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EXPERIMENTAL STUDY OF EQUILIBRIUM AIR TOTAL RADIATION

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1. Introduction

Thermal radiation from entry body flow fields has been investigated extensively for many years. Early studies were largely concerned with orbital and sub-orbital Earth entry. With the increased interest in superorbital entry velocities, many recent theoretical studies and laboratory and flight experiments have been concentrated in this regime. Through a simplified analysis of the atomic deionization and free-free mechanisms, Breene and his associates predicted that for hypervelocity entry body temperature and density levels the bulk of the energy radiated from a thin layer of gas (a 1 cm layer thickness was generally assumed) would be at wavelengths below $.2\,\mu$ (1) (2). Biberman and his associates have published high temperature theoretical results that showed the importance of the vacuum UV region (3) (4). This work concluded that the deionization and F-F mechanisms were important and also that atomic line radiation would be the most significant contributor to UV gas radiance over important ranges of temperature, density and layer thickness. Biberman's results lose some of their value, however, since the method of presentation, makes them difficult to use other than for direct comparison with radiative heat transfer (not intensity) measurements. Several other contributions to the theoretical aspects of this problem have been made; for example, see Refs. 5 and 6.

At the GE Space Sciences Laboratory, experimental interest in superorbital flight simulation started in 1960 with the initiation of the development of electrically driven shock tubes and tunnels (7). The need for a fast response total radiation measurement technique with wide spectral capability was recognized and led to the development of the thin film cavity gage (8). This gage can be used in models or in the walls of a shock tube and can be used with or without absorbing materials (windows, cooled test gas) in the path between the radiating sample and the sensor.

Work under contract to the Jet Propulsion Laboratory was initiated in 1962 (9) and continued under a new contract (10) in 1963. The initial direction for these studies was to investigate hypervelocity (to 45,000 ft/sec) entry into simulated Venusian atmospheres. Some of these results were published in Ref. 11. Of interest to the present study was the inclusion in the JPL program of the vacuum UV predictions of Breene and Nardone for N_2-CO_2 mixtures (1) and for air (2) (which were used to show that air and N_2-CO_2 mixtures have similar radiance properties at high velocities) and the interpretation of entry mission radiative heating including the UV contributions (11). After this part of the study, our JPL work was directed towards the study of Mars entry and was concentrated, therefore, on the lower entry velocity regime (less than 30,000 ft/sec).

The potential importance of vacuum UV radiance for the superorbital Earth entry of blunt bodies was discussed at the NASA Contractors' Conference on Entry Fluid Physics Research in Washington in December, 1963, and our present study contract with NASA-OART began in 1964.

To date, our work has shown the existence of an important contribution to air radiance over a simulated velocity range of 34,000 to 42,000 ft/sec and at wavelengths below those cut off by the usual window materials. The techniques used and some of our preliminary data were discussed at the NASA Contractors' Conference in March 1965 and are described in Ref. 12. Our most recent results are given in this progress report. An important part of our present program is to extend our investigation to the 60,000 ft/sec simulated velocity level to study the effects of convective-radiative energy coupling. The existence of a satisfactory test flow at this energy level has been demonstrated and will be discussed. We will also discuss several recent analytical investigations and their implication in entry flight.

Publications of interest to this problem area, not mentioned above and generated by SSL personnel, are given in the reference list (13) (14) (15) (16) (17).

2. Analytical Considerations

Calculations were made of the emission coefficient for free-bound transitions in air in local thermodynamic equilibrium at $\rho / \rho_o = 10^{-3}, 10^{-2}$ and 10^{-1}, over a range of temperatures between 10,000°K and 20,000°K. In performing the calculations, spectral absorption coefficients for N and O given in Ref. 6, which were obtained from the calculations of photoionization cross-sections according to Burgess and Seaton, were used. The particle concentrations of atomic nitrogen and oxygen in air at elevated temperatures were taken from the tabulations of Ref. 18. In Fig. 1 the integrated emission coefficient at $\rho / \rho_o = 10^{-3}$ for wave numbers $\tilde{\nu} > 88000 \text{ cm}^{-1}$ are compared with similar results of Hahne (5) and Breene (2).

In applying these data to actual radiation transfer, account was taken of both emission and absorption. This was accomplished by performing the integration of the transfer equation

$$\frac{dI(\lambda)}{dx} = -K(\lambda)\left[I(\lambda) - B(\lambda) \right]$$

between limits of x = 0 and L = 0.5, 1, 2, 5 cm. In this expression K is the sum of the absorption coefficients due to photoionization of O and N. The resultant monochromatic intensity was integrated from 500 Å to 1130 Å and added to Breene's predicted intensity for $\lambda > 1600$ Å. In Fig. 2 a comparison is made between the intensity so calculated and the earlier results of Ref. 2. The plotted curves correspond to model stagnation conditions in a shock tube flow at initial shock tube pressure $P_1 = 0.3$ mm which corresponds to a nominal point of the present experimental range. Here it should be pointed out that neither calculation includes contributions from atomic and ionic line radiation. It can be shown that most of this will appear in the UV range of the wavelength spectrum. To obtain an approximate assessment of the magnitude due to the line radiation one can refer to the calculations of Vorobev and Norman (3) for a nitrogen plasma-Fig. 3. At a temperature of 14000°K and a pressure of 1 atm, they predict that line radiation will exceed all other sources of emission (including free-bound transition in the vacuum UV) by a factor between 1.5-2.7 for L between 1 and 100 cm.

For application to the flight of spherically blunt bodies, radiating heating rates have been predicted by Biberman, et al (4). This work includes the mechanisms mentioned above and accounts for self absorption in the calculation of radiant energy transfer. A flight velocity-altitude correlation was developed using these results and the stand-off distance predictions of Serbin (19) - Fig. 4. It is interesting to note that over a region of spherical body nose radius - .3 ft. to 30 ft. - the radiative heat transfer is approximately proportional to $R_N^{.6}$ rather than directly to R_N which one would obtain for an optically thin shock layer. If the radiated energy becomes an appreciable fraction of the energy flux across the bow shock wave, properties of the flow in the shock layer will be different from those predicted on the basis of no radiation loss. Lines of constant ratio (γ) of the energy radiated away to the energy convected to the shock layer in the vicinity of the stagnation point are also plotted in Fig. 4. Using a simple stagnation flow model, Goulard (20) has shown that even for small values of γ an appreciable reduction of total (radiative and convective) heating can result compared to that calculated for the no-coupling assumption. Similar results have been obtained by Howe and Viegas (21) and Hoshizaki and Wilson (22).

To illustrate the variations possible in the use of different prediction methods, heat transfer calculations for a point typical of the trajectory of a Project Fire vehicle were made. The re-entry velocity and altitude were taken as 34,600 ft/sec and 171,600 ft, respectively. In Fig. 5 the results of several methods of arriving at the total heat transfer are shown. In all the approaches, the non-coupled stagnation point convective heat transfer rate was constant as given by Brunner, et al (23). The highest prediction results from the assumption of optically thin layer with no radiative coupling. There is a relatively small difference between calculations allowing self-absorption in the UV region of the spectra using Breene's intensities and the absorption coefficients of Sherman and Kulander. The uncoupled Biberman radiative heat transfer prediction (Fig. 4) is almost as high as the non-absorbed calculation. It should be remembered that this is only co-incidental since each method depends on different assumptions. Because of the relatively high level of energy radiated away by the shock layer in this case ($\gamma \approx .03$ for an $R_N = 2.5'$-Fig. 4), some allowance should be made for changes in the properties of the flow and the subsequent effect on radiative and convective heat transfer. Since we know of no method that adequately accounts for coupling with the type of self-absorbtion involved, we have simply used Goulard's corrections for a transparent gas to modify Biberman's predictions. The total heat transfer rate was reduced by approximately 24%. This result must be considered to be only an indication of the magnitude of the correction and not an accurate prediction.

3. Experimental Study

The experimental measurements of the total radiative intensity are made in electrical arc driven shock tube. The stagnation region shock layer ahead of a blunt model is the high temperature test gas sample. Before such studies could be conducted, the quality and duration of the uniform test conditions in the shock tube were investigated (16). Because of the wide spectral range in which air species radiate and for other considerations (12), a total radiation cavity gage in a windowless configuration was developed as a sensor of radiant energy. Several difficulties were encountered during the development stages. One of them was the photoemission from the thin platinum film used in the gage to sense the temperature of the quartz substrate. This was eliminated by filling the space inside the cavity gage with an inert gas mixture (He-Kr) characterized by a large collision cross-section for electrons. This gas apparently produces a space charge which inhibits the photoemission. A second problem was to conceive a method which would retain the inert gas mixture prior to the arrival of the incident shock wave at the model but which would permit the radiation from the shock layer to enter the gage during the test period. For this purpose a latex membrane shutter was developed which can be opened at a predetermined time. As we have gathered experience with this technique, it has been found that the inherent delay between the time of the capacitor discharge which supplies the heat pulse to the stretched latex membrane and the time of the opening is strongly dependent on the shape of the current pulse and on the homogenity of the latex.

Several oscilloscope traces of the cavity gage signal are shown in Fig. 6. The records were obtained in the windowless model filled with 50% He - 50% Kr gas mixtures at a pressure equal to the predicted stagnation point pressure. All runs (both with and without windows) were made at $P_1 = 0.33$ mm Hg. A plot of gas radiance data reduced from one of the runs is shown in Fig. 7. The flow about the blunt model requires approximately 6-8 μ sec. to be established. A uniform gage heat transfer rate follows for about 11 μ sec. at which time the test flow terminates and a mixed region of driven and test gases arrives at the model.

A series of runs was made with the cavity gage behind a LIF window in the hemispherical model. The interior of this model was also filled with a mixture of He and Kr. The reduced data, accounting for the shock layer thickness and hence for the effective volume of the radiating gas, are plotted in Fig. 8, where they are compared with theoretical predictions. The results follow closely the predictions of the total radiance in the spectral region between .16 and 10 μ. A single run obtained with a quartz window produced a result which lies close to the LIF window data.

Data obtained with the windowless cavity gage system are also shown in Fig. 8. The data points reported on earlier are indicated by crosses. The later results were obtained in models differing from the early models only in the internal design of the seal which holds the stretched latex membrane. As can be seen these results lie considerably higher than previous ones. Three points obtained in a model which had part of the translucent cap outside the entrance slit left uncovered are marked by squares. These points have been corrected analytically by using Breene's high wavelength predictions and assumed transmission characteristics for the cap. The results of Vorobev and Norman (3) shown in Fig. 3 predict that for the optical thickness of the present experiments it is possible to have the radiation from the lines far exceed the remaining contributions. An estimate of this contribution has been made and is shown in Fig. 8 with other predictions of gas radiance. The scatter exhibited in the windowless data shown in Fig. 8 is not considered to be satisfactory. Therefore, we are presently investigating the effects of several problems we have had which may influence the results. These include premature and late opening of the latex shutter and an induced electrical interference (other than photoemission) that appears on several sensors at the time of arrival of the incident shock wave at the model. The latter effect is not apparent in the cavity gage response on each run (see traces in Fig. 6). Until these problems are resolved the data presented here must be considered to be preliminary.

Fig. 9 shows a sidewall photomultiplier observation of the stagnation region of a blunt model in the shock tube. This is the technique we use standardly to identify test flow duration and uniformity. The P_1 and U_s values correspond to simulated flight velocity and altitude conditions of approximately 60,000 ft/sec and 135,000 ft, respectively. There are 9 microseconds of uniform test flow behind the incident shock wave of which about half are required to establish a steady flow around the model. This extreme test condition is obtained by using a small diameter driver with our relatively large capacity energy storage bank.

The model flow at these conditions is strongly coupled ($\gamma = .10$) even for the small diameter models used in the shock tube. Our plan during the present program is to extend our total radiation measurements to this flight velocity regime (and beyond) to determine the effects of coupling on gas radiance.

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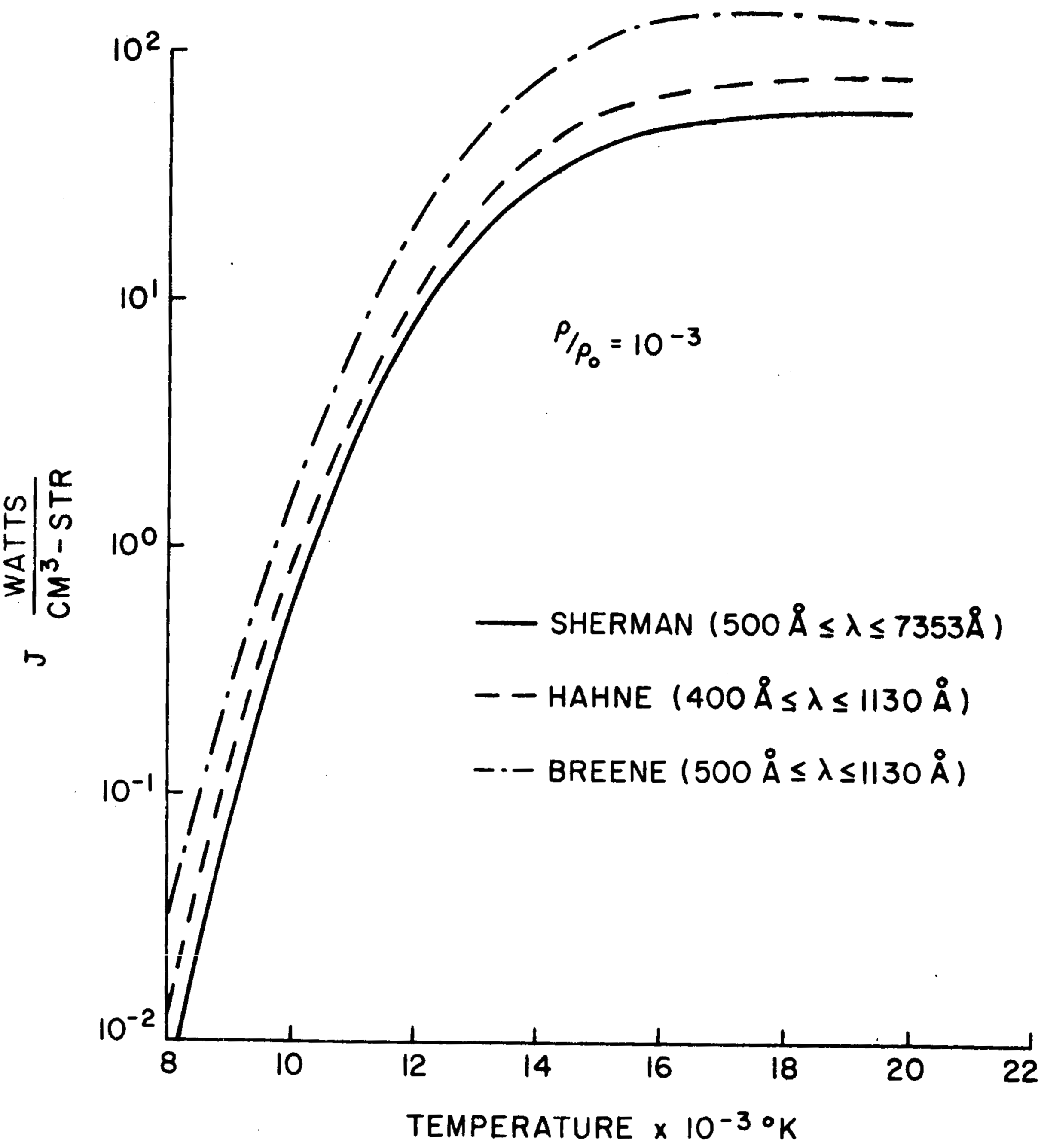


Figure 1. Comparison between several predictions of free-bound emission coefficients for air at $\rho/\rho_o = 10^{-3}$.

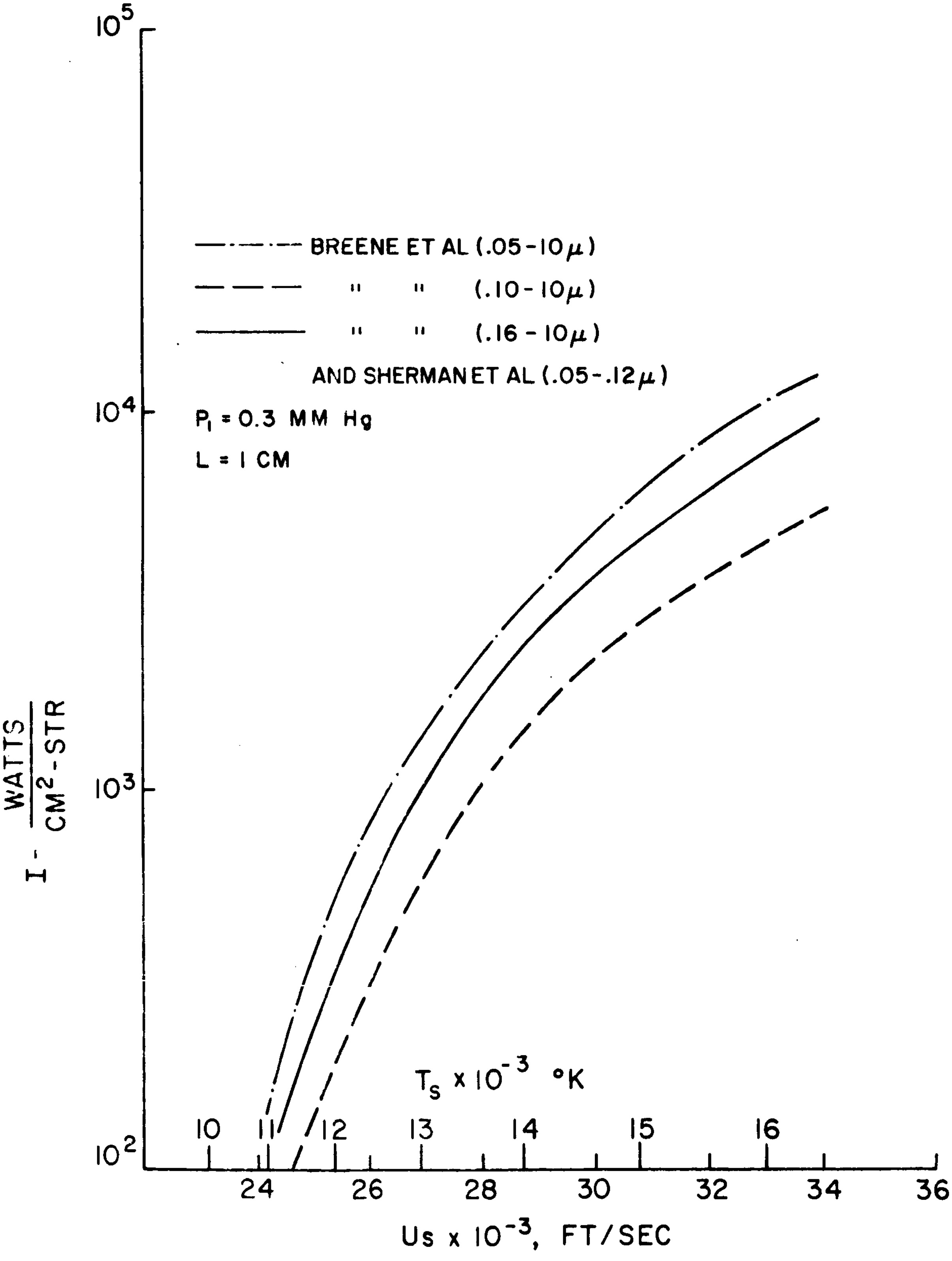


Figure 2. Radiative intensity of air for blunt model stagnation conditions in a shock tube.

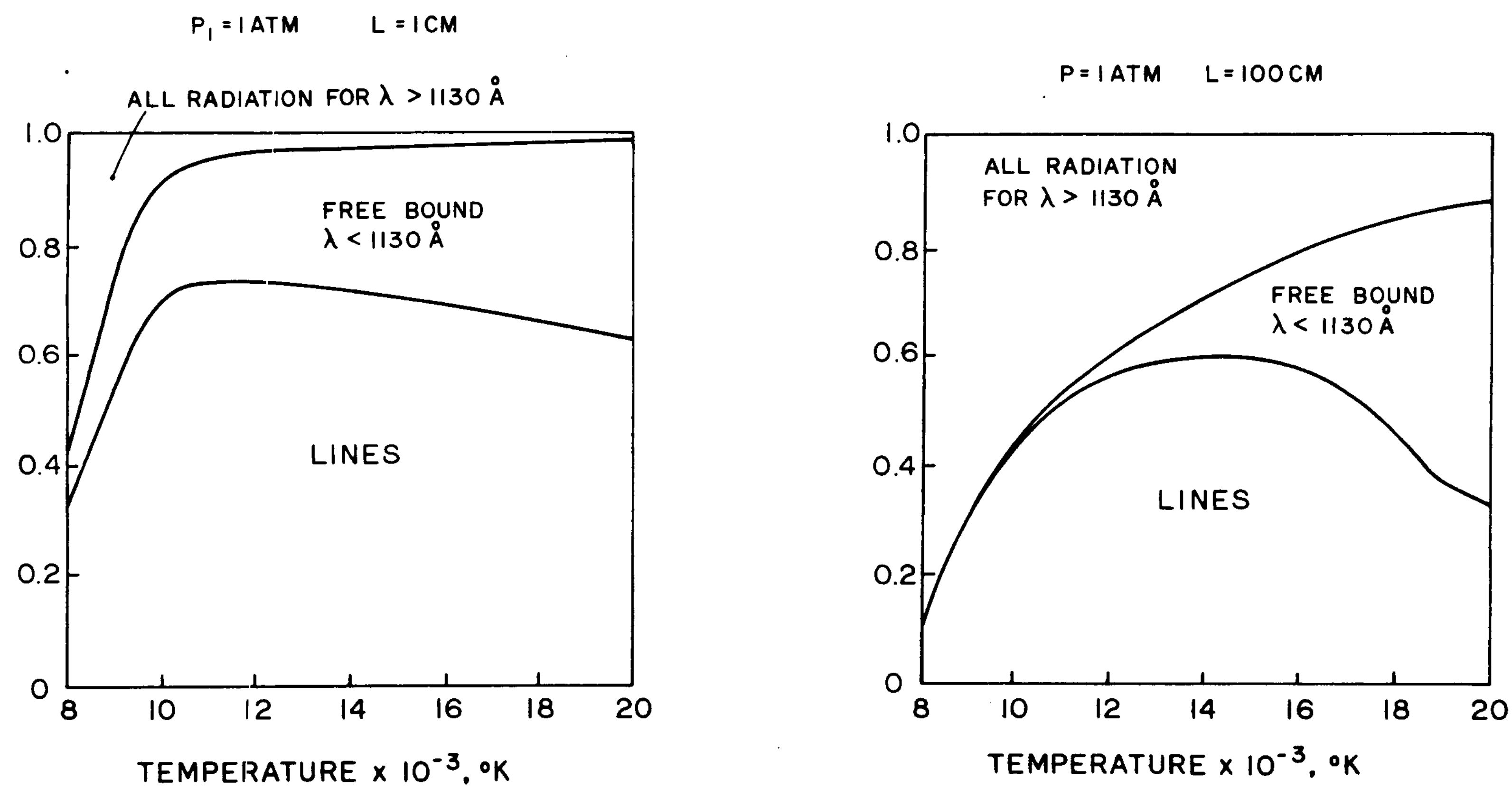


Figure 3. Contribution of various radiating systems in nitrogen taken from Ref. 3.

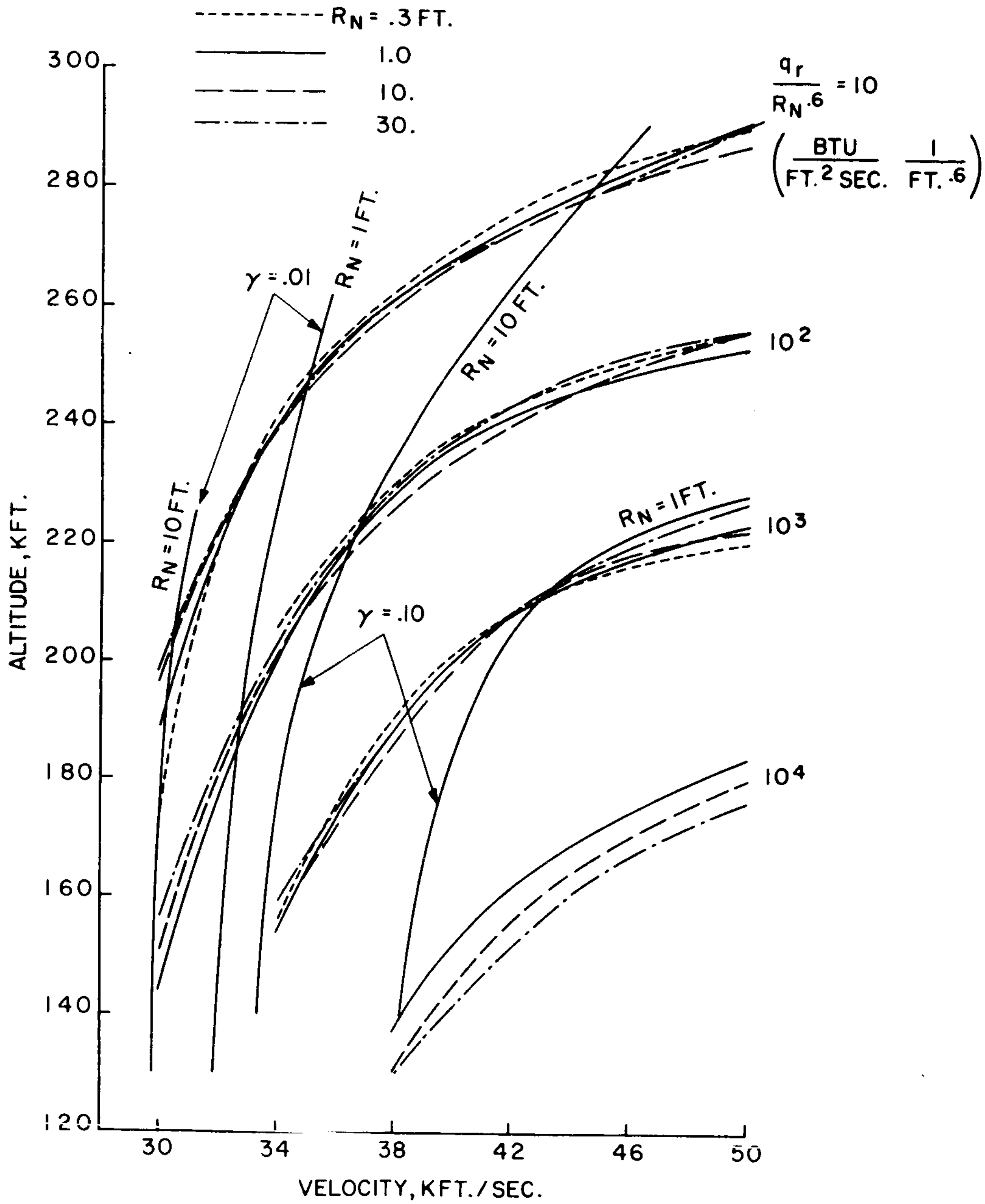


Figure 4. Equilibrium air radiative heating.

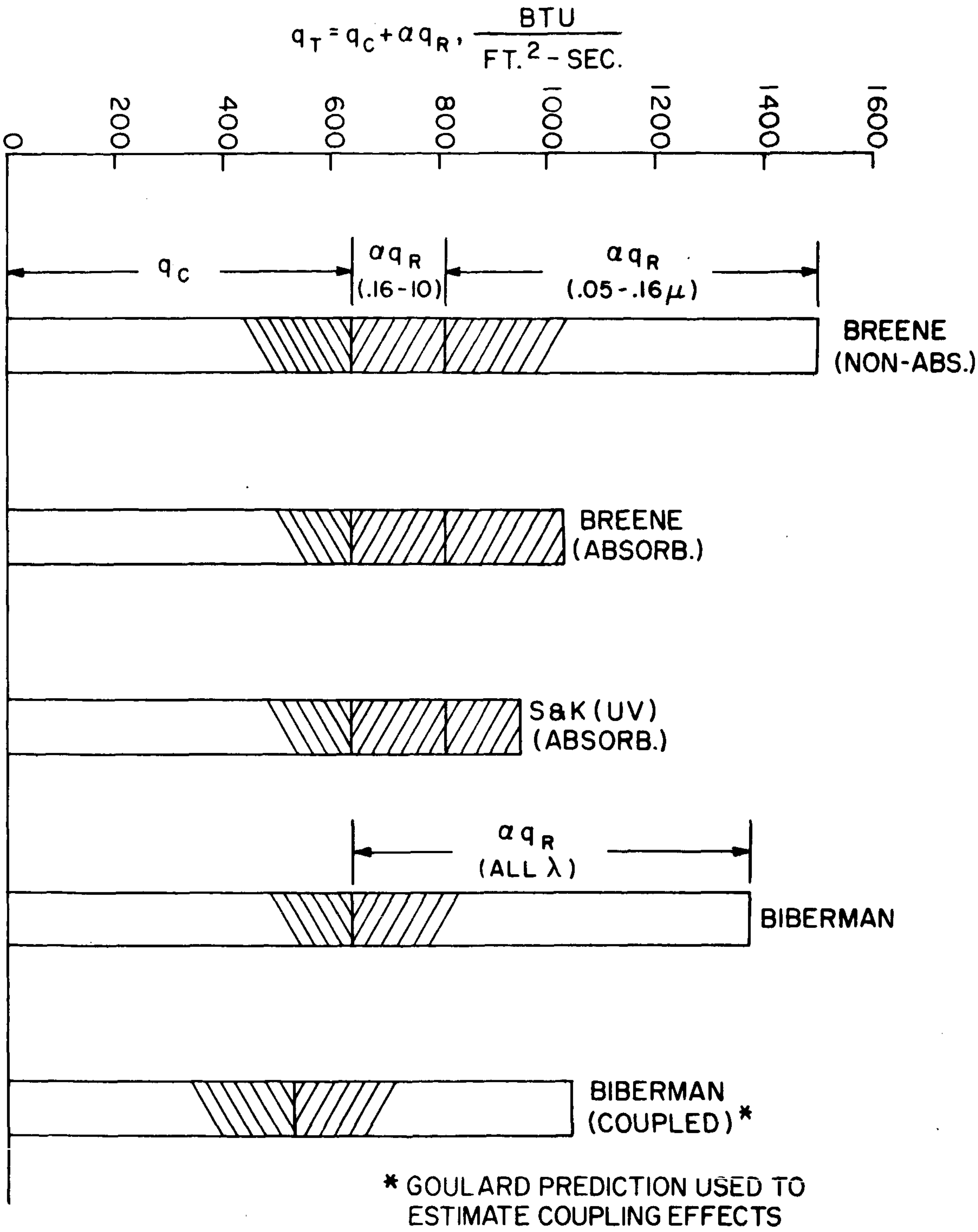


Figure 5. Convective and radiative heat transfer predictions for Project Five.

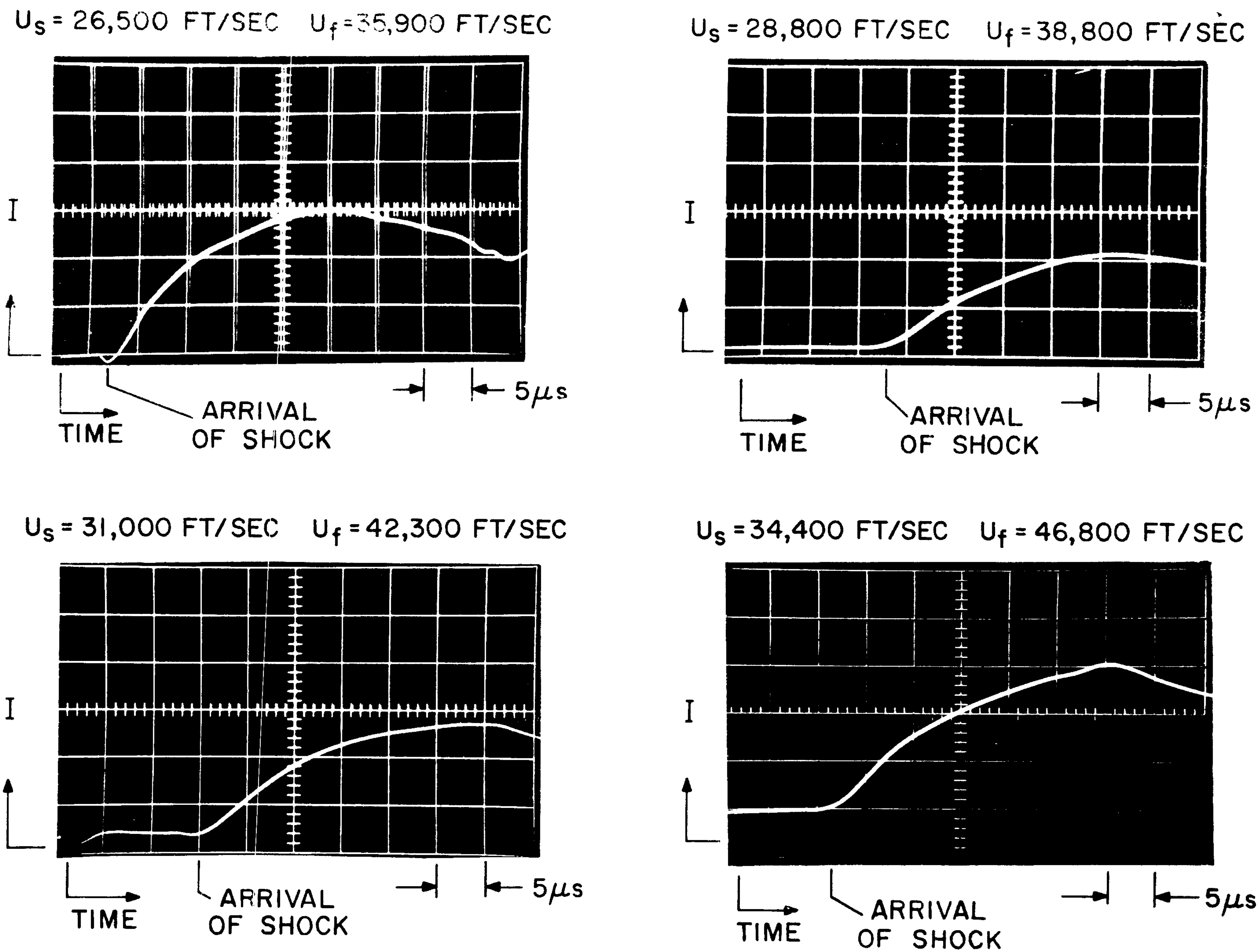


Figure 6. Oscilloscope traces of total radiation cavity gauge signals in a windowless model obtained at P_1 = 0.33 mm Hg.

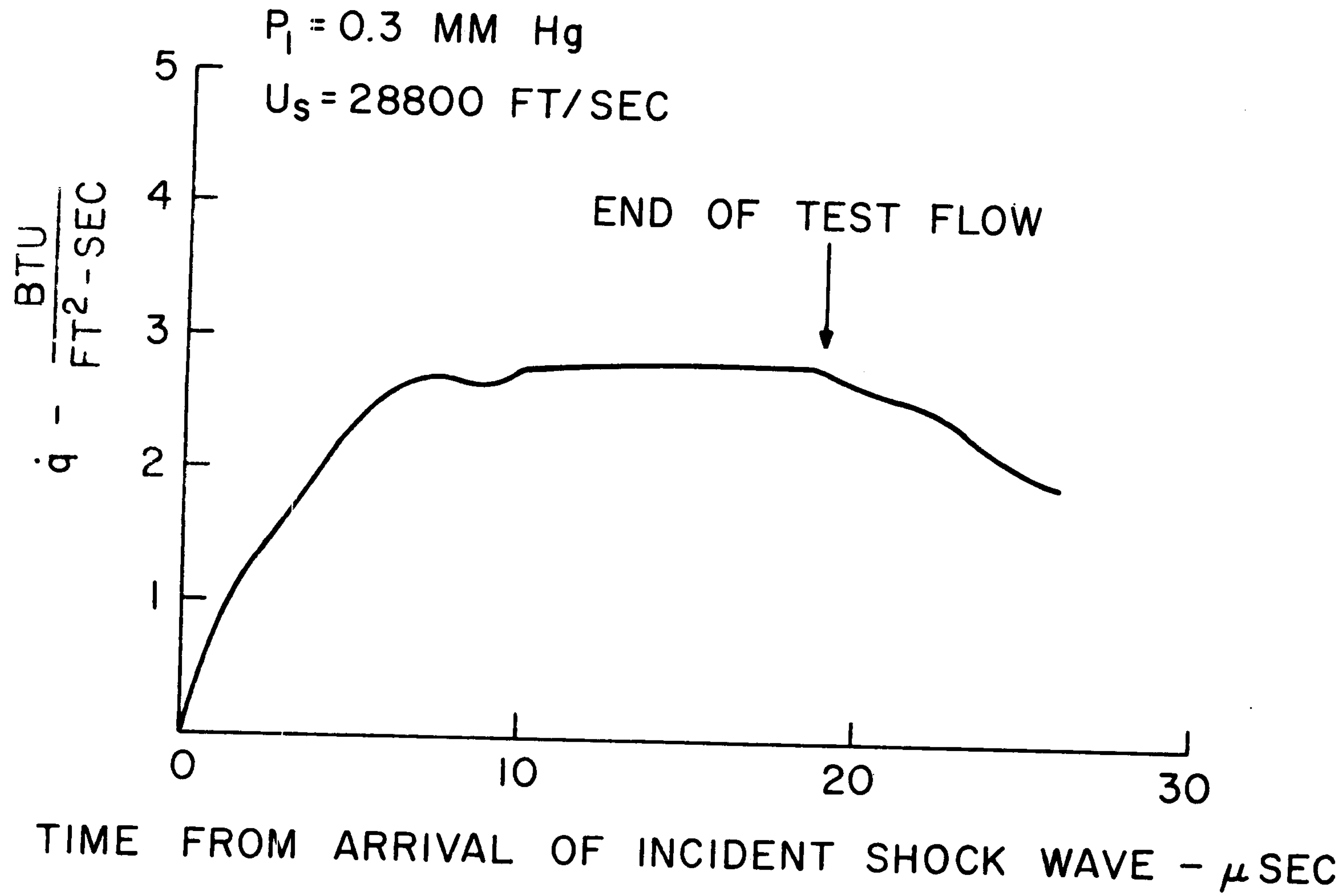


Figure 7. Cavity gage data reduced to heat transfer as a function of time after arrival of the incident shock wave.

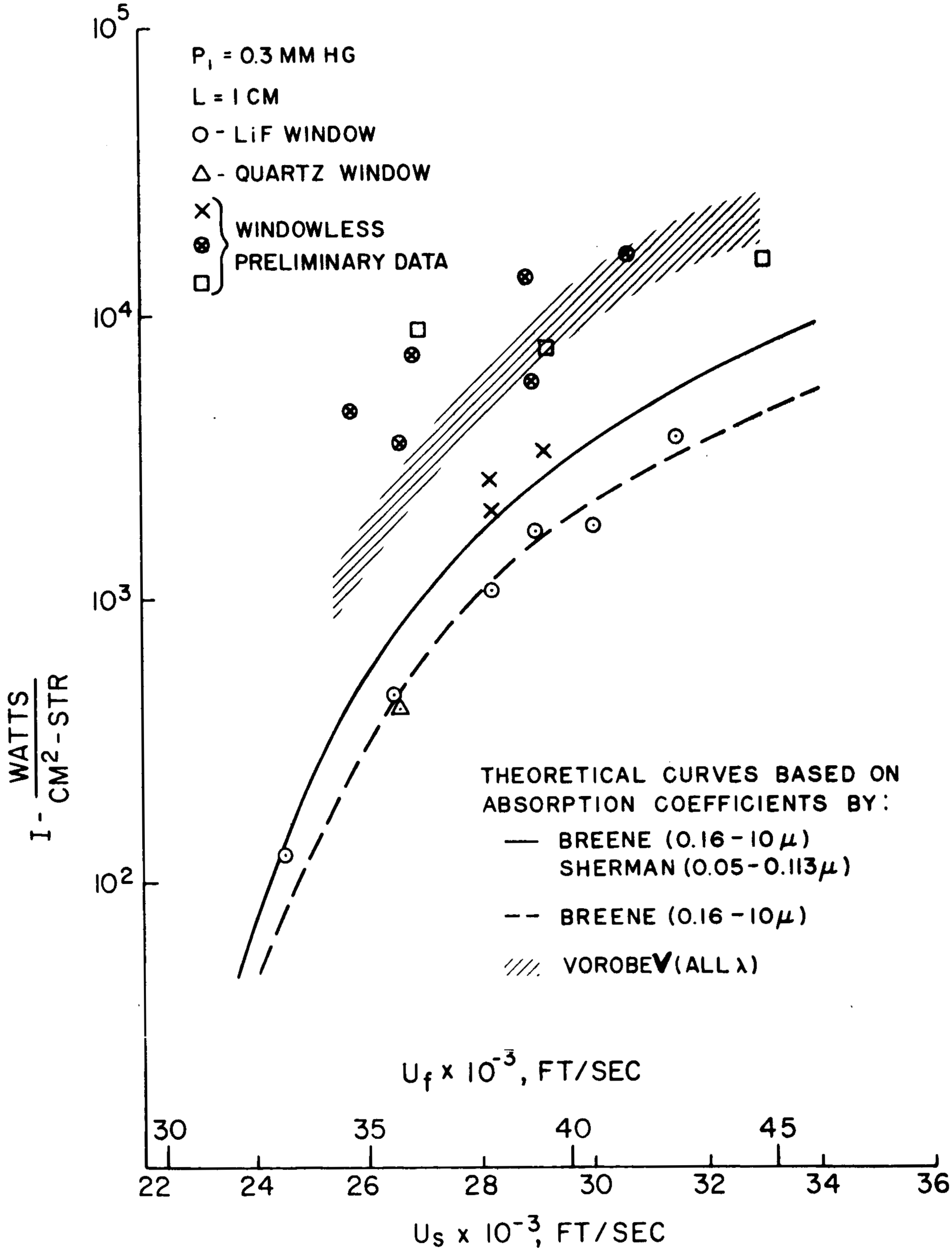
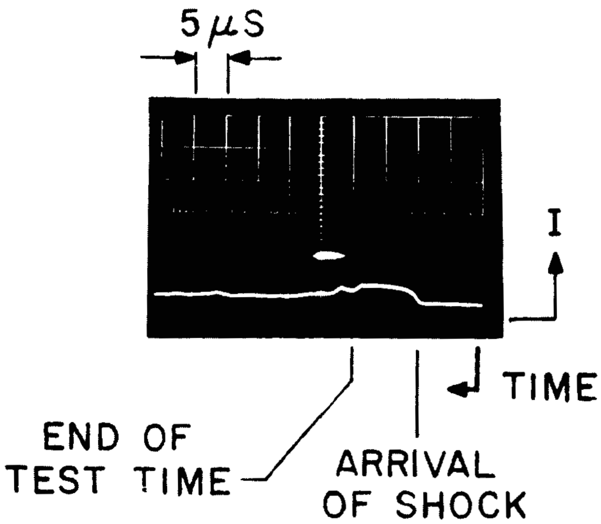


Figure 8. Experimental data of radiative intensity obtained in models with and without windows.



P_1 = 0.25 MM Hg

U_S = 44,000 FT / SEC

Figure 9. Oscilloscope trace of photomultiplier viewing model stagnation flow.