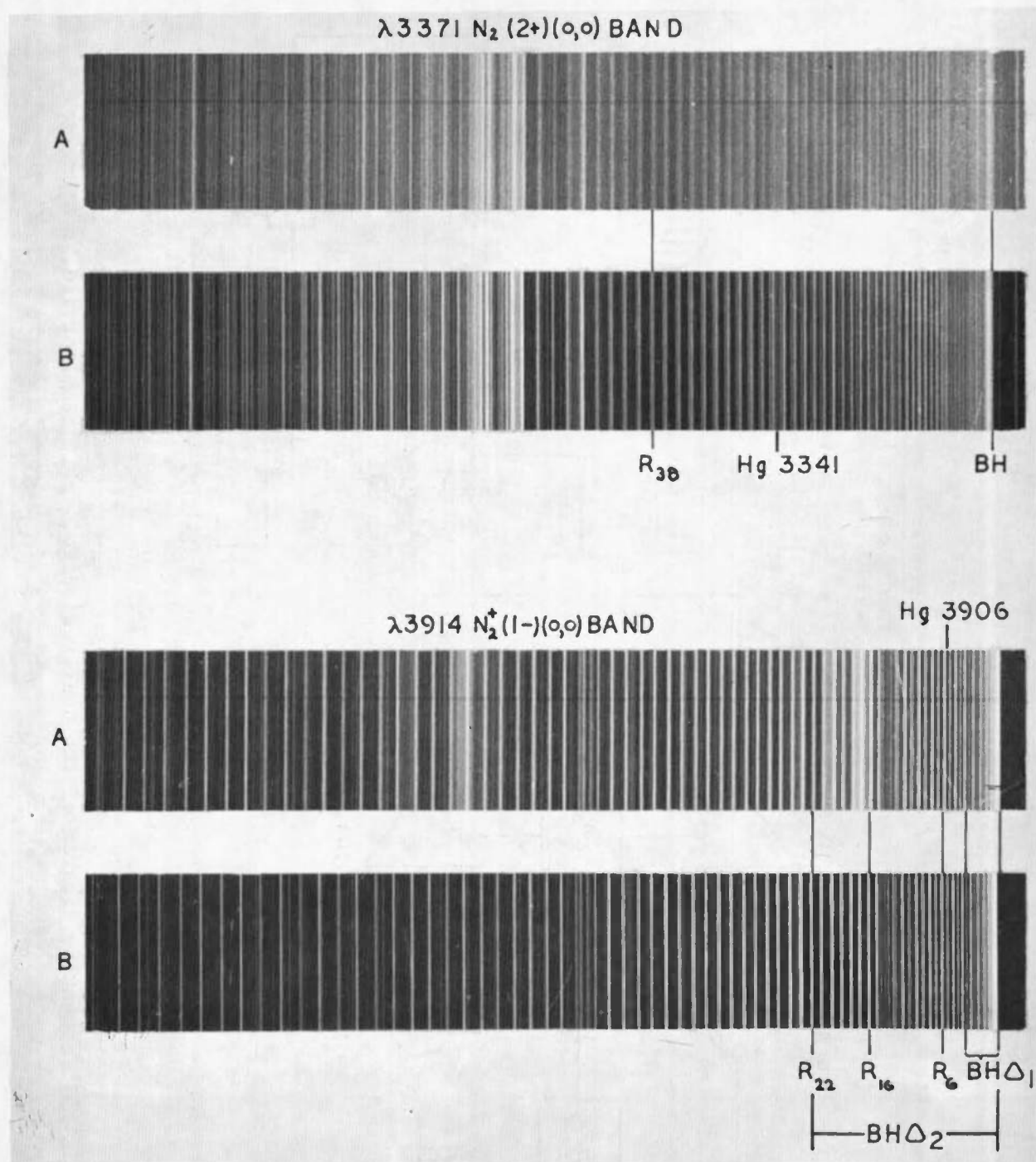


Fig. 2. Spectra of neutral and ionized nitrogen molecules emitted by 1 atm nitrogen plasmas in high (A) and low (B) temperature ranges.

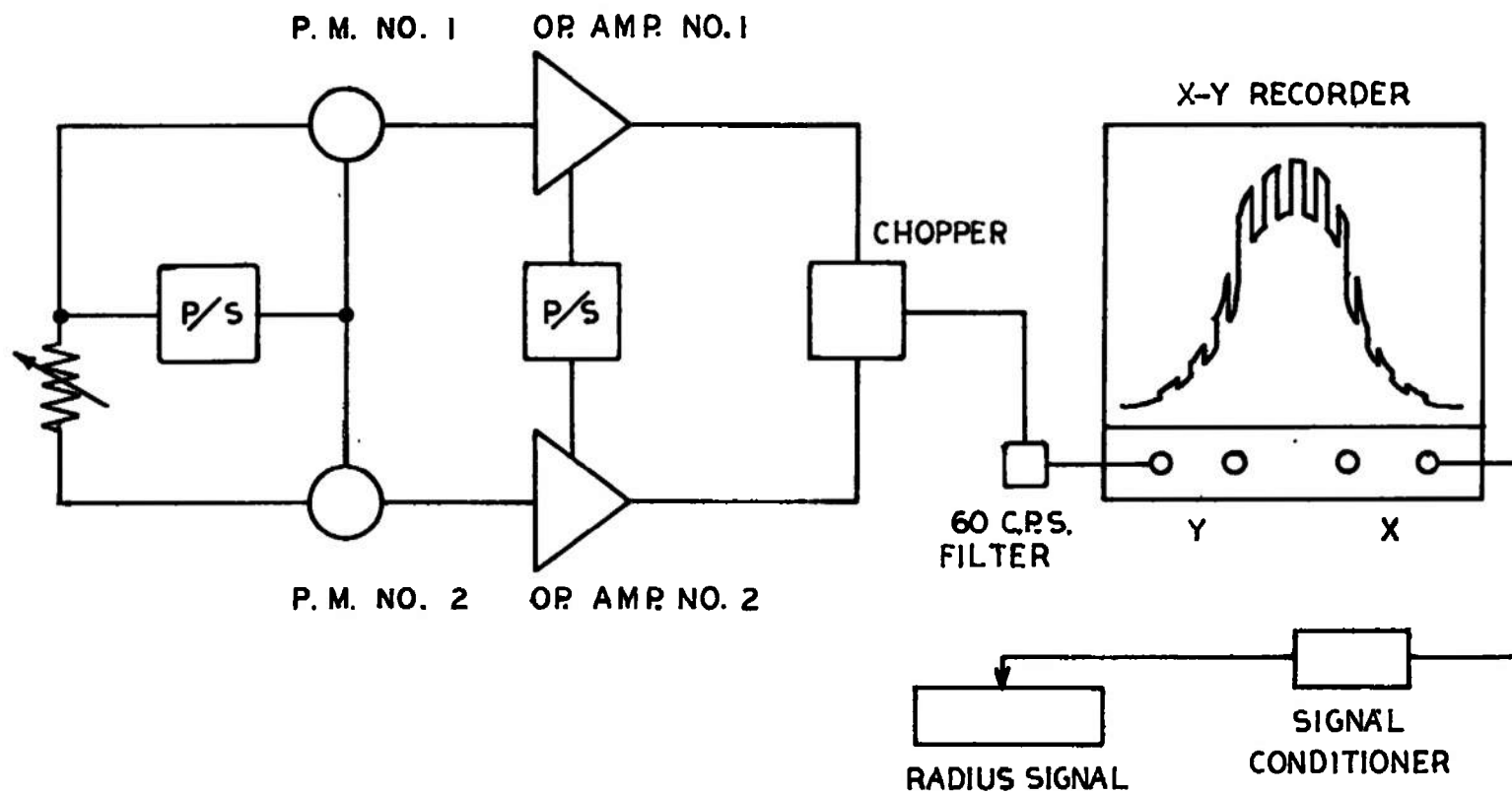


Fig. 3. Schematic diagram of the dual recording, split beam, optical system.

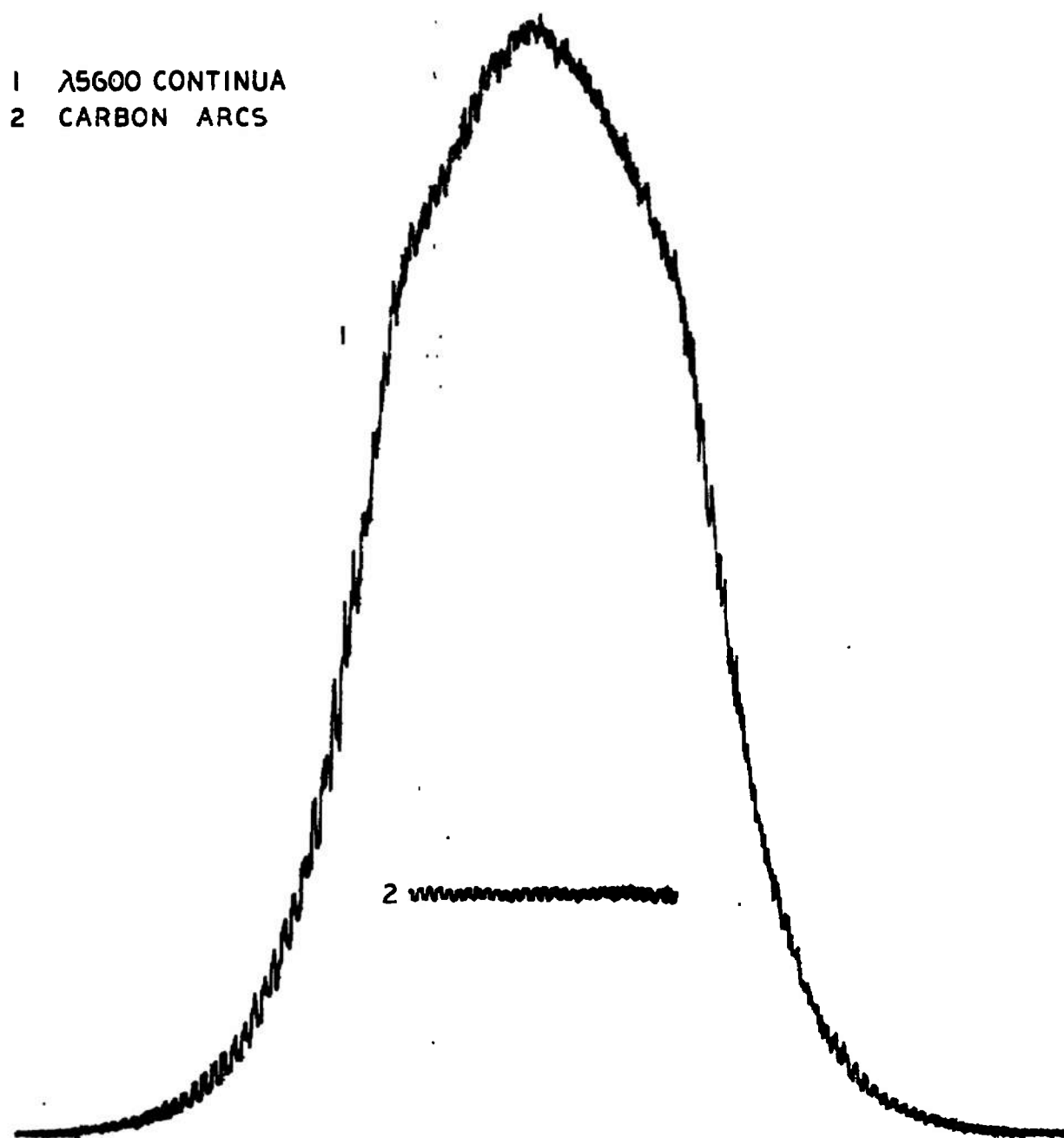


Fig. 4. Simultaneous recording of the $\lambda 5600$ continuum (on both spectrographs) using the chopped x-y recording system.

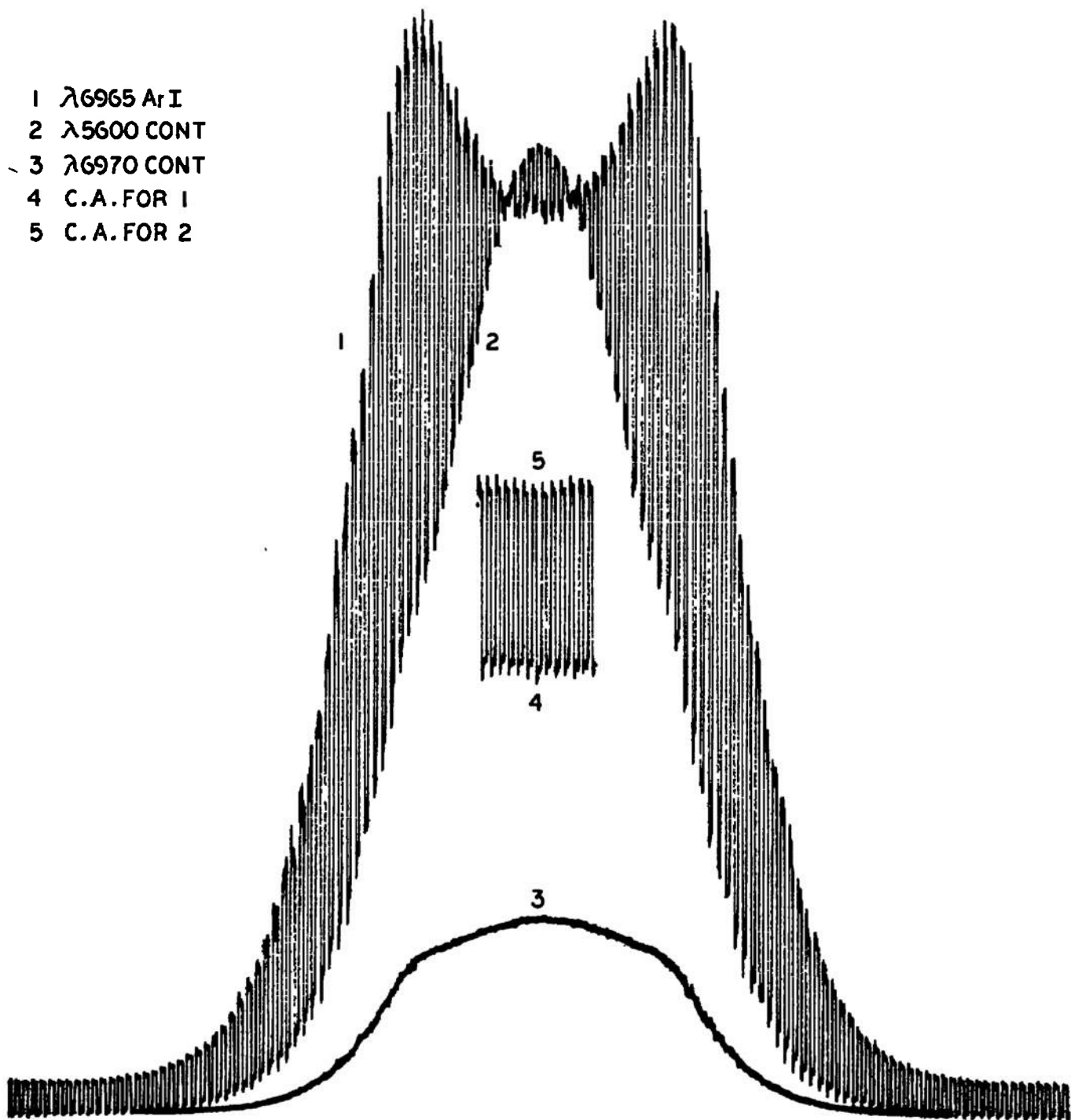


Fig. 5. Simultaneous recording of the $\lambda 6965$ Ar I atomic line and the $\lambda 5600$ continuum using the chopped x-y recording system.

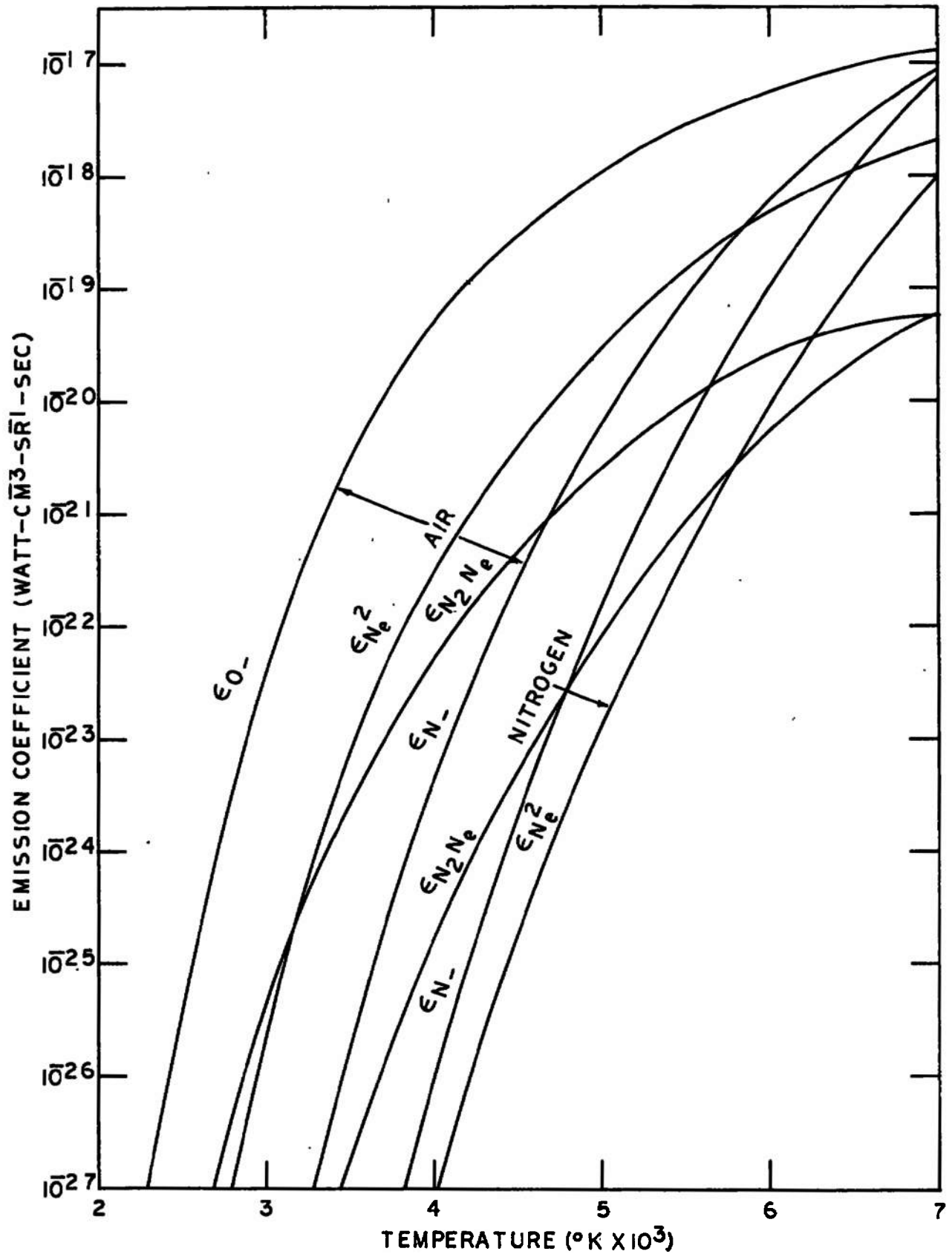


Fig. 6. Computed absolute emission coefficients of the several sources of continuum emitted by 1 atm nitrogen and air plasmas.

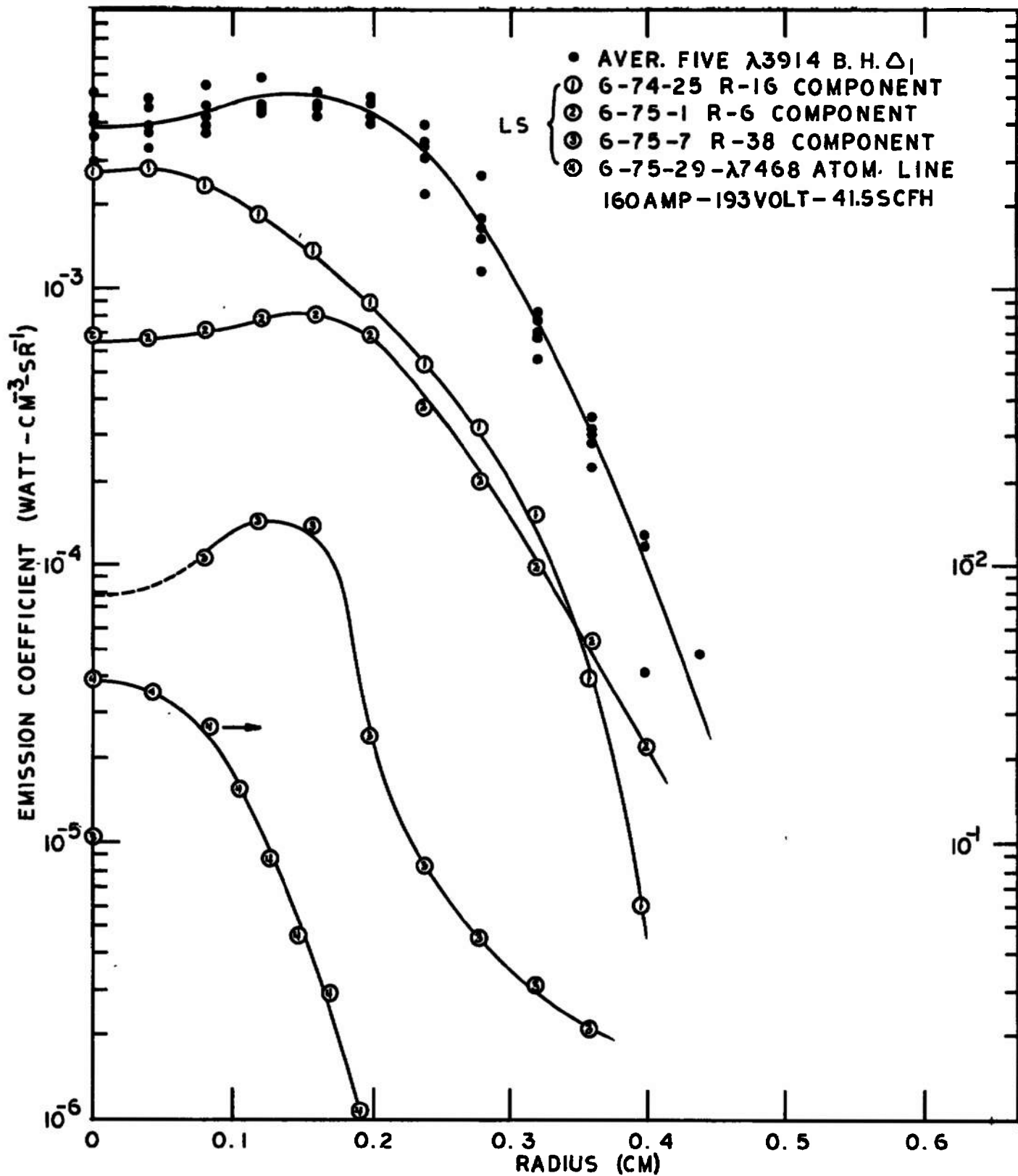


Fig. 7. Measured radial profiles of the emission coefficient for several species of radiation emitted by the nitrogen plasma at 1 atm.

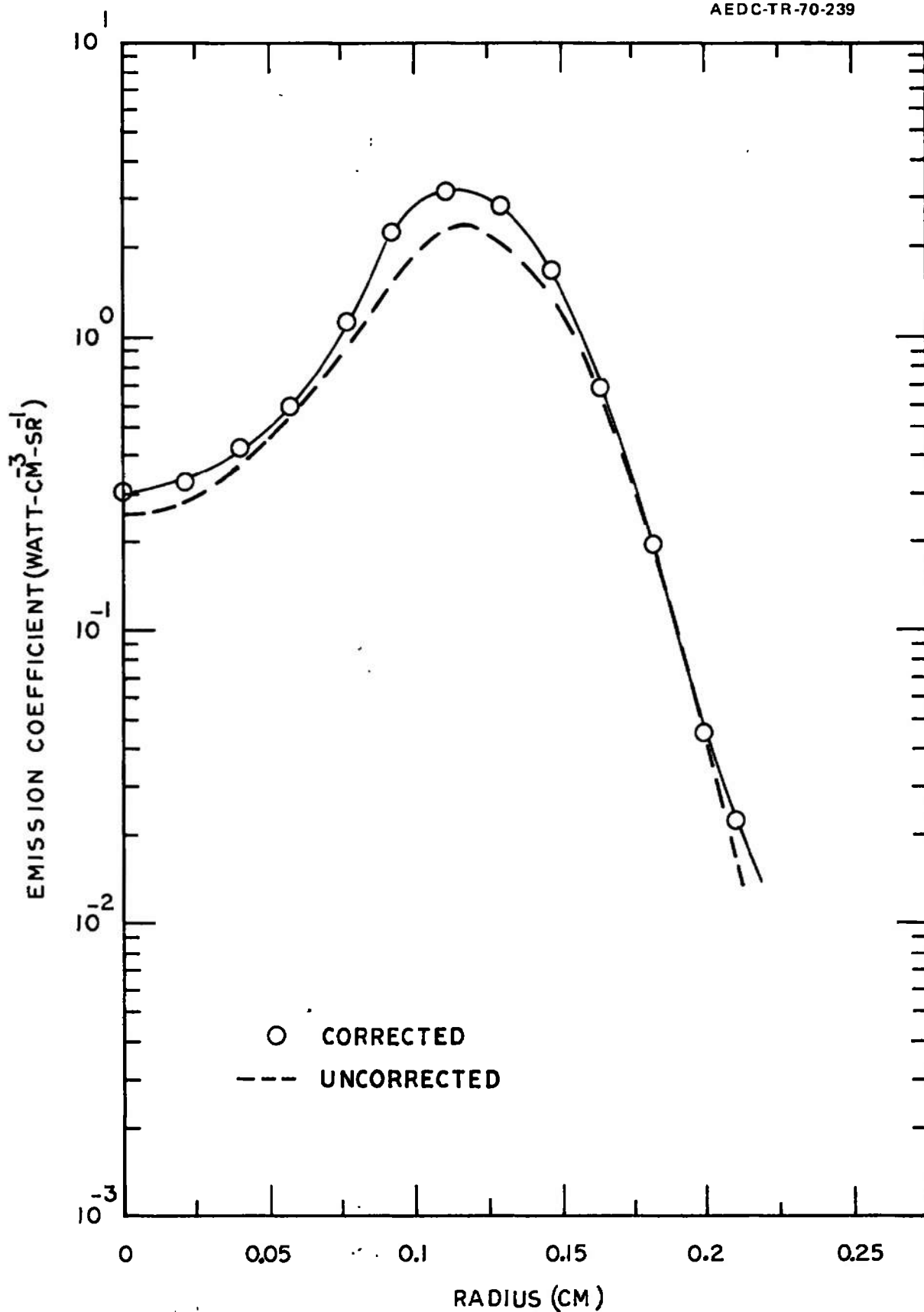


Fig. 8. Measured radial profile of the λ_{7468} NI line emission coefficient emitted by a 1 atm free-burning nitrogen arc with and without absorption correction.

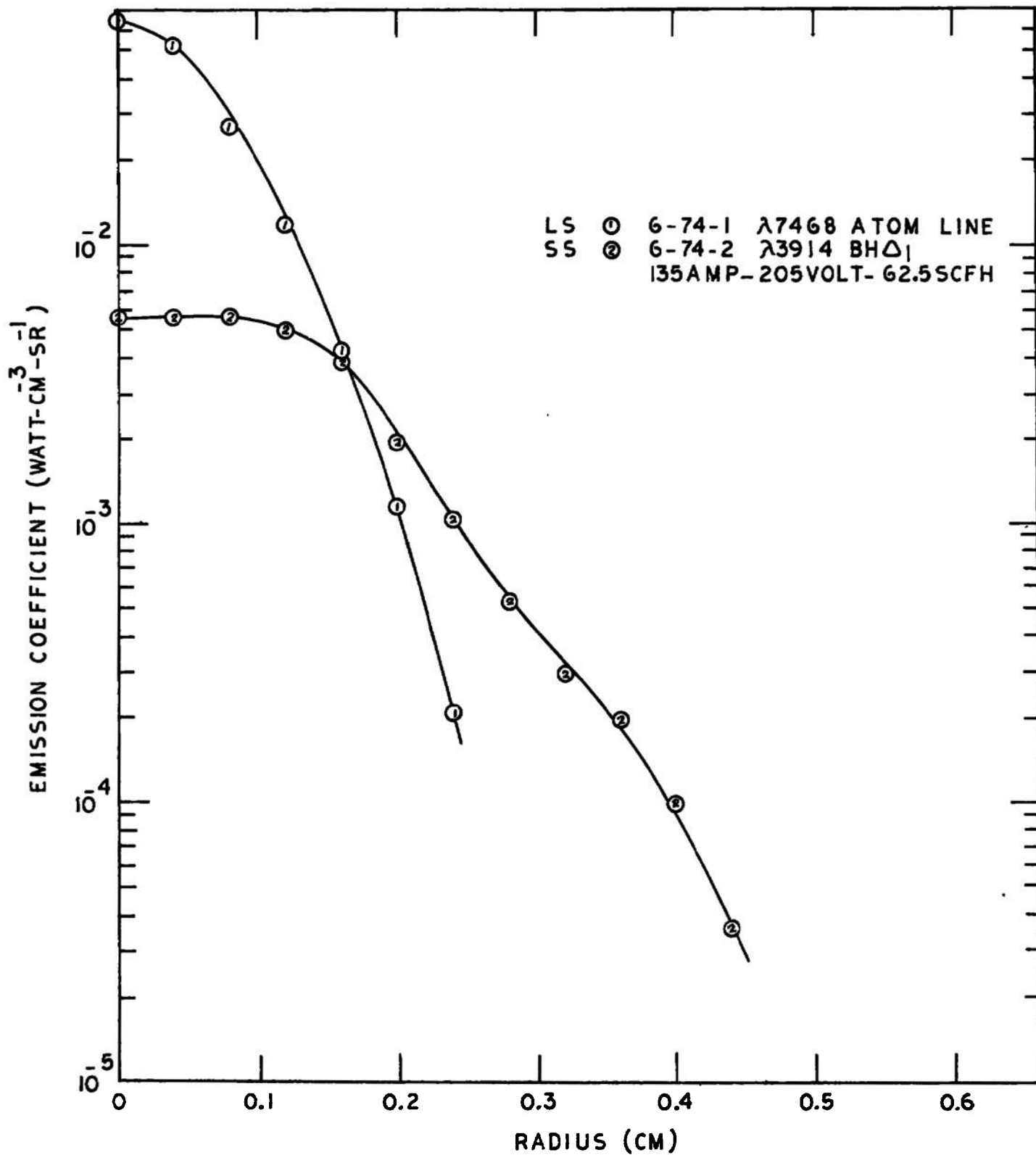


Fig. 9. Emission coefficient vs radius for the λ_{3914} BH Δ_1 increment and the λ_{7468} atomic line in a 1 atm nitrogen plasma jet at 62.5 scfh gas flow.

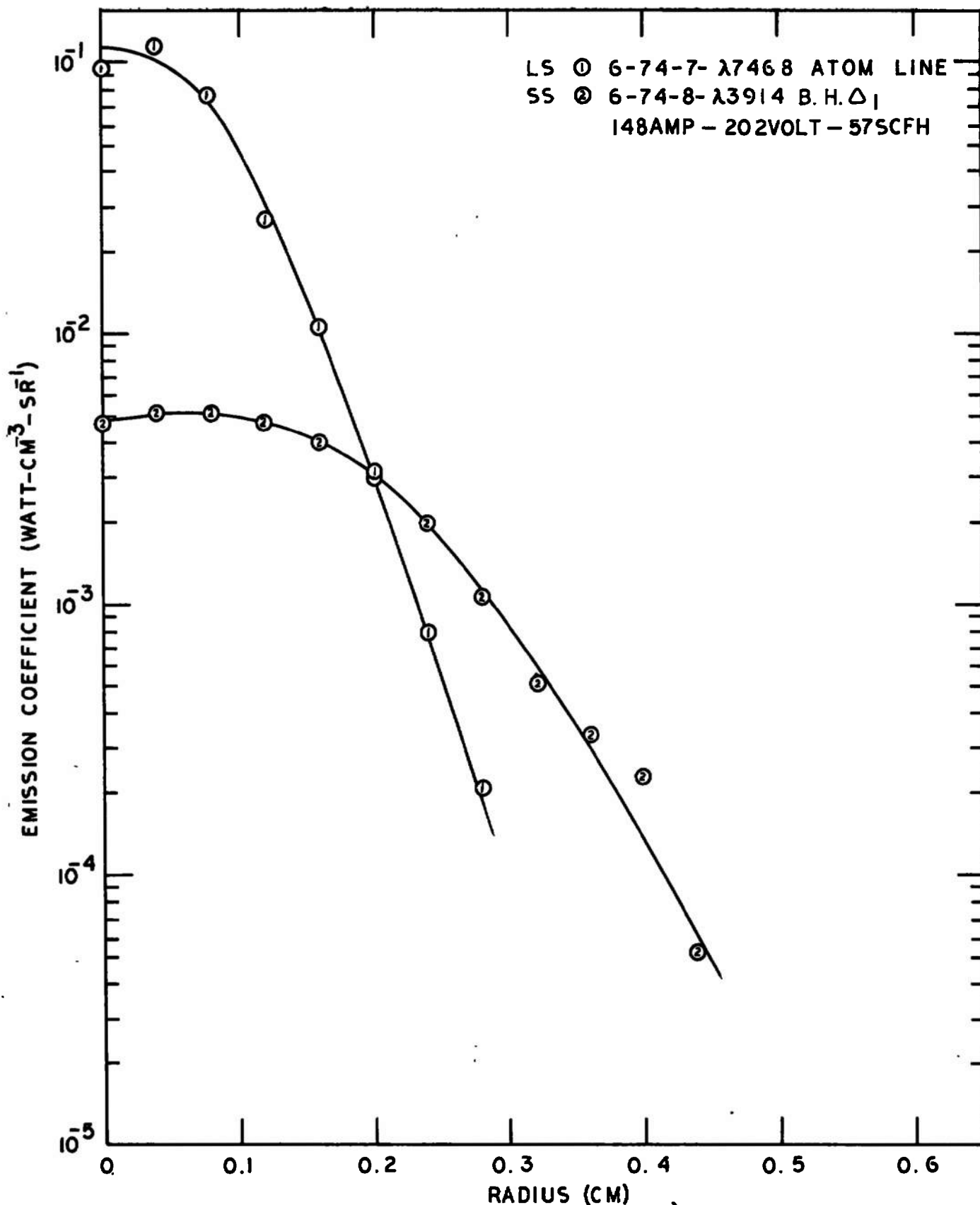


Fig. 10. Emission coefficient vs radius for the $\lambda 3914$ BH Δ_1 increment and the $\lambda 7468$ atomic line in a 1 atm nitrogen plasma jet at 57 scfh gas flow.

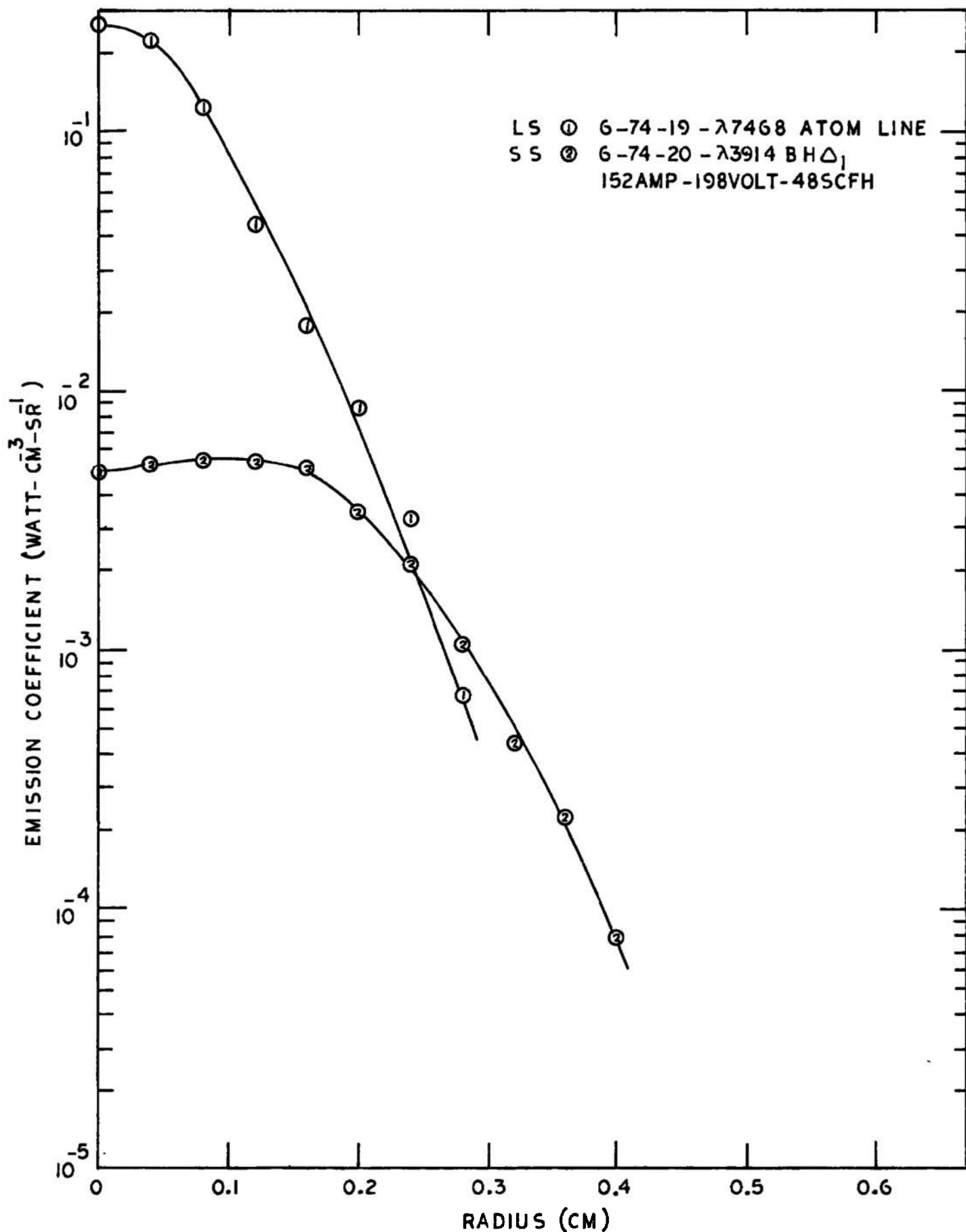


Fig. 11. Emission coefficient vs radius for the $\lambda 3914$ BH Δ_1 increment and the $\lambda 7468$ atomic line in a 1 atm nitrogen plasma jet at 48 scfh gas flow.

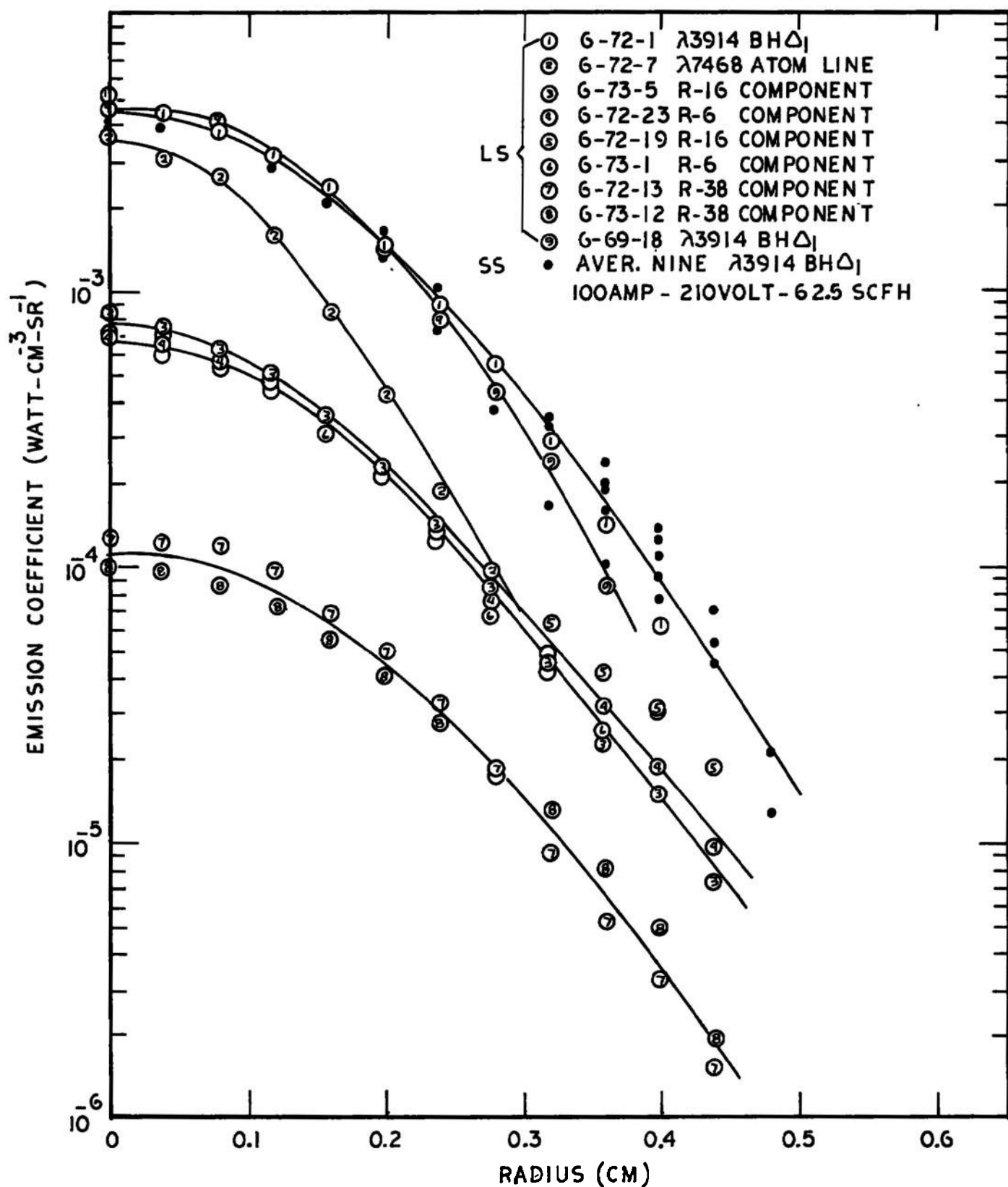


Fig. 12. Composite radial plots of emission coefficients for several species of radiation for a 1 atm nitrogen plasma jet at 62.5 scfh gas flow.

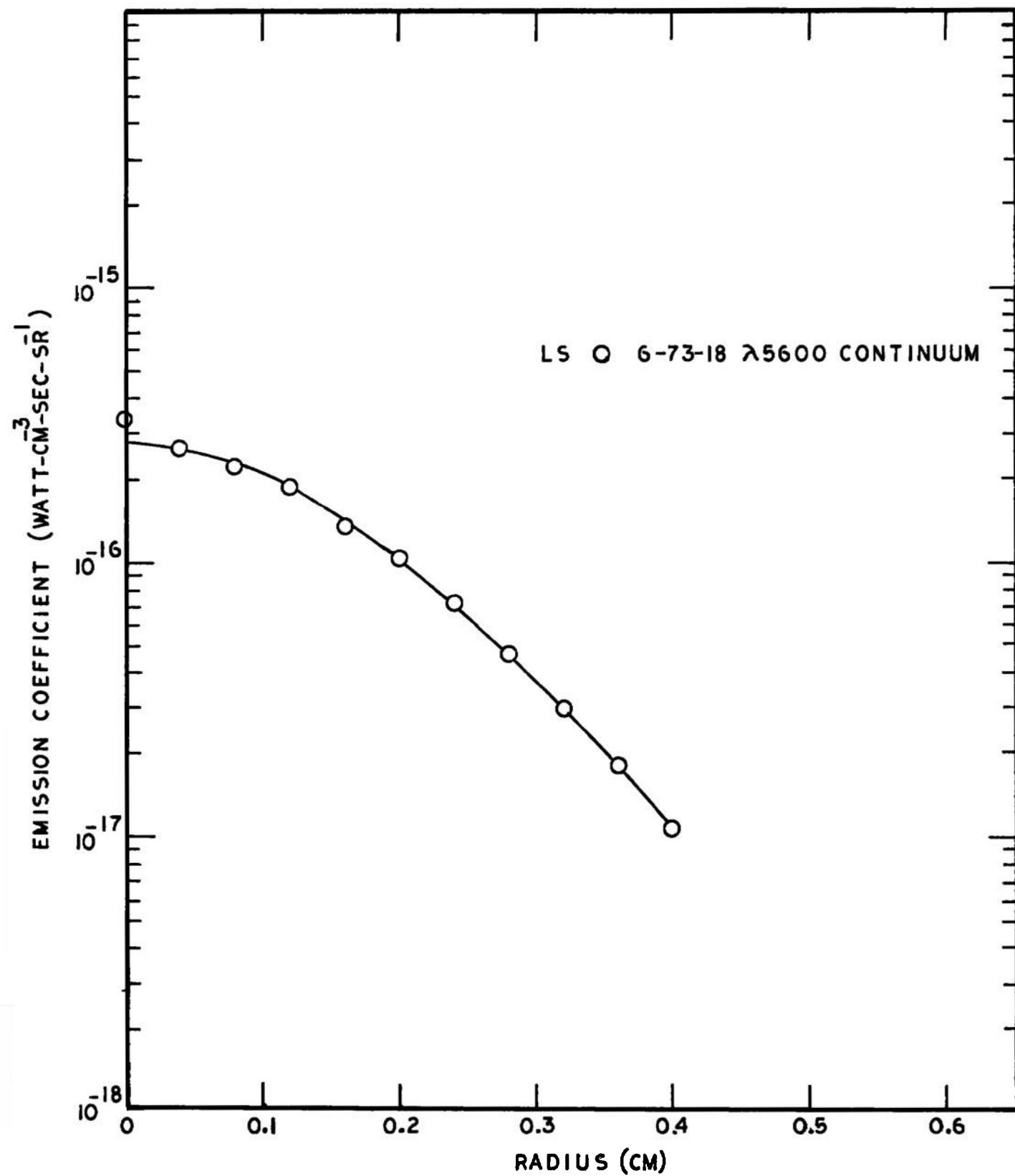


Fig. 13. Emission coefficient vs radius for the $\lambda 5600$ continuum in a 1 atm nitrogen plasma jet at 62.5 scfh gas flow.

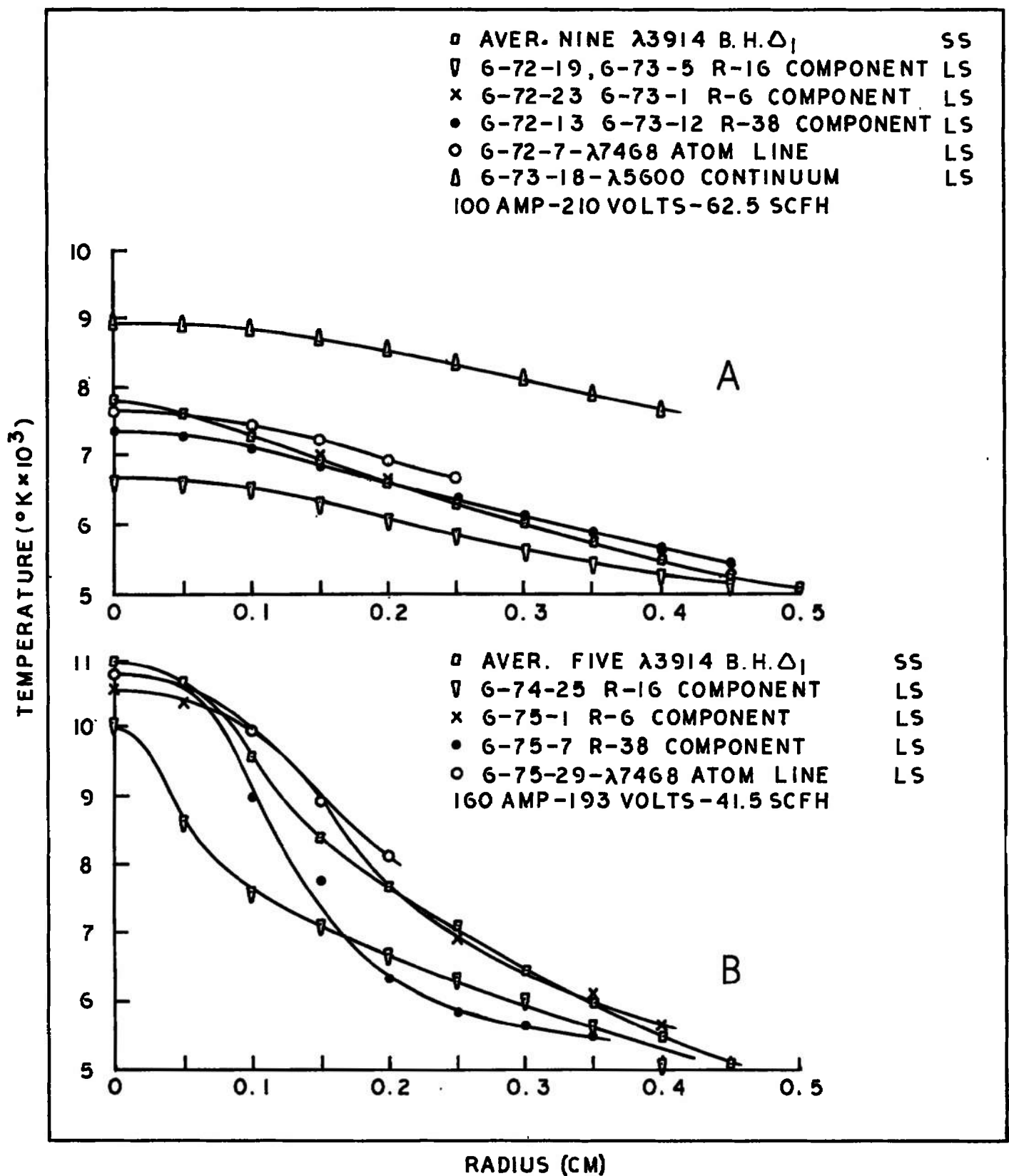


Fig. 14. Radial temperature profiles determined from data of Figs 7, 12 and 13 using calibrated emission coefficients.

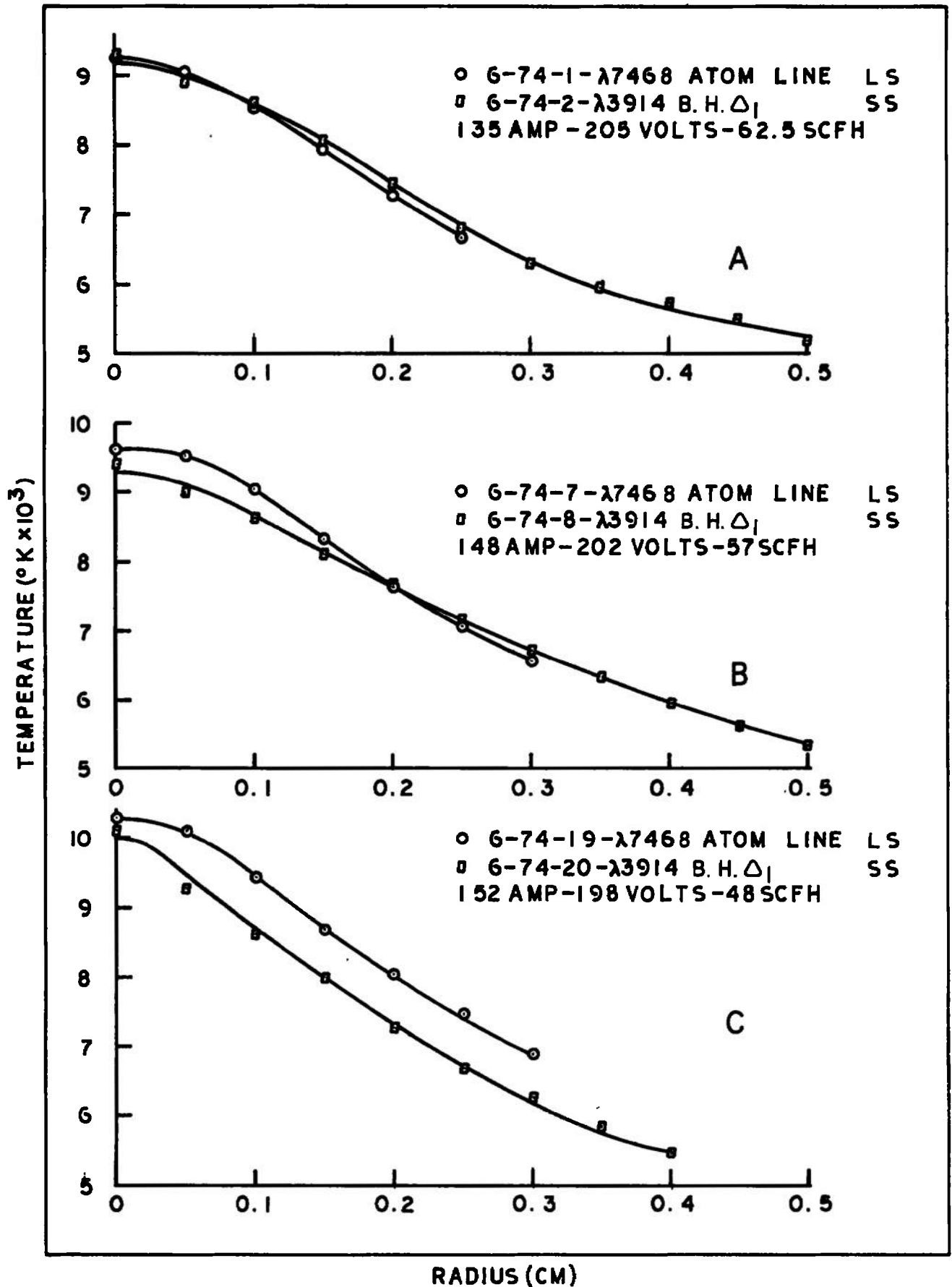


Fig. 15. Radial temperature profiles determined from data of Figs. 9, 10 and 11 using calibrated emission coefficients.

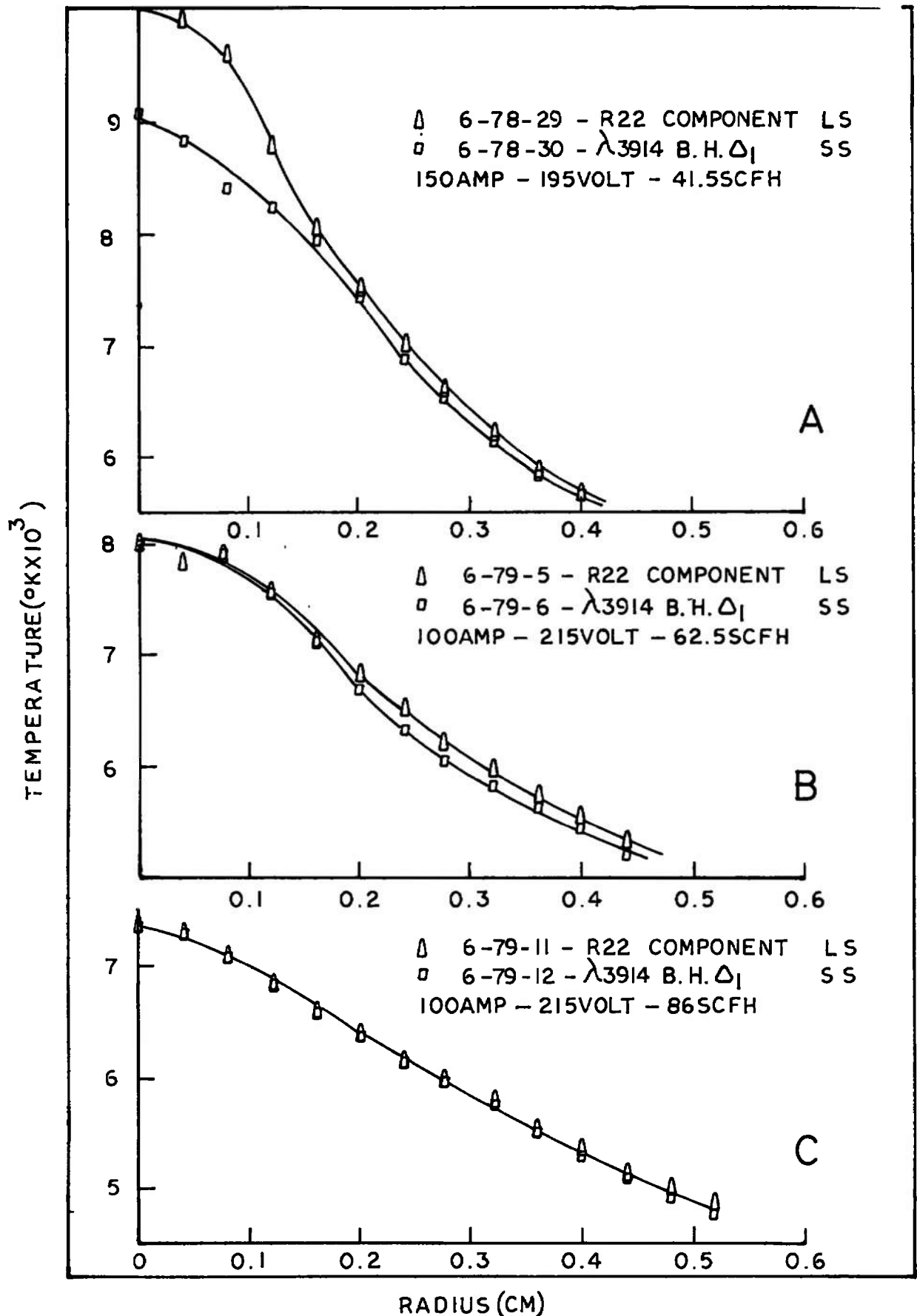
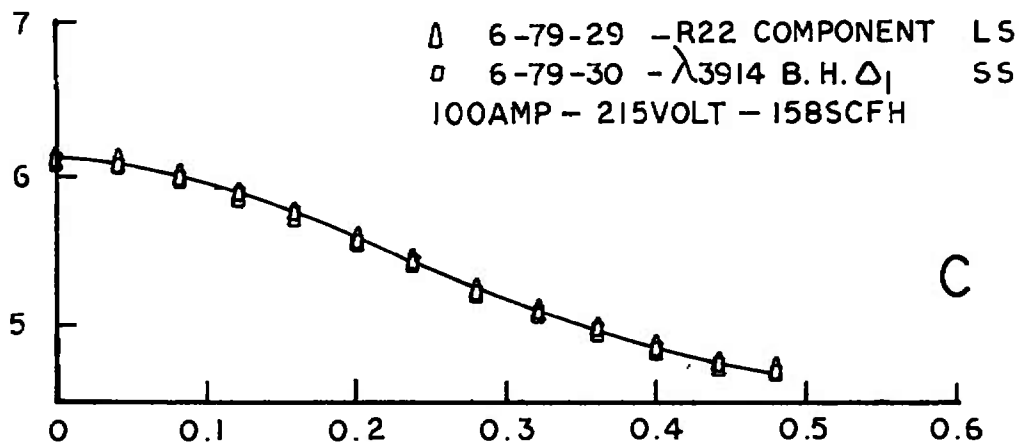
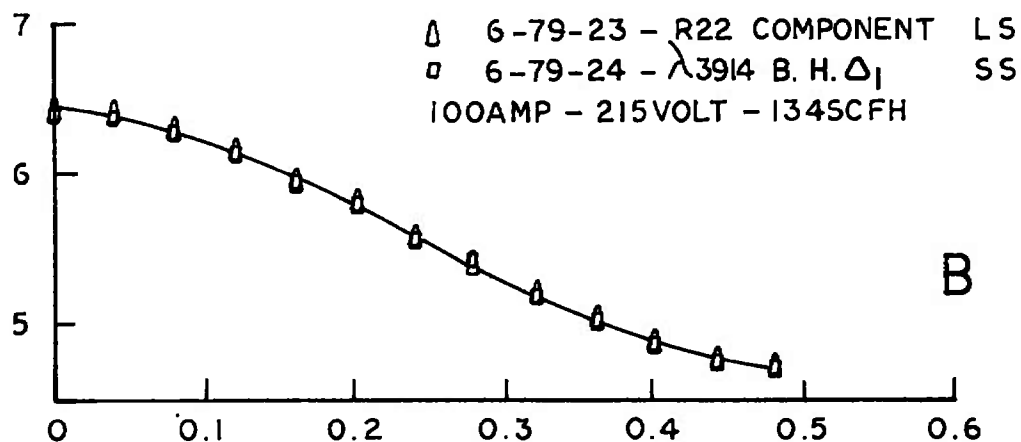
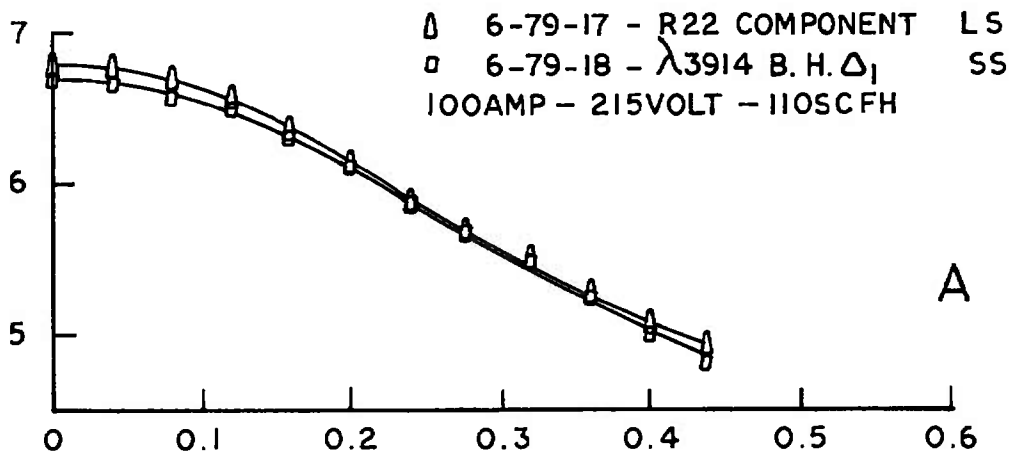


Fig. 16. Comparison of radial temperature profiles determined from the $\lambda 3914$ BH Δ_1 increment and the R_{22} component for several gas dilutions at low flow rates.

TEMPERATURE($^{\circ}\text{K} \times 10^3$)

RADIUS (CM)

Fig. 17. Comparison of radial temperature profiles determined from the $\lambda 3914$ BH Δ_1 increment and the R₂₂ component for several gas dilutions at high flow rates.

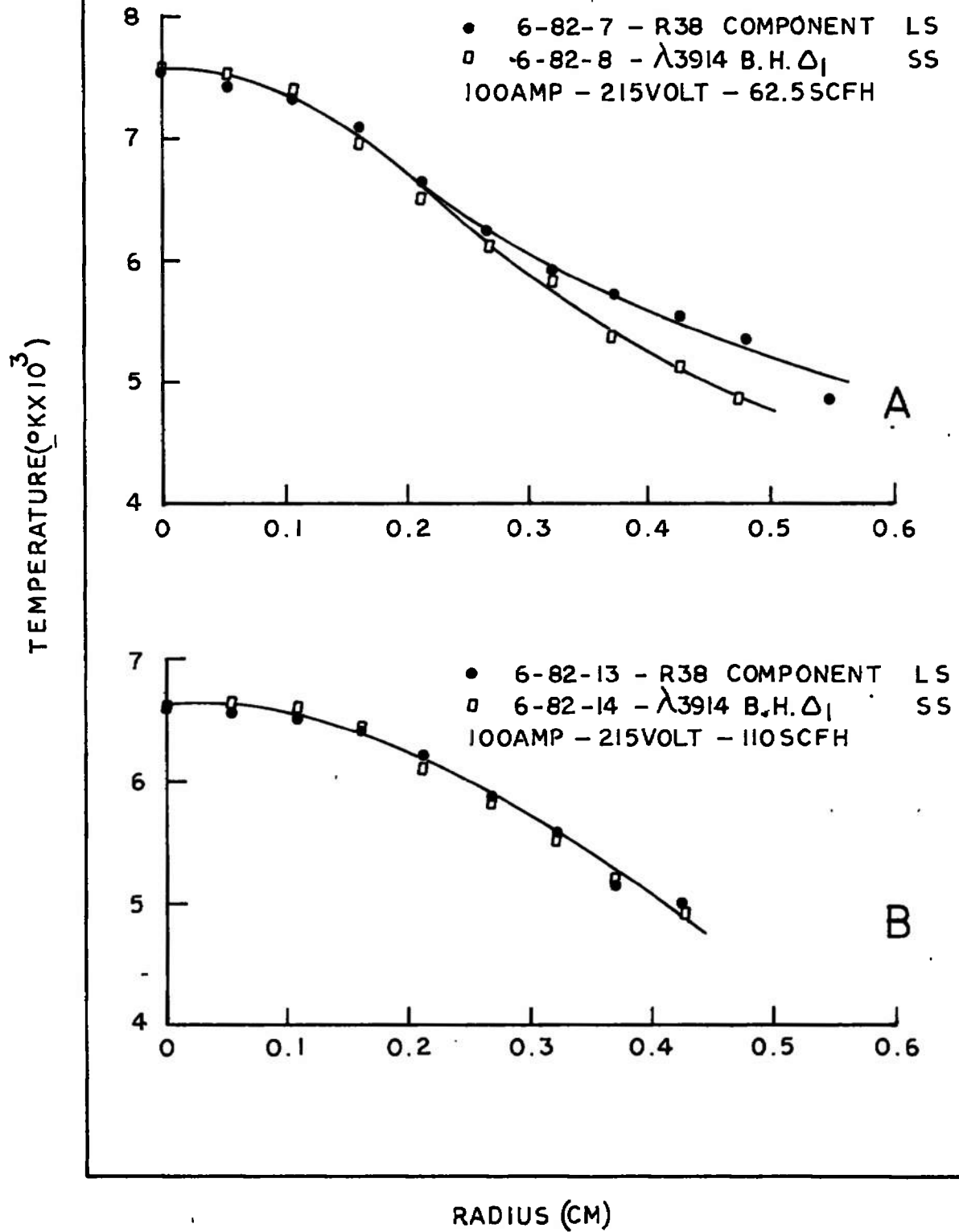


Fig. 18. Comparison of radial temperature profiles determined from the $\lambda 3371$ R₃₈ component and the $\lambda 3914$ BH Δ_1 increment for two gas dilutions.

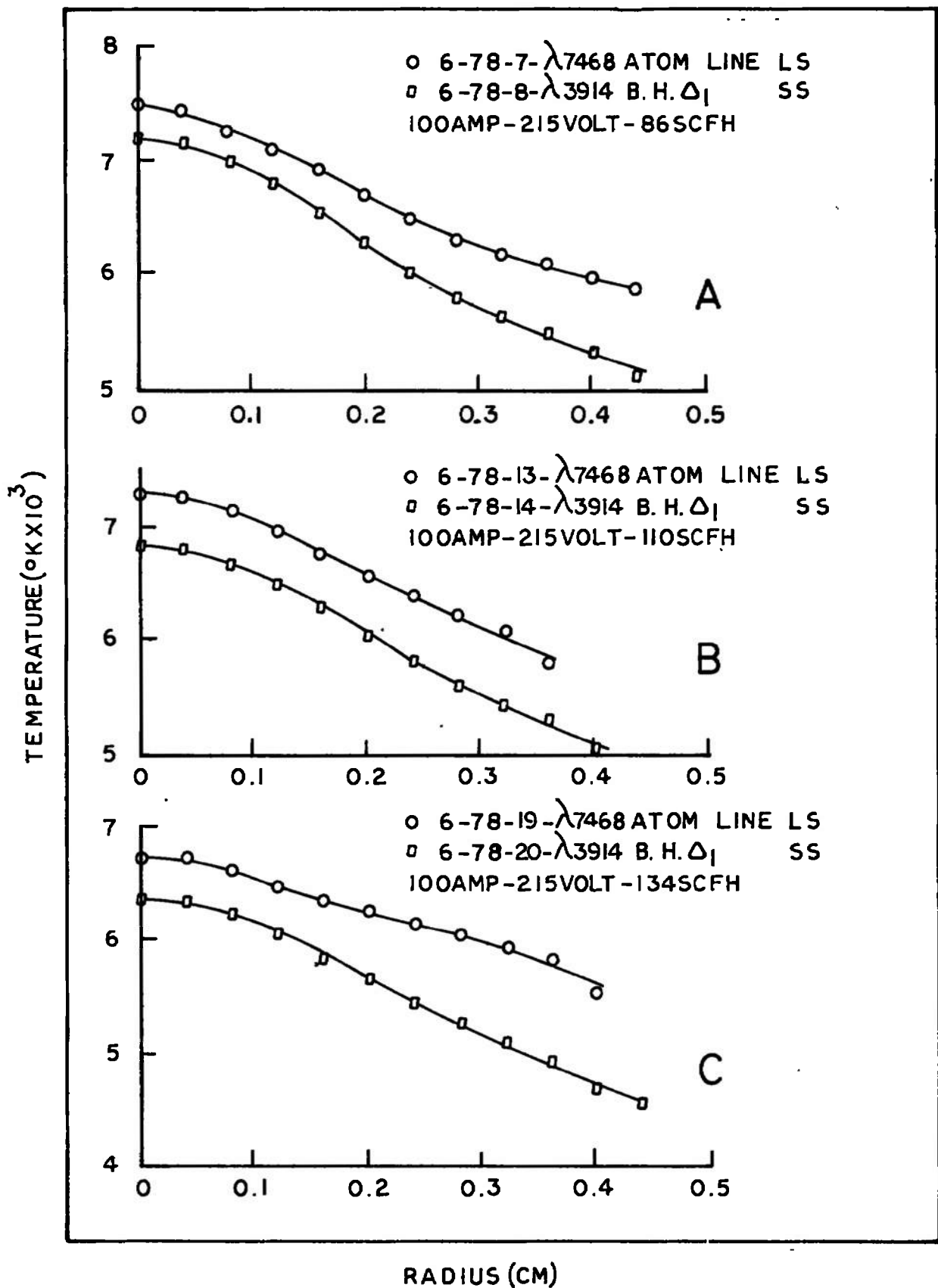


Fig. 19. Comparison of radial temperature profiles determined from $\lambda 7468$ atomic line and the $\lambda 3914$ BH Δ_1 increment for several gas dilutions.

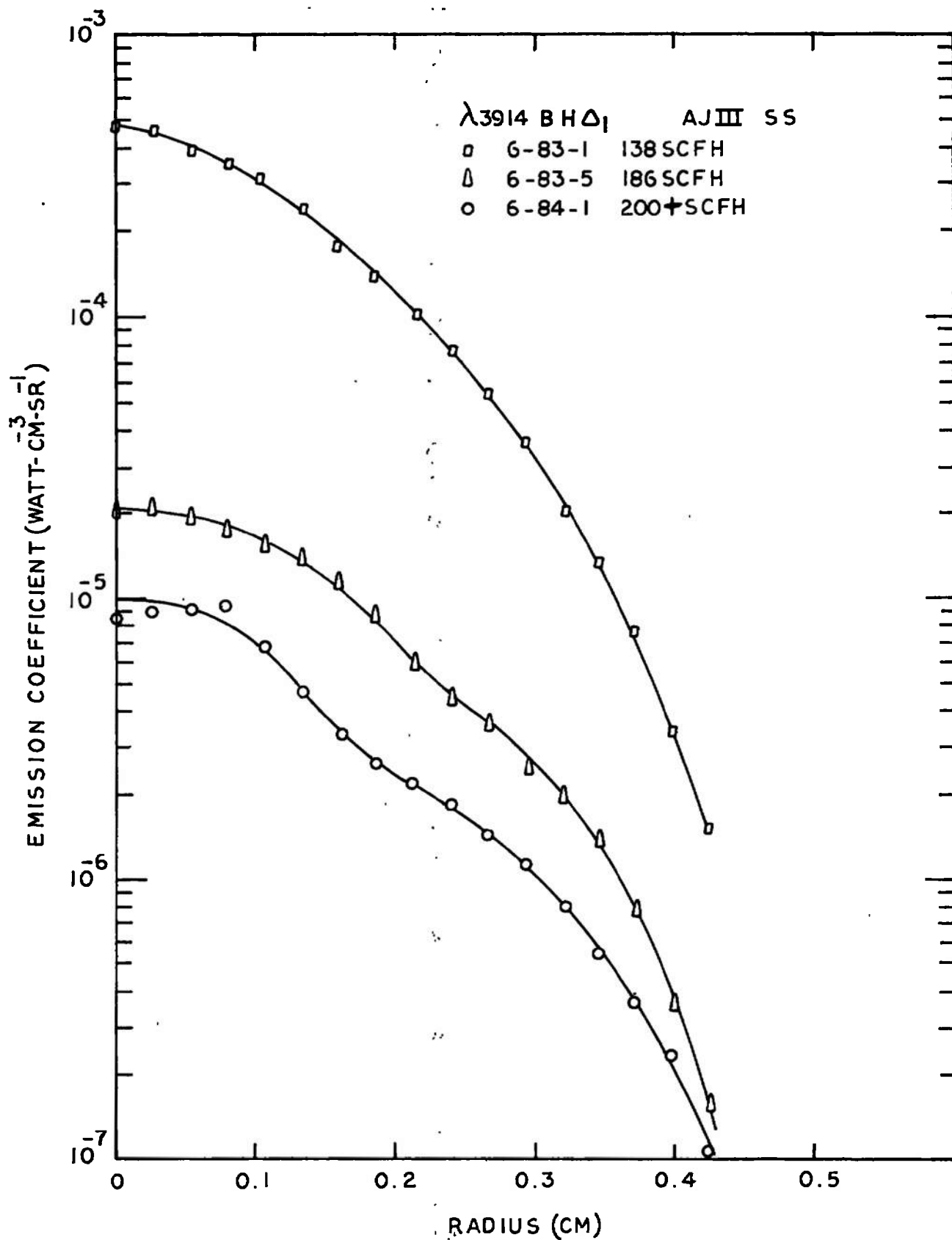


Fig. 20. Emission coefficients vs radius for the $\lambda 3914$ BH Δ_1 increment using arc jet III at three different gas flows.

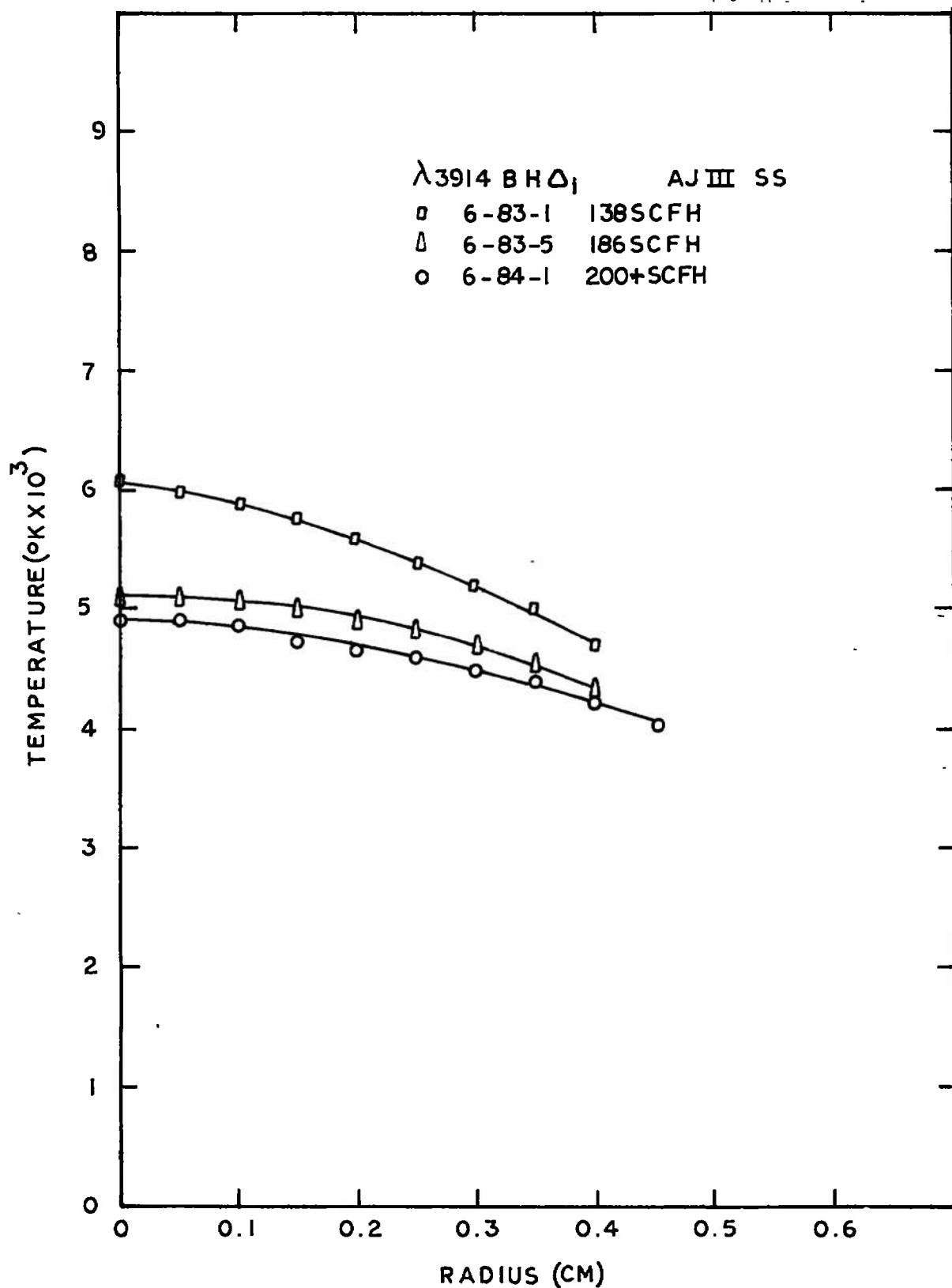


Fig. 21. Radial temperature profiles determined from the emission coefficient profiles of the $\lambda 3914 \text{ BH} \Delta_1$ increment shown in Fig. 20.

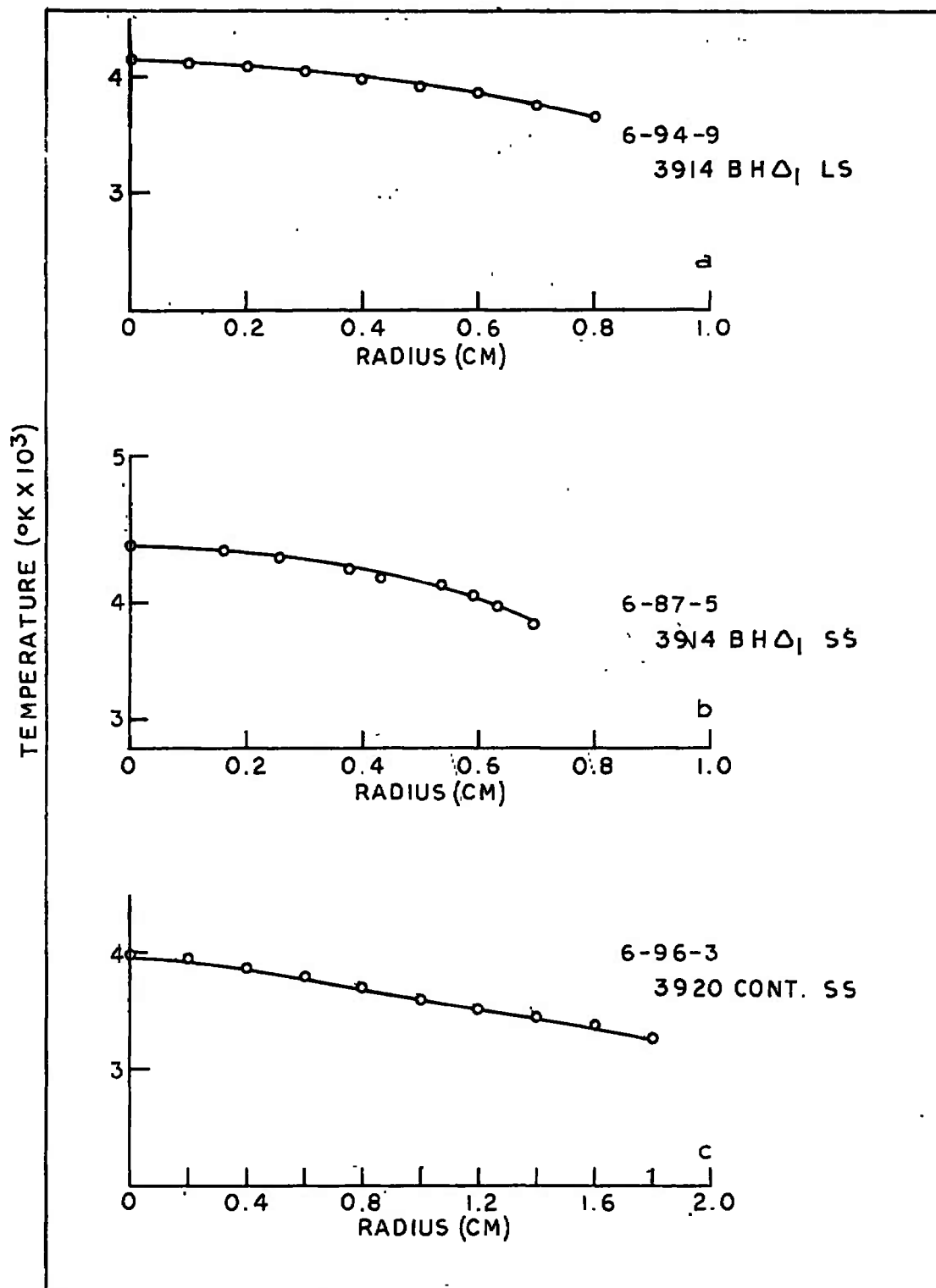


Fig. 22. Radial temperature profiles showing the low temperature limitations of the λ 3914 BH Δ_1 increment and the 28 A increment of the λ 3920 Cont.

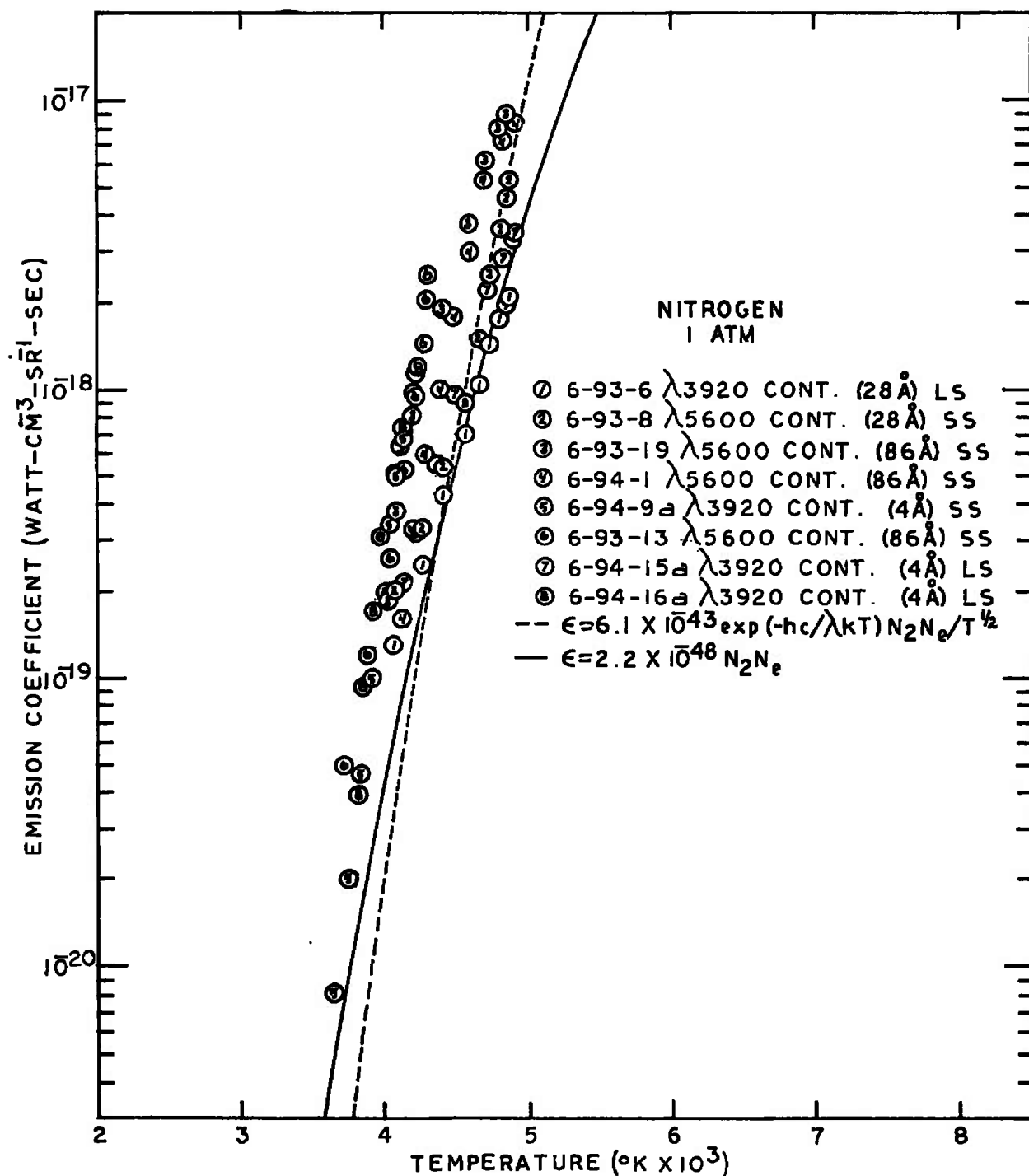


Fig. 23. Experimentally determined values of the continuum emission coefficient vs the temperature determined from the $BH\Delta_1$ increment of the λ 3914 N_2^+ band system.

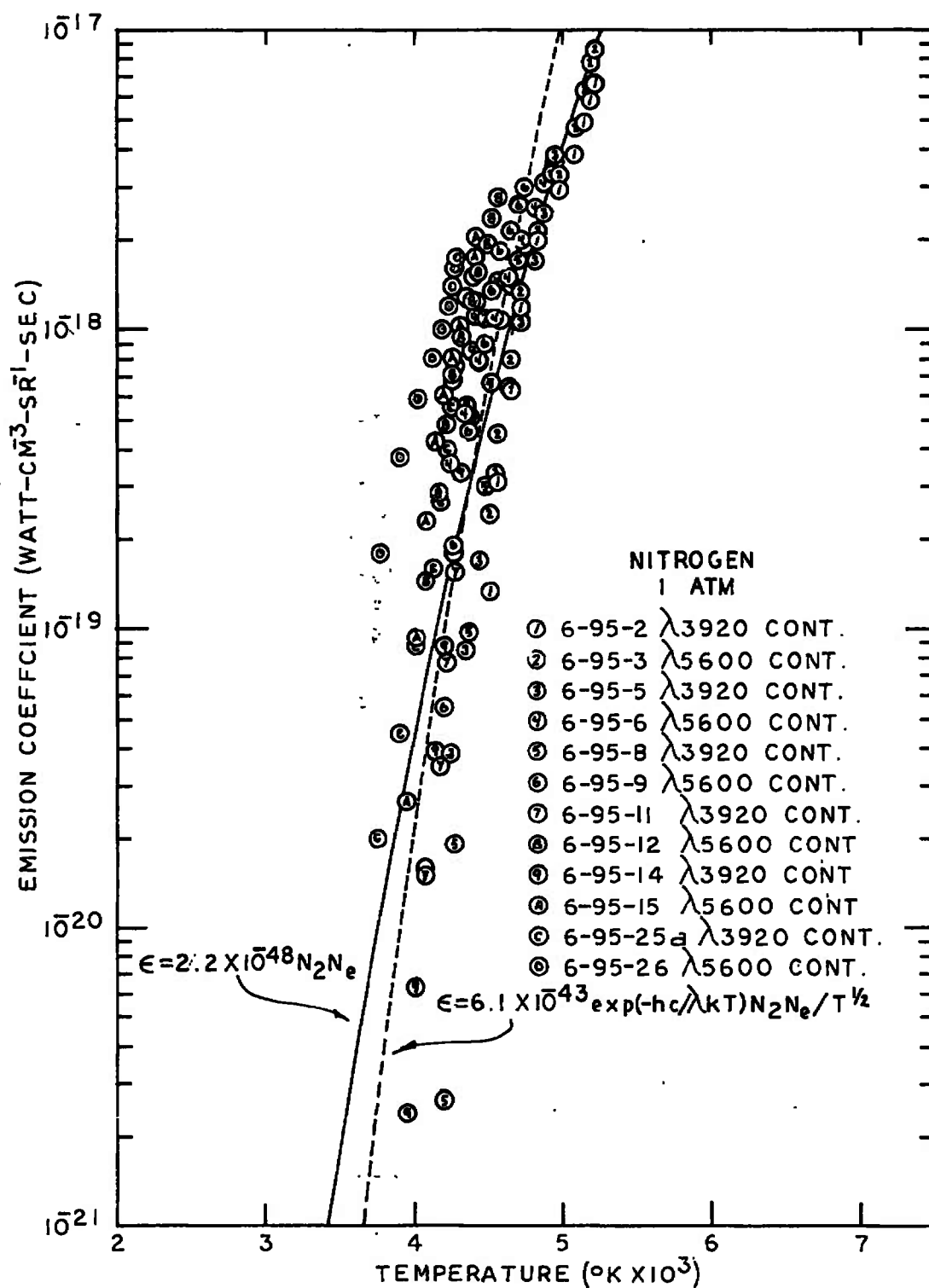


Fig. 24. Experimentally determined values of the continuum emission coefficient vs temperature determined from the $BH\Delta_2$ increment of the $\lambda 3914 N_2^+$ band system.

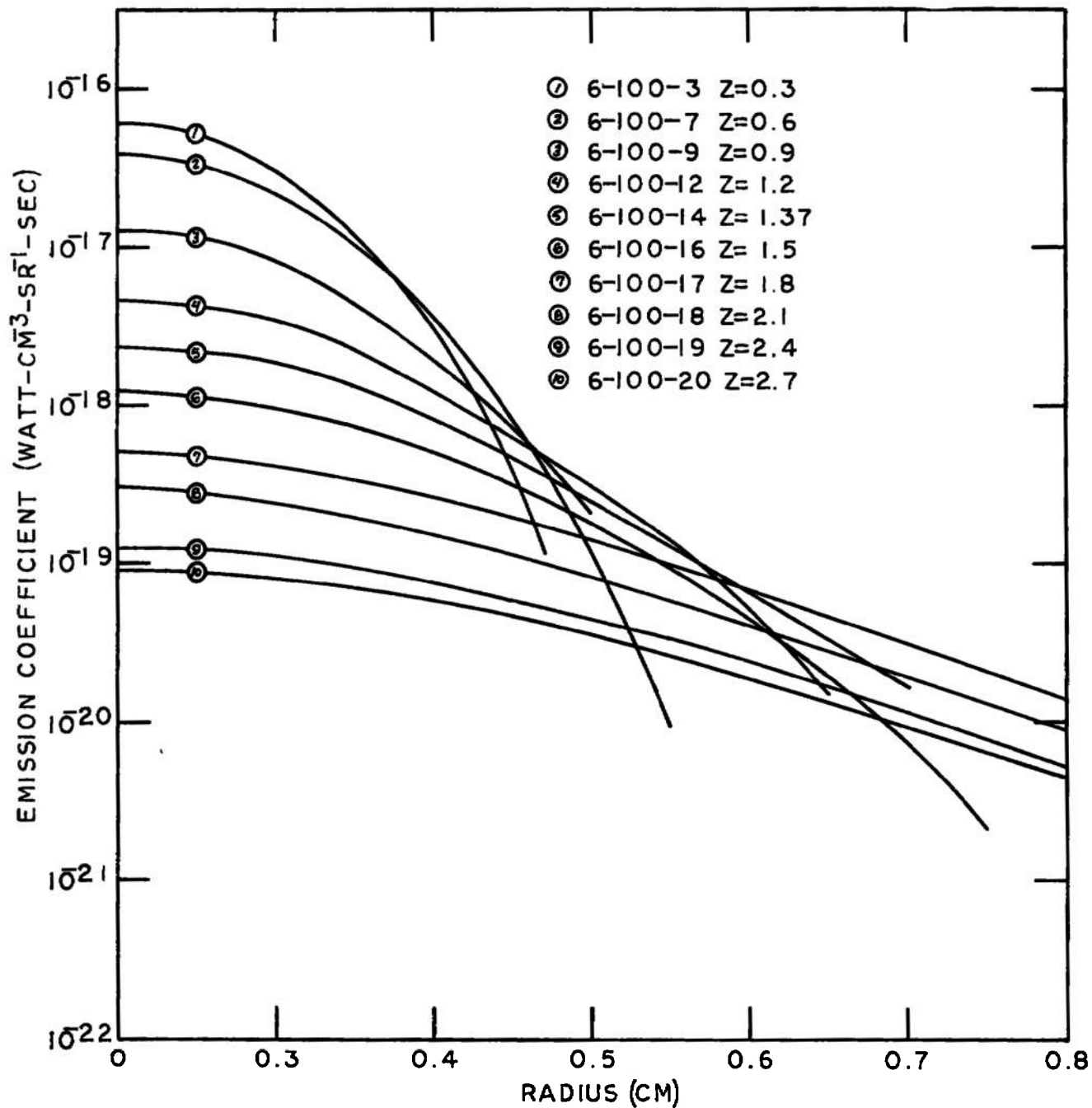


Fig. 25. Emission coefficient vs radius for the λ 3920 continuum with Z as a parameter at a constant flow rate of 111 scfh in a nitrogen-oxygen plasma.

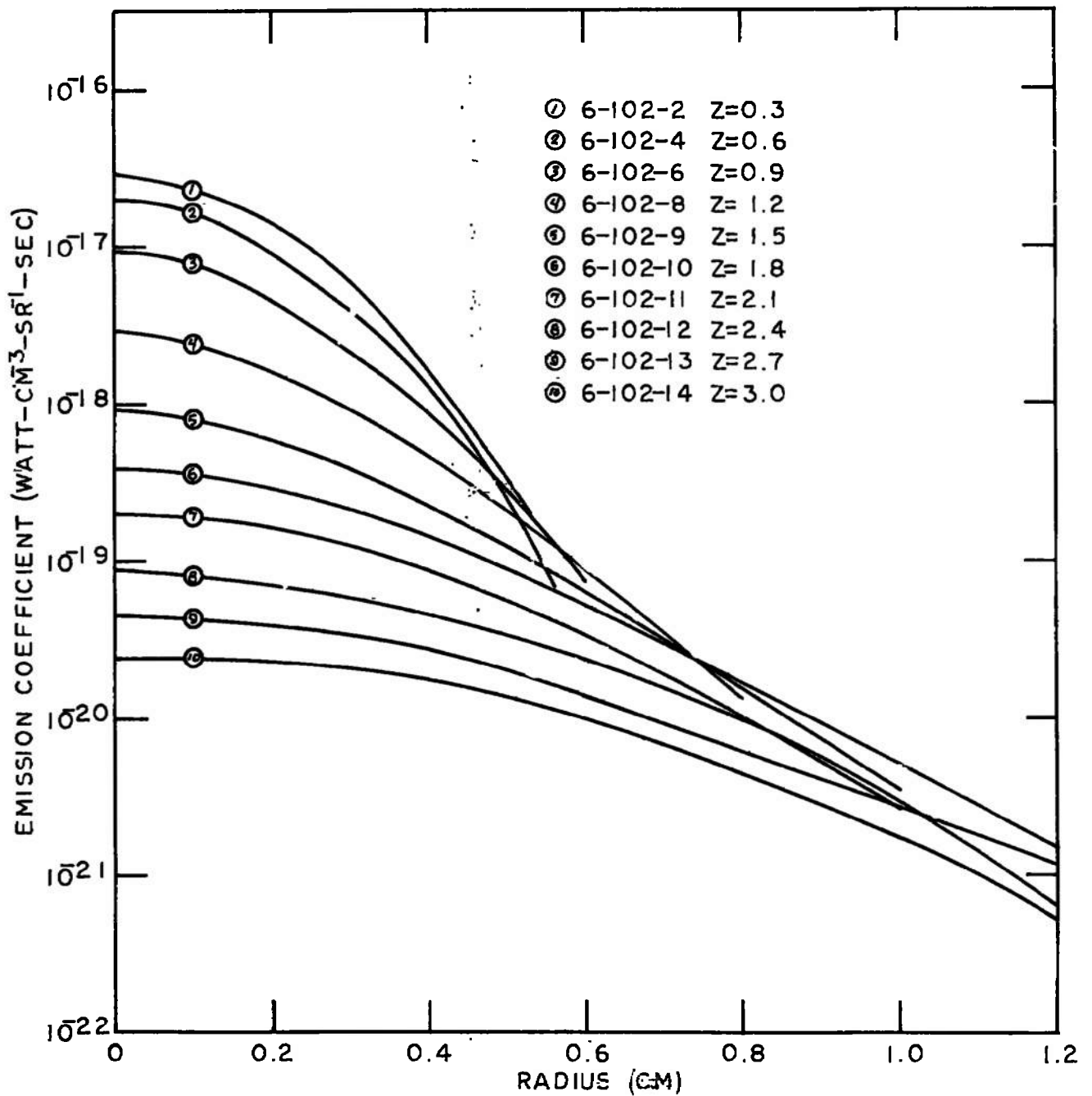


Fig. 26. Emission coefficient vs radius for the λ 3920 continuum with Z as a parameter at a constant flow rate of 141 scfh in a nitrogen-oxygen plasma.

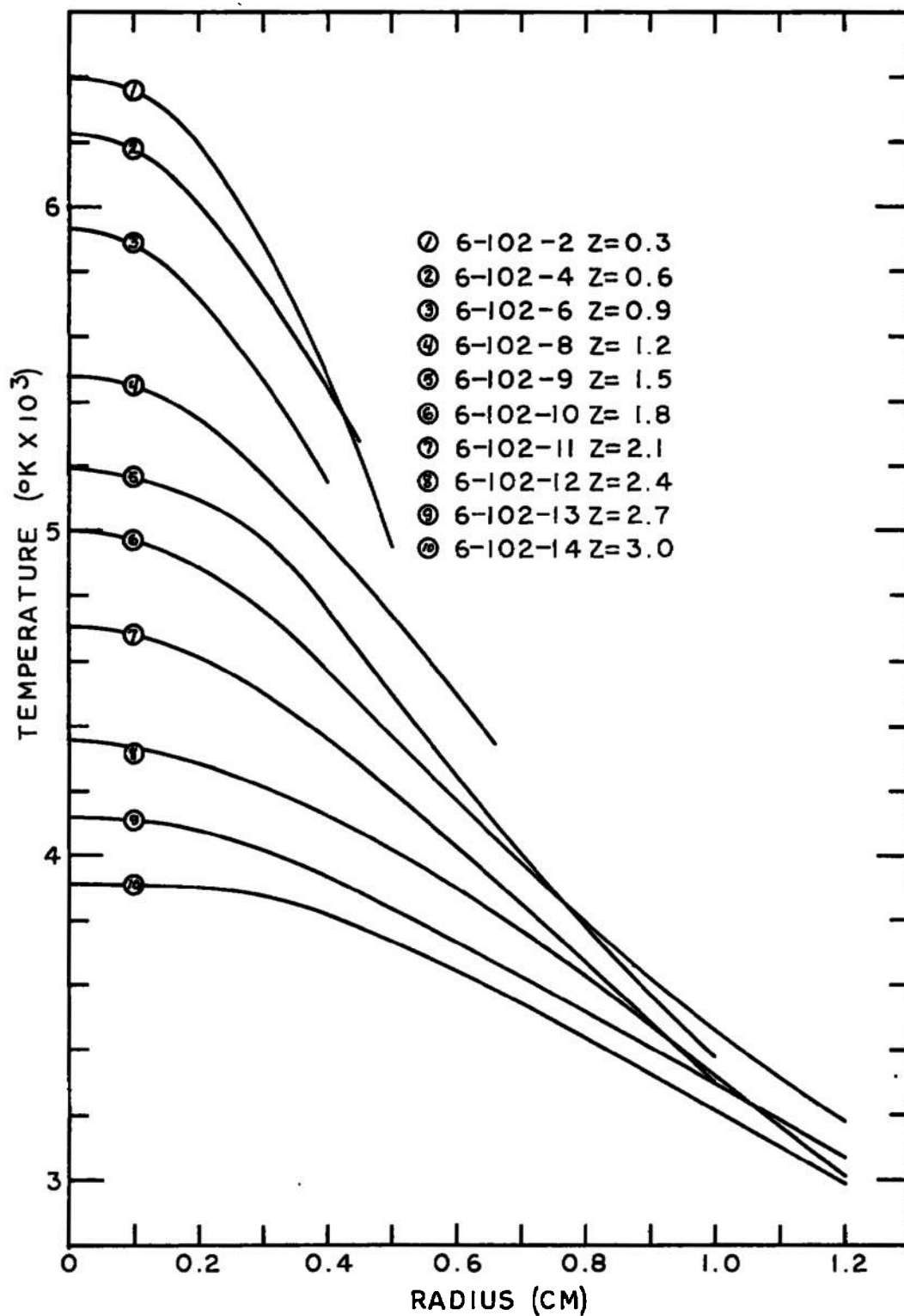


Fig. 27. Temperature vs radius for the nitrogen-oxygen plasmas determined from the data of Fig. 26 using the calibration curve of Fig. 23.

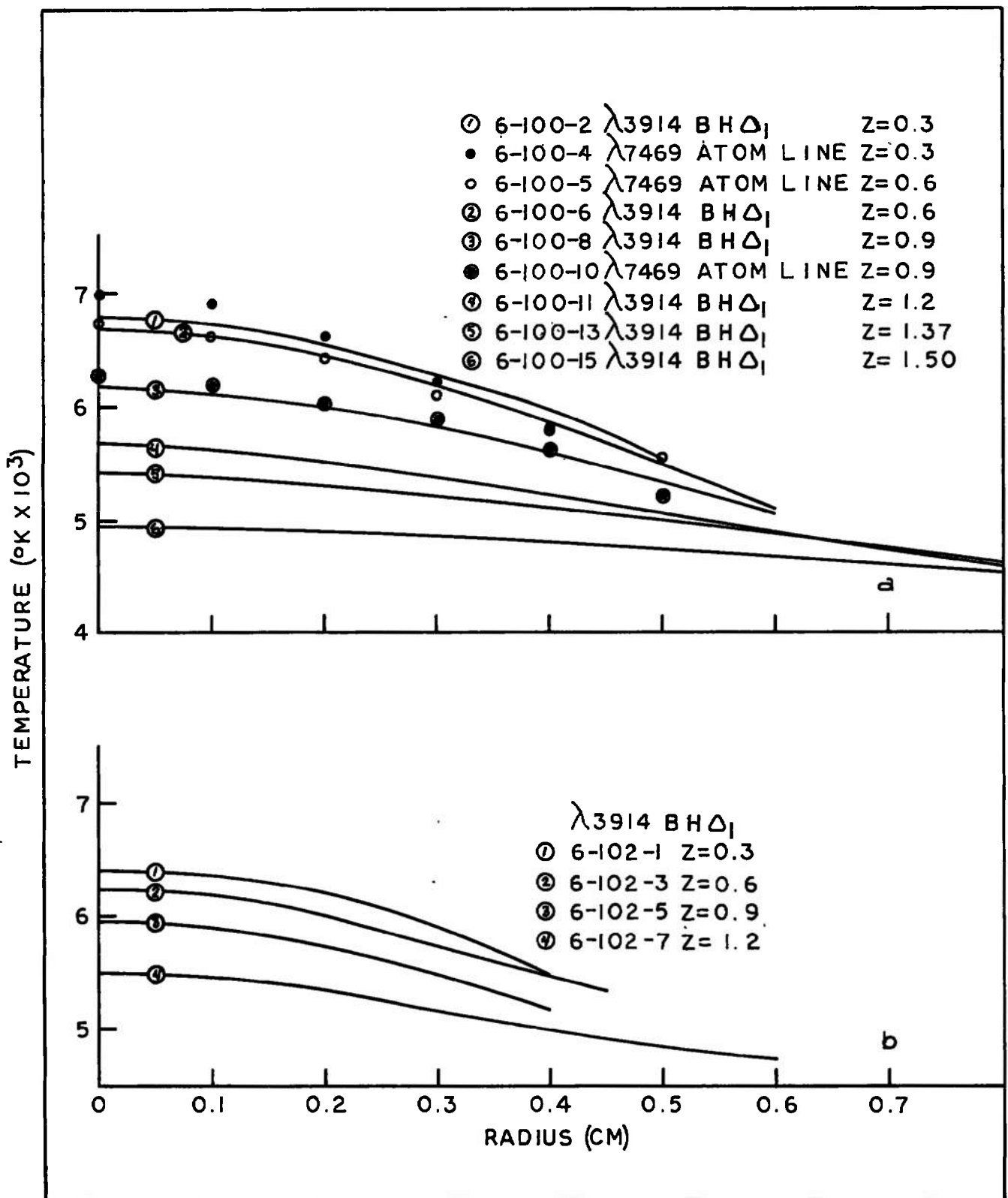


Fig. 28. Temperature vs radius for the two flow rates (a) 111 scfh and (b) 141 scfh in a nitrogen-oxygen plasma.

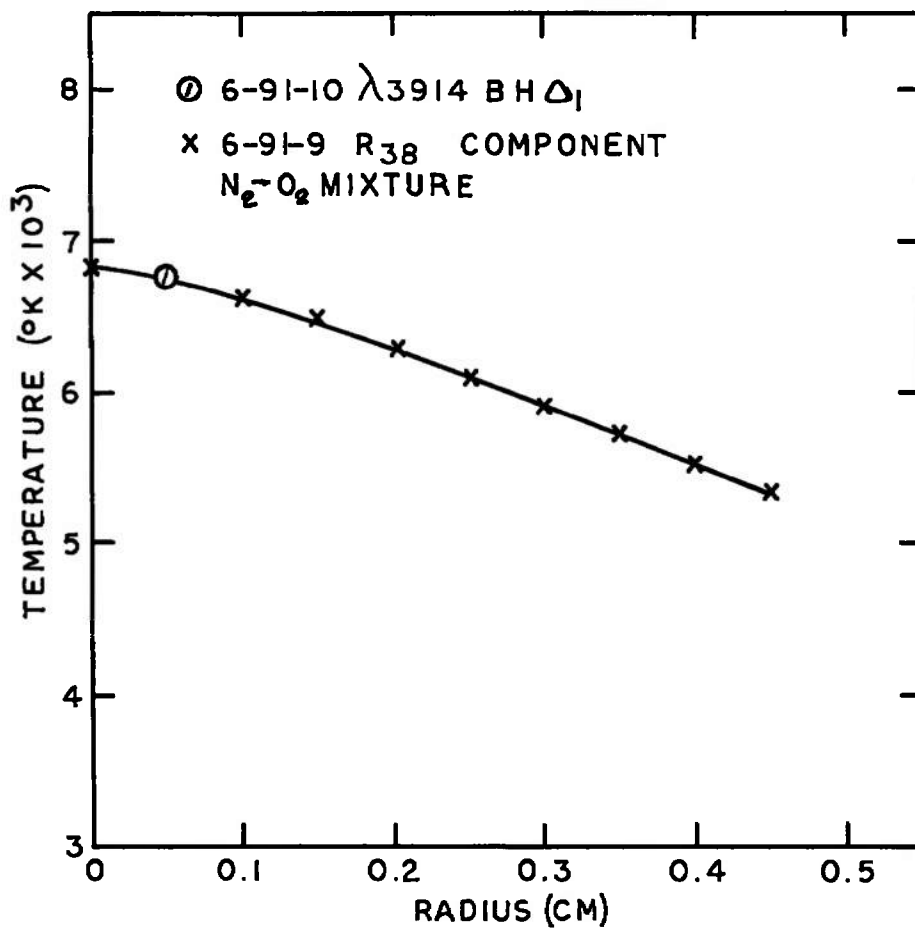


Fig. 29. Temperature vs radius for the λ_{3914} band head increment and the R_{38} component of the neutral band; the solid curve labeled (1) is for the band head.

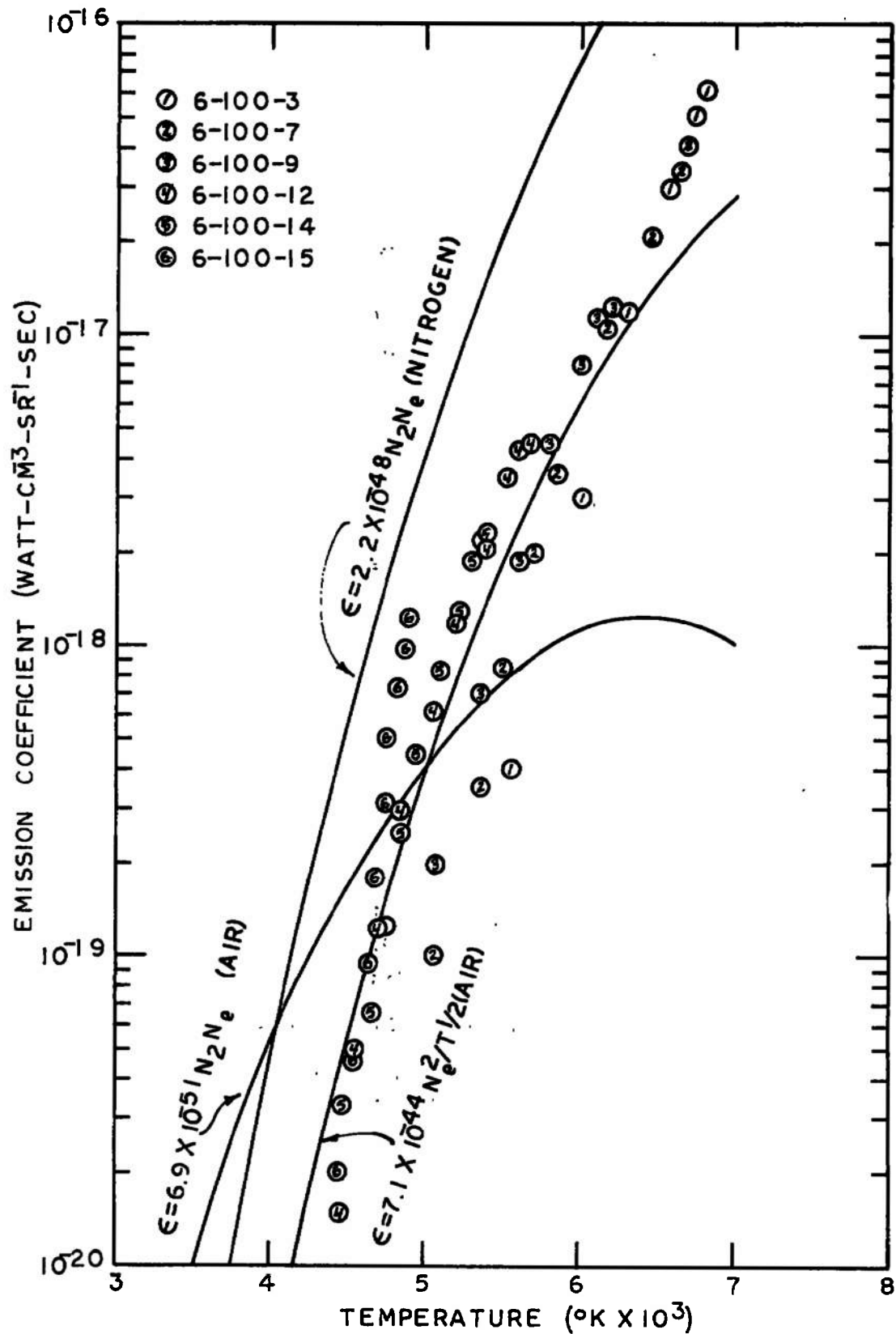


Fig. 30. Emission coefficient vs temperature for the $\lambda 3920$ continuum at a flow rate of 111 scfh in a nitrogen-oxygen plasma; temperature determined from $\lambda 3914 \text{ BH}\Delta_1$.

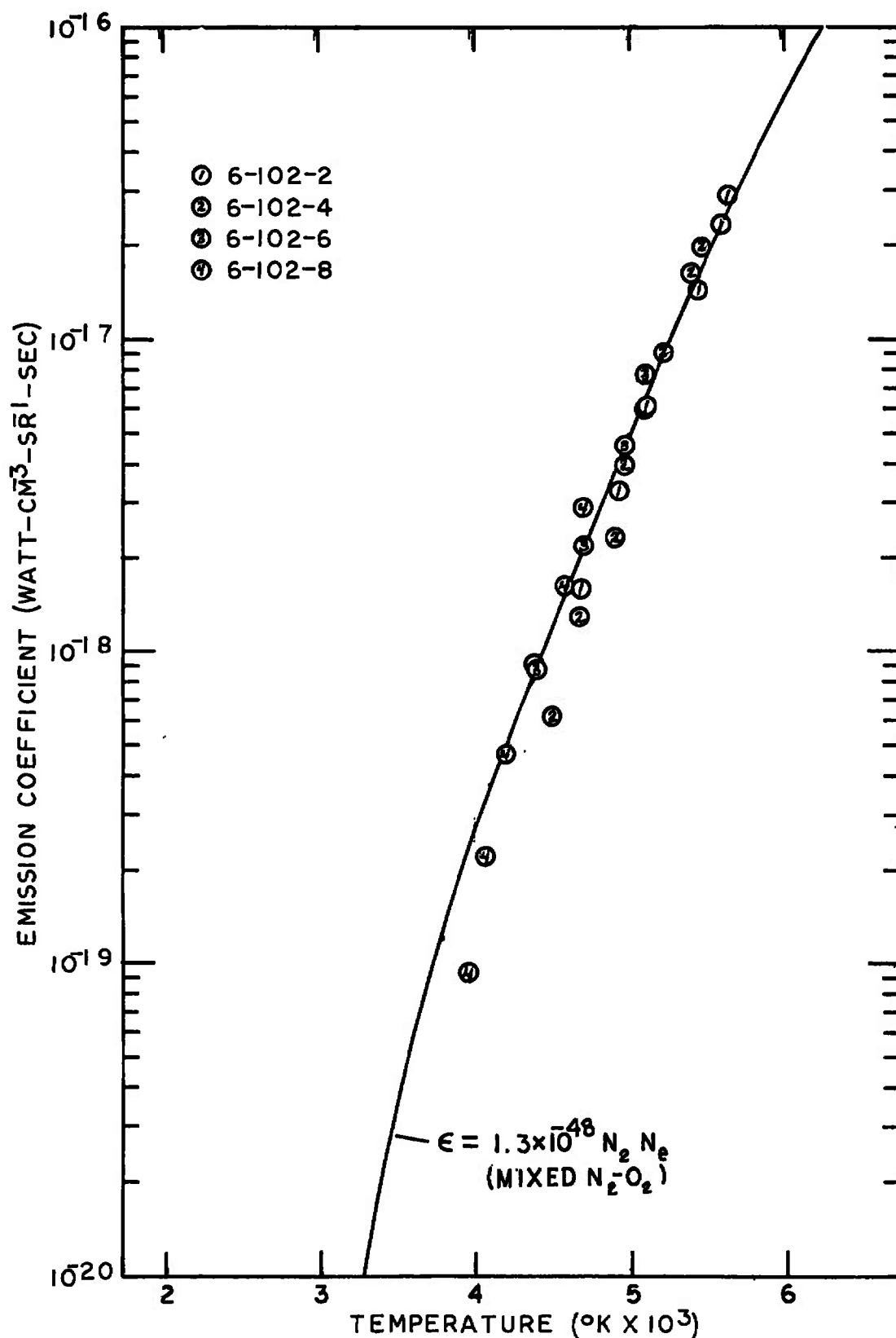


Fig. 31. Emission coefficient vs temperature for the λ_{3920} continuum at a flow rate of 141 scfh in a nitrogen-oxygen plasma; temperature determined from λ_{3914} $BH\Delta_1$.

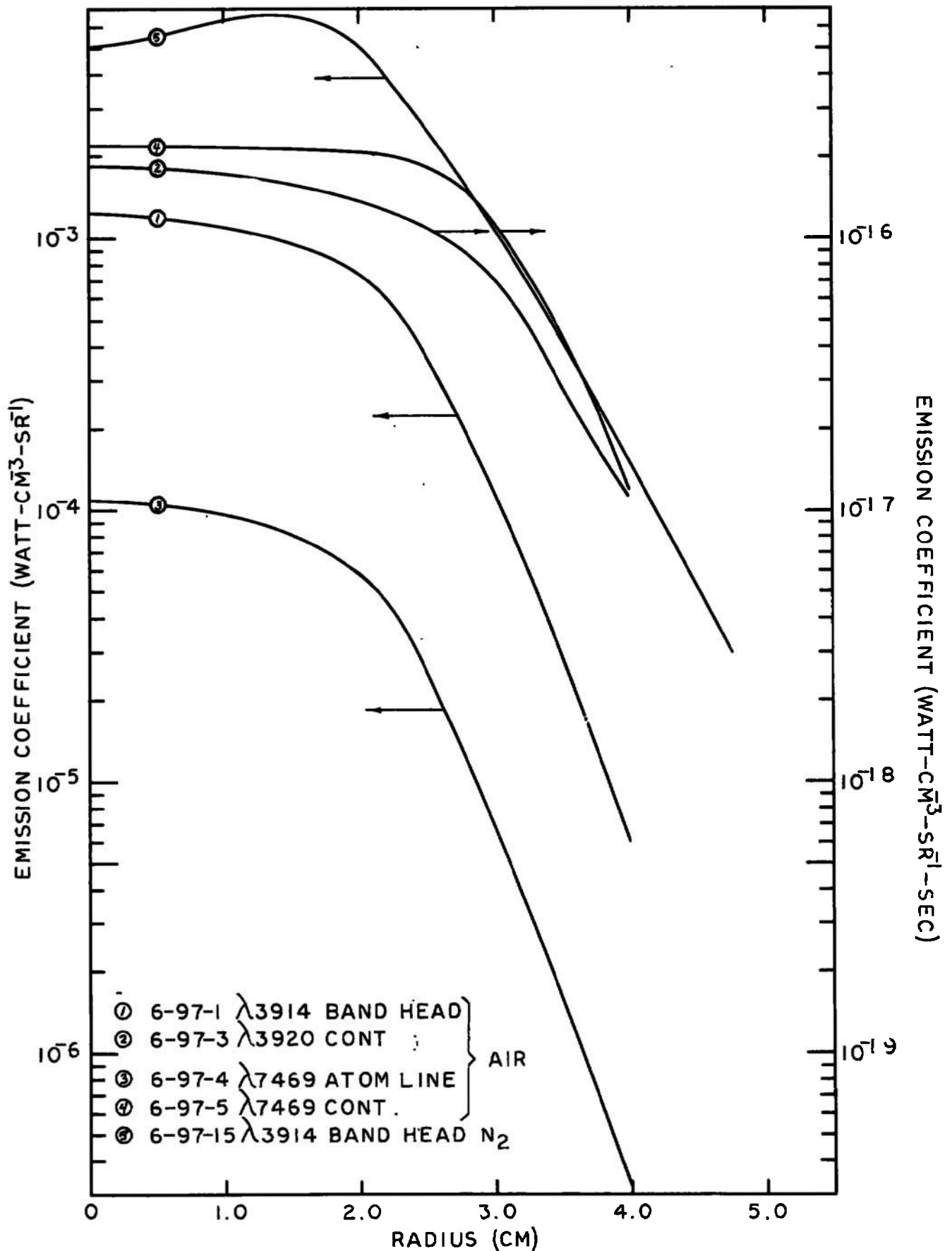


Fig. 32. Emission coefficient vs radius for nitrogen and air in an rf plasma.

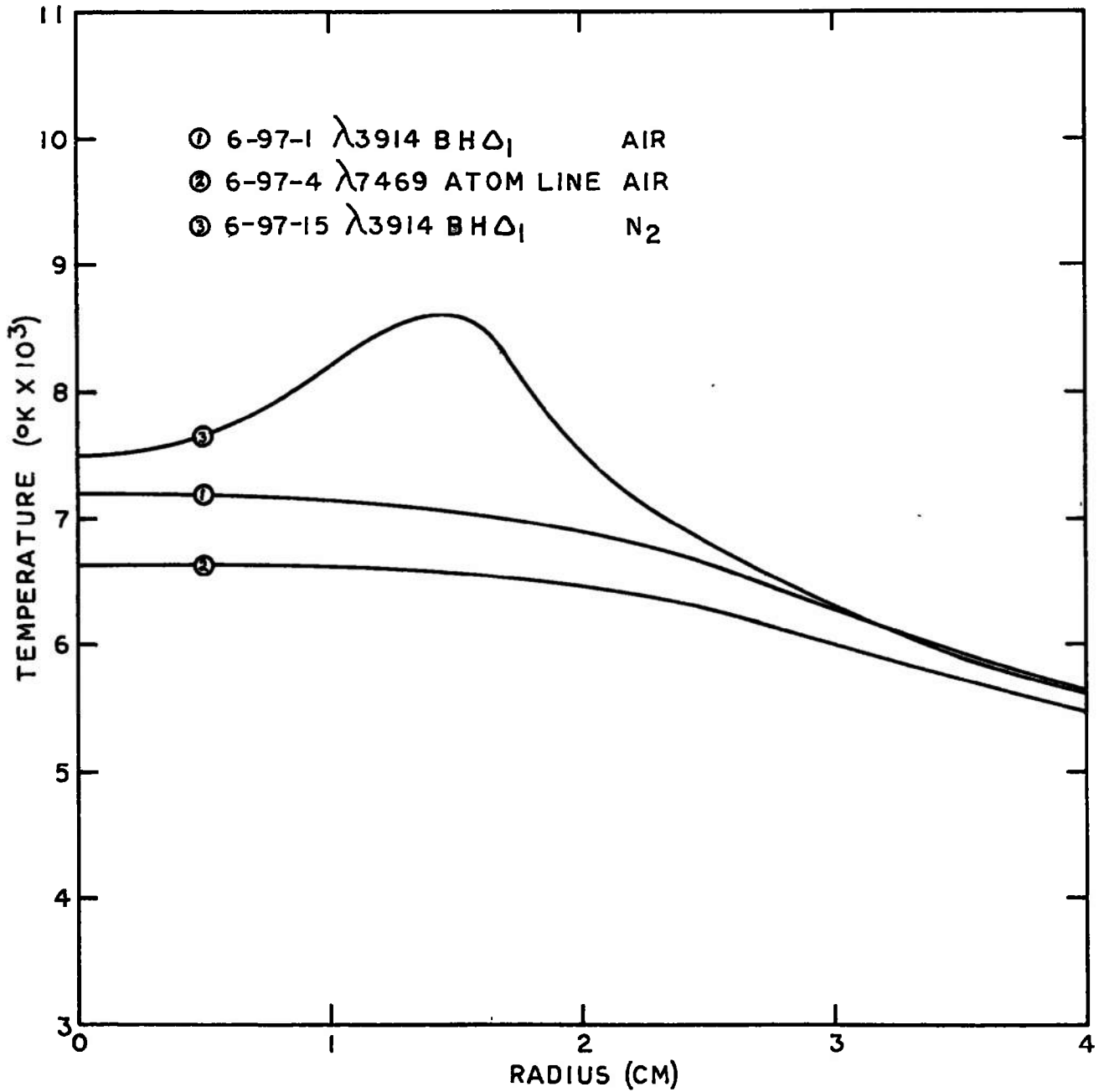


Fig 33. Temperature versus radius for nitrogen and air in an rf plasma.

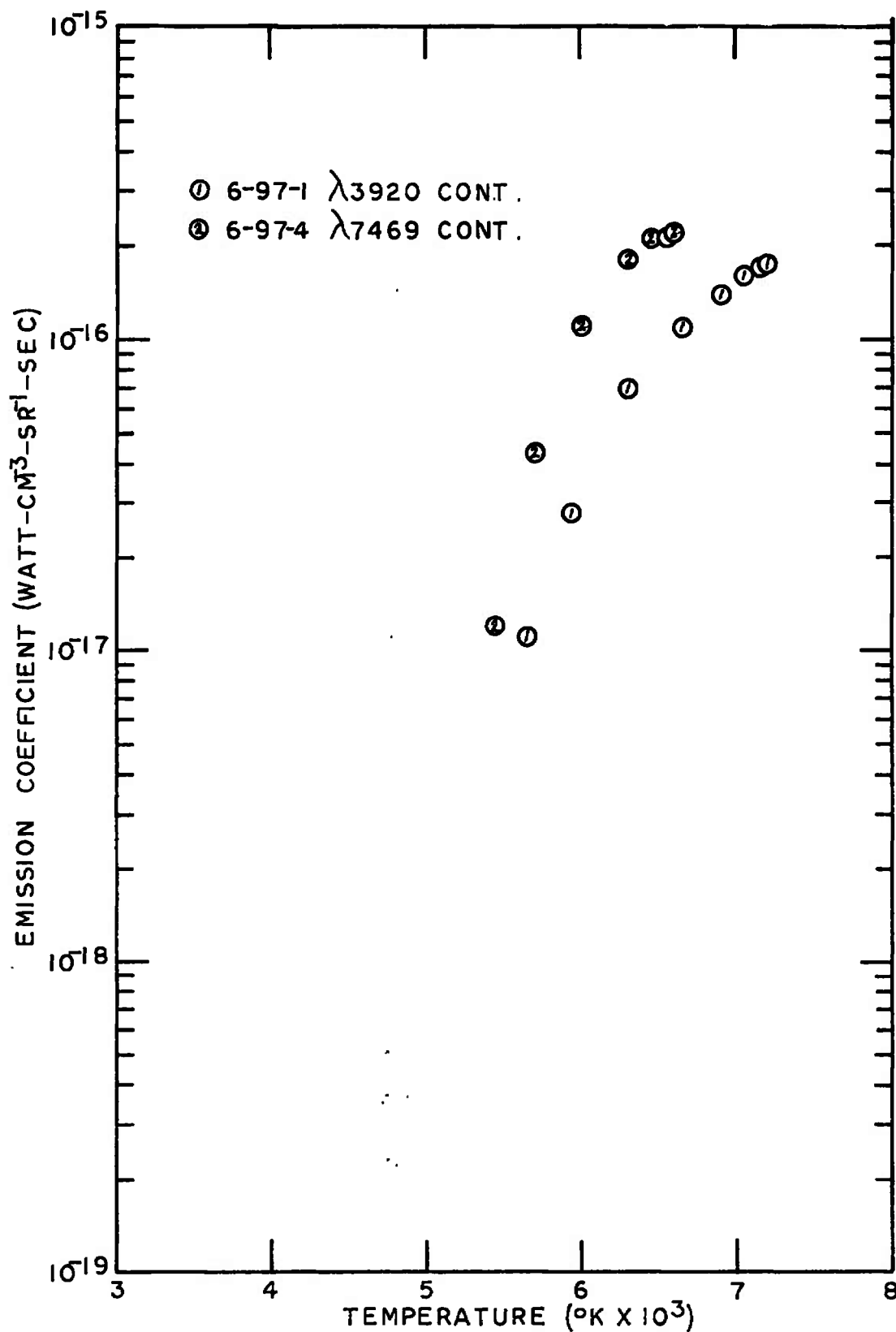


Fig.34. Experimental continuum emission coefficient versus temperature using the corresponding band head increment and atomic line for reference in an rf air plasma.

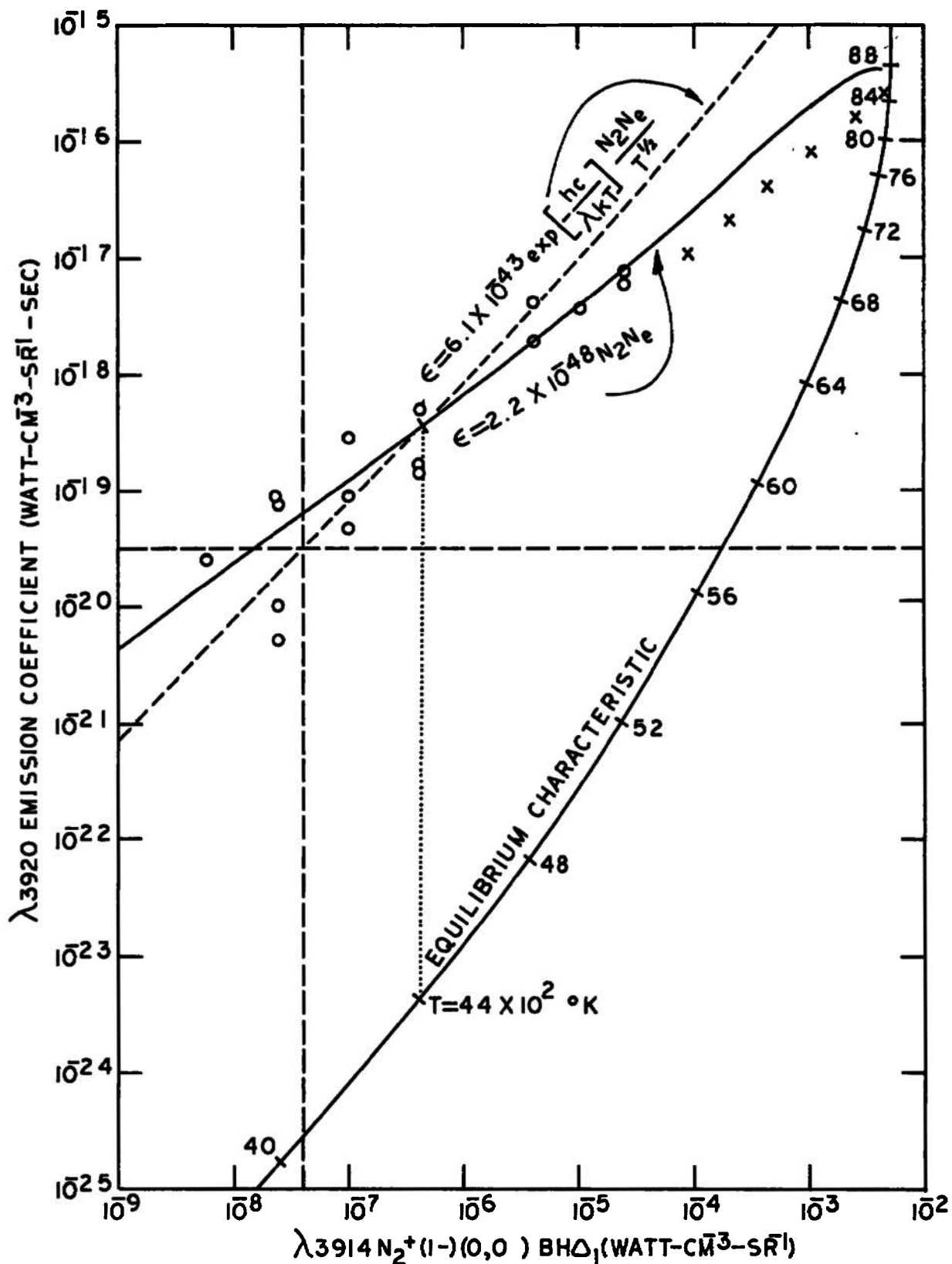


Fig. 35. Comparison of experimental data with equilibrium characteristic curve for 1 atm nitrogen plasma.

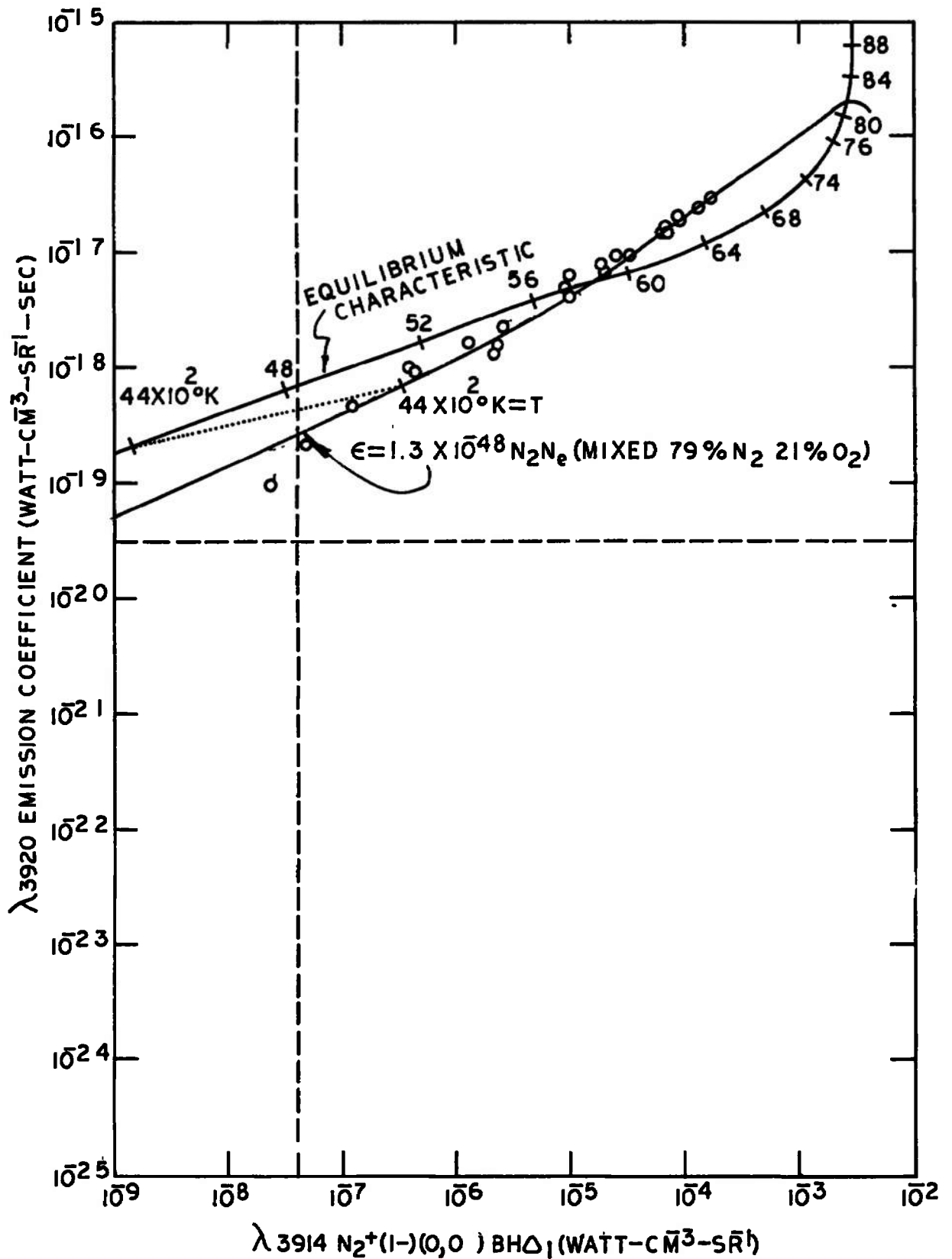


Fig. 36. Comparison of experimental data with equilibrium characteristic curves for 1 atm air and mixed nitrogen-oxygen plasmas.

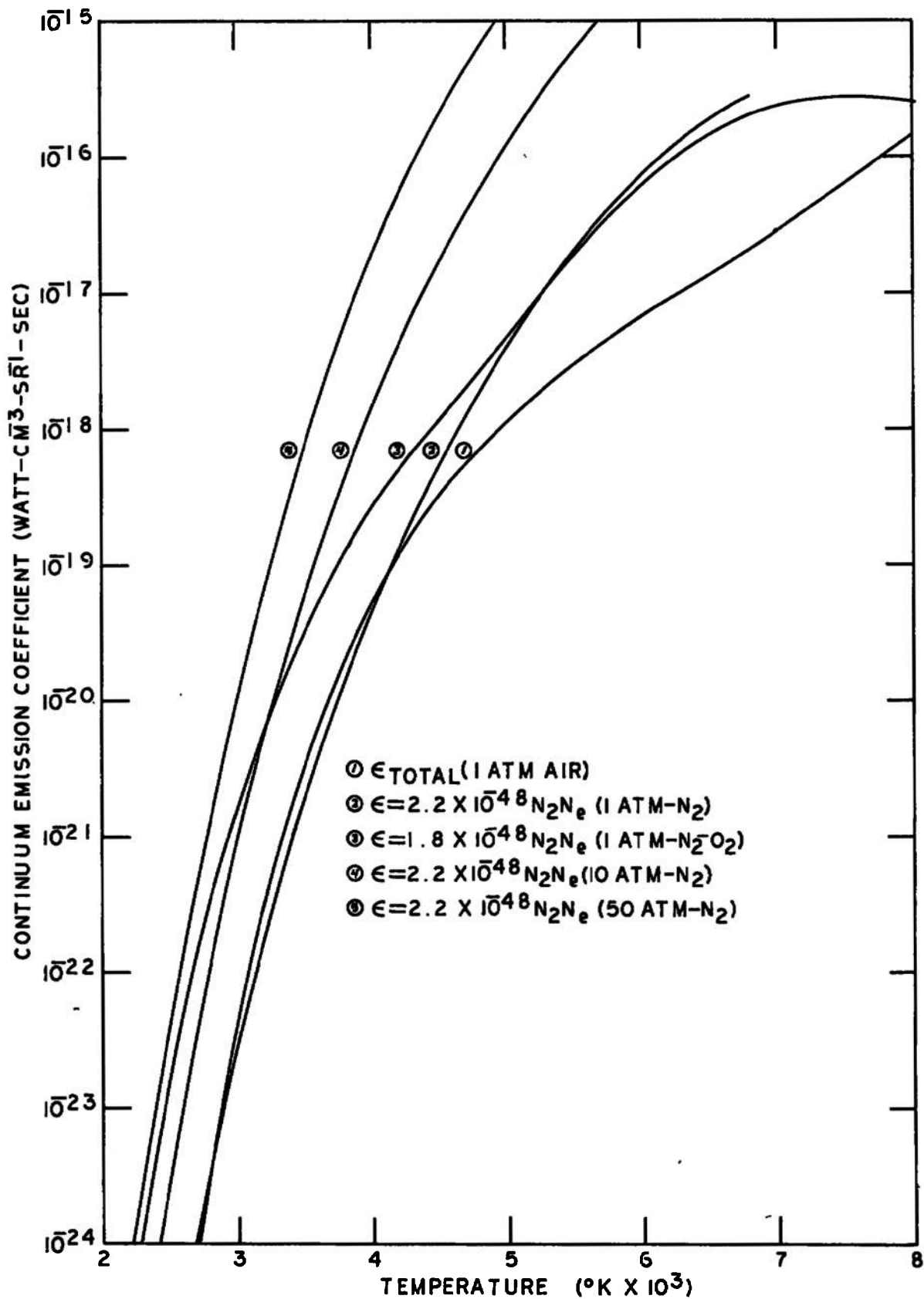


Fig. 37. Extrapolated calibration curves for λ_{3920} continuum for nitrogen, nitrogen-oxygen mixture and air plasmas.

TABLE I. PARTICLE NUMBER DENSITIES AND PARTITION FUNCTIONS USED IN ALL COMPUTATIONS.

T °K	PARTITION FUNCTIONS			PARTICLE NUMBER DENSITIES (cm^{-3})										
				NITROGEN - 1 ATM					AIR-1 ATM					
	U_2	U_2^+	U_0	N_2	N_2^+	N_-	N_0	N_e	N_2	N_2^+	N_-	N_0	N_e	O_-
2000	4.31 ^{2*}	9.26 ²	4.00	3.67 ¹⁸	1.43 ⁰⁰	1.02 ⁻¹	3.29 ⁰⁹	1.43 ⁰⁰	2.85 ¹⁸	4.11 ⁻⁷	1.73 ⁻⁸	2.92 ⁰⁹	3.51 ⁰⁶	2.835 ⁴
2400	5.59 ²	1.22 ³	4.00	3.06 ¹⁸	2.79 ⁰³	7.06 ⁻⁹	3.39 ¹¹	2.79 ⁰³	2.35 ¹⁸	1.12 ⁻²	6.65 ⁻⁴	1.98 ¹¹	4.94 ⁰⁸	7.846 ⁶
2800	7.05 ²	1.56 ³	4.00	2.62 ¹⁸	6.31 ⁰⁵	5.44 ⁻⁵	9.11 ¹²	6.32 ⁰⁵	1.98 ¹⁸	1.70 ⁰¹	1.14 ⁰⁰	7.94 ¹²	1.66 ¹⁰	3.895 ⁸
3200	8.69 ²	1.96 ³	4.00	2.29 ¹⁸	3.72 ⁰⁷	5.55 ⁻²	1.06 ¹⁴	3.72 ⁰⁷	1.66 ¹⁸	4.33 ⁰³	2.79 ⁰²	9.12 ¹³	2.22 ¹¹	6.067 ⁹
3600	1.05 ³	2.43 ³	4.00	2.04 ¹⁸	8.88 ⁰⁸	1.24 ⁰¹	7.12 ¹⁴	8.97 ⁰⁸	1.40 ¹⁸	3.48 ⁰⁵	1.73 ⁰⁴	5.93 ¹⁴	1.51 ¹²	3.788 ¹⁰
4000	1.25 ³	2.98 ³	4.01	1.83 ¹⁸	1.12 ¹⁰	9.32 ⁰²	3.23 ¹⁵	1.16 ¹⁰	1.21 ¹⁸	1.33 ⁰⁷	4.10 ⁰⁵	2.63 ¹⁵	6.27 ¹²	1.131 ¹¹
4400	1.47 ³	3.61 ³	4.02	1.66 ¹⁸	8.84 ¹⁰	3.22 ⁰⁴	1.11 ¹⁶	9.63 ¹⁰	1.07 ¹⁸	2.92 ⁰⁸	5.02 ⁰⁶	8.96 ¹⁵	1.86 ¹³	2.122 ¹¹
4800	1.70 ³	4.33 ³	4.03	1.50 ¹⁸	4.78 ¹¹	6.22 ⁰⁵	3.05 ¹⁶	5.80 ¹¹	9.64 ¹⁷	4.02 ⁰⁹	3.83 ⁰⁷	2.47 ¹⁶	4.42 ¹³	3.150 ¹¹
5200	1.96 ³	5.14 ³	4.05	1.34 ¹⁸	1.90 ¹²	7.69 ⁰⁶	7.12 ¹⁰	2.75 ¹²	8.61 ¹⁷	3.71 ¹⁰	2.03 ⁰⁸	5.73 ¹⁶	9.03 ¹³	4.106 ¹¹
5600	2.23 ³	6.06 ³	4.08	1.17 ¹⁸	5.84 ¹²	6.64 ⁰⁷	1.44 ¹⁷	1.08 ¹³	7.49 ¹⁷	2.47 ¹¹	8.13 ⁰⁸	1.16 ¹⁷	1.64 ¹⁴	4.893 ¹¹
6000	2.52 ³	7.09 ³	4.11	9.66 ¹⁷	1.43 ¹³	4.21 ⁰⁸	2.57 ¹⁷	3.59 ¹³	6.18 ¹⁷	1.24 ¹²	2.52 ⁰⁹	2.06 ¹⁷	2.69 ¹⁴	5.469 ¹¹
6400	2.84 ³	8.22 ³	4.14	7.40 ¹⁷	2.83 ¹³	2.01 ⁰⁹	4.05 ¹⁷	1.06 ¹⁴	4.22 ¹⁷	4.67 ¹²	6.40 ⁰⁹	3.24 ¹⁷	4.08 ¹⁴	5.700 ¹¹
6800	3.17 ³	9.47 ³	4.19	5.11 ¹⁷	4.61 ¹³	7.30 ⁰⁹	5.66 ¹⁷	2.61 ¹⁴	3.24 ¹⁷	1.31 ¹³	1.33 ¹⁰	4.51 ¹⁷	5.94 ¹⁴	5.710 ¹¹
7200	3.52 ³	1.09 ⁴	4.23	3.12 ¹⁷	6.23 ¹³	2.06 ¹⁰	7.05 ¹⁷	5.79 ¹⁴	1.97 ¹⁷	2.62 ¹³	2.52 ¹⁰	5.58 ¹⁷	8.87 ¹⁴	6.045 ¹¹
7600	3.89 ³	1.23 ⁴	4.29	1.71 ¹⁷	7.17 ¹³	4.66 ¹⁰	7.91 ¹⁷	1.15 ¹⁵	1.08 ¹⁷	3.82 ¹³	4.50 ¹⁰	6.24 ¹⁷	1.40 ¹⁵	7.018 ¹¹
8000	4.28 ³	1.40 ⁴	4.35	8.71 ¹⁶	7.36 ¹³	8.87 ¹⁰	8.25 ¹⁷	2.09 ¹⁵	5.52 ¹⁶	4.41 ¹³	7.63 ¹⁰	6.49 ¹⁷	2.26 ¹⁵	5.944 ¹¹
8400	4.69 ³	1.57 ⁴	4.42	4.36 ¹⁶	7.05 ¹³	1.49 ¹¹	8.23 ¹⁷	3.53 ¹⁵	2.75 ¹⁶	4.49 ¹³	1.22 ¹¹	6.46 ¹⁷	3.63 ¹⁵	1.110 ¹²
8800	5.13 ³	1.76 ⁴	4.49	2.20 ¹⁶	6.53 ¹³	2.60 ¹¹	8.01 ¹⁷	5.63 ¹⁵	1.38 ¹⁶	4.28 ¹³	1.84 ¹¹	6.25 ¹⁷	5.66 ¹⁵	1.415 ¹²
9200	5.58 ³	1.96 ⁴	4.56	1.15 ¹⁶	5.95 ¹³	3.35 ¹¹	7.69 ¹⁷	8.59 ¹⁵	7.26 ¹⁵	3.98 ¹³	3.22 ¹¹	6.03 ¹⁷	1.04 ¹⁶	1.790 ¹²
9600	6.06 ³	2.18 ⁴	4.64	6.13 ¹⁵	5.37 ¹³	4.62 ¹¹	7.33 ¹⁷	1.26 ¹⁶	3.92 ¹⁵	3.64 ¹³	3.63 ¹¹	5.75 ¹⁷	1.25 ¹⁶	2.217 ¹²
10000	6.57 ³	2.41 ⁴	4.72	3.37 ¹⁵	4.88 ¹³	6.08 ¹¹	6.95 ¹⁷	1.79 ¹⁶	2.18 ¹⁵	3.31 ¹³	4.77 ¹¹	5.44 ¹⁷	1.77 ¹⁶	2.685 ¹²

* Superscript means power of 10.

TABLE II A
(10 pages)

COMPUTED NORMALIZED EMISSION COEFFICIENTS FOR
INDIVIDUAL COMPONENTS AND SEXTET GROUPINGS OF
THE $N_2(2+)(0,0) \lambda_{.3371}^{\circ} \text{Å}$ BAND SYSTEM EMITTED
BY A 1 ATM NITROGEN PLASMA

LEGEND

T	Equilibrium Temperature, °K
J	Upper rotational state quantum number for the R_3 branch component (E3) of the ${}^3\Pi_2 \rightarrow {}^3\Pi_2$ subband
LAMBDA	λ_o of $R_{J'}^2$, single component (E3)
E1,...E6	$\epsilon_{J'}^{*i}, \text{ cm}^{-6} \text{ sr}^{-1} \text{ sec}^{-1}$
ET	$\sum_{i=1}^6 \epsilon_{J'}^{*i} = \epsilon_{J'}^*, \text{ cm}^{-6} \text{ sr}^{-1} \text{ sec}^{-1}$

Table with 7 columns: K, LAMDA, E1, E2, E3, E4, ET. Rows 1-22 for T = 5200.0.

Table with 7 columns: K, LAMDA, E1, E2, E3, E4, ET. Rows 1-22 for T = 5400.0.

Table with 7 columns: K, LAMDA, E1, E2, E3, E4, ET. Rows 1-22 for T = 5600.0.

Table with 7 columns: K, LAMDA, E1, E2, E3, E4, ET. Rows 1-22 for T = 5800.0.

TABLE II B
(10 pages)

COMPUTED NORMALIZED EMISSION COEFFICIENTS FOR
INDIVIDUAL COMPONENTS AND SEXTET GROUPINGS OF
THE $N_2(2+)(0,0)$ λ 3371 Å BAND SYSTEM IN A 1 ATM
AIR PLASMA

LEGEND

T	Equilibrium Temperature, °K
J	Upper rotational state quantum number for the R_3 branch component (E3) of the ${}^3\Pi_2 \rightarrow {}^3\Pi_2$ subband
LAMBDA	λ_o of R_J^2 , single component (E3)
E1,..E6	$\epsilon_{J,i}^*$, $\text{cm}^{-6} \text{-sr}^{-1} \text{-sec}^{-1}$
ET	$\sum_{i=1}^6 \epsilon_{J,i}^* = \epsilon_J^*$, $\text{cm}^{-6} \text{-sr}^{-1} \text{-sec}^{-1}$

TABLE III A
(14 pages)

COMPUTED NORMALIZED EMISSION COEFFICIENTS FOR
INDIVIDUAL COMPONENTS AND QUARTET GROUPINGS OF
THE $N_2^+(1-)(0,0) \lambda 3914 \text{ \AA}$ BAND SYSTEM IN AN
ATMOSPHERIC PRESSURE NITROGEN PLASMA

LEGEND

T	Equilibrium Temperature, °K
K	Upper rotational quantum number for R branch component (E2) of the ${}^2\Sigma_1 \rightarrow {}^2\Sigma_1$ subband
LAMBDA	λ_0 of $R_{K'}^1$ band component (E2) $\text{\AA}$
E1...E4	$\epsilon_{K'}^{*i} \text{ cm}^{-6} \text{ sr}^{-1} \text{ sec}^{-1}$
ET	$\sum_{i=1}^4 \epsilon_{K'}^{*i} = \epsilon_{K'}^* \text{ cm}^{-6} \text{ sr}^{-1} \text{ sec}^{-1}$

TABLE III B
(14 pages)

COMPUTED NORMALIZED EMISSION COEFFICIENTS FOR
INDIVIDUAL COMPONENTS AND QUARTET GROUPINGS OF
THE $N_2^+(1-)(0,0) \lambda_{3914} \text{ \AA}$ BAND SYSTEM IN AN
ATMOSPHERIC PRESSURE AIR PLASMA

LEGEND

T	Equilibrium Temperature, °K
K	Upper rotational quantum number for R branch component (E2) of the ${}^2\sum_1 \rightarrow {}^2\sum_1$ subband
LAMBDA	λ_o of $R_{K'}^1$ band component (E2) Å
E1,...E4	$\epsilon_{K'}^{*i} \text{ cm}^{-6} \text{ -sr}^{-1} \text{ -sec}^{-1}$
ET	$\sum_{i=1}^4 \epsilon_{K'}^{*i} = \epsilon_{K'}^* \text{ cm}^{-6} \text{ -sr}^{-1} \text{ -sec}^{-1}$

TABLE IV. COMPUTED NORMALIZED EMISSION COEFFICIENTS
IN 1 ATM NITROGEN AND AIR PLASMAS. **

T °K	NITROGEN			AIR		
	BH Δ_1 3.9A°	BH Δ_2 28A°	λ_{7468} NI	BH Δ_1 3.9A°	BH Δ_2 28A°	λ_{7468} NI
2000	1.09 ^{15*}	3.70 ¹⁶	4.11 ⁻⁴¹	3.14 ⁰⁸	1.07 ¹⁰	3.65 ⁻⁴¹
2400	1.96 ¹⁹	1.88 ²⁰	4.62 ⁻³⁴	7.90 ¹³	7.58 ¹⁴	4.07 ⁻³⁴
2800	3.56 ²²	3.68 ²³	4.94 ⁻²⁹	9.56 ¹⁷	9.89 ¹⁸	4.30 ⁻²⁹
3200	9.58 ²⁴	1.05 ²⁶	2.88 ⁻²⁵	1.11 ²¹	1.23 ²²	2.47 ⁻²⁵
3600	7.04 ²⁶	8.32 ²⁷	2.42 ⁻²²	2.76 ²³	3.26 ²⁴	2.02 ⁻²²
4000	2.17 ²⁸	2.67 ²⁹	5.25 ⁻²⁰	2.57 ²⁵	3.18 ²⁶	4.27 ⁻²⁰
4400	3.41 ²⁹	4.39 ³⁰	4.24 ⁻¹⁸	1.13 ²⁷	1.45 ²⁸	3.43 ⁻¹⁸
4800	3.22 ³⁰	4.31 ³¹	1.63 ⁻¹⁶	2.70 ²⁸	3.62 ²⁹	1.32 ⁻¹⁶
5200	2.01 ³¹	2.78 ³²	3.52 ⁻¹⁵	3.92 ²⁹	5.43 ³⁰	2.83 ⁻¹⁵
5600	8.92 ³¹	1.27 ³³	4.79 ⁻¹⁴	3.77 ³⁰	5.38 ³¹	3.84 ⁻¹⁴
6000	2.96 ³²	4.35 ³³	4.44 ⁻¹³	2.57 ³¹	3.77 ³²	3.57 ⁻¹³
6400	7.53 ³²	1.14 ³⁴	2.96 ⁻¹²	1.24 ³²	1.82 ³³	2.37 ⁻¹²
6800	1.53 ³³	2.36 ³⁴	1.47 ⁻¹¹	4.34 ³²	6.68 ³³	1.17 ⁻¹¹
7200	2.48 ³³	3.89 ³⁴	5.66 ⁻¹¹	1.04 ³³	1.61 ³⁴	4.48 ⁻¹¹
7600	3.32 ³³	5.33 ³⁴	1.74 ⁻¹⁰	1.77 ³³	2.83 ³⁴	1.37 ⁻¹⁰
8000	3.88 ³³	6.34 ³⁴	4.46 ⁻¹⁰	2.24 ³³	3.80 ³⁴	3.51 ⁻¹⁰
8400	4.16 ³³	6.90 ³⁴	1.00 ⁻⁹	2.64 ³³	4.39 ³⁴	7.87 ⁻¹⁰
8800	4.23 ³³	7.13 ³⁴	2.04 ⁻⁹	2.77 ³³	4.68 ³⁴	1.60 ⁻⁹
9200	4.17 ³³	7.14 ³⁴	3.83 ⁻⁹	2.79 ³³	4.78 ³⁴	3.01 ⁻⁹
9600	4.03 ³³	7.01 ³⁴	6.75 ⁻⁹	2.73 ³³	4.75 ³⁴	5.29 ⁻⁹
10000	3.82 ³³	6.75 ³⁴	1.12 ⁻⁸	2.63 ³³	4.63 ³⁴	8.79 ⁻⁹

* Superscript means power of 10.

** Similar data for R₆, R₂₂ and R₃₈ components are given in Tables I and II.

TABLE V. SUMMARY OF DATA

RUN #	TRACE #	TYPE	λ (Å)	ENTRANCE	SLIT	EXIT SLIT (Å)	SPEC	Z (IN.)	MAG	JET OPEN	QUENCH	H _{ave} (BTU/lb)	T _{ave} (°K)	SPECTRAL TEMP. RANGE (°K)
				WIDTH (IN.)	HEIGHT (IN.)									
1	6-69-18	B-H	3914	.002	.161	4.0	LS	0.3	+5	NO	YES	4227	5750	7900-5400
2	6-72-1	B-H	3914	.002	.161	3.81	LS	0.3	+5	NO	YES	4196	5700	7800-5400
3	6-72-7	ATOM	7468	.002	.161	3.81	LS	0.3	+5	NO	YES	4196	5700	7800-6900
4	6-72-13	R-38	3323	.002	.161	1.1	LS	0.3	+5	NO	YES	4196	5700	7400-5500
5	6-72-19	R-16	3895	.002	.161	1.1	LS	0.3	+5	NO	YES	4196	5700	6700-5200
6	6-72-23	R-6	3906	.002	.161	1.1	LS	0.3	+5	NO	YES	3849	5500	7800-5400
7	6-73-1	R-6	3906	.002	.161	0.9	LS	0.3	+5	NO	YES	3925	5600	7800-5400
8	6-73-5	R-16	3895	.002	.161	1.3	LS	0.3	+5	NO	YES	3925	5600	6700-5200
9	6-73-12	R-38	3323	.002	.161	1.3	LS	0.3	+5	NO	YES	3925	5600	7400-5500
10	6-73-18	CONT	5600	.002	.161	3.71	LS	0.3	+5	NO	YES	3925	5600	8800-8000
11	6-74-1	ATOM	7468	.002	.161	3.71	LS	0.3	+5	NO	YES	5132	6000	9300-6700
12	6-74-2	B-H	3914	.002	.031	4.53	SS	0.3	+5	NO	YES	5132	6000	9300-5200
13	6-74-7	ATOM	7468	.002	.161	3.71	LS	0.3	+5	NO	YES	5713	6150	9600-6600
14	6-74-8	B-H	3914	.002	.031	4.53	SS	0.3	+5	NO	YES	5713	6150	9400-5300
15	6-74-19	ATOM	7468	.002	.161	3.71	LS	0.3	+5	NO	YES	6979	6450	10300-6900
16	6-74-20	B-H	3914	.002	.031	4.53	SS	0.3	+5	NO	YES	6979	6450	10100-5500
17	6-74-25	R-16	3895	.002	.161	0.82	LS	0.3	+5	NO	YES	6041	6250	10000-5800
18	6-75-1	R-6	3906	.002	.161	0.82	LS	0.3	+5	NO	YES	6041	6250	10600-6000
19	6-75-7	R-38	3323	.002	.161	0.82	LS	0.3	+5	NO	YES	6041	6250	11000-5500
20	6-75-29	ATOM	7468	.002	.161	3.67	LS	0.3	+5	NO	YES	6041	6250	10800-8200
21	6-78-7	ATOM	7468	.002	.161	3.86	LS	0.3	+5	NO	YES	4707	5900	7500-5900
22	6-78-8	B-H	3914	.002	.031	4.26	SS	0.3	+5	NO	YES	4707	5900	7200-5100
23	6-78-13	ATOM	7468	.002	.161	3.86	LS	0.3	+5	NO	YES	3691	5500	7200-5800
24	6-78-14	B-H	3914	.002	.031	4.26	SS	0.3	+5	NO	YES	3691	5500	6800-5000
25	6-78-19	ATOM	7468	.002	.161	3.86	LS	0.3	+5	NO	YES	3117	5150	6700-5500

TABLE V (Continued)

RUN #	TRACE #	TYPE	λ Å	ENTRANCE	SLIT	EXIT SLIT Å	SPEC	Z (IN.)	MAG	JET OPEN	QUENCH	H _{ave} (BTU/lb)	T _{ave} (°K)	SPECTRAL TEMP. RANGE (°K)
				WIDTH (IN.)	HEIGHT (IN.)									
26	6-78-20	B-H	3914	.002	.031	4.26	SS	0.3	+5	NO	YES	3117	5150	6300-4600
27	6-78-29	R-22	3886	.002	.161	0.71	LS	0.3	+5	NO	YES	5791	6200	10000-5500
28	6-78-30	B-H	3914	.002	.031	4.26	SS	0.3	+5	NO	YES	5791	6200	9100-5500
29	6-79-5	R-22	3886	.002	.161	0.71	LS	0.3	+5	NO	YES	5187	6060	8000-5500
30	6-79-6	B-H	3914	.002	.031	4.26	SS	0.3	+5	NO	YES	5187	6060	8000-5500
31	6-79-11	R-22	3886	.002	.161	0.71	LS	0.3	+5	NO	YES	4543	5850	7600-4900
32	6-79-12	B-H	3914	.002	.031	4.26	SS	0.3	+5	NO	YES	4543	5850	7600-4900
33	6-79-17	R-22	3886	.002	.161	0.71	LS	0.3	+5	NO	YES	3691	5500	6700-5000
34	6-79-18	B-H	3914	.002	.031	4.26	SS	0.3	+5	NO	YES	3691	5500	6700-5000
35	6-69-23	R-22	3886	.002	.161	0.71	LS	0.3	+5	NO	YES	2804	4900	6400-4700
36	6-79-24	B-H	3914	.002	.031	4.26	SS	0.3	+5	NO	YES	2804	4900	6400-4700
37	6-79-29	R-22	3886	.002	.161	0.71	LS	0.3	+5	NO	YES	2093	3900	6100-4700
38	6-79-30	B-H	3914	.002	.031	4.26	SS	0.3	+5	NO	YES	2093	3900	6100-4700
39	6-81-19	ATOM	7468	.002	.031	12.6	LS	0.05	+5	-	-	-	-	26000-8000
40	6-82-7	R-38	3323	.002	.161	0.8	LS	0.3	+5	NO	YES	5467	6100	7500-5000
41	6-82-8	B-H	3914	.002	.031	4.53	SS	0.3	+5	NO	YES	5467	6100	7500-5000
42	6-82-13	R-38	3323	.002	.161	0.8	LS	0.3	+5	NO	YES	3100	5100	6600-4900
43	6-82-14	B-H	3914	.002	.031	4.53	SS	0.3	+5	NO	YES	3100	5100	6600-4900
44	6-83-1	B-H	3914	.002	.031	4.53	SS	0.3	+5	NO	YES	2344	4300	6100-5000
45	6-83-5	B-H	3914	.002	.161	4.53	SS	0.3	+5	NO	YES	1396	2600	5100-4500

TABLE V (Continued)

RUN #	TRACE #	TYPE	λ (Å)	ENTRANCE	SLIT	EXIT SLIT (Å)	SPEC	Z (IN.)	MAG	JET OPEN	QUENCH	H _{ave} (BTU/lb)	T _{ave} (°K)	SPECTRAL TEMP. RANGE (°K)
				WIDTH (IN.)	HEIGHT (IN.)									
46	6-84-1	B.H	3914	0.002	0.161	4.53	SS	0.3	+5	NO	YES	1508	2900	4900-4000
47	6-87-1	B.H	3914	0.002	0.031	4.53	SS	0.3	-4	NO	YES	2428	4300	5820-4620
48	6-87-5	B.H	3914	0.002	0.031	4.53	SS	0.3	-4	NO	YES	2428	2100	4500-3825
49	6-87-9	B.H	3914	0.002	0.031	4.53	SS	0.3	+5	NO	YES	3190	5170	6500-4700
50	6-88-1	B.H	3914	0.002	0.0635	4.07	LS	0.3	+5	NO	YES	3190	5170	6500-4700
51	6-88-2	B.H	3914	0.002	0.020	28.6	SS	0.3	+5	NO	YES	3190	5170	6550-4790
52	6-88-5	Cont	3920	0.002	0.020	28.6	SS	0.3	+5	NO	YES	3190	5170	6550-4790
53	6-88-10	B.H	3914	0.002	0.0635	4.07	LS	0.3	+5	NO	YES	1625	3120	5325-4225
54	6-88-11	B.H	3914	0.002	0.031	28.6	SS	0.3	+5	NO	YES	1625	3120	5325-4225
55	6-88-14	Cont	3920	0.002	0.031	28.6	SS	0.3	+5	NO	YES	1625	3120	5325-4225
56	6-89-7	B.H	3914	0.002	0.161	4.07	LS	0.3	+5	NO	YES	1860	3580	5410-4250
57	6-89-9	B.H	3914	0.002	0.161	28.6	SS	0.3	+5	NO	YES	1860	3580	5410-4250
58	6-89-19	B.H	3914	0.002	0.161	4.07	LS	0.3	+5	NO	YES	1720	3320	5300-4325
59	6-89-21	B.H	3914	0.002	0.161	28.6	SS	0.3	+5	NO	YES	1720	3320	5300-4325
60	6-91-2	B.H	3914	0.002	0.161	4.59	SS	0.3	+5	NO	YES	4615	5850	7500-5200
61	6-91-6	B.H	3914	0.002	0.161	4.59	SS	0.3	+5	NO	YES	3131	5120	6370-4900
62	6-92-2	B.H	3914	0.002	0.161	4.59	SS	0.3	+5	NO	YES	3370	5280	6800-4800
63	6-93-1	Cont	5575	0.002	0.161	6.0	LS	0.3	+5	YES	YES	4502	5850	8600-5370
64	6-93-2	B.H	3914	0.002	0.161	4.59	SS	0.3	+5	YES	YES	4502	5850	8600-5370
65	6-93-3	Cont	3920	0.002	0.161	4.59	SS	0.3	+5	YES	YES	4502	5850	8600-5370
66	6-93-6	Cont	3920	0.002	0.040	28.6	SS	1.22	-4	YES	YES	2739	4800	4880-4080
67	6-93-7	B.H	3914	0.002	0.040	28.6	SS	1.22	-4	YES	YES	2739	4800	4880-4080
68	6-93-8	Cont	5600	0.002	0.040	28.6	SS	1.22	-4	YES	YES	2739	4800	4880-4080
69	6-93-12	B.H	3914	0.002	0.040	4.06	LS	1.22	-4	YES	YES	1456	2800	4305-3710

TABLE V (Continued)

RUN #	TRACE #	TYPE	λ (Å)	ENTRANCE	SLIT	EXIT SLIT (Å)	SPEC	Z (IN.)	MAG	JET OPEN	QUENCH	H _{ave} BTU/lb	T _{ave} (°K)	SPECTRAL TEMP. RANGE (°K)
				WIDTH (IN.)	HEIGHT (IN.)									
70	6-93-13	Cont	5600	0.002	0.040	86	SS	1.22	-4	YES	YES	1456	2800	4305-3710
71	6-93-16	Cont	5600	0.002	0.040	86	SS	1.22	-4	YES	YES	2087	3900	5250-4280
72	6-93-17	Cont	5600	0.002	0.040	86	SS	1.22	-4	YES	YES	1917	3650	5180-3950
73	6-93-18	Cont	5600	0.002	0.040	86	SS	1.22	-4	YES	YES	1773	3400	5140-4020
74	6-93-19	Cont	5600	0.002	0.040	86	SS	1.22	-4	YES	YES	1542	2950	4850-4040
75	6-93-20	B.H	3914	0.002	0.040	4.06	LS	1.22	-4	YES	YES	1542	2950	4850-4040
76	6-94-1	Cont	5600	0.002	0.161	86	SS	1.22	+5	YES	YES	2781	4850	4910-4120
77	6-94-2	Cont	5600	0.002	0.161	86	SS	1.22	+5	YES	YES	2363	4350	4910-4120
78	6-94-3	Cont	5600	0.002	0.161	86	SS	1.22	+5	YES	YES	2053	3850	4910-4120
79	6-94-4	B.H	3914	0.002	0.161	4.06	LS	1.22	+5	YES	YES	2781	4850	4910-4120
80	6-94-8	B.H	3914	0.020	0.020	4.06	LS	1.22	-4	YES	YES	4728	5880	5960-4500
81	6-94-9	B.H	3914	0.020	0.020	4.06	LS	1.22	-4	YES	YES	2079	3900	4140-3660
82	6-94-9a	Cont	3920	0.020	0.020	4.06	LS	1.22	-4	YES	YES	2079	3900	4140-3660
83	6-94-11	B.H	3914	0.020	0.020	4.06	LS	1.72	-4	YES	YES	4728	5880	5220-4300
84	6-94-12	Cont	3914	0.020	0.020	4.06	LS	1.72	-4	YES	YES	1678	3210	4100-3450
85	6-94-15	B.H	3914	0.020	0.020	4.06	LS	1.72	-4	YES	NO	4728	5880	4910-4080
86	6-94-15a	Cont	3920	0.020	0.020	4.06	LS	1.72	-4	YES	NO	4728	5880	4910-4080
87	6-94-16	B.H	3914	0.020	0.020	4.06	LS	1.72	-4	YES	NO	3712	3210	4245-3820
88	6-94-16a	Cont	3920	0.020	0.020	4.06	LS	1.72	-4	YES	NO	3712	3210	4245-3820
89	6-95-1	B.H	3914	0.020	0.020	28.6	SS	1.72	-4	YES	NO	5243	6050	5220-4520
90	6-95-2	Cont	3920	0.020	0.020	28.6	SS	1.72	-4	YES	NO	5243	6050	5220-4520
91	6-95-3	Cont	5600	0.020	0.020	28.6	SS	1.72	-4	YES	NO	5243	6050	5220-4520
92	6-95-4	B.H	3914	0.020	0.020	28.6	SS	1.72	-4	YES	NO	4612	5850	4950-4260
93	6-95-5	Cont	3920	0.020	0.020	28.6	SS	1.72	-4	YES	NO	4612	5850	4950-4260

TABLE V (Continued)

RUN #	TRACE #	TYPE	λ (Å)	ENTRANCE	SLIT	EXIT SLIT (Å)	SPEC	Z (IN.)	MAG	JET OPEN	QUENCH	H _{ave} BTU/lb	T _{ave} (°K)	SPECTRAL TEMP. RANGE (°K)
				WIDTH (IN.)	HEIGHT (IN.)									
94	6-95-6	Cont	5600	0.020	0.020	28.6	SS	1.72	-4	YES	NO	4612	5850	4950-4260
95	6-95-7	B.H	3914	0.020	0.020	28.6	SS	1.72	-4	YES	NO	4117	5650	4740-4120
96	6-95-8	Cont	3920	0.020	0.020	28.6	SS	1.72	-4	YES	NO	4117	5650	4740-4120
97	6-95-9	Cont	5600	0.020	0.020	28.6	SS	1.72	-4	YES	NO	4117	5650	4740-4120
98	6-95-10	B.H	3914	0.020	0.020	28.6	SS	1.72	-4	YES	NO	3470	5350	4560-4075
99	6-95-11	Cont	3920	0.020	0.020	28.6	SS	1.72	-4	YES	NO	3470	5350	4560-4075
100	6-95-12	Cont	5600	0.020	0.020	28.6	SS	1.72	-4	YES	NO	3470	5350	4560-4075
101	6-95-13	B.H	3914	0.020	0.020	28.6	SS	1.72	-4	YES	NO	3093	5110	4415-3905
102	6-95-14	Cont	3920	0.020	0.020	28.6	SS	1.72	-4	YES	NO	3093	5110	4415-3905
103	6-95-15	Cont	5600	0.020	0.020	28.6	SS	1.72	-4	YES	NO	3093	5110	4415-3905
104	6-95-25	B.H	3914	0.020	0.020	28.6	SS	1.72	-4	YES	NO	3093	5110	4280-3760
105	6-95-25a	Cont	3920	0.020	0.020	28.6	SS	1.72	-4	YES	NO	3093	5110	4280-3760
106	6-95-26	Cont	5600	0.020	0.020	28.6	SS	1.72	-4	YES	NO	3093	5110	4280-3760
107	6-96-1	Cont	3920	0.020	0.020	28.6	SS	1.72	-4	YES	NO	4894	5950	5150-4050
108	6-96-2	Cont	3920	0.020	0.020	28.6	SS	2.37	-4	YES	NO	4894	5950	4720-3830
109	6-96-3	Cont	3920	0.020	0.020	28.6	SS	2.37	-4	YES	NO	2368	4350	4040-3200

TABLE V (Continued)

RUN #	TRACE #	TYPE	λ (Å)	ENTRANCE	SLIT	EXIT SLIT (Å)	SPEC	Z (IN.)	H_{ave} (BTU/lb)	T_{ave} (°K)	SPECTRAL TEMP. RANGE (°K)	FLOW (SCFH)
				WIDTH (IN.)	HEIGHT (IN.)							
110	6-97-1	B-H	3914	.002	.16	4.07	LS	0	—	—	7200-5600	AIR 30
111	6-97-3	CONT	3920	.002	.16	4.07	LS	0	—	—	7200-5600	AIR 30
112	6-97-4	ATOM	7469	.002	.16	4.07	LS	0	—	—	6600-5450	AIR 30
113	6-97-5	CONT	7475	.002	.16	4.07	LS	0	—	—	6600-5450	AIR 30
114	6-97-6	B-H	3914	.002	.06	4.07	LS	0	—	—	6300-5400	AIR 30
115	6-97-8	CONT	3920	.002	.06	4.07	LS	0	—	—	6300-5400	AIR 30
116	6-97-9	ATOM	7469	.002	.06	4.07	LS	0	—	—	6100-5800	AIR 30
117	6-97-10	CONT	7475	.002	.06	4.07	LS	0	—	—	6100-5800	AIR 30
118	6-97-15	B-H	3914	.002	.06	4.07	LS	0	—	—	8500-5500	N ₂ 30
119	6-99-1	B-II	3914	.020	.020	28	SS	0.3	4150	4800	7000-5900	N ₂ +O ₂ 111
120	6-99-2	CONT	3920	.020	.020	28	SS	0.3	4150	4800	7000-5900	N ₂ +O ₂ 111
121	6-99-3	B-II	3914	.020	.020	28	SS	1.09	4150	4800	6100-5450	N ₂ +O ₂ 111
122	6-99-4	CONT	3920	.020	.020	28	SS	1.09	4150	4800	6100-5450	N ₂ +O ₂ 111
123	6-99-5	B-II	3914	.020	.020	28	SS	1.26	4150	4800	5900-4850	N ₂ +O ₂ 111
124	6-99-6	CONT	3920	.020	.020	28	SS	1.26	4150	4800	5900-4850	N ₂ +O ₂ 111
125	6-99-7	B-H	3914	.020	.020	28	SS	1.37	4150	4800	5700-4800	N ₂ +O ₂ 111
126	6-99-7a	CONT	3920	.020	.020	28	SS	1.37	4150	4800	5700-4800	N ₂ +O ₂ 111
127	6-99-16	CONT	3920	.020	.020	28	SS	1.37	3000	3900	5500-3500	N ₂ +O ₂ 141
128	6-99-17	CONT	3920	.020	.020	28	SS	1.69	3000	3900	5200-3300	N ₂ +O ₂ 141
129	6-99-18	CONT	3920	.020	.020	28	SS	2.99	3000	3900	4900-3100	N ₂ +O ₂ 141
130	6-99-19	CONT	3920	.020	.020	28	SS	3.24	3000	3900	4800-3000	N ₂ +O ₂ 141
131	6-99-20	CONT	3920	.020	.020	28	SS	2.19	3000	3900	5600-3600	N ₂ +O ₂ 141
132	6-100-1	B-H	3914	.020	.020	6	LS	0.3	5080	6000	— —	N ₂ 88
133	6-100-2	B-II	3914	.020	.020	6	LS	0.3	3771	4500	6750-5100	N ₂ +O ₂ 111
134	6-100-3	CONT	3920	.020	.020	6	LS	0.3	3771	4500	6750-5100	N ₂ +O ₂ 111
135	6-100-4	ATOM	7469	.020	.020	6	LS	0.3	3771	4500	7000-5800	N ₂ +O ₂ 111
136	6-100-5	ATOM	7469	.020	.020	6	LS	0.6	3853	4550	6700-5500	N ₂ +O ₂ 111
137	6-100-6	B-H	3914	.020	.020	6	LS	0.6	3895	4550	6700-5100	N ₂ +O ₂ 111
138	6-100-7	CONT	3920	.020	.020	6	LS	0.6	3895	4550	6700-5100	N ₂ +O ₂ 111

TABLE V (Continued)

RUN #	TRACE #	TYPE	λ (Å)	ENTRANCE SLIT		EXIT SLIT (Å)	SPEC	Z (IN.)	H _{ave} (BTU/lb)	T _{ave} (°K)	SPECTRAL TEMP. RANGE (°K)	FLOW (SCFH)
				WIDTH (IN.)	HEIGHT (IN.)							
139	6-100-8	B-H	3914	.020	.020	6	IS	0.9	3895	4550	6200-5100	N ₂ +O ₂ 111
140	6-100-9	CONT	3920	.020	.020	6	IS	0.9	3895	4550	6200-5100	N ₂ +O ₂ 111
141	6-100-10	ATOM	7469	.020	.020	6	IS	0.9	3895	4550	6250-5450	N ₂ +O ₂ 111
142	6-100-11	B-II	3914	.020	.020	6	IS	1.20	3895	4550	5700-5050	N ₂ +O ₂ 111
143	6-100-12	CONT	3920	.020	.020	6	IS	1.20	3895	4550	5700-5050	N ₂ +O ₂ 111
144	6-100-13	B-H	3914	.020	.020	6	IS	1.37	3895	4550	5400-4500	N ₂ +O ₂ 111
145	6-100-14	CONT	3920	.020	.020	6	IS	1.37	3895	4550	5400-4500	N ₂ +O ₂ 111
146	6-100-15	B-H	3914	.020	.020	6	IS	1.50	3895	4550	4900-4500	N ₂ +O ₂ 111
147	6-100-16	CONT	3920	.020	.020	6	IS	1.50	3742	4500	4900-4500	N ₂ +O ₂ 111
148	6-100-17	CONT	3920	.020	.020	6	IS	1.80	3742	4500	5000-3000	N ₂ +O ₂ 111
149	6-100-18	CONT	3920	.020	.020	6	IS	2.10	3742	4500	4900-3000	N ₂ +O ₂ 111
150	6-100-19	CONT	3920	.020	.020	6	IS	2.40	3742	4500	5000-3000	N ₂ +O ₂ 111
151	6-100-20	CONT	3920	.020	.020	6	IS	2.70	3742	4500	4800-3000	N ₂ +O ₂ 111
152	6-102-1	B-II	3914	.020	.020	4	IS	0.3	2713	3700	6400-5000	N ₂ +O ₂ 141
153	6-102-2	CONT	3920	.020	.020	4	IS	0.3	2713	3700	6400-5000	N ₂ +O ₂ 141
154	6-102-3	B-H	3914	.020	.020	4	IS	0.6	2713	3700	6200-5200	N ₂ +O ₂ 141
155	6-102-4	CONT	3920	.020	.020	4	IS	0.6	2713	3700	5950-5300	N ₂ +O ₂ 141
156	6-102-5	B-H	3914	.020	.020	4	IS	0.9	2713	3700	5950-5300	N ₂ +O ₂ 141
157	6-102-6	CONT	3920	.020	.020	4	IS	0.9	2713	3700	5900-5100	N ₂ +O ₂ 141
158	6-102-7	B-H	3914	.020	.020	4	IS	1.2	2713	3700	5900-5100	N ₂ +O ₂ 141
159	6-102-8	CONT	3920	.020	.020	4	IS	1.2	2713	3700	5450-4350	N ₂ +O ₂ 141
160	6-102-9	CONT	3920	.020	.020	4	IS	1.5	2713	3700	5200-3350	N ₂ +O ₂ 141
161	6-102-10	CONT	3920	.020	.020	4	IS	1.8	2713	3700	5000-3300	N ₂ +O ₂ 141
162	6-102-11	CONT	3920	.020	.020	4	IS	2.1	2713	3700	4700-3300	N ₂ +O ₂ 141
163	6-102-12	CONT	3920	.020	.020	4	IS	2.4	2713	3700	4350-3300	N ₂ +O ₂ 141
164	6-102-13	CONT	3920	.020	.020	4	IS	2.7	2713	3700	4100-3100	N ₂ +O ₂ 141

TABLE V (Continued)

RUN #	TRACE #	TYPE	λ (Å)	ENTRANCE SLIT		EXIT SLIT (Å)	SPEC	Z (IN.)	H _{ave} (BTU/lb)	T _{ave} (°K)	SPECTRAL TEMP. RANGE (°K)	FLOW (SCFH)
				WIDTH (IN.)	HEIGHT (IN.)							
165	6-102-14	CONT	3920	.020	.020	4	LS	3.0	2713	3700	3800-3000	N ₂ +O ₂ 141

- NOTES: 1. Jet was open for runs 110-165.
 2. Magnification was - 4 for jet, - 7 for RF.
 3. Quench was removed for runs 110-165.
 4. Runs 110-118 are RF, runs 119-165 are jet.

UNCLASSIFIED

Security Classification

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13. ABSTRACT Using as a source a dc subsonic plasma jet operating in nitrogen and in nitrogen-oxygen mixtures at atmospheric pressure, emission coefficients of the $N_2(2+)(0,0)$ $\lambda 3371$ neutral molecule band, $N_2^+(1-)(0,0)$ $\lambda 3914$ ionized molecular band, $\lambda 7468$ NI atomic line, and the electron continuum have been measured over the temperature range of 3800 to 10000°K. The emission coefficients of the discrete radiation, calibrated on an absolute scale, were used to calibrate the simultaneously measured electron continuum over the temperature range. Approximate analytical treatments were used to extrapolate the calibrated continuum curves to lower temperatures where discrete radiations cannot be observed. The experimental results show considerably higher continuum emission coefficients at low temperature than can be accounted for by any existing theoretical treatments.			

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14.

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