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GASEOUS RADIATION IN HYPERSONIC
STAGNATION POINT FLOW

IITRI Project N6011

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Office of Naval Research
Washington 25, D. C.

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GASEOUS RADIATION IN HYPERSONIC
STAGNATION POINT FLOW

⑨

Contract No. DA-11-022-ORD-4012

⑪ IITRI Project N6011

for

Office of Naval Research
Washington 25, D.C.

⑬

January 1964

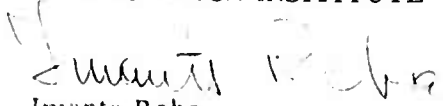
FOREWORD

This is the third semi-annual report for Contract No. Nonr-3884(00), ARPA order number 322-62 and Amendment I covering the period July 15, 1963 to December 15, 1963. The program is sponsored by the Advanced Research Projects Agency and is monitored by the Office of Naval Research with Mr. Morton Cooper the project technical monitor.


The assistance of Edward Wolthausen for his help in performing the experiments is acknowledged.

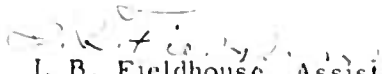
Respectfully submitted,

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I INTRODUCTION

In this research

This report covers the period from June 14, 1963 to January 14, 1964. The following objectives are being pursued:

1. The non-equilibrium flow regimes in the shock tube flow over blunt bodies are being identified by measurements of stagnation point radiation.

2. Spectral measurements of light intensity ^{are} and being made to assess the contribution of radiation to the stagnation point heating of blunt bodies.

3. Measurements with different model sizes are being performed to qualitatively describe the radiation intensity profile behind the bow shock. The information obtained may enable identification of the predominant equilibrium and non-equilibrium radiators in shock tube flows.

The assessment of radiant heat transfer to bodies entering the earth's atmosphere at hypersonic speeds presents many difficulties. One of these difficulties which has motivated this investigation concerns the uncertainty about the range of flow regimes in which reentry can be simulated in a shock tube. Specifically, measurements of gaseous radiation in shock tube flows can be used to predict the radiant heat transfer to an actual vehicle if the flow is in equilibrium and the actual temperatures and densities are duplicated. Under such conditions, the body geometry and size are the governing factors in scaling model results. On the other hand,

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where the shock tube flow is not in equilibrium, scaling of the results is difficult, if not impossible. Consequently, one must determine the relationships between test parameters such as pressure and temperature which define the limits of flow regimes where data are directly applicable to problems of reentry.

Although the problem of light radiation has been studied extensively by a number of investigators, the approach to the problem discussed in this report is quite different. Light radiating from the bow shock region is collected by a light tube extending to the stagnation point of the model. This technique constitutes a direct measurement of radiant flux at the stagnation point. Measurements made with models of two different characteristic dimensions (nose radius) enables the construction of radiation intensity profile in the bow shock region. It is generally accepted that the predominant region of impurity radiation is near the shock tube wall.⁽¹⁾ Hence, measurements made with a light tube mounted in the stagnation region of a body are not masked by the wall impurity radiation. Consequently, as evidenced by the test results, this technique yields good reproducibility of data.

II EXPERIMENTAL TECHNIQUES

A. Experimental Setup

The experiments to be discussed were performed in the IITRI 3-inch buffered shock tube using 3/8-inch and 3/4-inch diameter

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hemisphere-cylinders. The buffer gas in these experiments was dry air. This choice was based on earlier experience ^(2, 3), which indicated that the very diffuse argon-air contact interface causes inconsistencies in light intensity levels. Particular care has been exercised in preparation of the shock tube. Driver contamination is reduced after each run by thorough cleansing of the tube with a sequence of ethanol rinses. The effects of tube cleaning procedures upon test data will be discussed in the section on test results. After the ethanol rinses, the tube was repeatedly flushed with dry air, and then out-gassed at 1 micron pressure. To insure that the contamination level was the same for each run and that the out-gassing process was essentially complete, the tube was filled with dry air up to 20 microns pressure, evacuated to 1 micron pressure, and the required pumping time recorded. The process was repeated until no further reduction in pumping time occurred. This technique proved to be very effective in attaining good reproducibility in the data. Initial pressures in the shock tube were monitored with two Alphatron pressure gages, which were factory calibrated before this phase of investigation. The shock Mach number was monitored at two photomultiplier stations which are located 28 inches apart, immediately upstream of the test section. Photomultiplier signals were used to trigger and stop a Beckman counter. Simultaneously, signals were recorded on a Tektronix 555 oscilloscope.

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This method furnishes a permanent record of shock velocity and allows correction of any counter errors which result from variations in trigger and stopping sensitivity and signal rise-time characteristics.

Radiation measurements were made at the stagnation point of 3/8-inch and 3/4-inch hemisphere-cylinders. The tips of both models were equipped with profiled, flush mounted, opal glass windows to avoid aerodynamic disturbances. Through a passage in the model, a 3 mm diameter glass fibre bundle, encased in a Thermofax tubing, extended to the window. The opal glass window is necessary to attain light diffusion and hence good angular response characteristics. A Ferrand-Uvis monochromator, was used between the light tube output and the 1P-28 photomultiplier tube for spectral measurements. The output from the photomultiplier was recorded on Tektronix 555 oscilloscope.

B. Calibration Procedures

In order that the light tube pick up all radiation incident upon the stagnation point of the model, the angular sensitivity of the tube should vary as the cosine of the angle of incidence. The angular sensitivity calibration was performed using collimated light. Tests indicated that the angular sensitivity can be modulated by changing the light diffusion characteristics at the receiving end. This can be accomplished by a single opal glass window approximately 0.030 inch thick, or by a window which is made out of several layers of flushed-opal glass. The second method seems to be more favorable since light diffusion can be attained

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with a smaller reduction in light transmission. Figure 1 shows the calibration data as compared with the desired cosine variation. As seen from this figure, the agreement is quite good and the angular sensitivity did not change even after prolonged exposure to the shock environment.

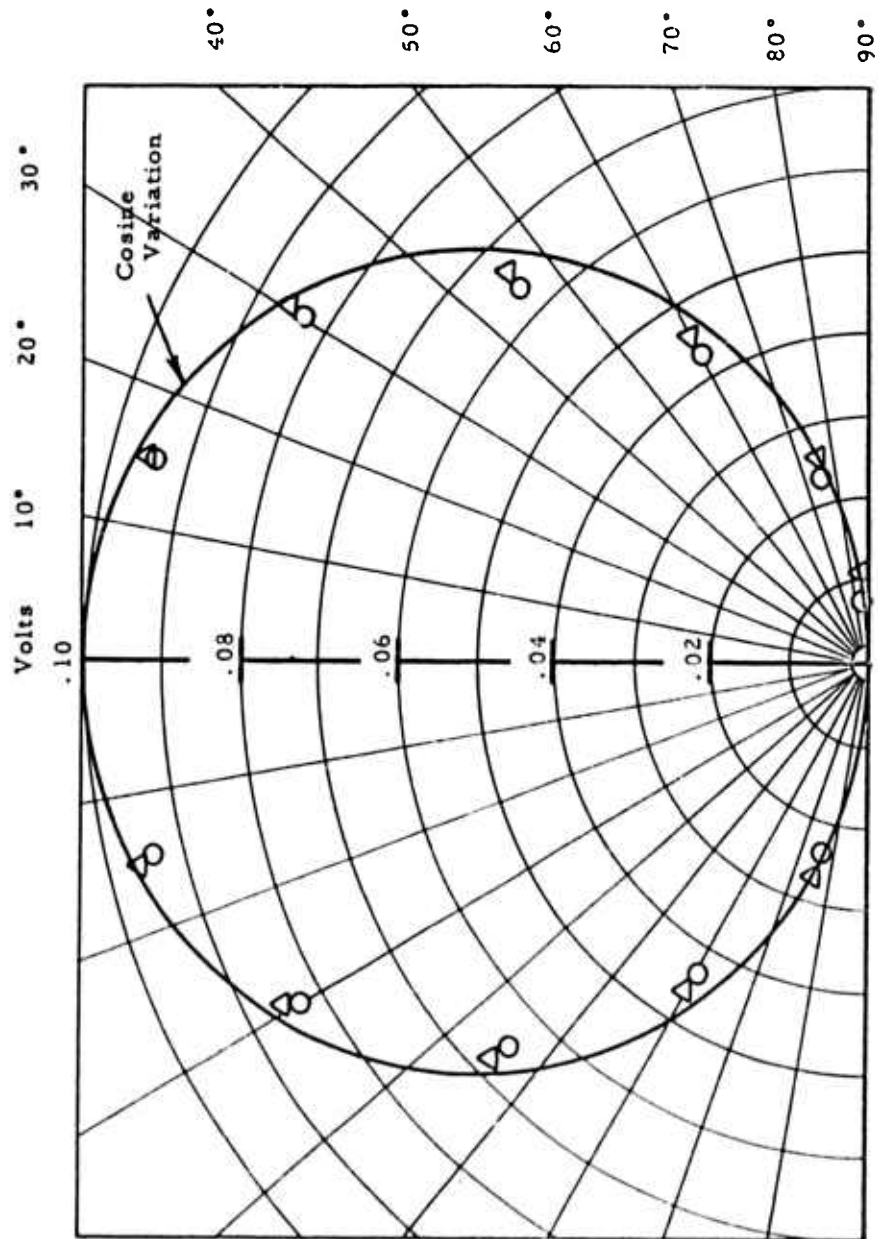
To establish calibration constants for the light intensity measurements, the complete light tube system was calibrated by comparison with the calculated intensities from a standard tungsten filament lamp. In this setup, a quartz lens was used to transpose the image of the tungsten lamp filament through an aperture to the receiving end of the light tube. Therefore, with a one-to-one magnification, the intensity of the filament is very nearly the same as the intensity of the image.

The output from the light tube was passed first through a monochromator having 0.5 mm (100A⁰ total band width) entrance and exit slits, and then into a 1P-28 photomultiplier tube. The calibration was performed over the spectral range from 3700A⁰ to 6400A⁰ at wavelengths to be investigated in the shock tube experiments. A calibration was performed prior to each run to compensate for any changes in the response characteristics of the light tube assembly.

The intensity of the tungsten lamp for a given wavelength is given by:

$$I(\lambda) = \frac{c}{2\pi} \frac{3.742 \times 10^4}{\lambda^5 \left(\exp \frac{6.4558}{\lambda} - 1 \right)} \frac{\text{watts}}{\text{cm}^2 \text{ - } \mu \text{ - ster}} \quad (1)$$

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- △ Output before shock tube tests
- Output after 50 shock tube tests

FIGURE 1 ANGULAR RESPONSE FOR THE LIGHT TUBE ASSEMBLY USING GLASS FIBER BUNDLE AND OPAL GLASS WINDOW AT THE STAGNATION POINT OF THE MODEL

where λ is wavelength in microns and ϵ is the emissivity of tungsten determined from deVos tables⁽⁴⁾. A detailed discussion of Eq (1) is presented in Reference 2. From the geometric arrangement of the calibration setup, the calibration form factor F_{12} can be established:

$$F_{12} = \frac{A_1}{r^2} \times A_2 \text{ cm}^2 \text{ster} \quad (2)$$

where A_1 is the area of the aperture, A_2 is the area of the lamp filament seen by the light tube, and r is the distance between the aperture and the light tube. If V_λ (cal) is the voltage output measured during calibration and V_λ (test) is the voltage output recorded during a shock tube run, then the radiative flux q_{RAD} is

$$q_{\text{RAD}} = \frac{I_\lambda F_{12} V_\lambda \text{ (test)}}{V_\lambda \text{ (cal)} A_2} \frac{\text{watts}}{\text{cm}^2 \mu} \quad (3)$$

In order to be consistent with the calibration data, runs were made with the same monochromator and photomultiplier system used for calibration. As for the calibration, the test runs were performed with monochromator slits of 0.5 mm covering a spectral band 100\AA^0 wide. Likewise, the voltages used to excite the photomultiplier tube were the same as used in the calibration. In cases where the light output exceeded the capacity of the photomultiplier tube, the exciting voltages were reduced so that the output would fall in the linear range of the photomultiplier.

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III SPECTRAL LIGHT INTENSITY MEASUREMENTS

If the flow behind the bow shock is in equilibrium, the intensity of light radiation to the stagnation point should vary almost linearly with the shock stand-off distance or proportionally to the model scale⁽⁵⁾. That is, the region behind the bow shock can be considered as a slab of gas having constant light radiation profile.

However, as the density is decreased and the relaxation region becomes appreciable in extent but less than the shock stand-off distance, the non-equilibrium radiation will dominate, and will depend only on the relaxation distance and not on model scale. Still, further reduction in density causes relaxation distance to increase to such an extent, that it becomes scale dependent again.

With hypothesis light intensity measurements made with at least two models having different nose radii, can be used to establish the character of radiation intensity profile in the bow shock region. This in turn may indicate the flow regimes where equilibrium no longer prevails and also may suggest possible predominant non-equilibrium air radiators, if spectral light intensity measurements are also made.

During the first phase of this effort total light intensity measurement (band width is limited by the photomultiplier - light tube system) were made over a range of initial densities with the stagnation temperature essentially constant⁽⁶⁾. The aim of this effort was to investigate the

earlier discussed effect of model scale on radiation intensity and to pinpoint flow regimes where spectral intensity measurements should be made. The results of this investigation are presented in Figures 2 and 3.

The data were obtained using 3/8-inch diameter hemisphere-cylinders therefore, the model scale factor is two. Figure 3 shows that the light intensity ratio is proportional to the model scale factor at initial pressures down to 0.3 mm; and according to the hypothesis this indicates constant light radiation profile and flow equilibrium. Lowering of the initial pressure with the stagnation temperature held essentially constant, results in deviations of intensity ratio from the scale factor, thus suggesting the onset of flow non-equilibrium. The radiation-intensity profiles which may explain such behavior are also depicted in Figure 3. Consequently, three flow regimes have been chosen for detailed spectral radiation intensity measurements. These are as follows:

- a. Equilibrium regime, (initial pressure 1 mm Hg)
- b. Non-equilibrium regime where relaxation distance is smaller than shock stand-off distance (initial pressure, 0.15 mm Hg)
- c. Advanced non-equilibrium regime where relaxation distance is larger than shock stand-off distance (initial pressure 0.1 mm Hg).

Spectral light intensity data have been obtained in these flow regimes using 3/8-inch and 3/4-inch diameter hemisphere cylinders, The shock Mach numbers have been chosen in such a manner that the equilibrium

I_R - Nondimensional Light Intensity, measured behind the bow shock

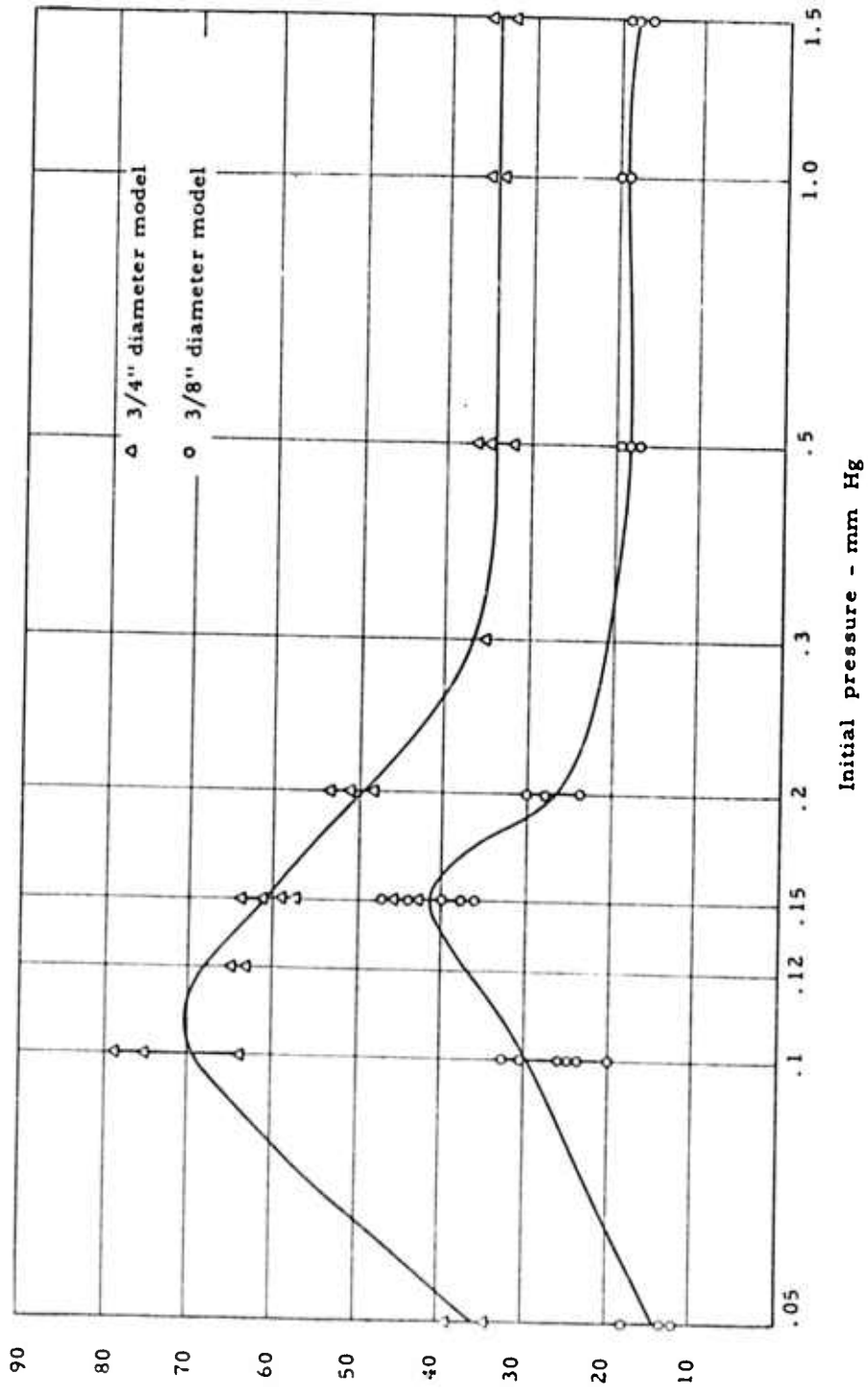


FIGURE 2 TOTAL LIGHT INTENSITY MEASUREMENTS

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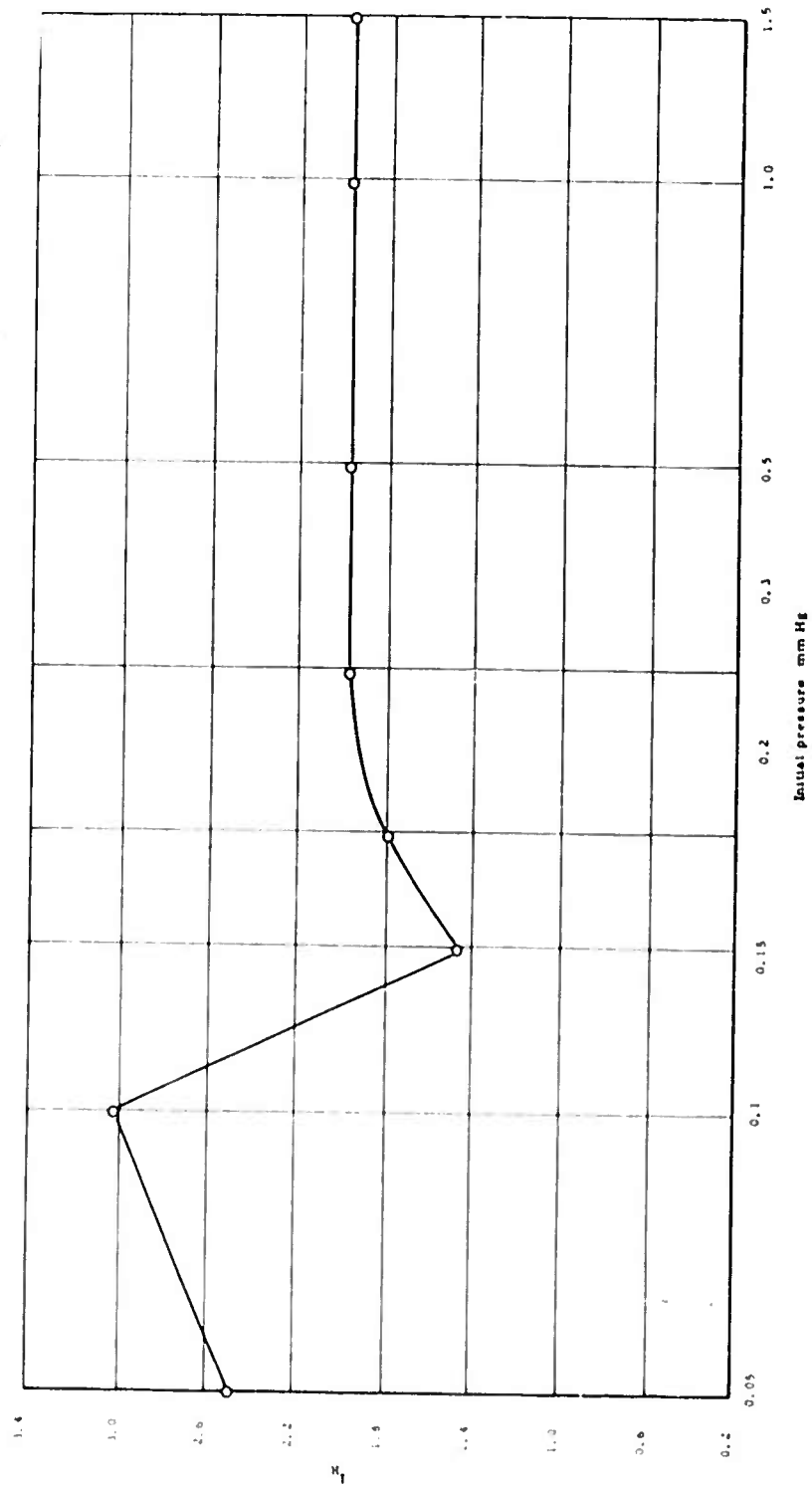


Figure 3 AVERAGE LIGHT INTENSITY RATIO $I_R = \frac{I_{1/4" \text{ dia. model}}}{I_{1/8" \text{ dia. model}}}$

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stagnation temperature of approximately 6200°K is maintained. Spectral intensity was measured using a light tube-monochromator-photomultiplier system over the visible portion of the spectrum (3700A° to 6400A°). The Ferrand monochromator with 0.5 mm entrance and exit slits has been used exclusively. The theoretical band-width for this slit size is 110 Angstrom units. Therefore, in order to insure full coverage of the region, data have been obtained at 100 Angstrom unit intervals.

IV DISCUSSION OF TEST RESULTS

The emphasis in the current work period was on gathering the data in flow regimes corresponding to the initial shock tube pressure of 0.15 and 0.10 mm Hg respectively. Altogether 300 data points have been obtained. These data, together with earlier reported spectral intensity measurements, (Ref 6) are presented in Figure 4.

For both models, as the initial shock-tube pressure is decreased from 1 mm to 0.15 mm Hg, the radiant flux intensity over the spectral region from 3800A° to 4300A° increases considerably. This order of magnitude increase of radiation intensity, although over a small band width (3800 to 4200A°), may explain the intensified radiation level below 0.2 mm pressure obtained from total radiation measurements and shown in Figure 2 (Ref 6). Likewise the more rapid decay in radiation level below 0.15 mm for the 3/8-inch diameter model as compared with the 3/4-inch diameter model at 0.1 mm pressure (Figure 2) is verified by the current spectral intensity measurements. On the other hand,

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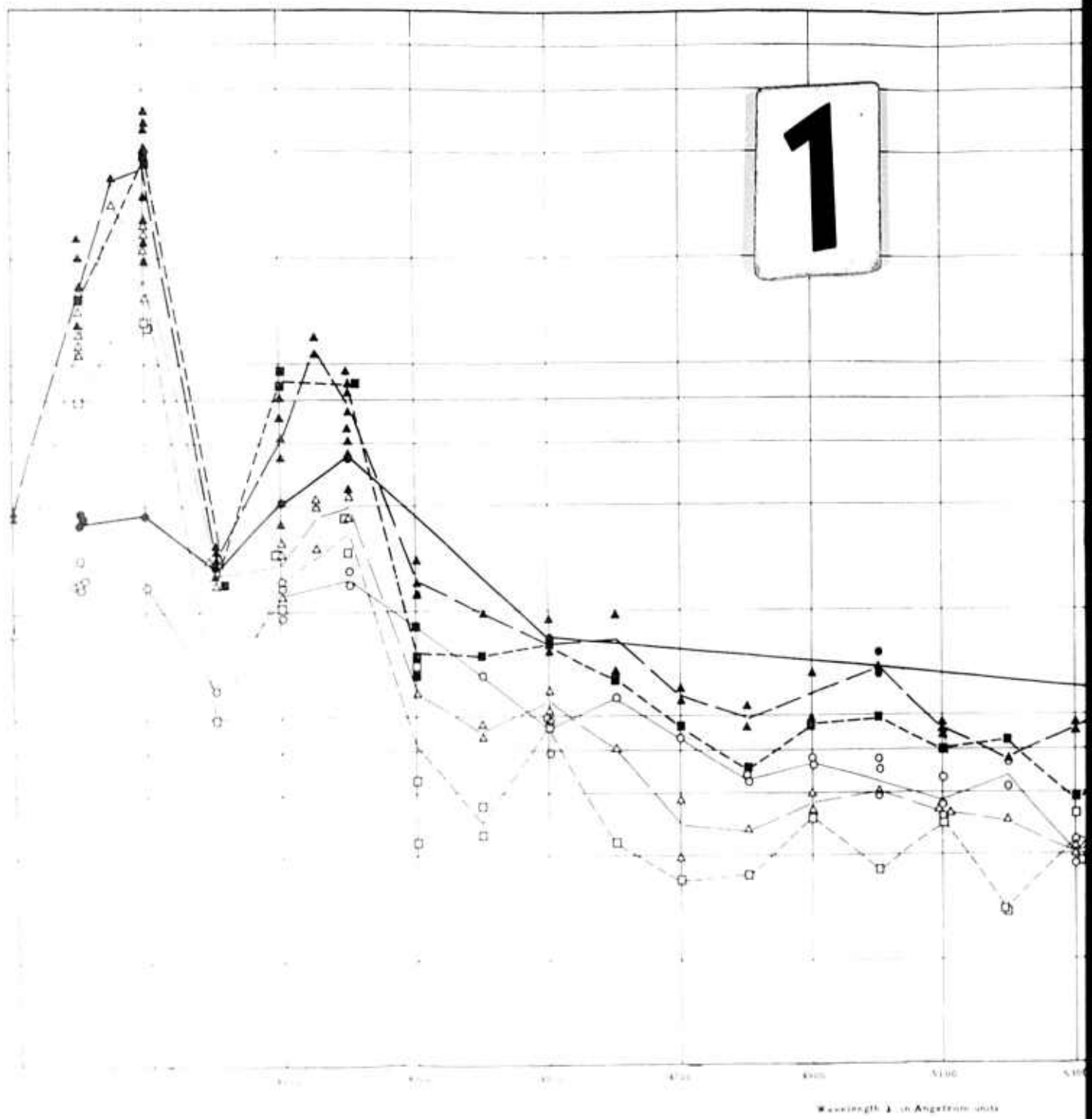
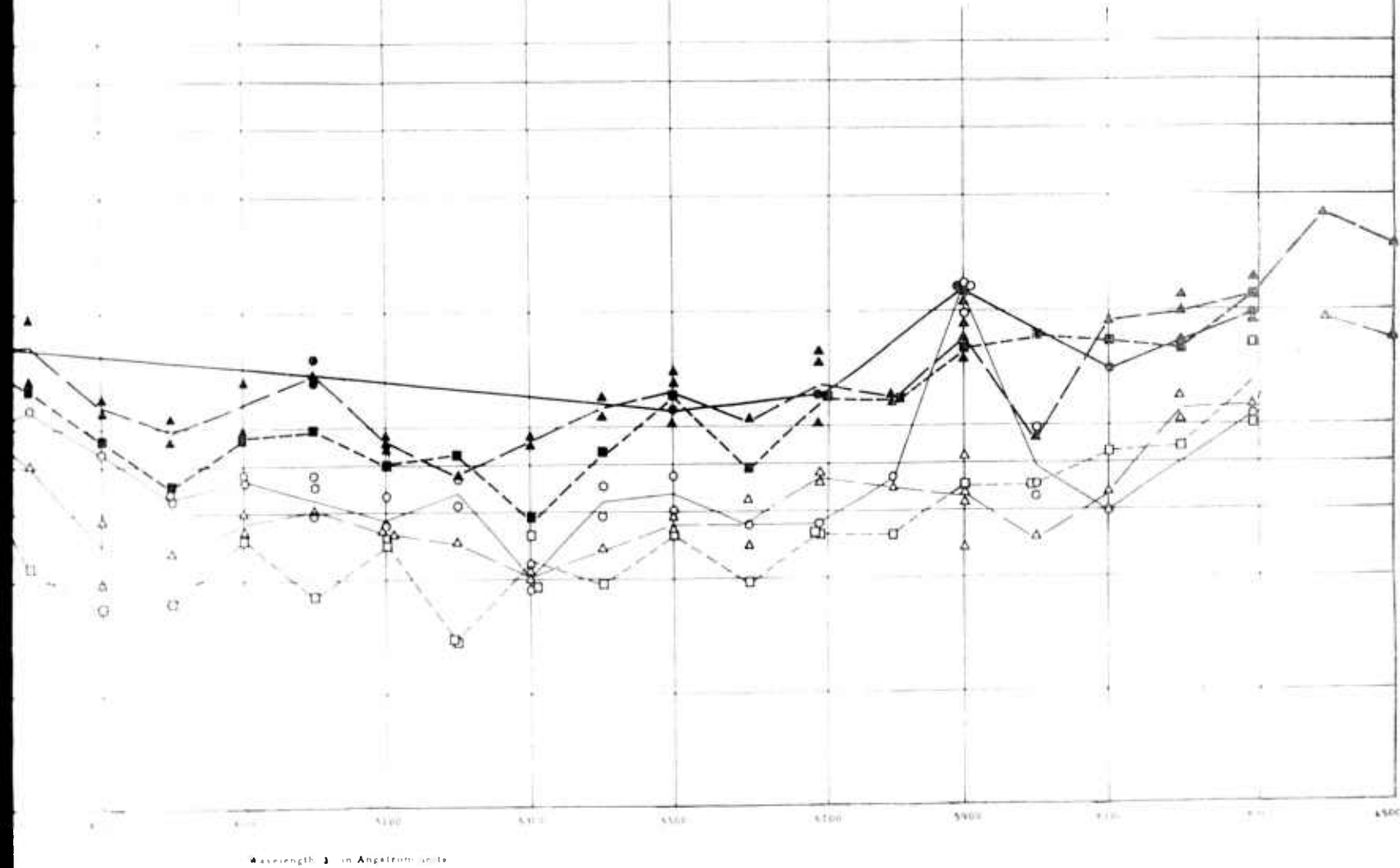


Figure 4. RADIATIVE HEAT FLUX TO THE STAGNATION POINT OF A BLUNT NOSE PROBE

2

- $P_1 = 1.0$ mm Hg, 1.8° model ○
- $P_1 = 1.0$ mm Hg, 3.4° model ●
- $P_1 = 0.15$ mm Hg, 3.4° model △
- $P_1 = 0.15$ mm Hg, 1.8° model ▲
- $P_1 = 0.10$ mm Hg, 1.8° model □
- $P_1 = 0.10$ mm Hg, 3.4° model ■
- Stagnation Temperature: 4200°K



Wavelength λ in Angstrom units

FIGURE 4. RADIATIVE HEAT FLUX TO THE STAGNATION POINT OF A HEMISPHERE CYLINDER

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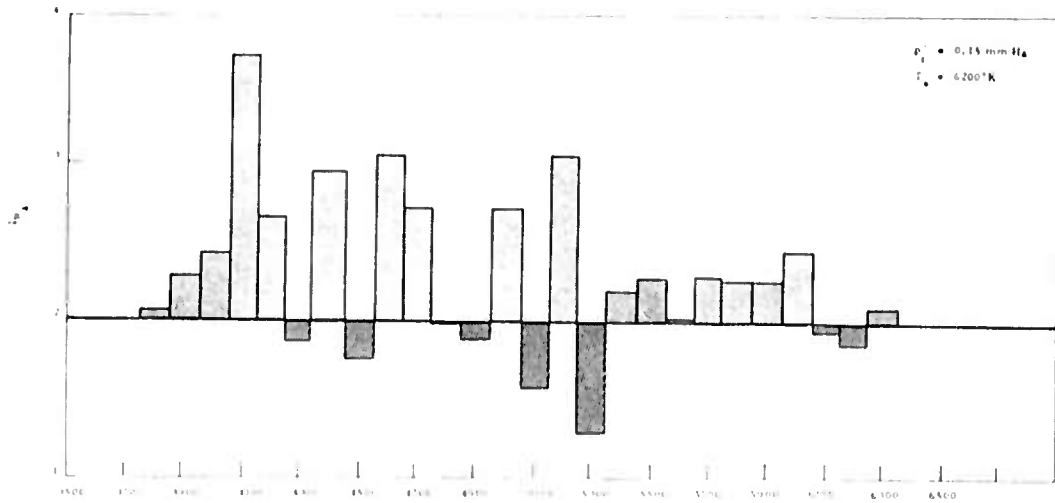
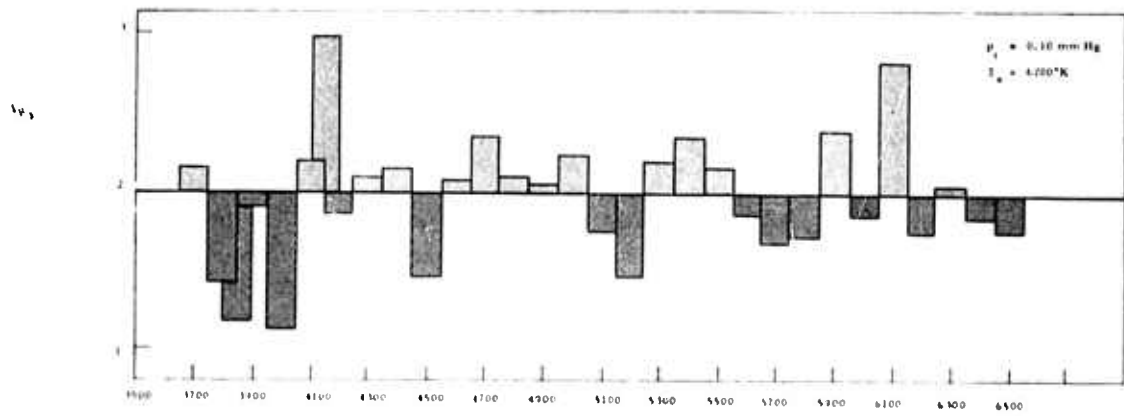
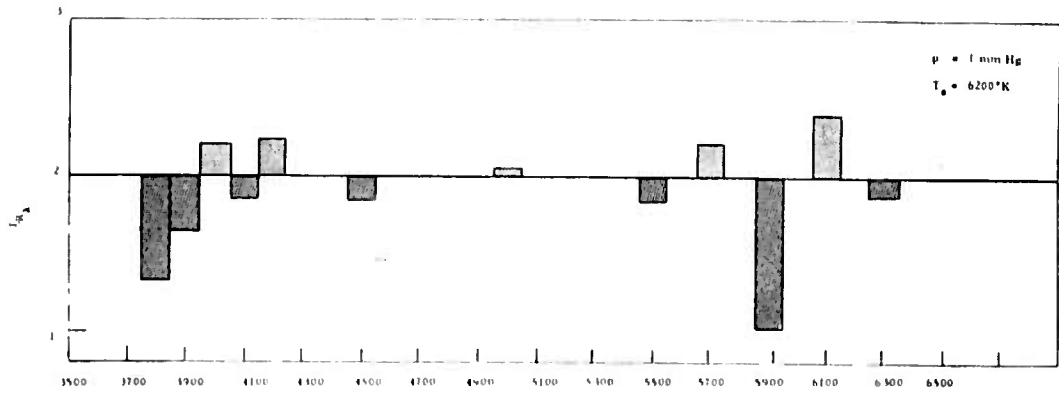


FIGURE 1. ABSORPTION SPECTRA OF ETHYLENE BANDA ν_2 AT $\lambda = 1.2 \mu\text{m}$ (1667 cm⁻¹)

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there are only small over-all changes in the intensity level from 4300A⁰ to 6300A⁰.

Further decrease in the initial pressure to 0.1 mm Hg is associated with larger over-all changes in the radiation intensity level. In the spectral region from 3800A⁰ to 4200A⁰, the radiation level is essentially the same as at 0.15 mm pressure. However, over the spectral region from 4200A⁰ to 5400A⁰ radiation intensity is lower than at 1 mm and 0.15 mm pressures. In particular, this is the case with the smaller (3/8-inch diameter) model. For the remaining portion of the spectrum, the intensity level is essentially the same as that measured at flow regimes corresponding to 1mm and 0.15 mm Hg pressures.

If the criterion for flow equilibrium is that the intensity ratio for the two models should vary in proportion to the model scale, deviations from this scale factor over the spectrum will give a measure of the extent of flow non-equilibrium.

Graphical presentations of light intensity ratios are shown in Figures 5a, 5b and 5c. Figure 5a gives averaged ratios obtained from spectral intensity measurements at 1 mm pressure. As discussed in the last Semi-annual Report⁽⁶⁾, this flow regime can be considered in equilibrium since the over-all deviations from the model scale factor are relatively small and, may be attributed mostly to the experimental errors. The large deviations observed at 3800A⁰ and 5900A⁰ may be caused, at least in part, by the impurity radiation.⁽⁶⁾

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Since the intensity ratios obtained from total radiation measurements (Figure 3) show reasonable agreement with the model scale down to densities corresponding to 0.3 mm Hg pressure, and verification from spectral measurements exist at one point in this region, it is reasonable to assume that the shock tube data in this region can be used for calculating heat loads to actual reentering vehicles.

The results of Figures 5b and 5c show a different behavior, however. At 0.15 mm Hg, the intensity ratios for 50 percent of the points are less than the model scale. This trend indicates that non-equilibrium overshoots exist as depicted in Figure 3b. The other half of the points show that the intensity ratio is greater than the model scale which, in turn, suggests various degrees of advanced non-equilibrium, characterized by the radiation profile in Figure 3c. Since the radiation level is much higher at the lower wavelengths where the intensity ratio is predominantly less than two, the average intensity profile should appear as anticipated from the total radiation measurements at this flow regime (Figure 3b).

Figure 5c indicates considerably more advanced non-equilibrium, since most of the data yield intensity ratios are greater than the model scale.

It is quite obvious that shock tube data obtained in these flow regimes cannot be applied to the calculation of reentry heating by simple geometric scaling laws. Nevertheless, the data obtained will enable analysis of non-equilibrium radiation processes. The intensity ratios given in Figures 5b

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and 5c, together with the radiant intensity flux, indicate spectral regions of the most important non-equilibrium radiations. Likewise, it is possible to qualitatively construct the changes in radiation profile with decreasing density. Consider, for example, radiation flux intensity together with the intensity ratios at 4100\AA and 4500\AA and 1 mm, 0.15 mm and 0.1 mm pressures. Figures 6 and 7 depict the resulting situation. The identities of the predominant radiators have not yet been identified but attempts in this direction will be made in the final phase of this study. The non-equilibrium radiation from shock fronts in air has been studied by a number of people, chiefly at AVCO⁽⁷⁻¹⁰⁾. Their work may provide some information, which will be useful in the analysis of currently obtained light tube measurements.

In general, the non-equilibrium radiation is produced by N_2 , N_2^+ , NO, NH, OH, and C_2 in various degrees (the last three being more unusual). These molecules have different rate constants and rate processes so that they respond in different manners to changes in temperature and pressure.

The changes in radiation intensity profiles with the initial pressure (Figure 6 and Figure 7) at particular spectral portions may be due to single or multiple species. For instance, an overlap of $\text{N}_2(2+)$ and NO (β) bands may exist. Since these radiating species have different rate processes and rate constants which depend not only on temperature but pressure also,

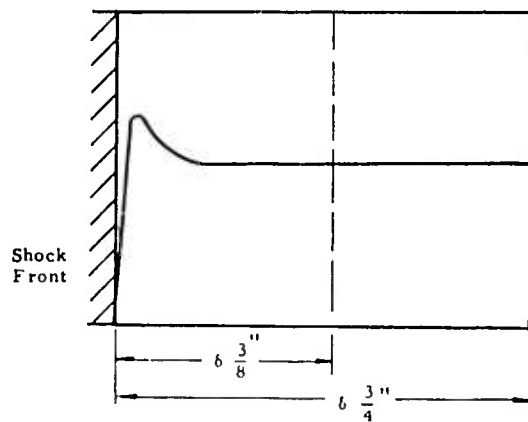
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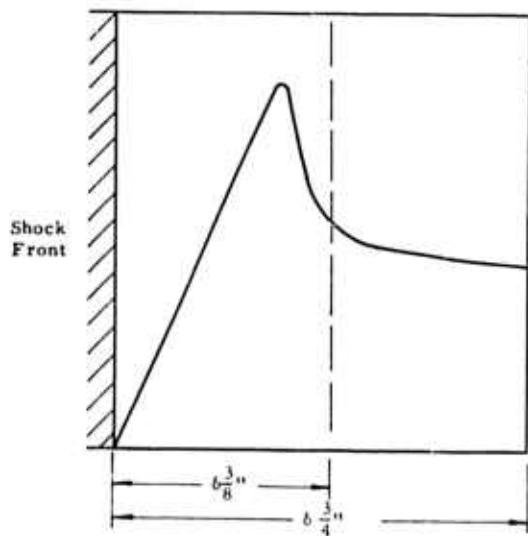
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$$\frac{I_{\frac{3}{4}}}{I_{\frac{3}{8}}} = 1.84$$

1 mm Hg pressure

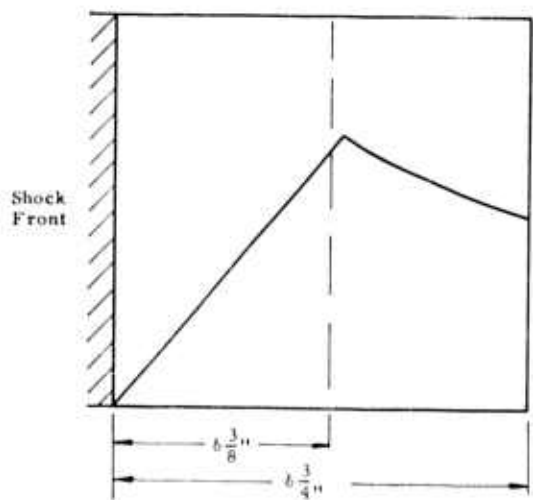
$$T_0 = 6200^\circ\text{K}$$



$$\frac{I_{\frac{3}{4}}}{I_{\frac{3}{8}}} = 2.2$$

0.15 mm Hg pressure

$$T_0 = 6200^\circ\text{K}$$



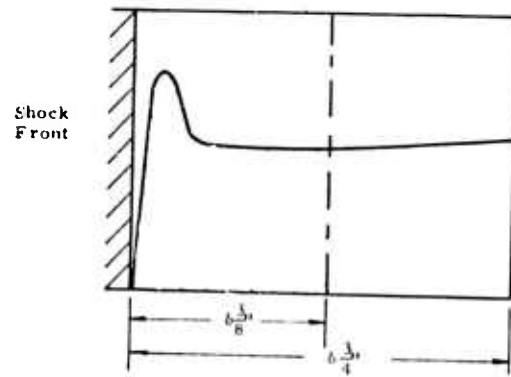
$$\frac{I_{\frac{3}{4}}}{I_{\frac{3}{8}}} = 3.7$$

0.1 mm Hg. pressure

$$T_0 = 6200^\circ\text{K}$$

Note: $b_{\frac{3}{8}}$ and $b_{\frac{3}{4}}$ are stand off distances for $\frac{3}{8}$ " and $\frac{3}{4}$ " diameter models respectively.

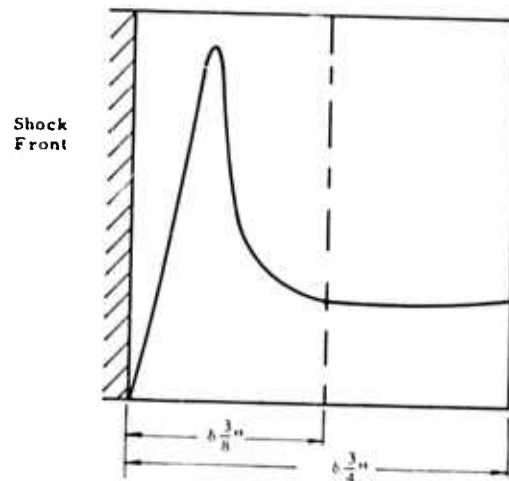
Figure 6 RADIATION INTENSITY PROFILES
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$$\frac{I_{3/4}''}{I_{3/8}''} = 1.83$$

1 mm Hg pressure

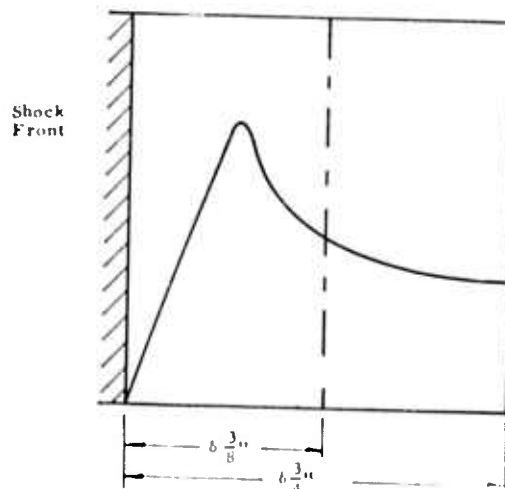
$$T_0 = 6200^{\circ}\text{K}$$



$$\frac{I_{3/4}''}{I_{3/8}''} = 1.44$$

0.15 mm Hg pressure

$$T_0 = 6200^{\circ}\text{K}$$



$$\frac{I_{3/4}''}{I_{3/8}''} = 1.75$$

0.1 mm Hg pressure

$$T_0 = 6200^{\circ}\text{K}$$

Note: $\delta 3/8''$ and $\delta 1/4''$ are stand off distances for $3/8''$ and $1/4''$ diameter models respectively.

Figure 7 RADIATION INTENSITY PROFILES

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changing the initial shock tube pressure to progressively lower value may decrease radiation from $N_2(2+)$, but at the same time may increase the radiation intensity from $NO(\beta)$ band.

These processes may take place in such a fashion that the over-all light intensity measured by the monochromator photomultiplier system is not altered appreciably, yet the radiation profiles within the low shock region are affected considerably. The spectral band width covered by a monochromator is rather large ($110A^\circ$) and only marginal resolution can be expected. Hence positive information regarding the identity of the species cannot be obtained. The highest radiation intensity peaks at 0.15 mm and 0.1 mm pressure occur around $3900A^\circ$ and $4150A^\circ$ which corresponds to the predominant band-heads of CN- violet system. Several tests were performed at $3900A^\circ$ and 0.15 mm pressure using identical shock tube cleansing processes, but varying the out-gassing pressure. The results are shown in Figure 8. It is evident that even after careful cleaning and flushing procedures, tube out-gassing processes affect contamination of the test gas. By increasing the out-gassing pressure from 0.1 to 2μ , the variation in radiant flux intensity increases approximately by a factor of four. The lowest values were reached by continuous out-gassing in excess of 18 hours pumping time, hence, such experimental procedures are not practical. The data shown in Figure 4 include points obtained with out-gassing pressures equal to or less than 1μ . Similar

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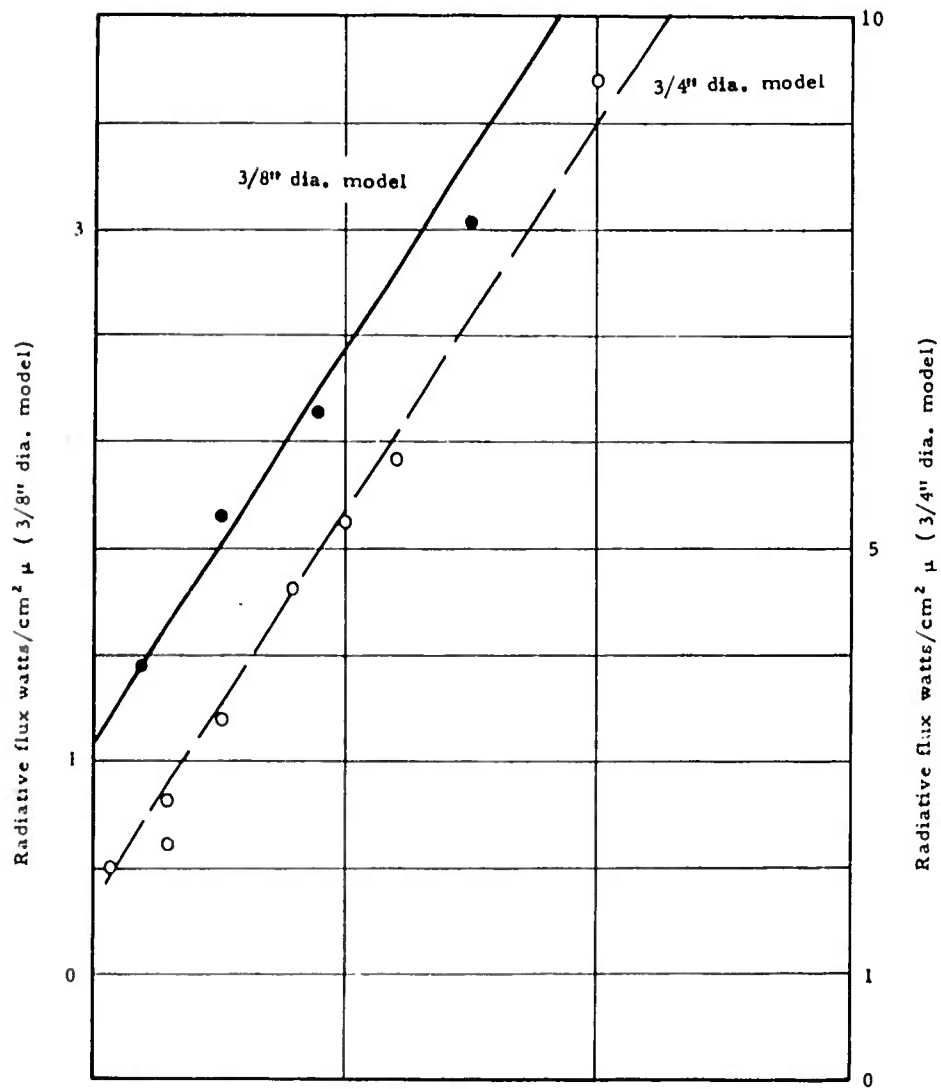


Figure 8 THE EFFECTS OF SHOCK TUBE OUTGASSING PRESSURE ON THE RADIANT FLUX INTENSITY AT $\lambda = 3900\text{\AA}$

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data dependency on out-gassing pressure was noticed also at 4100A° to 4300A° band widths, only to a lesser extent. This fact again is responsible, at least in part, for the scatter of data in these spectral regions.

Even the smallest output at 3900A° is considerably larger at 0.15 and 0.1 mm than at 1 mm pressure, hence part of the radiation at this wavelength may be due to $N_2(2+)$ and possibly $N_2(1-)$. The same reasoning may apply to the radiation peak at 4100 to 4300A° band width. In the remaining portion of the spectrum investigated (6500A°) the predominant radiators may be $N_2(1+)$ with some contributions from $NO(\beta)$.

V CONCLUSIONS

Spectral intensity data have been obtained over the visible portion of the spectrum at flow regimes corresponding to 1 mm, 0.15 mm and 0.1 mm Hg initial pressures and equilibrium stagnation temperature of approximately 6200°K. The data have been gathered using two different hemisphere-cylinders of 3/4-inch and 3/8-inch diameters respectively. Consequently, six radiation intensity curves have been generated. This data have enabled qualitative evaluation of the extent of flow equilibrium and non-equilibrium in these shock tube flow regimes.

In the flow regimes where non-equilibrium effects are present, an increase of the radiative flux is observed.

VI FUTURE WORK

In order to fully evaluate the data presented in this report information pertaining to the identity of radiating species is necessary.

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Consequently the last effort in this program will be concerned with spectrographic investigation. The advantages of light-tube spectrograph systems have been discussed in the last Semi-annual Report. The major advantage, of course, is that the impurity radiation from the boundary layer at the shock tube wall can be avoided. First attempts will be made to investigate the flow regime at 1 mm pressure, where flow duration and light intensity are most favorable. If this attempt is successful other flow regimes will also be investigated.

Supplementary intensity measurements will then be made at spectral portions which warrant detailed investigation.

In conjunction with this work the present data will be evaluated in the light of studies made by other investigators⁽⁷⁻¹⁰⁾. The results of these studies will be finalized and included in the forth coming final report.

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