Radiative Transfer Properties of a Shocked Venus Model Atmosphere

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An analytical investigation of the equilibrium radiation of shocked 80% CO_2, 20% N_2 was performed using the constant property flat slab model including non-gray self-absorption for typical Venus entry conditions. It was found that the important radiators are the fourth positive group of CO, the continuum from carbon, and the line emission from neutral carbon. The method was compared with available experimental data and good agreement was found. Most of the radiation was found to occur in the middle and far ultraviolet portions of the spectrum. The heat-transfer results are presented in a form which is useful for approximating radiation loads on a Venus entry vehicle.

Nomenclature

B_λ = Planck function
c = speed of light
E_ι = radiance
E_3 = third exponential integral
e = electron charge
f_i = oscillator strength
h = Planck constant
k = Boltzmann constant
m = electron mass
N_{Li} = number density of absorbing state
$\dot{q}^R$ = radiation flux
r_0 = classical electron radius
R_N = nose radius
U_∞ = freestream velocity
V_E = entry velocity
β = ballistic coefficient
Γ = radiation-cooling parameter
γ_E = entry angle
γ_i = half width
Δ = slab thickness
λ = wavelength
μ_λ = absorption coefficient
ν = frequency
ρ = density
ρ_0 = Earth standard density
ρ_∞ = freestream density
σ_λ = cross section for photon absorption

Subscripts

λ = at a wavelength
γ = at a frequency
1 = before shock

Introduction

STUDIES of entry into the atmosphere of Venus have shown the very important effects of radiative heat transfer from shock-layer gases on entry vehicle design. High heat-transfer rates, coupled with low shock layer pressures (relative to advanced ballistic missile, Earth re-entry conditions), result in sublimation of the ablation material during portions of the entry. The performance characteristics of typical heat shield materials during sublimation are not well-understood. Therefore testing of heat shield material under the combined radiative and convective heating environment becomes desirable. Convective heat-transfer rates are easily predicted. Calculations of radiative heat-transfer rates have tended to be quite inaccurate. A basic problem is to reduce the uncertainty in these predictions. This design problem is further compounded because the radiation heating capability of typical testing facilities[1] (e.g., the Ames advanced re-entry simulator) is less than the convective. Hence, the acceptable error in radiation estimates is small. An indication of the magnitude of the heat-transfer rates expected for typical Venus entry trajectories at the stagnation point is presented in Fig. 1, where convective and radiative heating rates are presented for two missions. It can be seen that the heating period is very short, the radiation heat transfer is comparable to the convective heat transfer (especially when the effects of ablation are considered), and the radiation load increases very sharply with increasing velocity. This paper presents the results of an analytical investigation that led to the predictions presented in Fig. 1.

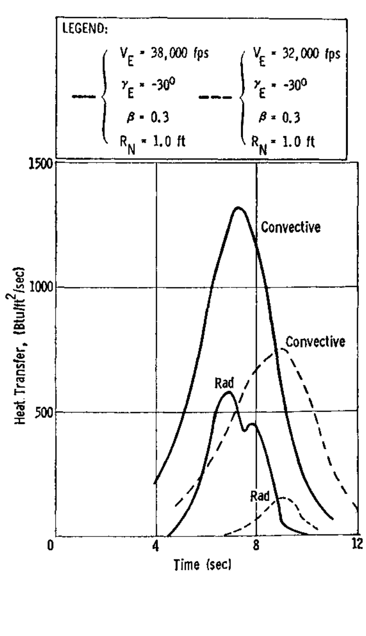

Fig. 1 Heat-transfer rates for Venus entry.

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Interest in exploring Mars and Venus has resulted in several experimental and theoretical investigations of the radiation properties of mixtures of shocked CO_2, N_2, and A. The ballistic range study by James[2] provided early comparisons of theory and experiment for Mars entry velocities. His work considered the spectral range between 0.2 and 1.0 μ and his theoretical considerations indicated that the most strongly radiating mixtures were about 10% CO_2, 90% N_2. This fact resulted in additional work by Gruszcynski and Warren[3] and Arnold, Reis, and Woodward,[4] which concentrated on CO_2 lean mixtures. Thomas and Menard[5] considered three CO_2, N_2, A mixtures including 100% CO_2, but this composition, unfortunately, was not thoroughly investigated. Perhaps the most significant problem with the experimental work is that windows in the measurement system excluded the radiation below 0.2 μ.

Several theoretical studies were made to evaluate the influence of the radiation in the ultraviolet. A theoretical study by Meyer, Ohrenberger, and Thompson[6] presented an indication of the importance of the fourth positive group of carbon monoxide and also indicated the disagreement between theory and experiment. Further theoretical work including self-absorption of CO(4+) and the CN systems was presented by Woodward.[7] Deacon and Boughner[8] used an approximate, yet accurate method for the absorption coefficient of CO(4+), showed the importance of this radiator to CO_2-rich mixtures, and presented design charts for estimating the heat transfer. Menard, Thomas, and Helliwell[9] presented a comparison of theory and experiment for 30% CO_2, 40% N_2, 30% A, and some serious disagreements were found. These disagreements (theory predicts the radiance to be lower by a factor of two to three than experiment at 9000°K) are especially serious since the spectral regime in which the disagreement was found is the one which has been most thoroughly investigated. Further, the results of Deacon and Rumpel[10] have shown that the large heat-transfer rates are expected at lower wavelengths, where only a few experiments have been performed. If predictions are to be made with any confidence in the middle and far ultraviolet, the discrepancies in the spectral range of 0.2–1.0 μ must certainly be resolved.

The Venera IV and Mariner V experiments have shown that the atmosphere of Venus is predominately (90 ± 10%) CO_2. This is unfortunate since it minimizes the utility of previous studies of small CO_2 percentage mixtures, and also because it increases the severity of the environment as compared to CO_2 lean mixtures. This paper presents the results of an analytical investigation of the equilibrium radiation from shocked 80% CO_2, 20% N_2. This mixture was chosen because design studies have indicated that it produces a larger heat-transfer load to typical entry vehicles than mixtures containing larger amounts of CO_2. The reason for this is the increased emission from the CN red and violet band systems at low velocities and the nitrogen continuum at higher velocities. In addition, self-absorption from carbon bearing species is a more important factor in reducing radiation loads from higher CO_2 compositions. The effects of self-absorption are accounted for in the detailed spectral computations of the radiation from molecular electronic transitions, free-free and free-bound continuum, and the atomic line contributions. The dominant emitters were found to be the CO(4+) transition, the carbon continuum, and the line emission from neutral carbon. The absorption coefficients for CO(4+) and the carbon continuum were treated as in Refs. 8 and 10, whereas the lines were treated using the tabulations of Wilson and Nicolet.[11] Heat-transfer rates are presented in the form of a chart for a constant property slab as a function of velocity, density, and shock standoff distance. Radiative decay was not considered.

Table 1 Radiance parameters

Molecular transitions			
Transition	λi (μ)	f_i	f_i, Ref.
CO(4+)	0.149	0.24	15
CN (Violet)	0.4	0.027	16
CN (Red)	1.1	0.0064	17
C_2 (Swan)	0.194	0.034	4

Theoretical Methods

This section presents the several techniques which were used to estimate the contribution of each of the radiating species to the heat transfer from the shock-layer gases. The shock layer was approximated by a constant property slab of thickness Δ where Δ is equal to the shock standoff distance. No reflections were accounted for at either the body surface or the shock. Under these conditions the heat transfer is given by the integral equation[12]

$$\dot{q}^R = \pi \int_0^\infty B_\lambda \left[1 - 2E_3(\mu_\lambda \Delta)\right] d\lambda \tag{1}$$

where the Planck function

$$B_\lambda = (2hc^2/\lambda^5)\, 1/[\exp(hc/kT\lambda) - 1] \tag{2}$$

The μ_λ is the spectrally dependent absorption coefficient, and E_3 is the third exponential integral. This function can be replaced by the exponential with small error in the heat-transfer prediction:

$$\dot{q}^R = \pi \int_0^\infty B_\lambda \left[1 - \exp(-2\mu_\lambda \Delta)\right] d\lambda \tag{3}$$

The temperature and number densities of the several radiating species can be easily obtained by free energy minimization techniques.[13] Therefore, determination of μ_λ is a problem in determining transition probabilities. Previous work by Deacon and Boughner[8] has shown that the CO(4+) transition is an important contributor to the radiation at velocities below 35,000 fps, that self-absorption is significant, and that the other molecular radiators considered in that investigation are so weak that the transparent gas approximation is appropriate. The method for estimating the absorption coefficient for the CO(4+) radiation was originally proposed by French.[14] In the course of this investigation, it was found that the C_2 Fox-Herzberg system, which has an unusually large F number of 0.82 (Ref. 9), presented a significant heat-transfer rate at high values of density and shock standoff distances. Therefore, the effect of self-absorption was investigated. The average value of the Franck-Condon factor was assumed to be 0.1 for this band system as suggested by French.[14] When absorption was included, the heat transfer was found to be small. The C_2 Fox-Herzberg system was then treated as absorbing throughout this study. The other molecular species were treated with the transparent gas approximation

$$\dot{q}^R = E_t \Delta/2 \tag{4}$$

where

$$E_t = (8\pi^2 hc^2 r_0 N_i f_i/\lambda_i^3) \exp(-hc/kT\lambda_i) \tag{5}$$

The oscillator strengths and central wavelengths used in Eq. 5 are presented in Table 1. With these physical properties, the radiation from molecular band systems is easily estimated.

The radiation characteristics of the neutral carbon continuum have been investigated[10] using the cross sections of Wilson and Nicolet.[11] These are based on the Biberman and Norman[19] approximation for the electron-ion recombination transition probabilities. Wilson and Nicolet presented the results of this method in terms of a cross section for both carbon ion-electron recombination and neutral carbon free-free radiation. The absorption coefficient was easily obtained from the expression

$$\mu_\lambda = \sigma_\lambda N_c \quad (6)$$

The primary features concerning the carbon continuum are that the carbon cross section is about an order of magnitude greater than the nitrogen cross section for wavelengths greater than 850 Å, that the carbon continuum has 85% of its emission at wavelengths less than 1250 Å, and that the interaction of the CO(4+) band system and the carbon continuum is negligible for heat-transfer considerations. Since the cross sections of Wilson and Nicolet are felt to be the best available, they were used in the present work.

The contributions of the nitrogen and oxygen continua to the radiative flux were computed using the transparent gas approximation. These sources are negligible compared to the carbon continuum for CO_2 rich mixtures since the cross sections are so small. However, they were included for completeness and also because of their larger contributions to the emission of CO_2 lean mixtures. The experimental results of Morris, et al.[18] were used as expressed by the relation in Table 2. The heat transfer from these radiators for all Venus entry trajectories and vehicle configurations considered was negligible.

The contributions of the lines were estimated in essentially the same manner as the CO(4+) and carbon continuum contributions. The 82-line oscillator strengths and Stark broadening half-widths tabulated by Wilson and Nicolet were used in the following expression for the absorption coefficient of the lines:

$$\mu_\nu = \frac{e^2\pi}{mc} \sum_{i=1}^{82} N_{Li} f_i \frac{\gamma_i}{(\nu - \nu_0)^2 + \gamma_i^2} \quad (7)$$

where the line shift has been neglected. The number density of the carbon atoms in the absorbing or lower state of a transition was determined, using the tables presented by Gilmore.[20] The contribution of the nitrogen and oxygen lines was computed using the above method for the gas composition 80% CO_2, 20% N_2. The lines and physical parameters of Wilson and Nicolet were also used for nitrogen and oxygen. Emphasis was placed on the neighborhood of 10,000°K, $\rho_1/\rho_0 = 1 \times 10^{-3}$, and a shock standoff distance of 1 cm. In all cases investigated, the contribution of nitrogen and oxygen lines to the heat transfer was negligible. This conclusion is consistent with the observation that nitrogen and oxygen lines in air contribute about the same amount as the nitrogen continuum at about 10,000°K. Since the carbon continuum is much stronger than that of nitrogen, it follows that nitrogen and oxygen lines are of secondary importance.

The effect of stimulated emission is negligible for the present problem. A 25% error in the absorption coefficient at 14,000°K is the maximum possible for wavelengths less than 7400 Å, whereas a 10% error is the largest possible if this effect is neglected for wavelengths less than 4350 Å. It will be shown below that the greatest portion of the radiative transfer is at wavelengths less than 2000 Å. Hence, this effect is clearly not important.

Comparison of Theory and Experiment

The only real verification of a theory is by comparison with experiment. This is not possible for the present computations, since the needed experiments have not been performed. However, experimental results which have been reported in the literature allow a partial verification or refutation of the method presented above. Since the present work is concerned with CO_2 rich mixtures, the large number (Refs. 2–5) of 10% and 25% CO_2, balance N_2 are not applicable. However, the 100% CO_2 measurements of Thomas and Menard, the 30% CO_2, 40% N_2, 30% A mixture analyzed by Menard, Thomas, and Helliwell, and the 60% CO_2, 40% A measurements of Gruszczynski[21] are available for comparison.

Table 2 Nitrogen and oxygen continua

$E_t = 1.435 \times 10^{-34} N_e T^{1/2} [0.164 N_N + 2.4 N_{N+} + 0.256 N_O + 2.74 N_{O+}]$	18

A comparison of the theory and experiment of Menard, Thomas, and Helliwell[9] shows marked disagreement. Figure 2 presents the data for the radiance of a 30% CO_2, 40% N_2, 30% A mixture, and the theoretical predictions for the lines and total radiance by both Menard, Thomas, and Helliwell and by the present technique. The latter method gives better agreement with the experiment because heat transfer resulting from lines was found to be larger than that in the MTH prediction. Although this agreement is gratifying, it must be acknowledged that the gas mixture is not a reasonable approximation for the atmosphere of Venus, and further, that theory and experiment are restricted in this comparison to wavelengths greater than 2000 Å.

The experimental results of Gruszczynski[21] with 60% CO_2, 40%A were also analyzed. The latter are especially pertinent since they include the radiation at wavelengths between 850 and 2000 Å. This region includes the CO(4+) radiation, which is important at the test conditions. Figure 3 presents the comparison of theory and experiment for gases with and without quartz windows. The effect of variation in oscillator strength for the CO(4+) band system is also indicated. Excellent agreement is obtained for the cylindrical model. The agreement between theory and experiment for the hemispherical model is not as good. Gruszcynski noted this disagreement and postulated that the latex diaphragm may not have been completely removed from the viewing port. The small number of data points is evident.

Figure 4 presents the comparison of theory and experiment for the 100% CO_2 results of Thomas and Menard.[5] These results include a quartz window and therefore include only a portion of the radiative flux. Most of the data appear to agree within 50%. This is not too bad, especially when agreement of a factor of two is representative of comparisons of theory and experiment for air.[22]

Although the agreement between theory and experiment is gratifying, the limitations of the comparisons must be recognized. The most obvious problem is the very small number of truly definitive experiments in general and the even smaller number which include the vacuum ultraviolet portions of the spectrum. Further, the composition of primary interest, i.e., 80% CO_2, 20% N_2, has not been experimentally investigated.

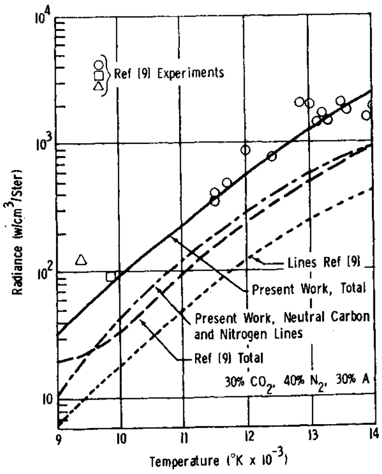

Fig. 2 Comparison of theory and experiment for a 30% CO_2-40% N_2-30% A mixture.

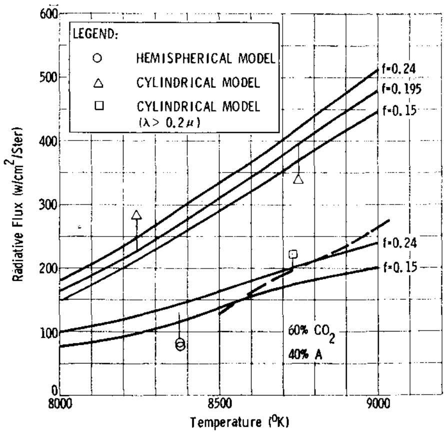

Fig. 3 Comparison of theory and experiment for a 60% CO_2-40% A mixture.

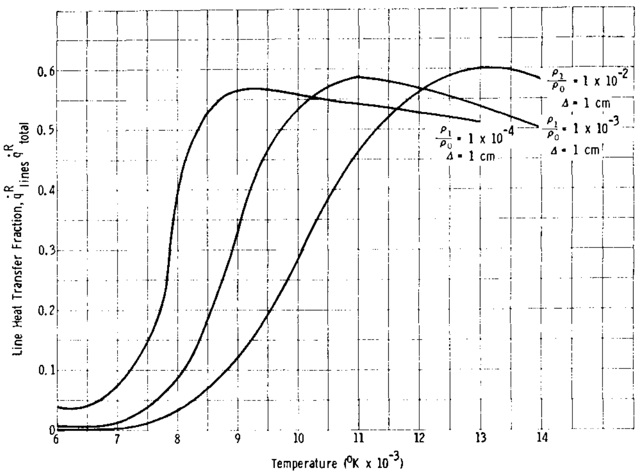

Fig. 5 Neutral carbon line radiation.

Spectral Characteristics

In the present formulation, the individual radiation modes [CO(4+), carbon continuum, carbon lines] are considered independently. That is, it is assumed that a photon produced from a carbon line transition does not interact to photoionize neutral carbon or to excite the electronic structure of carbon monoxide. The influence of this approximation on the heat-transfer results must be estimated. In Ref. 10 it was shown that the interaction of the CO(4+) system and the carbon continuum did not affect the heat-transfer results to any appreciable extent. The same effect must be evaluated for the interaction of carbon lines with the continuum and molecular radiation.

One striking characteristic of the carbon continuum is that the radiation is very strong at wavelengths less than 1240 Å. Hence, to determine if the carbon lines and continuum interact and significantly influence the heat transfer in this spectral regime is important. The interaction was investigated by forming the ratio

$$\dot{q}^R_{\text{line}},\ \lambda < 1240\ \text{Å}/\dot{q}^R_{\text{total}}$$

over the range of velocities (20–45 kfps) and freestream densities (10^{-2}–10^{-4} amagats) representative of Venus entry. This fraction never exceeded 0.1. Therefore treating the carbon continuum and carbon lines independently in this spectral region can result in an error in heat transfer which is no more than 10%. This error is certainly negligible. The radiation from the carbon continuum at wavelengths greater than 1240 Å can be shown to be optically thin for typical standoff distances (1.0 cm). This is a result of the rapid dropoff in cross section for the carbon continuum radiation for wavelengths greater than 1240 Å. Therefore, for typical Venus entry conditions, the .nteraction in the higher wavelength spectral regions may be considered negligible and not important.

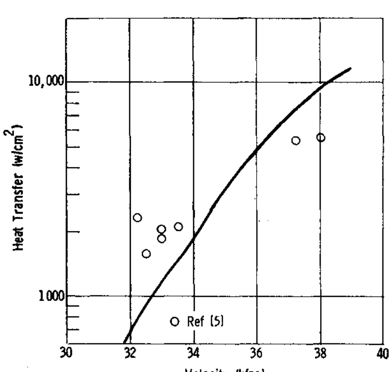

Fig. 4 Comparison of theory and experiment for 100% CO_2.

A similar problem exists in the spectral region, 1260 to 1930 Å, where both the carbon lines and the CO(4+) band system have large contributions to the heat transfer. Deacon and Boughner showed that the CO(4+) system is important for velocities less than 35,000 fps. Therefore, the fraction of the radiative transfer resulting from lines in this portion of the spectrum must be determined. If this fraction is small, the lines and CO(4+) radiation can be treated independently. Computations showed that

$$\dot{q}^R_{\text{line}},\ 1260\ \text{Å} < \lambda < 1930\ \text{Å}/\dot{q}^R_{\text{total}}$$

is always less than 0.25 for velocities less than 35,000 fps. Hence, the maximum error which could occur [only if CO(4+) were black in this spectral regime] is 25%, an acceptable error. These considerations justify treating the carbon continuum, carbon lines, and CO(4+) system, which are the dominant emitters, independently.

A quantity of considerable interest is the fraction of the radiative transfer contributed by neutral carbon lines. This quantity is of the order of 0.5 for temperatures greater than about 10,000°K and shock standoff distances of 1 cm. Figure 5 presents this fraction as a function of temperature and freestream density. This fraction varies considerably. As a further example of the roles of the several emitters, Fig. 6 presents the radiation heat-transfer load for a typical Venus entry trajectory. This shows that the lines are dominant with important continuum contributions during the high velocity portions and that the CO(4+) system is dominant for the lower velocity portion.

Since most experiments do not include the radiation at wavelengths less than 2000 Å, the fraction of the carbon line flux in this ultraviolet regime is of interest. Figure 7 presents the ratio of heat transfer resulting from lines in the spectral region less than 2000 Å, to the heat transfer due to total carbon lines for three ambient densities and a standoff distance of 1 cm. It can be seen that this fraction is a strong function of shock velocity. Since the fraction of the total heat flux due to lines at reasonable optical depths ($\rho_1/\rho_0 \sim 1 \times 10^{-3}$, $\Delta \sim 1$) is about 0.5 (Fig. 5), about 25% of the total radiative flux is from carbon lines below 2000 Å. Also at velocities above 38,000 to 40,000 fps about the same percentage of the total flux is from lines at wavelengths greater than 2000 Å, that is 25%, and about half of the flux is from the neutral carbon and nitrogen continua.

The considerations of this section indicate that interactions of radiating species are not important for estimating shock layer radiative heat transfer during Venus entry. It is significant to note the relatively large role played by the neutral carbon lines at the higher temperatures. The fraction of the flux due to these emissions is about 0.5. This is very similar

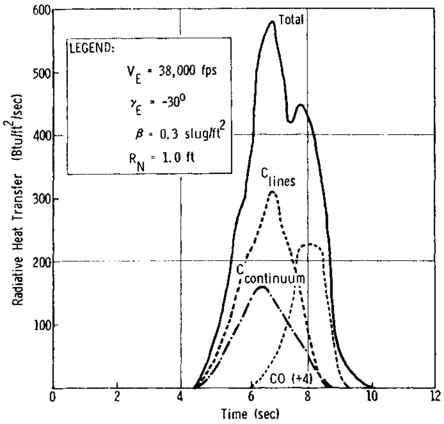

Fig. 6 Radiative heat transfer for Venus entry.

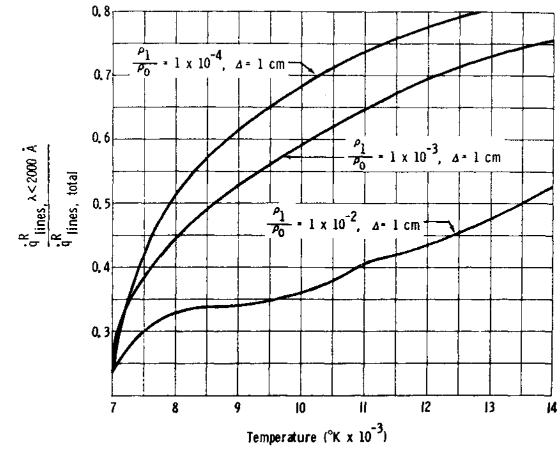

Fig. 7 Carbon line heat-transfer ratios.

to the role of nitrogen lines in air radiation. Since the carbon continuum is so much more intense than the nitrogen continuum, CO_2-rich mixtures may be expected to present a much larger radiation load than air at the same pressure and temperature.

Total Heat Flux

To allow easy estimation of the total radiative heat transfer to a planetary entry vehicle, Fig. 8 is presented. The ratio of the flux to the shock standoff distance $\dot{q}^R/\Delta$ is plotted as a function of the shock velocity with freestream density and shock standoff distance as parameters. This technique is useful for approximating radiative heating loads in trajectory calculations.

It is noted that the predictions furnish an upper bound for the equilibrium radiative heat flux. Radiative cooling effects have not been included in the calculations. The cooling parameter defined as

$$\Gamma = 2\dot{q}^R/\tfrac{1}{2}\rho_\infty U_\infty{}^3$$

by Goulard[23] is commonly applied to approximate the radiative decay. Lack of applicable data for CO_2 mixtures in the flight regimes of interest has prevented such an estimate to be made in the present case. Examination of the cooling effect for air[24,25] indicates that reductions of a factor of 2 to 3 are possible. However, applicability of the air correlation to the CO_2–N_2 mixture is not well-founded. Thus the present work must be considered conservative.

Concluding Remarks

The present results provide rapid determination of the equilibrium radiation heat transfer for Venus entry for constant property shock layers. The limitations of the work with respect to the total design problem should, however, be acknowledged. A major limitation is the lack of correction for the nonadiabatic characteristics of the shock layer. An estimation of cooling effects can be made using methods given in Refs. 24 and 25 for air. Another obvious weakness is that the nonequilibrium region behind the shock wave has been neglected. Very little work has been done to understand the influence of this zone on the heat-transfer environment of vehicles entering the atmosphere of Venus (see, for example, the unreduced results of Ref. 5). Some preliminary unpublished work on this problem has been done by the present authors, which indicates that the overshoot from the CO(4+) system may be quite important. This is certainly a fruitful and important area of research.

The effect of the boundary layer at the stagnation point has not been considered in this paper. At moderate Reynolds numbers, the boundary layer can make up a sizable fraction of the shock layer. The effects of absorption by this low temperature region, as well as the effects of absorption by the products of heat shield sublimation may be of considerable importance. A related problem involving nonuniform shock-layer gases exists on the very important rearward portions of the body. The temperature may be relatively constant between the shock wave and the entropy layer (neglecting the nonequilibrium zone); however, it rises in the entropy layer and then falls in the boundary layer. The results reported here are applicable if the boundary layer and entropy layer are thin, but important missions can be postulated where these nonuniform layers are important.

In spite of the analytical difficulties mentioned above, success has been attained in predicting the results of available radiation experiments using the constant properties flat slab model. Specifically, an analytical model for the radiation from almost pure CO_2 has been developed, compared with

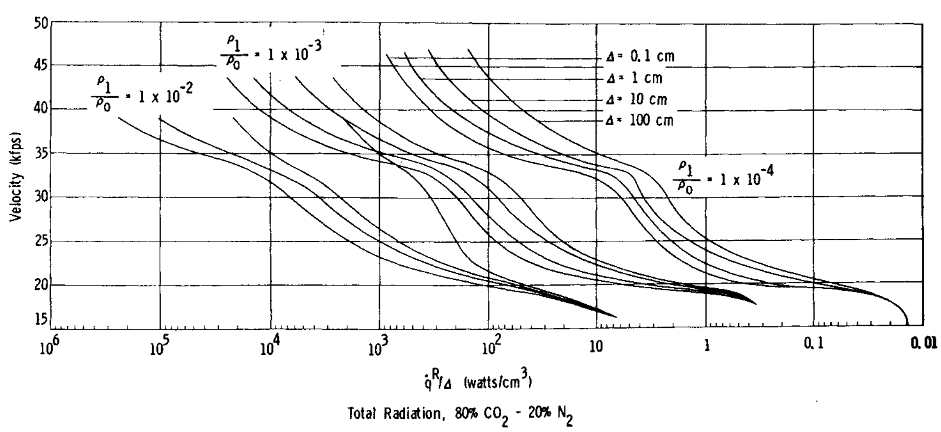

Fig. 8 Equilibrium radiative heat-transfer chart.

available experiments, and used to develop a chart for the approximate determination of radiative heat-transfer rates. The detailed spectral analysis showed that the dominant radiators for 80% CO_2, 20% N_2 are CO(4+), C lines, and the carbon continuum. Radiators of lesser importance are CN red, CN violet, C_2 (Fox-Herzberg) and the nitrogen continuum. Further, it was found that most of the radiation during Venus entry will be at wavelengths less than 2000 Å. These conclusions imply that the physical properties of radiation from CO_2 at Venus entry conditions are reasonably well understood. Therefore, attempts to solve the difficult numerical problems associated with nonuniform shock layers are meaningful and timely.

References

[1] Gowen, F. E., Lundell, J. H., and Wick, H. B., "Facilities for Simulating Combined Convective and Radiative Entry Heating Environments," 13th Annual Institute of Environmental Sciences Technical Meeting and Equipment Exposition, Washington, D.C., 1967.

[2] James, C. S., "Experimental Study of Radiative Transport from Hot Gases Simulating in Composition the Atmospheres of Mars and Venus," AIAA Paper 63-455, Cambridge, Mass., 1963.

[3] Gruszczynski, J. S. and Warren, W. R., Jr., "Study of Equilibrium Air Total Radiation," AIAA Paper 66-103, New York, 1966.

[4] Arnold, J. O., Reis, V. H., and Woodward, H. T., "Studies of Shocklayer Radiation of Bodies Entering Planetary Atmospheres," *AIAA Journal*, Vol. 3, No. 11, Nov. 1965, pp. 2019–2025.

[5] Thomas, G. M. and Menard, W. A., "Experimental Measurements of Nonequilibrium and Equilibrium Radiation from Planetary Atmospheres," *AIAA Journal*, Vol. 4, No. 2, Feb. 1966, pp. 227–237.

[6] Meyer, H. G., Ohrenberger, J. T., and Thompson, T. R., "Emission and Absorption of Radiant Energy in a Model Planetary Atmosphere," *AIAA Journal*, Vol. 3, No. 12, Dec. 1965, pp. 2203–2210.

[7] Woodward, H. T., "Predictions of Shock-Layer Radiation from Molecular Band Systems in Supposed Planetary Atmospheres," TN D-3850, 1967, NASA.

[8] Deacon, H. J., Jr. and Boughner, R. E., "Equilibrium Radiative Heating of Shocked CO_2," *AIAA Journal*, Vol. 5, No. 7, July 1967, pp. 1358–1360.

[9] Menard, W. A., Thomas, G. M., and Helliwell, T. M., "Experimental and Theoretical Study of Molecular Continuum and Line Radiation from Planetary Atmospheres," *AIAA Journal*, Vol. 6, No. 4, April 1968, pp. 655–664.

[10] Deacon, H. J., Jr. and Rumpel, W. F., "Radiation Heating Characteristics of Venus Entry," *Proceedings of American Astronautical Society Symposium*, AAS Astronautics microfishe series, Vol. 8, 1968.

[11] Wilson, K. H. and Nicolet, W. E., "Spectral Absorption Coefficients of Carbon, Nitrogen, and Oxygen Atoms," *Journal of Quantitative Spectroscopy and Radiative Transfer*, Vol. 7, No. 6, 1967, pp. 891–941.

[12] Goulard, M. and Goulard, R., "One-Dimensional Energy Transfer in Radiant Media," *International Journal of Heat Mass Transfer*, Vol. 1, 1960, pp. 81–91.

[13] Horton, T. E., "The Thermochemistry and Normal Shock Computer Program," TR 32-660, 1964, Jet Propulsion Lab., Pasadena, Calif.

[14] French, E. P., "Approximate Absorption Coefficients for Vibrational Electronic Band System," *AIAA Journal*, Vol. 2, No. 12, Dec. 1964, pp. 2209–2211.

[15] Meyer, V. D., Skerbele, A., and Lassettre, E. N., "Intensity Distribution in the Electron-Impact Spectrum of Carbon Monoxide at High-Resolution and Small Scattering Angles," *The Journal of Chemical Physics*, Vol. 43, No. 3, Aug. 1965, pp. 805–816.

[16] Bennett, R. G. and Dalby, F. W., "Experimental Oscillator Strength of the Violet System of CN," *The Journal of Chemical Physics*, Vol. 36, No. 2, Jan. 1962, pp. 399–400.

[17] Jeunehomme, M., "Oscillator Strength of the CN Red System," *The Journal of Chemical Physics*, Vol. 42, No. 12, June 1965, pp. 4086–4088.

[18] Morris, J. C. et al., "Continuum Radiated Power for High-Temperature Air and Its Components," *AIAA Journal*, Vol. 4, No. 7, July 1966, pp. 1223–1226.

[19] Biberman, L. M. and Norman, G. E., "Recombinational and Bremsstrahlung Plasma Radiation," *Journal of Quantitative Spectroscopy and Radiative Transfer*, Vol. 3, 1963, pp. 221–245.

[20] Gilmore, F. R., "Thermal Radiation Phenomena, Volume 1, The Equilibrium Properties of High Temperature Air," Defense Documentation Center Defense Supply Agency AD 654054, May 1967, Lockheed Missiles & Space Co., Palo Alto, Calif.

[21] Gruszczynski, J. S., "Experimental Investigations of Self-Absorption and Vacuum UV Molecular Radiation in Simulated Planetary Atmospheres," AIAA Paper 68-665, Los Angeles, Calif., 1968.

[22] Wood, A. D. et al., "Measurements of the Total Radiant Intensity of Air," *AIAA Journal*, Vol. 7, No. 1, Jan. 1969, pp. 130–139.

[23] Goulard, R., "Preliminary Estimates of Radiative Transfer Effects on Detached Shock Layers," *AIAA Journal*, Vol. 2, No. 3, March 1944, pp. 494–502.

[24] Olstad, W. B., "Correlations for Stagnation-Point Radiative Heat Transfer," *AIAA Journal*, Vol. 7, No. 1, Jan. 1969, pp. 170–172.

[25] Page, W. A. et al., "Radiative Transport in Inviscid Nonadiabatic Stagnation-Region Shock Layers," AIAA Paper 68-784, Los Angeles, Calif., 1968.