SPECTROSCOPIC INVESTIGATIONS AND MEASUREMENTS OF CERTAIN ARC JET PARAMETERS

Final Report
NASA/ASEE Summer Faculty Fellowship Program--1987
Johnson Space Center

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Date:	August 14, 1987
Contract Number:	NGT-44-001-800

ABSTRACT

The NASA/JSC Atmospheric Re-entry Materials and Structures Evaluation Facility (ARMSEF) has been intensively and extensively been involved in ground testing of spacecraft materials and thermal protection systems (TPS) in simulated re-entry conditions. Ground experiments on surface catalytic efficiency of such TPS requires a knowledge of the flow system in the arc jet. In the work described in this report, spectroscopic diagnostic techniques are used to determine the free stream constituents. Specifically, the emission spectrum of the free stream constituents was obtained and the species therein identified.

A laser system has been added on, which will give the added capability of studying the arc jet flow using Laser Raman Spectroscopy (LRS). The LRS technique will complement information obtained from the emission spectra.

A short list of further work that can be done in the area of spectroscopic investigations on the arc jet is mentioned.

INTRODUCTION

The arc jet facility, located at NASA/JSC in Building 222, has played a varied role in simulating re-entry conditions for the purposes of testing spacecraft materials and models in a simulated environment on the ground. The facility consists of two test legs designated TP1 and TP2 arc tunnels. Each test leg consists of:

a. an arc heater
b. test nozzles
c. test chamber with model insertion system
d. a diffuser and a heat exchanger
e. a four stage steam ejector vacuum pumping system

The arc heater is a device for converting electrical energy into thermal energy. A continuous high voltage direct current is established between a cathode and an anode at either end of a segmented column. Gases are then injected into the column and heated by the arc. The heated high energy gas is then expanded through a nozzle to produce a very high supersonic or hypersonic gas stream. The gases used are typically a mixture of nitrogen and oxygen, although it is possible to use other gases.

As explained above, TPS are among one of the many test objects studied at this facility. In order to fully understand the catalytic efficiencies of these TPS (1-3), it is necessary to have a complete knowledge of the flow chemistry, species concentrations, shock temperatures, etc.

Although some of these quantities can be obtained by the strict use of the laws of fluid dynamics, it has been amply demonstrated that spectroscopic techniques (4-5) can also be used to determine some of these quantities. The spectroscopic techniques are non-intrusive and provide a means of making in-situ measurements. At present spectroscopic methods are being used to study only the TP2 component of the facility.

SPECTROSCOPIC SET-UP DESCRIPTION AND EXPERIMENTAL PROCEDURE

A block diagram of the spectroscopic facility is given in Fig. 1. As can be seen from the figure the radiation from the arc jet flow exits the tunnel through a window and is condensed on to mirror M1, which reflects the beam on to a second lens L2, which in turn condenses the light beam on to the slit entrance of the spectrograph. The spectrograph itself is a Spex Triple-Mate spectrograph in which the resolution can be varied to three different settings. The detection is accomplished by a 1024 element linear diode array. The output is recorded on a magnetic disc using an EG&G/PARC optical multichannel analyzer (OMA), which also performs other needed calculations.

In the preliminary set of experiments, a 600 line/mm grating was used which yielded a pixel resolution of 0.069 nm. The first step in the experimental procedure was to calibrate the instruments. The calibration was accomplished in two steps. First the relative sensitivity of the instrument (intensity calibration) was carried out using a standardized carbon-filament, which was operating at a constant current of 38.0A. The wavelength calibration was accomplished using standard Oriel pen lamps. In the wavelength calibration procedure, usually three or four standard lines are chosen and a linear relationship between their cursor position and the wavelength is sought. The relationship between the wavelength λ and the cursor position C is thus given by

$$\lambda = A_0 + A_1 (C-1) \qquad (1)$$

where A_0 and A_1 are constants.

In practice the arc jet is turned and set at the appropriate power level and the mass flow rate. The radiant energy from the arc jet is incident upon the slit of the spectrograph, is dispersed by the spectrographic optics and is then analyzed by the OMA. An X-Y recorder attached to the OMA makes it possible to obtain a hard copy of the spectrum.

The first task in this project was to determine the composition of the free flow at different operating conditions. In Table I, test conditions used are given.

TABLE I

Arc Jet Test Conditions Used to Obtain Spectra of the Free Stream

Flow Rate (lb-mass/sec*)	Current (A)	Power (MW)	Enthalpy Btu/lb**
0.05	500	0.87	7,000
0.05	1000	1.76	10,500
0.05	1800	2.76	13,000
0.10	1000	2.38	9,800
0.30	500	2.34	5,000

* To convert to SI unit of Kg/Sec multiply by 0.454

** To convert to SI unit of MJ/Kg multiply by 2.32×10^{-3}

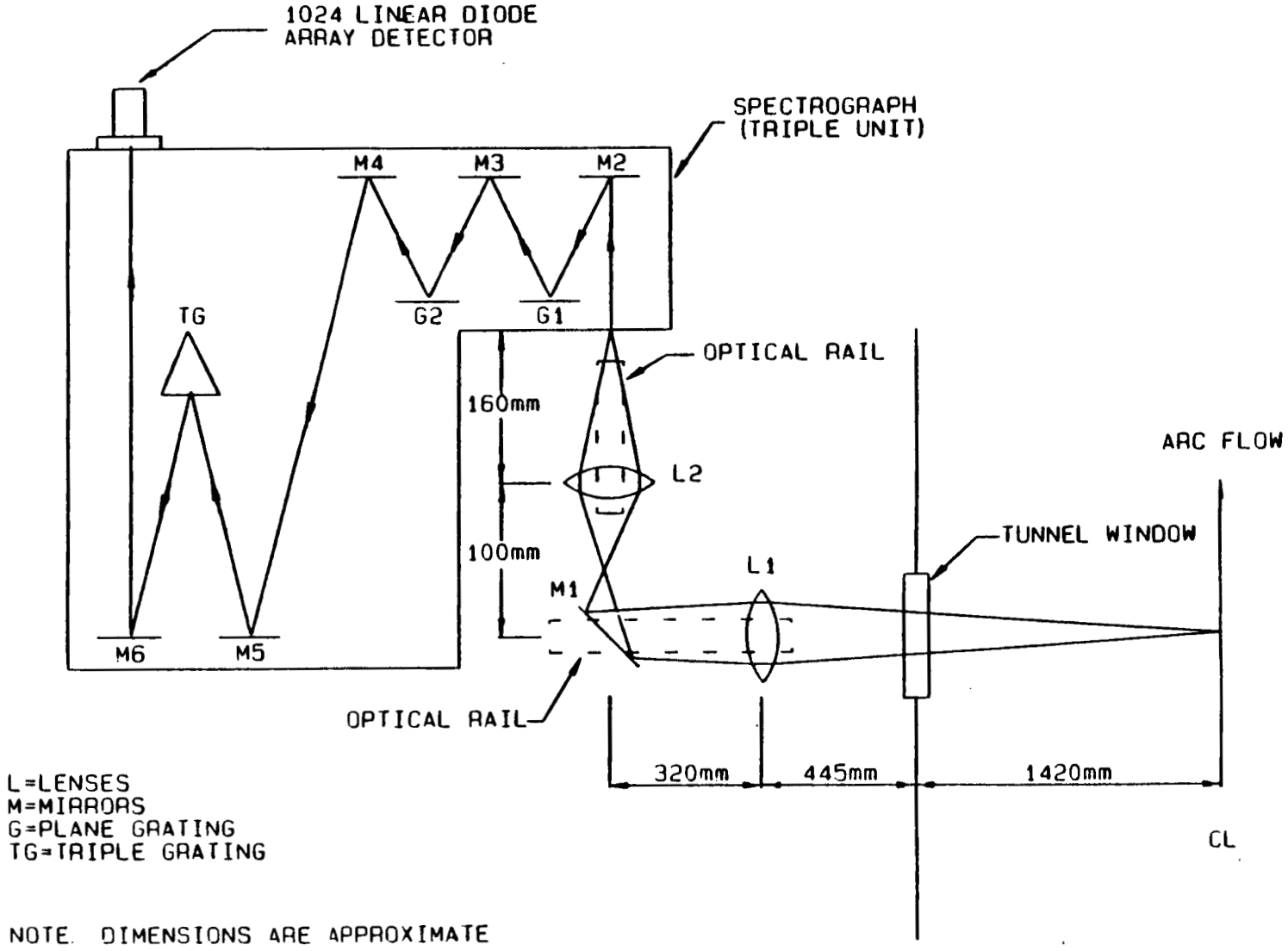

Figure 1.- Spectrograph side optical train (not to scale).

RESULTS AND DISCUSSION OF SPECTRA OBTAINED

It appeared at the very outset that a spectrum obtained depended more on the enthalpy than on the power setting. At low enthalpy settings i.e., at both 5000 Btu/lb and at 7000 Btu/lb, the low wavelength part of the spectrum was totally unreadable, because the signal to noise ratio was very poor. In general the quality of the spectrum was bad and the band heads were not clearly defined. At the enthalpy of 5000 Btu/lb (about 3.85 eV per O_2 or N_2 molecule), the probability of dissociation of either molecule is small. This is borne out by the fact that the majority species discovered in the spectrum at that setting was neutral N_2 molecule and some O_2 molecular bands. One atomic oxygen line was observed at 700.2 nm. The identification of all species were done with the aid of a) the MIT Wavelength Tables (6), b) Pearses' "Handbook on Identification of Molecular Spectra" (7), c) Herzberg's "Atomic Spectra" (8). Plates recorded by Willey (9) were also consulted in the process to aid in the identification process.

Since the catalog of spectral information recorded and species identified is voluminous, it is being compiled into an appendum to this report and is available by contacting John Grimaud at the JSC arc jet facility.

The high enthalpy conditions gave some extremely interesting results. In the highest enthalpy condition that was run it was discovered that entire low wavelength side of the spectrum was inundated with tungsten spectral lines. The cathode of the arc is made of a tungsten alloy, but that fact on its own does not explain the abundance of highly intense tungsten lines throughout the spectrum. Tungsten burns in air with a white flame, however, an observer standing near the arc jet during these measurements reported seeing a yellow radiation from the arc jet. This discounts to a large extent the notion that a large piece of the tungsten electrode may have become dislodged from the cathode and was burning in the stream. Besides the tungsten, nitrogen, oxygen, copper, and thorium lines were found. Examples of spectra recorded are shown in the accompanying figures (Figs. 2-4).

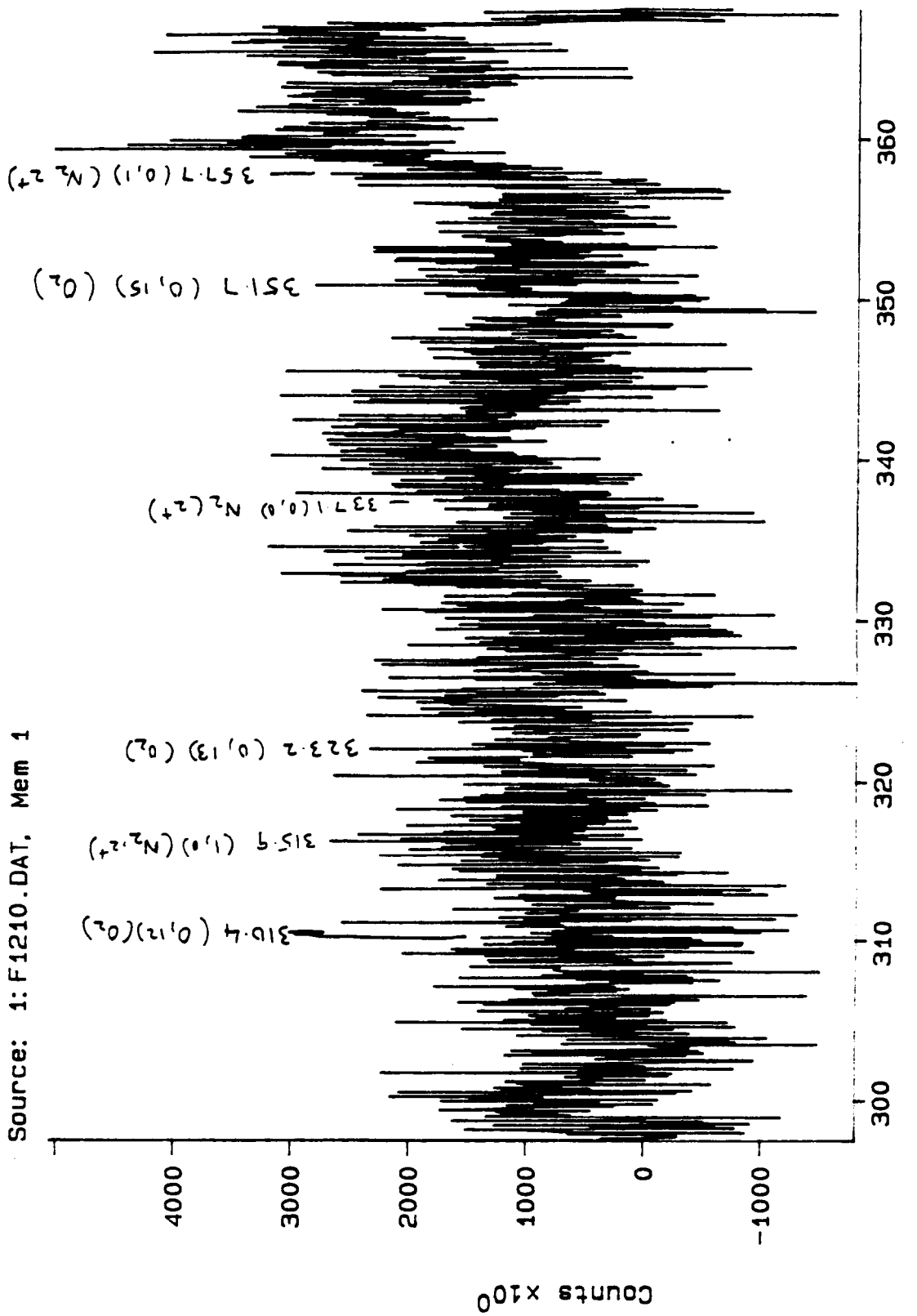

Figure 2.- Part of the spectrum of the free stream recorded at a low enthalpy condition, showing N_2 and O_2 bands. Notice the poor quality of the spectrum and the band heads.

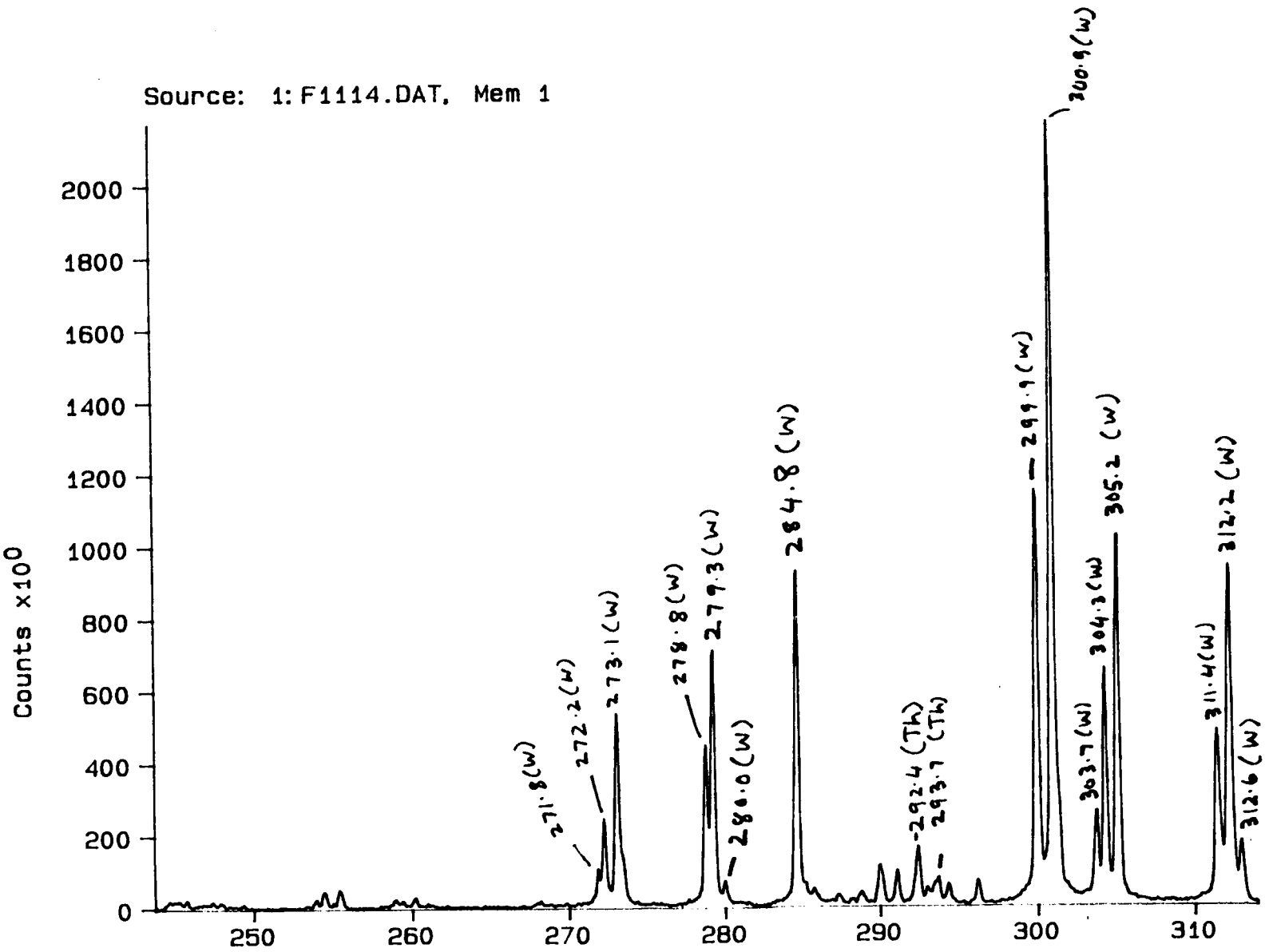

Figure 3.- Part of the free stream spectrum taken at an enthalpy of about 1000 BTU/lb, showing the lines due to tungsten.

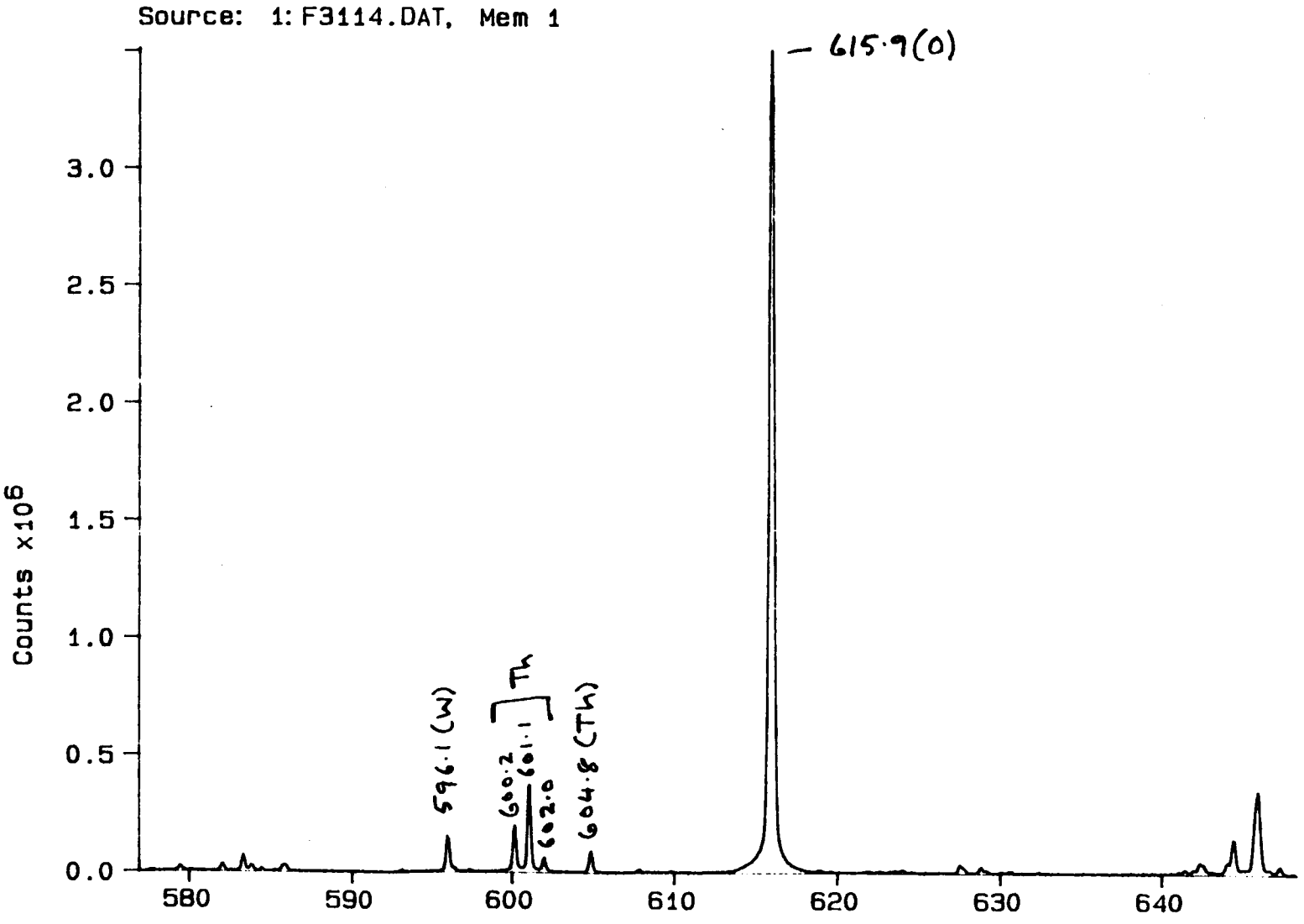

Figure 4.- Another part of the free stream spectrum taken at high enthalpy conditions, showing thorium lines and an oxygen line.

LASER DIAGNOSTICS

Since the advent of the high powered laser (both continuous wave and pulsed), they have come into use increasingly as diagnostic probes (10). The list of the laser techniques which have come into vogue is a long one. There are four major techniques which should be enumerated here.

1. Spontaneous Raman Spectroscopy (SRS). A technique which allows species identification, concentration measurement and measurement of temperatures.

2. Laser Induced Fluorescence (LIF). A technique by which species identification, concentrations and temperatures can be measured. The technique, however, can be used only for a handful of molecules and free radicals, most of which are reaction intermediates.

3. Coherent Anti-Stokes Raman Spectroscopy (CARS). A superior technique for the measurement of temperature.

4. Laser Doppler Velocimetry (LDV). A technique used for determining particle velocities and from which the size of the particles can be inferred indirectly.

The laser methods in general have the following advantages.

- Non-intrusive (no probes, thus capable of penetrating and investigating hostile environments such as the arc jet)
- High spatial resolution ($\sim 10^{-3}$ mm^3)
- High temporal resolution (10^{-8} sec)
- High spectral resolution ($\sim 10^{-2}$ nm)
- High sensitivity ($\sim$ ppm)
- Multiplex advantages (simultaneous measurements of several species at one point or of one species at several points)

It therefore behooves us to attempt one or more of the above mentioned techniques in the study of the free flow and/or shock layer in the arc jet. It was decided by the arc-jet facility coordinators that SRS should be the first technique that should be tried. A schematic of the SRS phenomenon is shown in Fig. 5. As can be seen from this figure an atom, molecule or free radical is excited to a virtual state and the transition back to the lower states results in scattering with one component on the higher wavelength of the incident radiation and one component on the lower wavelength side of the excitation radiation (11).

Classical Theory of Raman Effect. In order to simplify this classical derivation (11) of the Raman Effect, consider a diatomic molecule of polarizability α_Z. Thus an electric field E_Z along the Z axis would result in a dipole moment $\mu_Z = \alpha_Z E_Z$. The molecular polarizability (unlike in the case of an atom) depends on the internuclear separation and also on the angle between the molecular axis and the electric field. If the normal frequency of vibration is ν_{Vib} and r is the vibration amplitude then to a first order approximation,

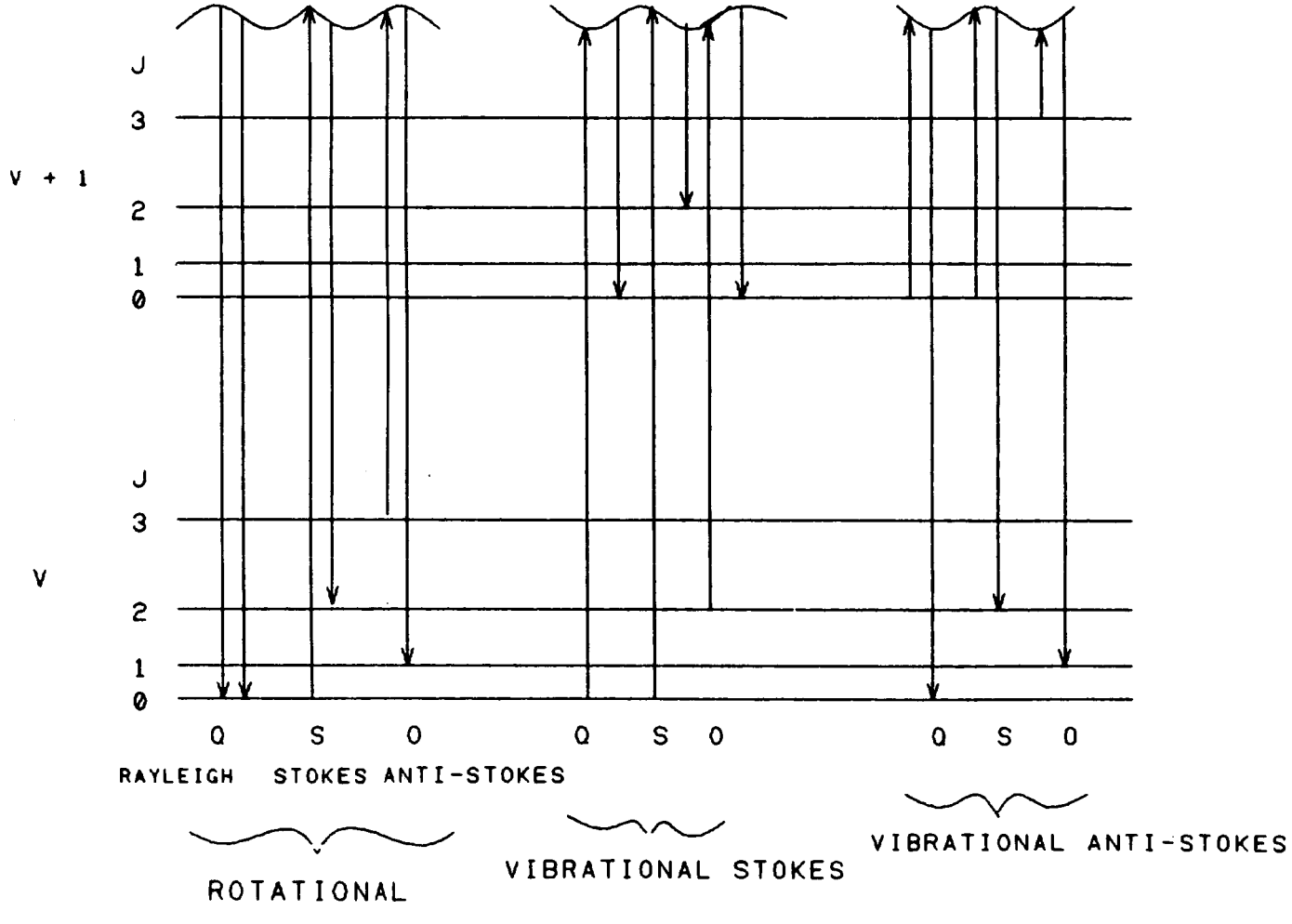

Figure 5.- Rotational and vibrational-rotational Raman scattering processes.

$$\alpha_z = \alpha_{oz} + \gamma \frac{\partial \alpha}{\partial R} \cos 2\pi \nu_{Vib} - t \qquad (2)$$

In other words the polarizability fluctuates sinusoidally about a mean value of α_{OZ}. In an electric field E_Z of radiation of frequency ν_0

$$E_z = E_o \cos 2\pi \nu_o t \qquad (3)$$

Combining the two equations we get

$$\mu_z = E_z \alpha_z = E_{oz} \cos 2\pi \nu_o t + E_{oz} \gamma \frac{d\alpha}{dR} \cos 2\pi \nu_{Vib} t \cos 2\pi \nu_o t \qquad (4)$$

The first term in the above equation in this classical model gives rise to the elastic Rayleigh scattering. Using a well known trigonometric identity, the second term can be rewritten as

$$\frac{1}{2} E_{oz} \gamma \frac{\partial \alpha}{\partial R} \cos 2\pi (\nu_o + \nu_{Vib}) t + \frac{1}{2} E_o \gamma \frac{d\alpha}{dR} \cos 2\pi (\nu_o - \nu_{Vib}) t \qquad (4')$$

Thus the classical theory predicts that in addition to Rayleigh Scattering there will be radiation with frequencies $\nu_o \pm \nu_{Vib}$ and we identify them with the observed anti-Stokes and Stokes lines of Raman Scattering.

Laser Raman Spectroscopy In the Arc Jet.

A 5 Watt laser (Spectra Physics Series 2000 Argon/ion laser) was chosen for setting up the Raman Scattering Experiment. A series of high reflectance mirrors and high quality focusing lenses were used in order to guide the laser beam into the arc jet. The optical arrangement and the laser beam path are shown in Fig. 6 and Fig. 7. The beam scattered at right angles to the incident beam exits the tunnel and is then analyzed by the spectrographic set up. At the time of writing of this report, no experimental data was obtained.

FURTHER WORK TO BE ACCOMPLISHED.

1. Recently the vibrational temperature (12) in the shock layer was obtained by examining the vibrational bands of the first negative system of singly ionized nitrogen molecule. Remarkable agreement was obtained between the experimental results and results obtained from the computer code NEQAIR (13). This computer code plots a theoretical spectrum when certain parameters (temperature included) are input.

The next obvious step is to determine the rotational temperature in the shock layer by examining the rotational lines of certain bands of N_2^+ (first negative system). The technique used has been described in textbooks (14). An outline of the procedure to be followed to obtain the rotational temperature has been chalked out and it is expected that it will be followed up.

2. At the time of writing of this report, the necessary optics was partially in place for the Raman set-up. The laser was turned on and it operated satisfactorily. It is expected that the optics will be completely in place

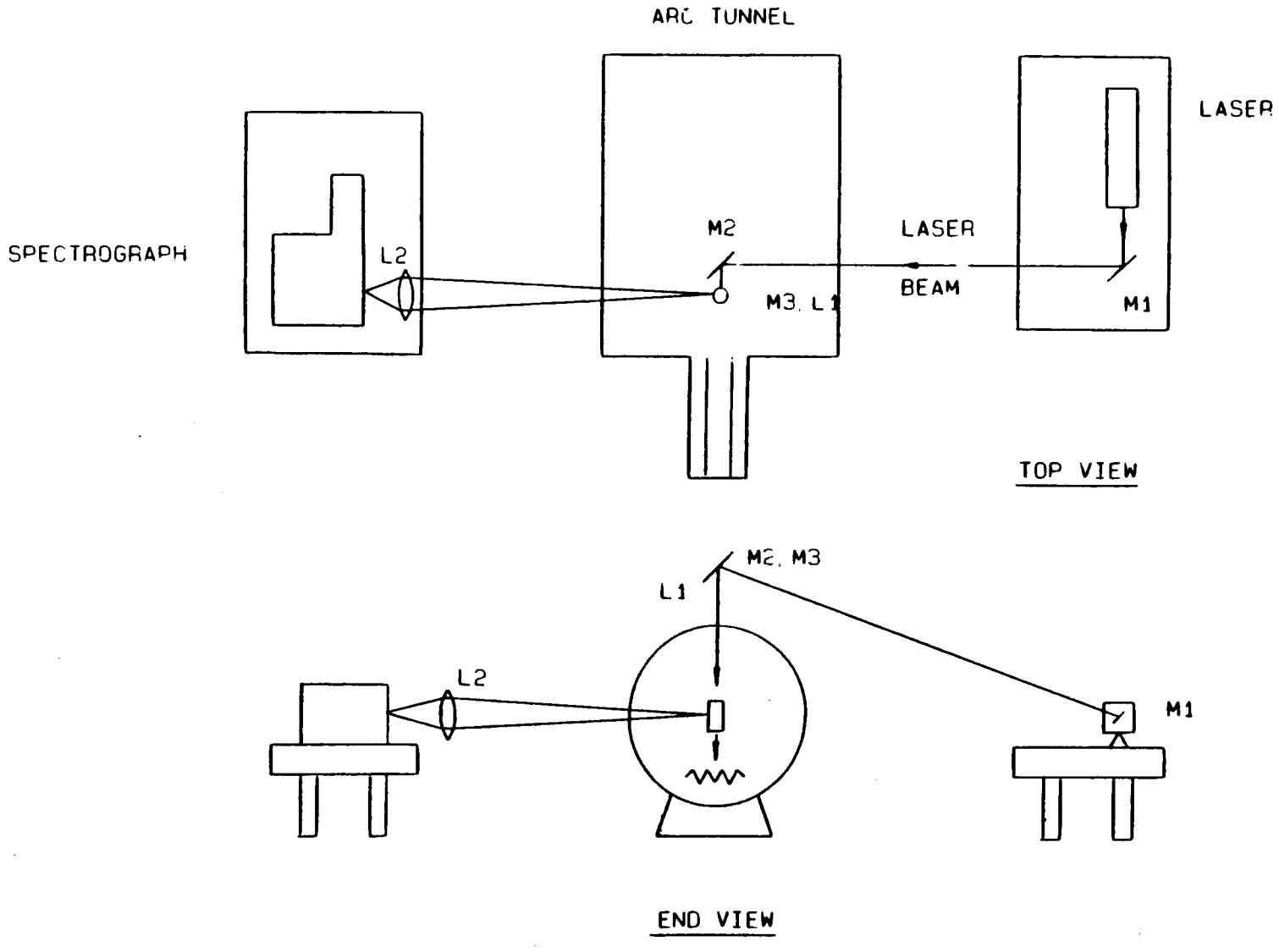

Figure 6.- Spectrograph optical path schematic (not to scale).

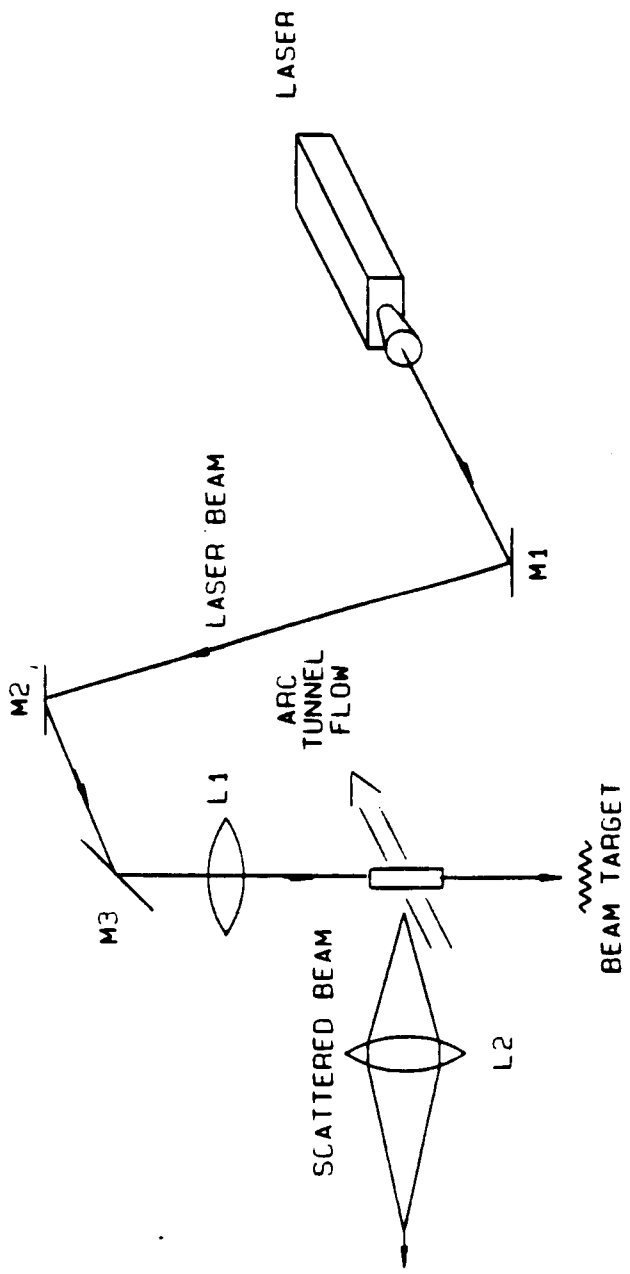

Figure 7.- Three-dimensional path.

anytime now. One of the first experiments scheduled is to determine the Raman shifts of NO, N_2 and O_2 in the free stream. Table II shows the results of a simple, calculation giving the location of the Stokes and anti-Stokes line for some of the excitation wavelengths obtainable from the laser.

TABLE II

Argon Ion laser λ = 514.5 nm

Species	Raman Shift cm^{-1}	$\Delta\lambda$ (nm)	Stokes (nm)	Anti-Stokes (nm)
O	226	6.0	520.5	508.5
N_2	2331	61.7	576.2	452.8
NO	1876	49.7	564.2	464.8
O_2	1556	41.2	555.7	473.3
		λ = 476.5 nm		
O	226	5.1	481.6	471.4
N_2	2331	52.9	529.4	423.6
NO	1876	42.6	519.1	433.9
O_2	1556	35.3	511.8	441.2
		λ = 454.5 nm		
O	226	4.7	459.2	449.8
N_2	2331	48.2	502.7	406.3
NO	1876	38.8	493.3	415.7
O_2	1556	32.1	486.6	422.1

In real applications it is necessary to consider the effect of the rotational energy levels upon the observed scattered spectrum. For diatomic molecules, the selection rules for radiative scattering are $\Delta V = 0, \pm 1$ and $\Delta J = 0, \pm 2$, where V is the vibrational quantum number, and J is the rotational quantum number. Of the three branches $\Delta J = 0$ (Q branch) is brighter than the other two namely $\Delta J = -2$(O) branch and $\Delta J = 2$ the S branch.

If the Stokes and anti-Stokes intensities can be measured in a medium, which is in local thermodynamic equilibrium, then the temperature can be uniquely determined from the ratio of these measurements. The ratio of a Stokes and an anti-Stokes lines corresponding to the same J value in the Q Branch is given by (15)

$$\frac{I_{STOKES}}{I_{ANTI\text{-}STOKES}} = \left[\frac{\nu_0 - \frac{\Delta E}{h}}{\nu_0 + \frac{\Delta E}{h}}\right]^4 e^{\Delta E/KT}$$

where ν_o is the frequency of the incident radiation and Δ E is the energy of the rotational lines assumed constant for all lines in the Q branch. This might be difficult in the arc jet where thermal equilibrium is difficult to achieve. Perhaps in the shock layer this condition might be met and the method might be successful in shock layer temperature determination.

Other techniques have been used to determine temperature and species concentration in hypersonic flows using rotational Raman spectra (16). These techniques need to be examined to see if they can be applied to the arc jet conditions.

3. There have been suggestions made by professionals here that the flow velocity be determined experimentally. A knowledge of the flow velocity would yield other parameters of the flow. At present an in-depth study of this problem needs to be undertaken and a clear-cut procedure established and demonstrated.

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ACKNOWLEDGMENTS

I wish to thank NASA and ASEE for the financial support given to me for this work. I wish to thank my JSC colleagues, John Grimaud and Carl Scott, for their guidance and support throughout this work. I extend my sentiments of appreciation to my fellow Summer Faculty Fellow, Ronald Willey, and also to Fred Wierum, who taught me the various aspects of the facility. Finally, my thanks to all of NASA and the Lockheed personnel of the arc jet facility who made my stay here very pleasant and rewarding.