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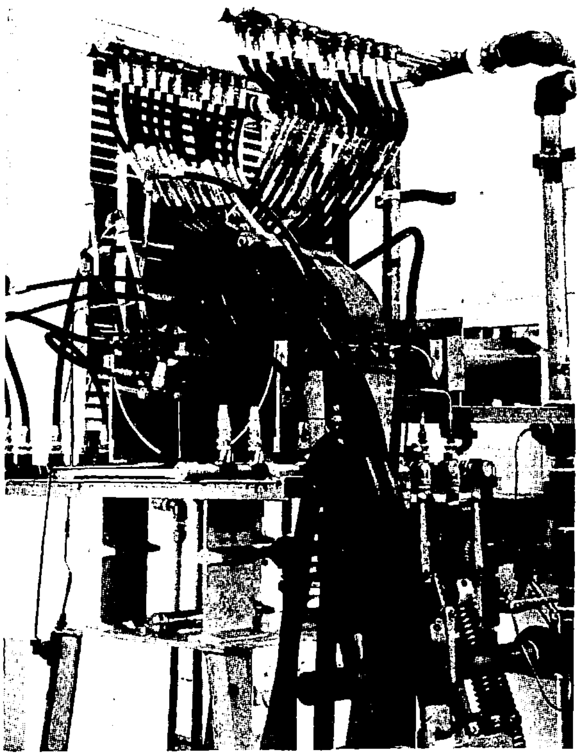
SUMMARY

An electron beam apparatus which permits measurements of free-stream vibrational and rotational temperatures and density by spectrographic analysis is discussed and results of the experiment are presented. The beam was used to probe the free stream of an arc-heated hypersonic wind tunnel with a 1.5-megawatt power supply. At a tunnel stagnation chamber temperature of about 3700° K and a pressure of 22 atmospheres the test-section Mach number was about 12. By using the electron beam to probe this airflow it was found that the nitrogen molecules were in rotational equilibrium (rotational temperature of 155° K) but in vibrational nonequilibrium (vibrational temperature of approximately 1600° K). The equilibrium free-stream temperature was calculated to be 143° K. The free-stream density measurement proved to be accurate under field-free conditions but, when the arc coil was energized, this measurement was found to contain a small unevaluated error because of magnetic-field effects on the electron beam. The vibrational temperature of the nitrogen molecules in the free stream appears to be a function not only of the stagnation temperature but also of the amount of arc contaminants present in the stream.

INTRODUCTION

The investigation described in this report was undertaken as a part of a research program to analyze the high Mach number, high enthalpy airstream produced by a 1-foot hypersonic arc tunnel at the Langley Research Center (ref. 1 and figs. 1 and 2). Since this hypersonic stream (Mach number 12) has a rather low test-section density, the electron beam is an extremely useful research tool for defining some of the static properties in the test section because it has a negligible effect on the flow. The technique for interpreting the measurements has been previously developed in observations of the aurora borealis (ref. 2) and has been applied to a low-density facility by Muntz (ref. 3).



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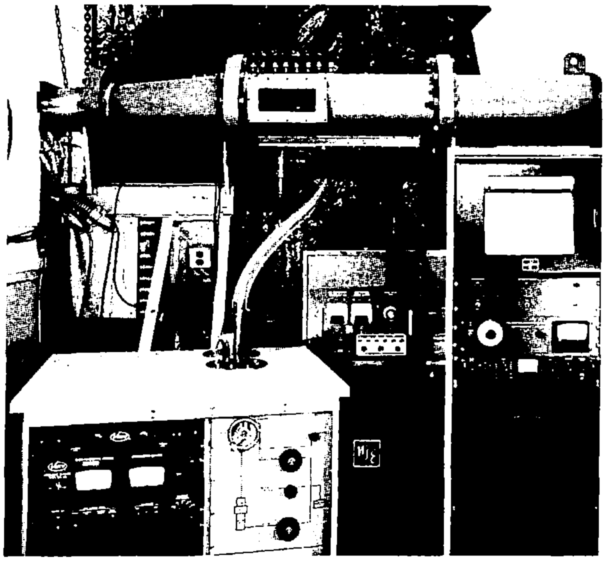
(a) Arc heater. (Center electrode removed.)



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(b) Conical nozzle, test section, and diffuser with electron beam gun attached to bottom of test section.

Figure 1.- Details of 1-foot hypersonic arc tunnel at the Langley Research Center.

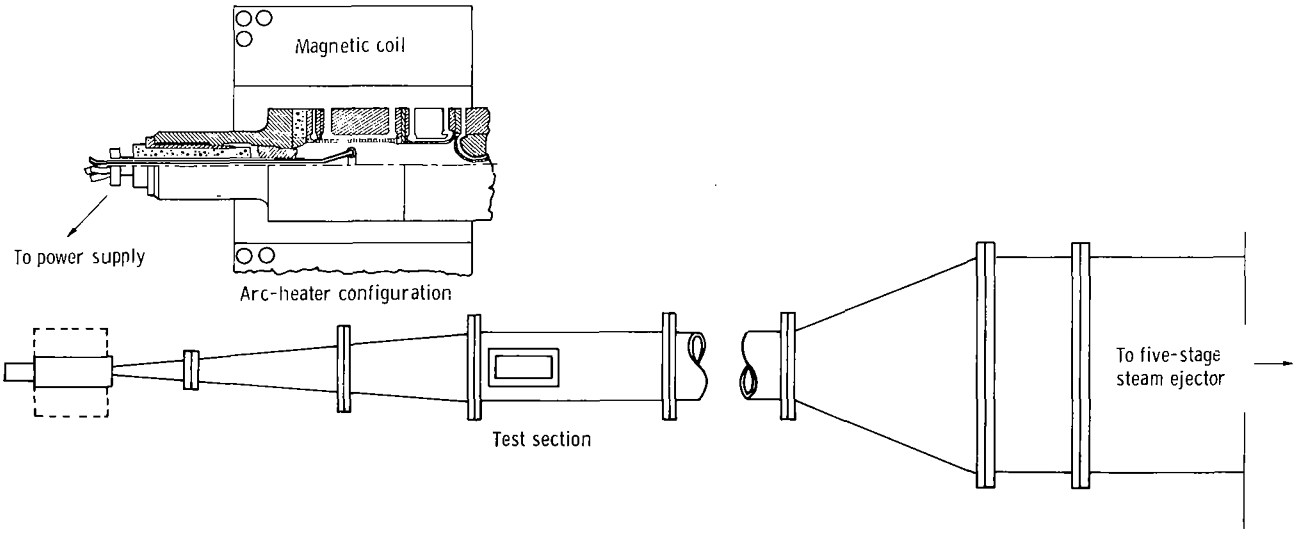

Figure 2.- Sketch of 1-foot hypersonic arc tunnel at Langley Research Center.

In the electron beam technique, a narrow column of electrons (10 to 50 kV) is produced by an electron gun and is passed normal to the flow through the test section. (See figs. 3 and 4.) These fast electrons excite a small number of the particles making up the flow, and the resulting emission of light from the excited particles (fig. 3) is observed spectrographically to determine the vibrational and rotational temperatures and the number density of the species observed.

Although the spectrum-line reversal method has been used successfully for similar studies of the vibrational temperature in shock tunnels (ref. 4), the use of an independent method to measure any nonequilibrium effect is clearly desirable inasmuch as vibrational and rotational relaxations are fundamental in the exchange of molecular energy.

In air, the light observed is dominated by the first negative system of N_2^+. Since absolute intensities of the emitted light are difficult to measure, relative measurements are used throughout. To determine the vibrational temperature, a comparison was made of the ratios of the relative intensities of the various vibrational bands as a function of vibrational temperature. To determine the rotational temperature, measurements were obtained of the variation of the relative intensities of the rotational lines in a vibrational band as related to the rotational quantum number with rotational temperature. To determine the number density, the relative intensity of the total light of the first negative system was calibrated as a function of density for a given electron beam current. A theoretical description of these measurements is presented. It should be remembered that the measurements taken apply only to the nitrogen molecules in the air. Since no oxygen bands were observed in the electron beam, the measurements do not indicate the condition of the oxygen unless equilibrium conditions exist between the two species. A detailed description showing the

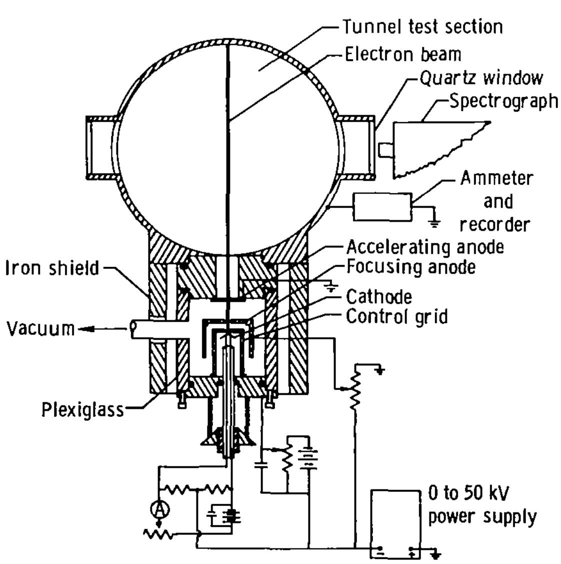

Figure 3.- Electron gun attached to test section of 1-foot hypersonic arc tunnel.

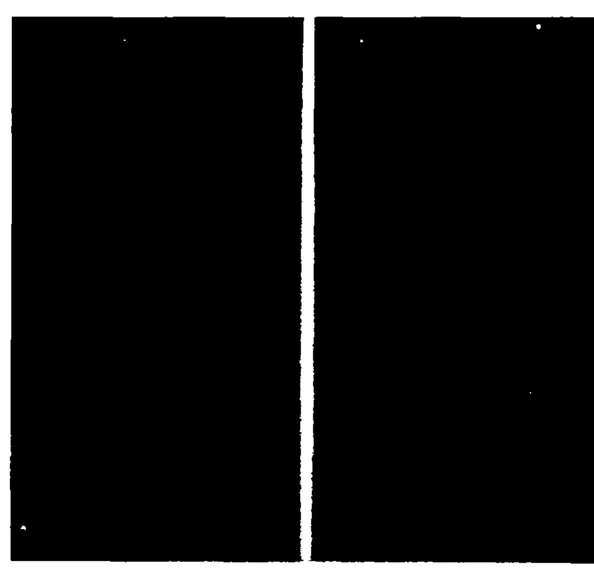

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Figure 4.- A 12.5-kV electron beam in air. p = 70 microns Hg; T = 303° K; beam current = 200 μA.

negligible effects of secondary electrons, self-absorption, and flow velocities on the electron beam can be found in references 3, 5, and 6. An experimental measurement of the lifetimes of the first negative bands of N_2^+ $\left(10^{-8}\text{ sec}\right)$ can be found in reference 7.

SYMBOLS

A	area
A_{nm}	Einstein's transition probability of spontaneous emission
B_{nm}	Einstein's transition probability of absorption
B	rotational constant
C,D,F,α_e	constants
c	speed of light
E	proportionality constant
(G)	function of K and T_r (see ref. 3)
$G_{O(v)}$	term values for vibrational levels
h	Planck's constant
I	intensity of radiation
J	rotational quantum number with electron spin
K	rotational quantum number with no electron spin
k	Boltzmann constant
M	Mach number
N	number of particles
$N_2^+B^2\Sigma$	upper electronic state of nitrogen ion N_2^+
$N_2^+X^2\Sigma$	ground state of nitrogen ion N_2^+
$N_2X^1\Sigma$	ground state of nitrogen molecule
N_o	number of $N_2X^1\Sigma$ molecules

n	number density
p	pressure
Q_v	vibrational state sum
R	gas constant
$\bar{R}_e$	electronic transition moment
R_{nm}	transition moment
$\lvert R_{nm} \rvert^2$	Franck-Condon factor
r	internuclear distance
T	temperature, $^{\circ}K$
v	vibration state or vibrational quantum number
y	relative number of oscillators in a quantum level
ν	wave number
σ	collision diameter
ψ	eigenfunctions

Subscripts:

e	electronic
g	ground state
m	lower state
n or u	upper state
r	rotational
t	total or stagnation
∞	free stream
1	designates the state $N_2X^1\Sigma$
2	designates the state $N_2^+X^2\Sigma$

A prime with a symbol indicates upper state in transition.

A double prime with a symbol indicates lower state in transition.

An asterisk with a symbol indicates throat conditions.

APPARATUS AND PROCEDURE

A schematic diagram of the electron gun and electrical circuit is shown as figure 3. The electron gun is shown in cross section as it appeared when attached to the bottom of the tunnel test section. The electron emitter is a heated tungsten wire bent into the shape of a sharp "V." The potential difference between this cathode and the grounded accelerating anode determines the energy of the electrons in the beam. The electrode nearest the cathode is the control grid which is usually slightly negative with respect to the cathode. The first anode which is adjusted to some intermediate potential between the cathode and ground is used to focus the beam. The electron gun is maintained at a pressure below 10^{-5} mm Hg by an auxiliary vacuum system, whereas the pressure in the tunnel test section through which the beam travels can vary up to about 1 mm Hg. The amount of this pressure differential maintained across the accelerating anode separating the two regions dèpends on the size of the pinhole and the pumping speed of the vacuum system. The electron gun produces a well-defined beam up to 500 μA with energy up to 50 kV in the electrostatic-field-free region past the accelerating anode.

Although the magnetic coil of the arc heater was located about 6 feet from the tunnel test section and the electron gun, it was necessary to use a 1-inch-thick iron pipe for a magnetic shield (fig. 3). The gun could be shielded but not the beam in the test section, so that a slight deflection of the beam occurred when the coil was energized. This deflection did not affect the temperature measurements but did have an effect on the density measurement, as is explained subsequently.

To measure the vibrational temperature, the light emission from the excited nitrogen molecules along the electron beam path in the test section was observed through the quartz window by a 2.25-meter spectrograph with a 30,000-line-per-inch grating. A 12.5-kV beam was used throughout the experiment since this voltage was found to be high enough to form a virtually unattenuated beam. With the entrance and exit slits completely opened, the vibrational band intensities were resolved and measured in

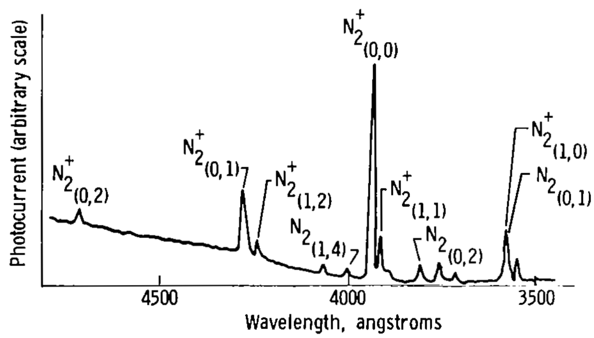

Figure 5.- Emission spectrum observed from electron beam in tunnel airstream as measured by direct readout attachment on spectrograph.

the first order by using the photoelectric readout attachment on the spectrograph. With this attachment, the portion of the spectrum under study could be scanned over a considerable range of speeds by using a 1P28 photomultiplier as a sensing element. The 1P28 photomultiplier was selected because of its spectral range and the fact that it has a quartz envelope. The output of this photomultiplier was fed to a micro-microammeter whose output was then displayed on a strip recorder. A typical scan is shown in figure 5. The solid angle of light accepted by the spectrograph was measured in the region of the electron beam and was found to have a cross-sectional diameter of 1/2 inch so that the measurements are actually integrated values over a 1/2-inch segment of the electron beam located in the center of the test section. Previous pitot-probe measurements indicated a uniform 5-inch-diameter flow core. The readings taken from the strip recorder had to be corrected for the spectral sensitivity of the 1P28 photomultiplier in order to obtain proper intensity ratios.

To measure the rotational temperature, the rotational lines of the vibrational bands were resolved in the first order by using a 100-micron entrance slit and photographing the spectra with 103a-0 spectrographic plates. A typical spectrum showing the rotational structure is given in figure 6. Ten tests were necessary to achieve the proper exposure (22 min) for a spectrogram in the tunnel because of a 3-minute limit on operating time due to the existing tunnel water supply. The plate was calibrated for intensity by use of the 2:1 intensity ratio between alternate lines.

To determine the free-stream number density of the nitrogen molecules, the light emission of the N_2^+ bands as a function of density for a constant beam current was measured before each test by varying the pressure at constant temperatures. The intensity of these bands during the test gave the free-stream density as explained in the analysis.

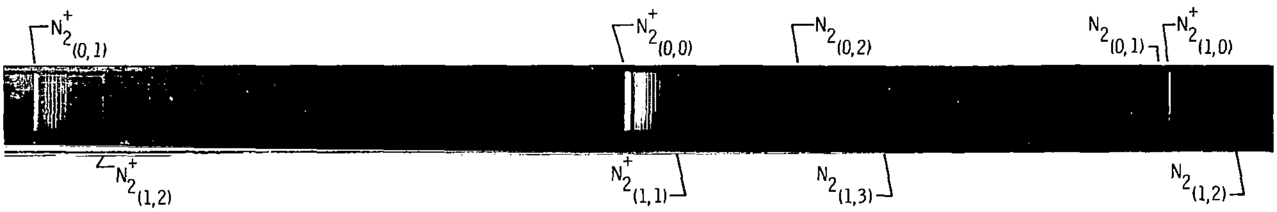

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Figure 6.- Emission spectrum observed from electron beam as measured with a 2.25-meter spectrograph using 103a-0 plates.

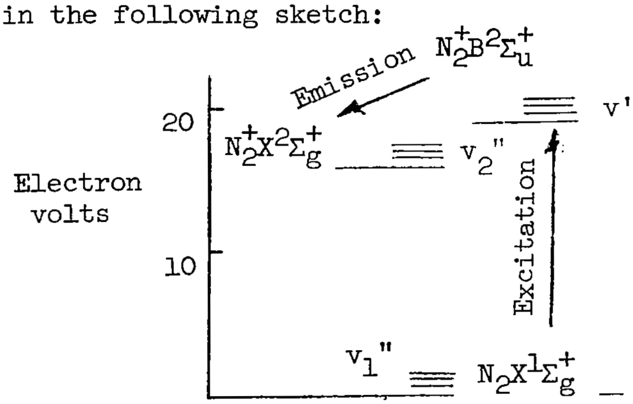
METHODS OF ANALYSIS

Vibrational Temperature

When excited by an electron beam the first negative system of N_2^+ has been proved by Muntz (ref. 3) to follow, according to the Franck-Condon principle, the excitation and emission paths given by

$$N_2X^1\Sigma_g^+ \xrightarrow{\text{Excitation}} N_2^+B^2\Sigma_u^+ \xrightarrow{\text{Emission}} N_2^+X^2\Sigma_g^+ \tag{1}$$

and illustrated in the following sketch:



The intensity of the emission lines in the rotational-vibrational spectrum (ref. 8) for the bands under study is given by

$$I_{v'v_2''} = N_{v'}hc\nu_{v'v_2''}A_{v'v_2''} \tag{2}$$

where

$$A_{v'v_2''} = \frac{64\pi^4\nu_{v'v_2''}{}^3}{3h}\left|R_{v'v_2''}\right|^2 \tag{3}$$

is the Einstein spontaneous emission probability. The Franck-Condon factor of emission which is proportional to the transition probability of emission is

$$\left|R_{v'v_2''}\right|^2 = \bar{R}_e{}^2\left(\int \psi_{v'}\psi_{v_2''}\,dr\right)^2 \tag{4}$$

The number of particles in the v' state is given by

$$N_{v'} = E\frac{N_o}{Q_v}\sum_{v_1''}\left(e^{-G_0(v_1'')\frac{hc}{kT_v}}B_{v'v_1''}\right) \tag{5}$$

where

$$B_{v'v_1''} = \frac{8\pi^3}{3h^2c}\left|R_{v'v_1''}\right|^2 \tag{6}$$

is the Einstein transition probability of absorption and

$$\left|R_{v'v_1''}\right|^2 = \bar{R}_e^{\,2}\left(\int \psi_{v'}\psi_{v_1''}\,dr\right)^2 \tag{7}$$

is the Franck-Condon factor of absorption. Combining these terms in equation (2) then gives

$$I_{v'v_2''} = E\frac{N_o}{Q_v}\sum_{v_1''}\left(e^{-G_0(v_1'')\frac{hc}{kT_v}}\frac{8\pi^3}{3h^2c}\left|R_{v'v_1''}\right|^2\right)\left(hc\nu_{v'v_2''}\frac{64\pi^4\nu_{v'v_2''}^{\;3}}{3h}\left|R_{v'v_2''}\right|^2\right) \tag{8}$$

or

$$I_{v'v_2''} = D\nu_{v'v_2''}^{\;4}\left|R_{v'v_2''}\right|^2\sum_{v_1''}\left(e^{-G_0(v_1'')\frac{hc}{kT_v}}\left|R_{v'v_1''}\right|^2\right) \tag{9}$$

where

$$D = E\frac{N_o}{Q_v}\left(\frac{8\pi^3}{3h^2c}\right)\left(\frac{64\pi^4}{3h}\right)hc \tag{10}$$

and the intensity ratio of any two bands, such as the (0,1) to the (1,2) first negative bands of N_2^+, is given by

$$\frac{I_{0,1}}{I_{1,2}} = \frac{\nu_{0,1}^{\;4}}{\nu_{1,2}^{\;4}}\,\frac{\left|R_{0,1}\right|^2}{\left|R_{1,2}\right|^2}\left[\frac{\displaystyle\sum_{v_1''=0,1,2,\ldots}\left(e^{-G_0(v_1'')\frac{hc}{kT_v}}\left|R_{0,v_1''}\right|^2\right)}{\displaystyle\sum_{v_1''=0,1,2,\ldots}\left(e^{-G_0(v_1'')\frac{hc}{kT_v}}\left|R_{1,v_1''}\right|^2\right)}\right] \tag{11}$$

The intensity ratios $I_{0,1}/I_{1,0}$ and $I_{0,1}/I_{1,2}$ are shown in figure 7. To obtain these curves, the relative populations of the vibrational levels of $N_2X^1\Sigma$ as a function of temperature, assuming a Boltzmann distribution, are calculated by the following equation:

$$\frac{y_{v_1''}}{y_t} = e^{-G_0(v_1'')\frac{hc}{kT_v}} = e^{-\frac{v_1''h\nu}{kT_v}} \qquad (12)$$

Then, by setting $y_t = 1$ and using $h\nu/k = 3336^\circ$ K, which corresponds to the natural vibrational frequency of N_2, equation (12) gives the relative population $y_{v_1''}/y_t$ as a function of temperature for $v_1'' = 0, 1, 2, \ldots$. The absorption probabilities and wavelengths used in equation (11) can be found in reference 9. Because of uncertainties found in the literature for values of emission probabilities, the ratios $\frac{|R_{0,1}|^2}{|R_{1,2}|^2}$ and $\frac{|R_{0,1}|^2}{|R_{1,0}|^2}$ were experimentally measured. This procedure was accomplished by measuring the intensity ratios at a known temperature under static conditions and then computing the emission probability ratio by use of equation (11). From the curves in figure 7 it is seen that the greatest sensitivity to vibrational temperature is between 500° K and 2500° K when this method is used; very little sensitivity can be obtained below 500° K.

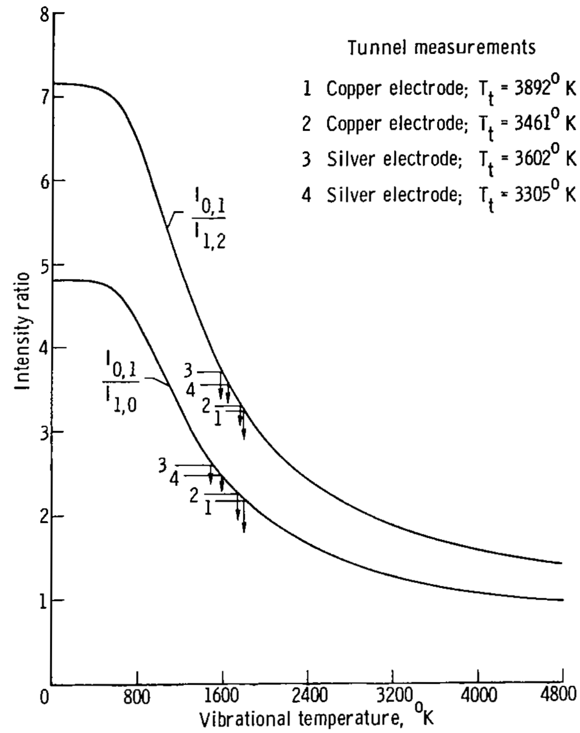


Figure 7.- Vibrational band intensity ratio as a function of vibrational temperature for negative bands of nitrogen as excited by collisions with electrons.

The use of the relative intensities of the vibrational bands in emission to measure the vibrational temperature of the unexcited nitrogen molecules in the flow is explained by the Franck-Condon principle (refs. 3 and 8). This principle indicates that the electron jump in the molecules is so fast relative to the inter-molecular motion that the internal motion of the molecules does not have time to adjust. Consequently, the thermal distribution for electron-beam excited nitrogen is that of the N_2 ground state. For this reason the relative populations of the vibrational levels of the N_2 ground state and the absorption probabilities determine the variation of intensity ratios with temperature in equation (11).

The accuracy of this theoretical analysis is difficult to calculate and until an experimental assessment of the error involved is achieved, no estimation will be attempted by the authors.

The intensity ratios of these bands (fig. 7) were taken from a direct read-out scan (such as that shown in fig. 5) after they were corrected for the spectral sensitivity of the 1P28 photomultiplier. The intensities are integrated values of the complete band. It can be seen from figure 5 that the (0,1) and

(1,2) bands of N_2^+ are completely resolved but that the (1,0) band of N_2^+ is not resolved from the (0,1) band of N_2. The light emission of the (0,1) band of N_2 can be separated from the (1,0) band of N_2^+ because of a constant ratio between the resolved (0,2) band of N_2 and the (0,1) band of N_2. This constant ratio is due to the fact that both bands come from the same upper level. The relative intensity of the (1,0) band of N_2^+ was therefore found by subtracting the contribution due to the (0,1) band of N_2, which was obtained by measuring the (0,2) band of N_2 and multiplying this intensity by the ratio of the (0,1) band to the (0,2) band of N_2.

Measurements taken in the free stream of the tunnel for the intensity ratios $I_{0,1}/I_{1,0}$ and $I_{0,1}/I_{1,2}$ are also shown in figure 7. These measurements are for various stagnation temperatures and for electrodes made of two different materials - namely, silver and copper. Little or no vibrational-temperature change is apparent over the range of stagnation temperatures measured; however, there appears to be a higher vibrational temperature in the free stream when the copper electrodes were used than when the silver electrodes were used. The vibrational temperature is approximately 1775° K with copper electrodes and about 1575° K with silver electrodes. It can be seen in figure 7 that there is a good correlation of temperature for the three bands used. The higher vibrational temperature when copper electrodes were used was assumed to be due to a greater contamination of electrode materials in the stream. This contamination was measured qualitatively by the background continuum partly shown in figure 5 which started at 4000 Å and built up at greater wavelengths; this is discussed in detail in a subsequent section. The identification of the bands in figure 5 was made from the photograph of the spectrum of the electron beam in air shown in figure 6. This spectrum was found to be identical with an electron beam spectrum of pure nitrogen. The spectrum shows the rotational lines of the vibrational bands which were resolved by using a 100-micron entrance slit.

Rotational Temperature

The intensity of the lines in the rotational structure for low vibrational temperature is given (refs. 3 and 8) as

$$I = C(G)\nu^4(J' + J'' + 1)e^{-\frac{B_v J'(J'+1)hc}{kT_r}} \tag{13}$$

For the R branch of a $^2\Sigma$ - $^2\Sigma$ transition, as in the first negative bands of N_2^+, this equation simplifies to

$$I = F(G)\nu^4 K' e^{-\frac{B_v K'(K'+1)hc}{kT_r}} \tag{14}$$

If $\log_e \frac{I}{K'(G)\nu^4}$ is plotted against $K'(K' + 1)$, the slope of the straight line gives $-\frac{B_v hc}{kT_r}$ from which the rotational temperature T_r can be computed. The use of the relative intensities in the rotational structure of the emission to measure the rotational temperature of the unexcited nitrogen molecules in the flow is also explained by the Franck-Condon principle. For this reason the vibrational constant B_v used in equations (13) and (14) is for the molecular ground state $N_2X^1\Sigma^+$.

The function (G) in equation (14) is a correction factor and tabulated values of $(G)\nu^4$ as a function of quantum number and temperature are given in reference 3.

When the vibrational temperature is high, there is a significant excitation of vibrational levels of $N_2X^1\Sigma$ other than the $v_1'' = 0$ as can be shown from equation (12). For the (0,0) band of N_2^+ the transitions from upper levels of $N_2X^1\Sigma$ to the $v' = 0$ level of $N_2^+B^2\Sigma$ must be accounted for, and equation (14) becomes

$$I = F\nu^4(G)K' \sum_{v_1''}\left[\left|R_{0,v_1''}\right|^2 e^{-G_0(v_1'')\frac{hc}{kT_v}} e^{-B_{v_1''}\frac{K'(K'+1)hc}{kT_r}}\right] \tag{15}$$

It was found by use of equation (12) that at the vibrational temperature measured in the tunnel, the number of molecules occurring in $v_1'' = 1, 2, \ldots$ was relatively small. It can also be seen from the tables of reference 9 that the Franck-Condon factors from these states up to the $v' = 0$ level of $N_2^+B^2\Sigma$ are quite small so that the error involved in using equation (14) was reasonable (approximately 2 percent) for the purpose of this experiment. The value of $B_{v_1''}$ was also found to be only slightly dependent on the value for v_1'' and is given by

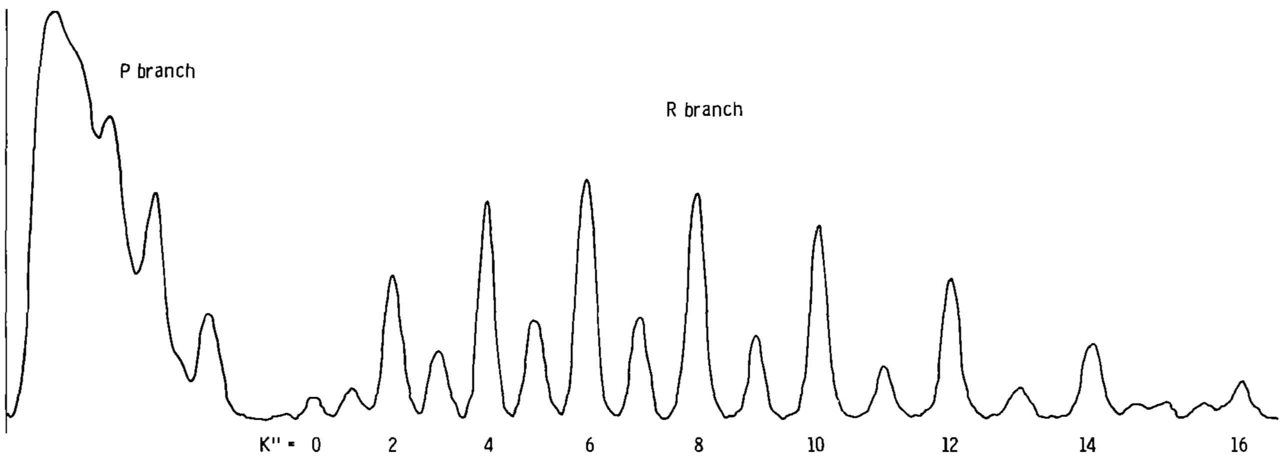
$$B_{v_1''} = B_e - \alpha_e\left(v_1'' + \frac{1}{2}\right) \tag{16}$$

For the $N_2X^1\Sigma$ state, $B_e = 2.01$ and $\alpha_e = 0.0187$ (ref. 8).

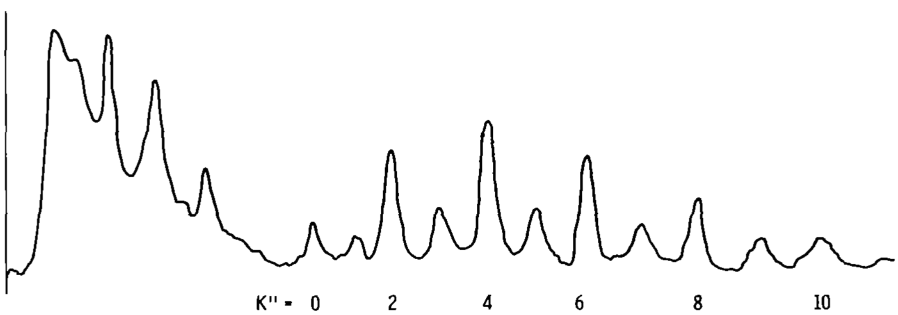
Figure 6 shows a typical spectrogram of the rotational structure of the emission of air at room temperature when the gas is excited by an electron beam. A densitometer trace of the (0,0) band of N_2^+ taken from this spectrum is presented in figure 8(a) and shows the rotational structure as a function of quantum number; a densitometer trace of the same band taken from a spectrogram of the electron beam in the tunnel free stream is shown in figure 8(b). A plot of $\log_{10} \frac{I}{K'(G)\nu^4}$ as a function of $K'(K' + 1)$ for the two traces of figure 8 is presented in figure 9.

The temperature computed from the slopes of figure 9 gives a tunnel free-stream rotational temperature of 155° K and a reference room temperature of 303° K. The actual room temperature was measured at 302° K and these values were computed only to test the accuracy of the method. The average tunnel stagnation temperature and pressure during these tests were 3322° K and 18.75 atmospheres, respectively.

The two densitometer traces of figure 8 show the effect of temperature on the rotational structure in that the peak intensity of the lines moves to higher quantum numbers at a higher temperature. This can be seen in both the P and the R branches. On the basis of repeatability of data, the error for measuring rotational temperatures was estimated to be within ±2 percent.



(a) Static measurements at 302° K.



(b) Tunnel free-stream measurements.

Figure 8.- Densitometer traces through (0,0) band of first negative system of nitrogen taken from 103a-O plates for electron beam.

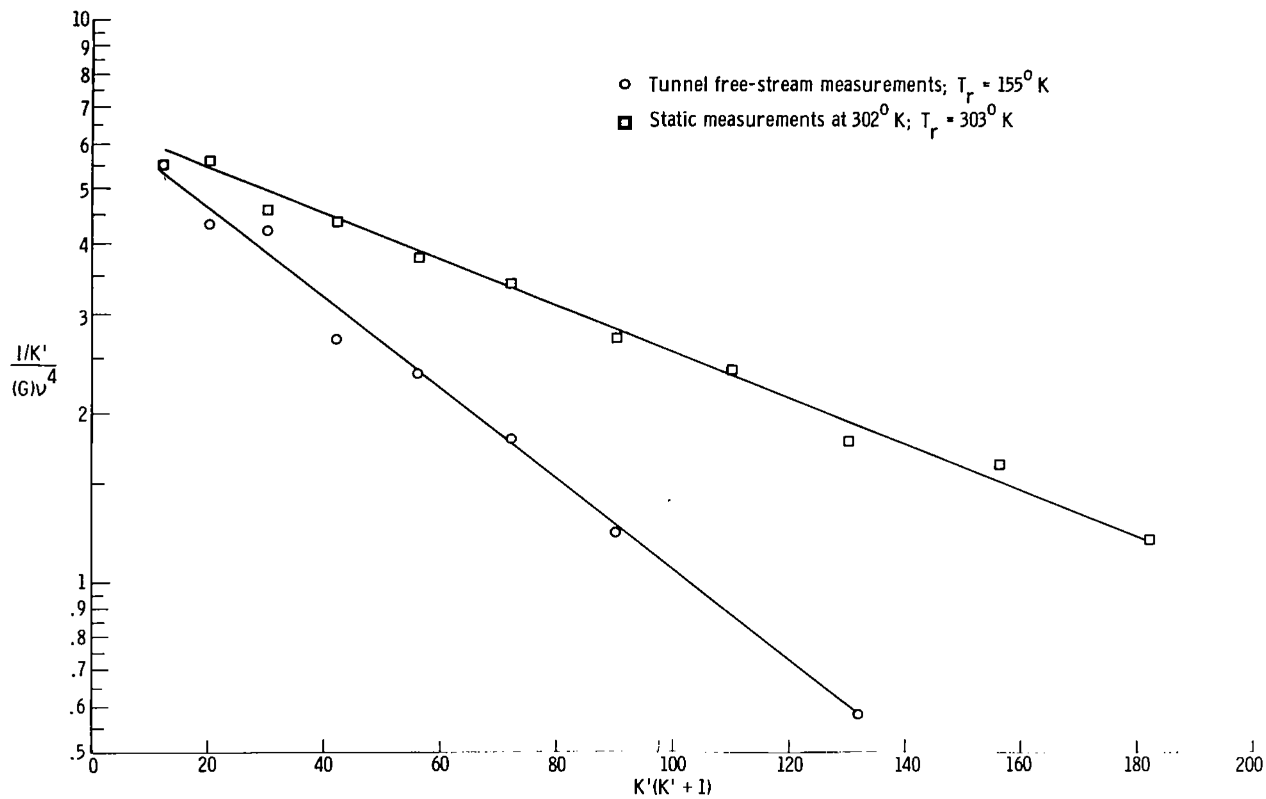


Figure 9.- Variation of $\log_{10} \frac{I}{K'\nu^4(G)}$ with $K'(K' + 1)$ for (0,0) band of N_2^+ to determine the rotational temperature in tunnel free stream and the accuracy of measuring rotational temperature with the electron beam.

Number Density as a Function of Intensity

The emission intensity from the electron beam as a function of number density is given by (ref. 3)

$$I = \frac{nhc\nu_{nm}}{1 + \frac{2n\sigma^2\sqrt{4\pi RT}}{A_{nm}}} \tag{17}$$

Since most of the light due to the electron beam comes from the (0,0) band of the first negative system of nitrogen, the intensity of this band was observed as a function of density by means of a spectrograph and direct readout attachment.

In actual practice the intensity was calibrated as a function of density by varying the pressure in the tunnel test section at room temperature before the test. The intensity during the test was then applied to this curve to obtain the stream density. The intensity of the (0,0) band as a function of density is found in figure 10 for a 12.5-kV beam; a measurement of intensity taken during a typical test is also plotted on the curve. The measured value of air density in the tunnel test section was 2.5×10^{-7} slug/cu ft and the calculated value with equilibrium flow assumed in the nozzle was 2.2×10^{-7} slug/cu ft.

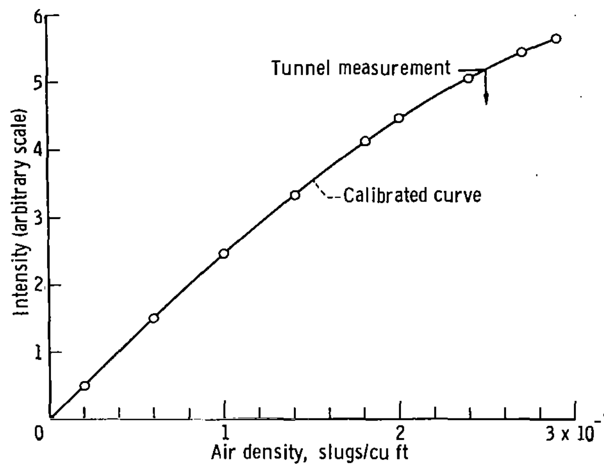


Figure 10.- Variation of relative intensity (photocurrent) with density for a 12.5-kV electron beam in air.

It was observed during a test that the magnetic field from the arc coil deflected the electron beam, and even though the electron gun could be shielded, the beam inside the test section could not. The deflection was of the order of three-eighths of an inch in the center of the test section, and to compensate for any change in the intensity the calibration was carried out with the coil energized and the arc off. It was found, however, that the arc affected the magnetic field during a test and the coil current changed as it was heated so that some undetermined error still existed in the density measurements.

DISCUSSION

The electron beam apparatus described in this report has proved useful as a research tool for defining some of the static properties of certain types of high-enthalpy arc-heated tunnels. The measurements described herein show that, for values of T_t of about 3322° K and p_t of 18.75 atm in the 1-foot tunnel, the rotational temperature is in equilibrium and the vibrational temperature diverges from an equilibrium expanding flow in the 10° conical nozzle. This condition is consistent with some theoretical predictions and other measurements in which the spectrum-line reversal method was used to obtain vibrational temperature (ref. 4).

For the range of stagnation temperatures used in this experiment, a change in vibrational temperature due only to changes in T_t could not be detected because of the small variation in T_t and the limitations due to the error in measuring T_t and T_v. As noted previously with reference to figure 7, a consistently higher vibrational temperature of the nitrogen molecules was measured when copper electrodes were used than when silver electrodes were used. This increase in T_v is believed to be a result of the greater amount of electrode contamination in the free stream when copper electrodes were used because copper electrodes have been observed to erode faster than silver electrodes and a greater background continuum was found to exist in the free stream when copper electrodes were used.

The background continuum was measured by scanning through the spectrum with a 2.25-meter spectrograph and the direct readout. The spectrograph was alined normal to the stream flow and viewed a solid angle of light from the incandescent core with a cross-section diameter of about 1/2 inch in the center of the stream.

A part of this continuum can be seen in the scan of figure 5. Averaged curves of the intensity corrected for spectral sensitivity of the 1P28 photomultiplier are shown in figure 11 as a function of wavelength for the copper and silver electrodes. The intensity of the background continuum for the copper electrodes is approximately $2\frac{1}{2}$ times that for the silver electrodes and both curves appear to have a shape similar to that for black-body radiation. With Wien's displacement law, the location of the peaks at 5700 Å would give a black-body temperature of 5085° K. This temperature is of particular interest in that the arc temperature for the elements of copper and silver, which have ionization potentials of 7.7 and 7.6 volts, respectively, is 5400° K (ref. 10). One explanation which appears likely is that the background continuum is due largely to copper or silver incandescent metallic vapor from the arc. Because the amount of this contaminant in the stream is greater when copper electrodes are used than when silver electrodes are used and because the contaminant is relatively hot (5085° K), the vapor keeps the air molecules at a higher energy level than they would be normally in an expanding flow. This condition would be particularly possible near the throat of the nozzle where the density is relatively large and many collisions can take place between the air molecules and the massive metallic particles. No quantitative relation has been found between the intensities of figure 11 and the amount of contamination in the stream. Crude estimates made by measuring the amount of copper eroded during a series of tests indicated a contamination level on the order of 0.2 percent by weight for these electrodes.

The light emission of the continuum background could easily be removed from the nitrogen bands under study, and no self-emission of these bands was observed from the flow. A summary of the aforementioned vibrational- and

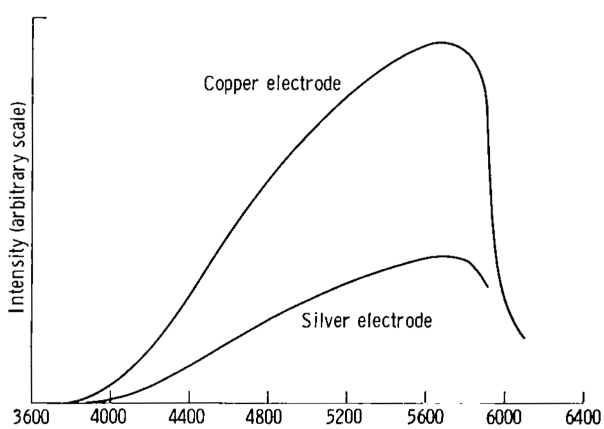


Figure 11.- Intensity of continuum background as a function of wavelength in the 1-foot hypersonic arc tunnel as measured with the direct readout of the 2.25-meter spectrograph.

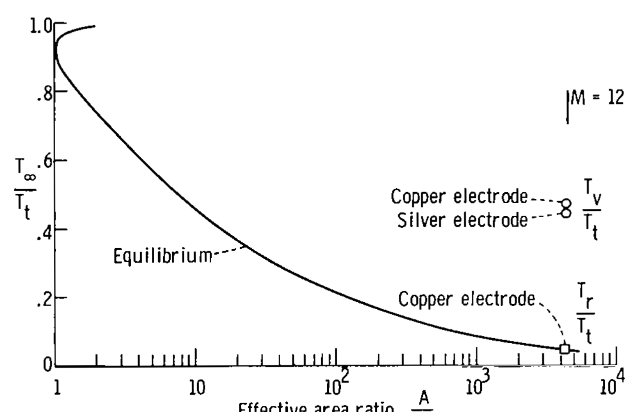


Figure 12.- Comparison of typical measured vibrational and rotational temperatures with theoretical air expansion in a 10° conical nozzle. T_t = 3750° K; p_t = 19.8 atm.

rotational-temperature measurements is presented in figure 12. The measured vibrational and rotational temperatures divided by the total temperature are compared with the theoretical equilibrium curve for the expansion of air in a 10° conical nozzle at the measured stagnation conditions.

The vibrational internal energy for air at 1775° K obtained with the harmonic oscillator model and a composition of 20 percent oxygen and 80 percent nitrogen is approximately 80 Btu/lb. This energy stored in the vibrational mode is relatively small compared with the total energy (approximately 1900 Btu/lb) and, therefore, the fact that the vibrational temperature diverges from equilibrium should only have minor effects on flow properties.

No consideration of dissociative nonequilibrium was taken into account.

CONCLUDING REMARKS

In the experiment described in this report, thermal nonequilibrium effects were observed and density was measured in the expanding flow of a 1-foot hypersonic arc tunnel at the Langley Research Center. It has been shown that the electron beam probe when used with spectrographic techniques is a useful tool in measuring these quantities in a hypersonic arc tunnel.

The results obtained indicate that, while rotational temperature is in equilibrium, a definite nitrogen vibrational lag exists in the expanding stream. It should be pointed out, however, that although the vibrational temperature diverges from equilibrium, it remains much closer to equilibrium during expansion than predicted by some of the existing theories (AIAA Preprint 63-439).

The existence of arc contaminants at relatively high temperature was also observed in the expanding stream, and it appears that these particles may have an effect on the nonequilibrium conditions of the flow.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., August 17, 1964.

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