Experimental Study of Radiative Transport from Hot Gases Simulating in Composition the Atmospheres of Mars and Venus

CARLTON S JAMES*
NASA Ames Research Center, Moffett Field, Calif

Measui ements have been made of gross specti al quality and intensity of thei mal radiation from the hot gas cap of small polyethylene models flying through mixtures of CO_2 and N_2 Mixture proportions and ambient pressure were varied from pure N_2 to nearly pure CO_2 and from 0 004 to 0 08 atm, 1 espectively Model flight velocity varied from 5 to 8 km/sec Sti ong radiation from CN, formed in the shock layer, is obsei ved for a wide range of mixture proportions Variation of the total intensity of gas-cap radiation with ambient pressure, flight velocity, and mixture pi oportions is defined Radiation from the mixtures is compared with radiation from air The total intensity of gas-cap radiation from the CO_2-N_2 mixtures is found to be seveı al times that from air at the same flight conditions except when high CO_2 concenti ations are combined with low velocities Comparison of the measurements with available equilibrium calculations indicates agi eement within factors of two or thi ee over the test range

Nomenclature

E	=	local total radiant intensity in shock layer w/cm³
E_T	=	total radiant intensity behind normal shock wave, w/cm³
E_λ	=	radiant intensity per unit wavelength, w/cm³-μ
p_∞	=	ambient (freestream static) pressure, mm Hg abs
$p_{\oplus SL}$	=	standard Earth sea-level pressure, 760 mm Hg abs
T_2	=	equilibrium temperature behind normal shock wave, °K
T_∞	=	ambient (freestream static) temperature, °K
V_∞	=	flight velocity, km/sec
v	=	geometric volume of gas cap viewed by radiation detector, cm³
v_{ff}	=	effective radiating volume, cm³
λ	=	wavelength
ρ_2	=	equilibrium mass density behind normal shock wave, g/cm³
ρ_0	=	mass density of gasm ixture at 293°K and 760 mm Hg abs, g/cm³

Introduction

ONE mechanism by which heating of a body during high-speed entry into a planetary atmosphere may occur is through thermal radiation emitted from the high-temperature plasma behind the bow shock wave For an atmosphere of air, a considerable amount of research has been done in the past few years and has resulted in a reasonably good understanding of this phenomenon For other gas mixtures, such as those believed to comprise the atmospheres of Mars and Venus, relatively little information of a quantitative nature is known The notion that radiation effects in these planetary atmospheres might be more prominent than in air, because of the formation of carbon-nitrogen compounds, was first proposed by Gazley [1] Boobar and Foster,[2] in an exploratory theoretical treatment, confirmed this with the prediction that for the conditions of a Mars entry the formation of cyanogen in the high-temperature environment of the shock layer might result in radiant intensities as much as two orders of magnitude greater than would occur in an air atmosphere The present study was undertaken to obtain quantitative experimental measurements of thermal radiation from gas mixtures simulating the atmospheres postulated for Mars and Venus with which to compare theoretical predictions, and to gain a better understanding of the radiative heating to be expected during a Mars or Venus entry Early results[3] of this study showed that, although the predictions of Boobar and Foster appeared to overestimate the radiative intensities for the assumed Martian entry conditions, these intensities would nevertheless be several times more severe than if the atmosphere were air

The principal constituents of the atmospheres of both Mars and Venus are believed to be carbon dioxide and nitrogen Small amounts of argon and water vapor are also thought to be present Considerable uncertainty exists as to the proportions of these constituents There is also a considerable uncertainty in the predicted altitude profiles of temperature and density Because of these uncertainties, it was necessary, in studying the gaseous radiation problem, to investigate a range of environmental conditions Accordingly, a parametric study was made in which the gross spectral quality and intensity of thermal radiation from the hot plasma or gas cap in the stagnation region of small plastic models flying through a mixture of CO_2 and N_2 were measured The proportions of the mixture and its density (pressure), as well as the velocity of the model, were systematically varied to cover as broad a range of probable environmental conditions along the entry-flight profile as possible within the limitations of the test facility The mixture composition was varied from pure N_2 to nearly pure CO_2 Tests were made at three freestream pressures: 3, 15, and 60 mm Hg abs, corresponding to 0 004, 0 02, and 0 08 Earth atmospheres The flight velocity was varied from approximately 5 to 8 km/sec

Facility and Instrumentation

Figure 1 is a sketch of the Ames Pilot Hypersonic Free-Flight Facility in which the present tests were made The shock-tube driver and nozzle, which are normally used to produce a countercurrent air stream, were not used with these gas mixtures, but were isolated from the test section by a diaphragm A model is launched from a light gas gun and flies into the test section, which has been filled with a gas mixture at the appropriate pressure In the test section the model passes two spark shadowgraph stations at which its velocity and attitude are determined The model continues past a group of nine photometric detectors that surround its flight path With these detectors, radiation from the model

Presented as Preprint 63 455 at the AIAA Conference on Physics of Entry into Planetary Atmospheres, Cambridge, Mass , August 26–28, 1963; revision received December 26, 1963

* Head, Flow Fields and Stability Section, Hypersonic Free-Flight Branch Member AIAA

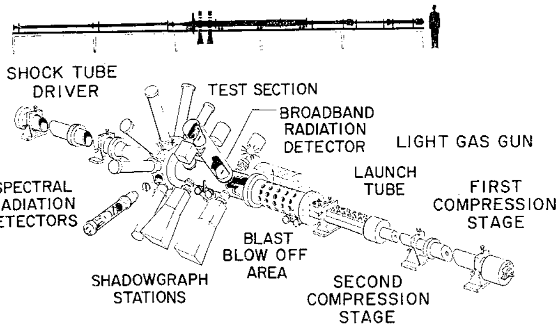

Fig 1 Pilot hypersonic free-flight facility

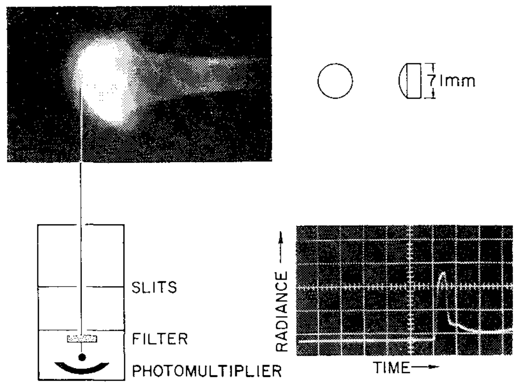

Fig 2 Details of experiment

shock layer is measured at different wavelengths between 0 22 and 1 05 μ The bandwidths of the detectors vary from 300 to 1000 Å, approximately, at 50% of peak response Each detector has been calibrated to measure absolute radiance in its particular band by referencing it, in the test apparatus, to a secondary standard tungsten source, which has been compared by the National Bureau of Standards to a primary standard source The output of each detector is fed into an oscilloscope and photographically recorded

A sketch of the model configuration for this study is shown in Fig 2 at the upper right All models were made of polyethylene and had spherical-segment front faces of 5 08 mm radius At the upper left of Fig 2 is a self-luminous photograph, taken with an image-converter camera, of a model in flight through a mixture of 2% CO_2 and 98% N_2 at a velocity of 8 5 km/sec The relation of its flight path to the photometric detectors is indicated by the sketch below it A typical oscilloscope trace is shown at the lower right By limiting the viewing angle of the detectors with slits placed normal to the model flight path, sufficient spatial resolution to distinguish the gas-cap radiation from that of the afterbody and wake flow was provided In the oscilloscope trace, the initial rise represents the appearance of the model gas cap in the detector field of view The small additional rise after the abrupt change in slope represents radiation from the model afterbody and base region The abrupt drop corresponds to disappearance of the gas cap from the detector field of view The remainder of the trace represents wake radiation

In order to convert the detector outputs to radiance per unit volume of radiating gas, each output must be divided by the effective radiating volume of the gas cap seen by the detector This effective volume is defined as the volume of gas behind a normal shock wave which will yield the same quantity of radiant emission as that behind the curved shock wave of the model Mathematically, this definition may be expressed by

$$v_{eff} = \int_V E\, dv / E_T$$

That portion of the gas-cap volume obscured from the detector by the curvature of the model face is not included in the integral The effect of the temperature and density variation in the gas cap was accounted for to a first approximation by assuming the distribution to be that for air in local equilibrium; that is, E and E_T were calculated from the equilibrium radiation predictions for air of Kivel and Bailey[4] and of Meyerott et al [5] The calculation was made for a freestream pressure of 0 02 atm A value for v_{eff} of 0 007 cm^3 was found and was used to reduce all of the measurements

Results

Radiation Spectra

Typical low-resolution spectra obtained from the detector outputs are shown for four different gas mixtures in Fig 3 Omnidirectional radiance is plotted vs wavelength The radiance measured by each detector is plotted as a short horizontal line, the length of which represents the detector bandwidth at 50% of peak response The spectral characteristics of radiation from the gas cap of models flying in air, N_2, a CO_2-rich mixture, and a CO_2-lean mixture are compared at a common set of freestream conditions The corresponding temperatures and densities in the stagnation region of the gas cap are shown on the curves for each gas These temperatures and densities were obtained from crossplots of charts of equilibrium thermodynamic properties for various gases [6–9] Note that the differences in both temperature and density for the three upper curves are small, whereas the CO_2-rich mixture is somewhat cooler and more dense For all of these gases, most of the energy is radiated in the 0 3- to 0 4-μ region at the freestream conditions chosen The overall radiant intensity is greater in N_2 than in air and still greater in a 16% CO_2 mixture There is also an increasing concentration of the radiant power in the 0 37- to 0 39-μ region

The total power radiated by the 16% CO_2 mixture is roughly ten times that radiated by the air, whereas its peak intensity is nearly 20 times the peak for air This peak occurs in the wavelength region of the violet bands of CN and is therefore attributed to the formation of CN in the gas cap The two- to fourfold increase in intensity in the 0 6- and 1 0 μ region may be largely due to radiation from the CN-red system With a high concentration of CO_2 in the mixture, the CN peak is no longer present This is evident in the lower curve of Fig 3

As might be expected, the spectral quality is found to depend more on the proportions of original species composing the gas mixture than on either the model-flight velocity or the freestream pressure In Fig 4 the effect of the two latter variables on the gross spectral quality is shown for a mixture of $7\frac{1}{2}$% CO_2–$92\frac{1}{2}$% N_2 and for pure N_2 In each case, the effect of varying velocity or pressure is characterized by an

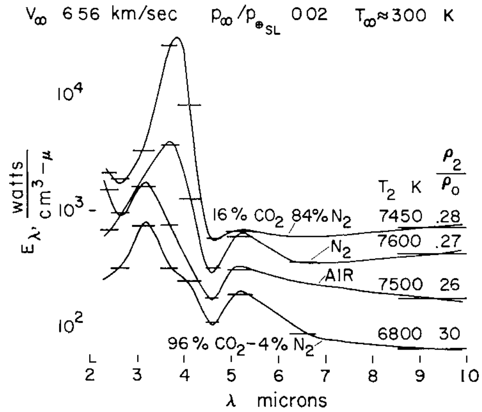

Fig 3 Spectral distribution of gas-cap radiation

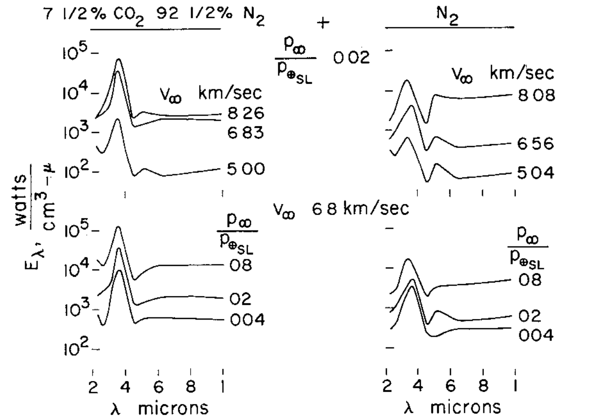

Fig 4 Effect of freestream conditions on spectral quality

approximately proportional change in radiant intensity at all wavelengths In the two lowest curves for 0 004-atm ambient pressure, significant amounts of nonequilibrium radiation are present; yet this does not appear to affect the spectral quality of the radiation within the resolution of the measuring apparatus Similar behavior is observed with nearly pure CO_2 and with air

It is important to note that the test conditions chosen for the present study correspond to equilibrium shock-layer temperatures and densities at which dissociation of the original species has progressed significantly but at which important ionization has not yet occurred In this test range, the proportions of strongly radiating species may be relatively insensitive to temperature and density variations The behavior demonstrated in Fig 4, therefore, cannot be expected a priori to continue at much higher flight velocities than those at which the measurements were made

Total Radiation

A large number of spectral curves, such as those of Figs 3 and 4, were obtained at different test conditions These curves were then integrated to obtain the total radiant energy emitted at each condition It was found that the ambient pressure, the flight velocity, and the gas composition were all important variables affecting the total radiant intensity in the gas cap

Effect of ambient pressure

The variation of total intensity with freestream static pressure is shown for several proportions of the CO_2-N_2 mixture in Fig 5 Experimental data for air, obtained during the same study and reduced in the same manner, are also shown as a basis for comparison The comparison shows that the radiant intensity of the mixtures is much greater than that of air at these conditions The radiant intensity of the $7\frac{1}{2}\%$ CO_2 mixture is six to eight times that of air The calculated values of Kivel[10] for equilibrium air at these conditions are plotted on the figure and agree exceptionally well with the experimental air curve in the higher-pressure region where the model gas cap is essentially in thermochemical equilibrium

The decreasing slope of the experimental curve at the lower ambient pressures in air is attributed to the increasing contributions of nonequilibrium radiation with decreasing pressure or shock-layer density [11 12] From examination of Fig 5, it may be anticipated that this effect is qualitatively the same for the mixtures as for air The dissociative relaxation of CO_2 behind normal shock waves has been studied theoretically by Howe and Viegas [13] From their results it can be shown that the distance behind a normal shock wave at which 80% of the CO_2 has dissociated to CO and O is less than 5% of the shock standoff distance for the conditions of Fig 5 at an ambient pressure ratio of 0 08, and is somewhat greater than 15% of the shock standoff distance at an ambient pressure ratio of 0 02 but greater than the total standoff distance at an ambient pressure ratio of 0 004 If the CN forms according to $CO + N \rightleftarrows CN + O$, the reaction is limited by the supply of dissociated CO_2 and N_2 available The fact that the spectral curves of Fig 4 show no relative attenuation of CN radiation with decreasing pressure indicates that CN must form rapidly behind the shock wave It seems reasonable to assume, for present purposes, that the relaxation distance for CO_2 can be used as an approximate measure of the out-of-equilibrium condition of the gas cap insofar as it affects the dominant source of radiation It is believed, therefore, that the high-pressure ends of these curves represent essentially equilibrium radiation Any effect of mixture proportion on the slope of the curves in this region lies within the scatter of the data The average slope of the group is 1 3 In the absence of data at higher ambient pressures, it is tentatively concluded that, for these CO_2-N_2 mixtures in equilibrium, the total radiant intensity is proportional to the 1 3 power of pressure compared to the 1 7 power of pressure for equilibrium air

Some recent equilibrium calculations by Spiegel and Horton[14] have been made for several different proportions of a CO_2-N_2 mixture A curve for $7\frac{1}{2}\%$ CO_2, plotted in Fig 5, shows a predicted pressure dependence of radiation somewhat stronger than that estimated from the present measurements The predicted intensities are about 50% greater than the measured values at the higher pressures Since the calculations of Spiegel and Horton have not as yet been reported elsewhere, it seems appropriate here to outline briefly their approach In their analysis, the species concentrations and state conditions behind a normal shock wave were obtained by use of a computer program that coupled the thermochemistry with the Rankine-Hugoniot normal-shock relations In the program, 32 species were used to obtain the species concentrations, and 16 of these were treated as radiators Gaseous emissivities were taken directly from Kivel and Bailey,[4] except that the oscillator strength of 0 027 obtained for CN-violet by Bennett and Dalby[15] was used for both CN-violet and CN-red CO was not treated as a radiator

Effect of flight velocity

The velocity dependence of gas-cap radiance is shown in Fig 6 Data for three ambient pressures and six mixture proportions are represented The total radiance has been normalized by the pressure dependence (1 3 exponent) indicated from Fig 5 The data, in general, now define a single curve for each mixture proportion, except that the lowest-pressure points are high by an increment attributed to the nonequilibrium radiation contribution

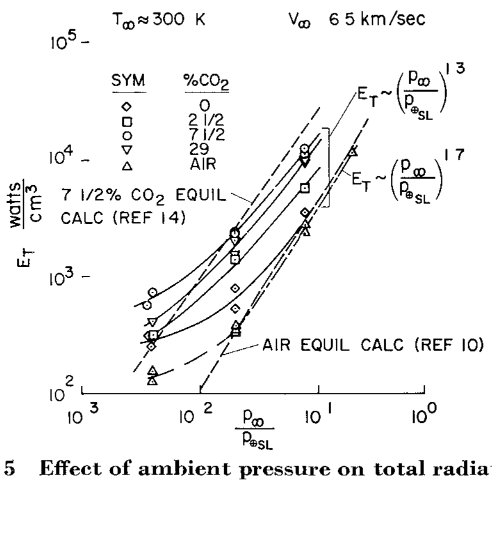

Fig 5 Effect of ambient pressure on total radiation

Equilibrium calculations of Spiegel and Horton and of Breene and Nardone (as reported in Ref 16) are compared with the experimental intensities at the most closely matching mixture proportions The calculations of Breene and Nardone were matched to freestream conditions through the incident shock relations given by Pugmire[7] In general, the qualitative character of the predicted intensity variations with velocity are in agreement with the experiment, although there are significant differences in magnitude

In order to better visualize the change in velocity dependence with mixture proportion, lines of constant slope have been

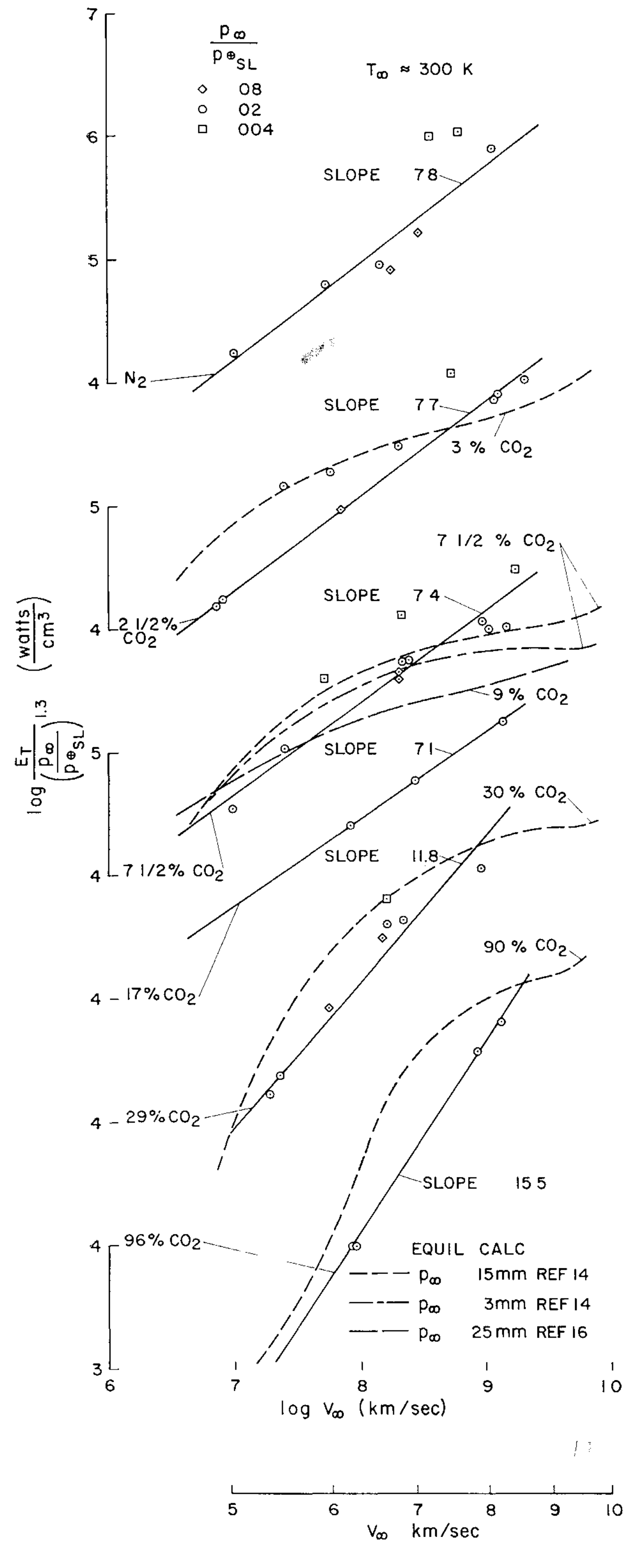

Fig 6 Effect of velocity on total radiation

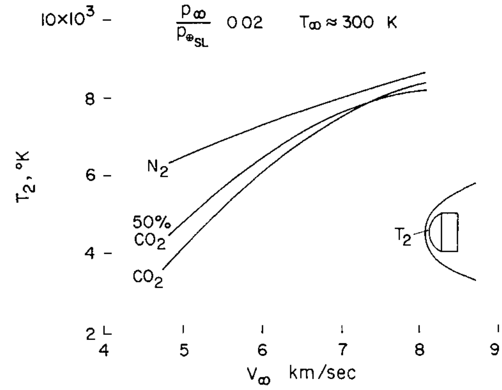

Fig 7 Gas-cap temperatures

faired through the data for each mixture These lines represent an exponential dependence of radiance on velocity, with the slope of the line defining the exponent (Note that the abscissa scale is ten times that of the ordinate) It is clear that, in the velocity range of the present test, the CO_2-rich mixtures are much more strongly dependent on the flight velocity than are the CO_2-lean mixtures The explanation for this phenomenon, at least in large measure, can be found in the effect of mixture proportion on the variation of shock-layer temperature with flight velocity In Fig 7, the temperature in the model gas cap ahead of the stagnation point is plotted vs flight velocity for three gases: N_2, CO_2, and a 50% CO_2-N_2 mixture The gas-cap temperatures of both CO_2 and the 50% mixture are lower than that of N_2 in this range of flight velocities but are much stronger functions of flight velocity The curve for CO_2 represents approximately a $\frac{3}{2}$-power variation of gas-cap temperature with flight velocity, whereas the curve for N_2 represents a $\frac{1}{2}$-power variation There is, therefore, in this velocity range, a factor of three difference in the exponent of velocity for the two gases This consideration by itself, without accounting for other effects of temperature and CO_2 concentration, would lead one to expect for the dependence of radiance on velocity an exponent of velocity for CO_2 three times greater than the corresponding exponent for N_2 Conversely, one would expect a much weaker effect of mixture proportions if the proportionality were based on stagnation temperature rather than on flight velocity

Effect of gas composition

The variation of total radiance with the concentration of CO_2 in the CO_2-N_2 mixture is plotted in Fig 8 for a constant ambient pressure and three different flight velocities, and in Fig 9 for a constant flight velocity and three different pressures The middle curve, for the condition of 6 5 km/sec and 0 02 atm, is common to both figures The corresponding measured total intensities from air are shown also for comparison Measurements at the lowest pressure (lower curve of Fig 9), both for the CO_2-N_2 mixtures and for air, contain significant amounts of nonequilibrium radiation, as noted from Fig 5 Two points on the lower curve of Fig 8, marked by "×," are extrapolated from the velocity plots of Fig 6 because data were not available for these conditions

For all conditions, the radiant intensity from pure N_2 is seen to be two to three times that from air at the same freestream conditions As the concentration of CO_2 is increased from pure N_2, the radiance of the mixture increases, reaching a maximum when the CO_2 concentration is 10 to 20%, and then falls off with further increase in CO_2 concentration The maximum radiation from the CO_2-N_2 mixture is nearly an order of magnitude greater than that from air at these velocities The mixture proportions at which this maximum occurs (i e , the 10 to 20% CO_2 region) are those which are currently thought most likely to occur in the atmospheres of

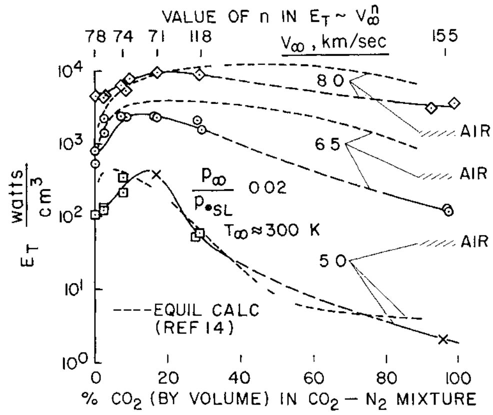

Fig 8 Effect of CO_2 concentration on total radiation; p_∞ = const

Mars and Venus The result of the difference in velocity de pendence at different mixture proportions is evident in the shape change of the curves with increasing velocity The intensity at the right (CO_2-rich) edge of the figure increases more rapidly than does the intensity at the left (CO_2-lean) edge of the figure At the lower velocity the radiation from pure CO_2 is an order of magnitude less than that from air, whereas at the higher velocity the radiation from pure CO_2 is three times greater than that from air

The equilibrium radiation predictions of Spiegel and Horton[14] are shown also in Fig 8 The qualitative agreement with the experimental results is quite good as to trends, and the quantitative agreement is almost within a factor of two everywhere, except for the higher concentrations of CO_2 at a flight velocity of 6 5 km/sec

Principal radiators

As a final point, it is possible to infer, from a combination of experimental and theoretical evidence, something about the principal radiating species in these mixtures The curves of Fig 10 were obtained from the calculations of Woodward[8] and show, at the conditions indicated in the figure, the equilibrium concentrations of certain radiating chemical species in the gas cap as functions of the mixture proportions Notice the similarity in the way the CN concentration varies with mixture proportion and the way the radiation intensity varies with mixture proportion in Figs 8 and 9 It is this feature, together with the strong emission observed in the 0 38-μ region for the CO_2-N_2 mixtures, as noted in Figs 3 and 4, that leads to the conclusion that CN is the principal radiator in mixtures containing, say, between 2 and 40% CO_2 For higher concentrations of CO_2, carbon monoxide may become the principal radiator In this connection, the reasonable agreement between the measured and calculated intensities for mixtures containing nearly all CO_2, as shown in Figs 6 and 8, may be fortuitous inasmuch as the calculations do not account for radiation from CO, while possibly overesti mating theco ntribution of the CN-red system (There is inference from the recent work of Fairbairn[17] and from the spectral curves of Fig 3 that the oscillator strength for CN-red may be considerably less than that for CN-violet)

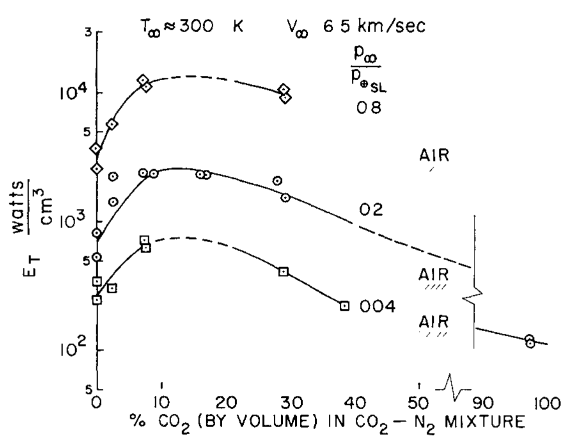

Fig 9 Effect of CO_2 concentration on total radiation; V_∞ = const

Fvaluation of Sources of Error

The various potential sources of error have been examined or monitored throughout the test in order to assess the over-all reliability of the radiation measurements

Direct Errors of Measurement

Those errors that accumulate from the calibrations of various instruments, such as radiometers and oscilloscopes, tend to have a systematic effect on the measurements From considerations of calibration repeatability, filter band-pass characteristics, and the like, the net effect of these systematic errors of measurement is estimated to be less than 20% of the measured radiation, but the sign of this uncertainty is not known

Errors of a random nature include those connected with the measurement of gas pressure and flight velocity, the variation of model angle-of-attack, and the fairing of the spectral distribution profiles Uncertainties in the pressure and velocity measurements are within ± 2 and $\pm 1\%$, respectively Other random errors have been individually considered but are believed best evaluated from their aggregate effect on the scatter of the experimental data

Sources of Systematic Uncertainty

Ablation product radiation

Ablation of the model surface in the stagnation region in jects heated material into the shock layer Radiation from this heated material is observed by some of the photometric detectors, which cannot discriminate between this ablation product radiation and radiation from the gas mixture Poly ethylene was chosen as the model material for these tests in order to minimize uncertainties due to radiation from this source Recent work by Craig and Davy[18] shows that the contribution of polyethylene ablation radiation in air is less than about 25% of the total gas cap radiation in the pressure range of these tests Under similar test conditions, Steinberg et al [19] find no appreciable enhancement of gas-cap radiation due to polyethylene ablation, at least in the spectral range in which the present instrumentation is sensitive By assuming the ablation radiation measurements of Craig

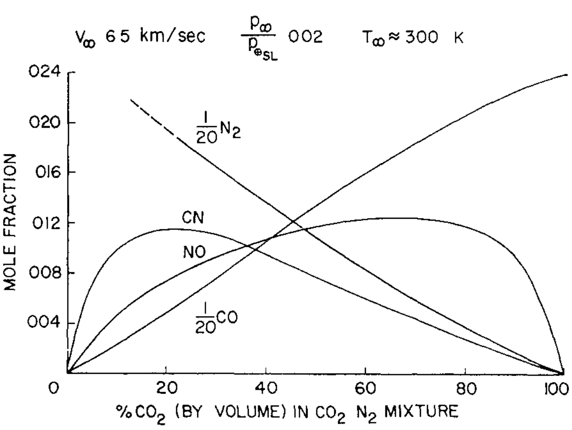

Fig 10 Concentiations of strong ıadiatoıs

and Davy to apply in CO_2-N_2 mixtures, it is estimated that the contribution of ablation radiation in the present series of measurements amounts to 5 to 10% of the total A single comparison of radiation from two shots at 6 km/sec into a mixture containing 2 5% CO_2 (one with a polyethylene model and one with a nonablating aluminum model) is in agreement with this estimate

Calculation of effective radiating volume

The accuracy of the results in the form of radiance per unit volume of radiating gas is directly dependent upon the accuracy of the calculated effective radiating volume v_{ff} A value calculated for air at an average flow condition was used to convert the measurements to this form Some very recent calculations of v_{ff} for a mixture of 9% CO_2 and 91% N_2 have been made by J O Arnold of the Ames Research Center, who made use of the thermodynamic properties of Browne[20] and the theoretical equilibrium gas predictions of Breene and Nardone, as given by Gruszczynski and Warren [16] He obtained values of v_{ff} of 0 0065 cm³ and 0 0067 cm³ at 6 4 and 8 2 km/sec, respectively, and at a freestream pressure of 0 02 atm These moie refined calculations would suggest that the values of the E_T presented here are low by perhaps 5% at the highest velocity and 10 or 15% at the lowest velocity It is interesting to observe that the effect of uncertainity in v_{ff} and the effect of ablation product radiation are of approximately like magnitude but opposite sign

Gaseous contaminants

Contamination of the gas mixture in the test section by small amounts of air due to unavoidable inward leakage was monitored by drawing a gas sample from the test section im mediately prior to each model shot Each sample was later analyzed on a mass spectrometer The O_2 content of the samples was typically less than 0 5% by volume; in a few cases it measured between 0 5 and 1 5%, and one sample contained 4 6% O_2 The effect of these amounts of O_2 on the radiation measurements was too small to be detected The presence of H_2O and of A in the samples was less than 0 4% by volume in all cases

Concluding Remarks

Fiom a parametric study of the radiation from the shock layer in the stagnation region of small blunt bodies in free flight through mixtures of CO_2 and N_2, the variation of radiant intensity with ambient pressure, flight velocity, and mixture proportions has been defined The conditions of the study simulate, in the velocity range from 5 to 8 km/sec, the en vironmental conditions expected to be encountered by early instrumented probes during their final descent through the atmospheres of the planets Mars and Venus In comparison with radiation from air under the same conditions, the radiant intensity of the mixtures was generally found to be higher by as much as an order of magnitude for some conditions The higher intensities are primarily due to strong radiation from CN formed in the shock layer Thus, greater radiative heating loads will be encountered during atmospheric braking for entries into Mars or Venus than for comparable entries to Earth

Although the velocity range of the present study is sufficient to include the estimated flight conditions at peak radiative heating during a Martian entry, it is not high enough to simulate conditions estimated for peak heating during entry into Venus Nor is the range of conditions simulated in this study sufficiently broad to include probable manned entry trajectories for Mars The increased ionization and more complete dissociation of chemical species associated with higher speeds makes the extrapolation of the present results hazardous, to say the least Further measurements at higher velocities are needed In addition, nonequilibrium effects and scaling rules need to be examined and compared to present knowledge for air

References

[1] Gazley, C , Jr , ' Deceleration and heating of a body entering a planetary atmosphere from space, Rand Corp Rept P-955 (February 1957)

[2] Boobar, M G and Foster, R M , ' Some aerothermodynamic considerations for Martian entry and heat shield design, IAS Paper 62-163 (1962)

[3] James, C S and Smith, W G , "Experimental studies of static stability and radiative heating associated with Mars and Venus entry," IAS Fairchild Fund Paper FF-34 (January 1963)

[4] Kivel, B and Bailey, K , "Tables of radiation from high temperature air," Res Rept 21, Avco Res Lab (1957)

[5] Meyerott, R E , Sokoloff, J , and Nicholls, R W , "Absorption coefficients of air,' Geophys Res Paper 68 (July 1960)

[6] Ahtye, W F and Peng, T -C , "Approximations for the thermodynamic and transport properties of high-temperature nitrogen with shock-tube applications," NASA TN D-1303 (1962)

[7] Pugmire, T K , "Experimental planetary entry research for Mars and Venus—1962, ' General Electric Missile and Space Vehicle Div R62SD84 (October 1962)

[8] Woodward, H T , "Thermodynamic properties of carbon-dioxide and nitrogen mixtures behind a normal shock wave," NASA TN D-1553 (1963)

[9] Ziemer, R W , ' Extended hypervelocity gas dynamic charts for equilibrium air," Space Technology I abs STL/TR-60 0000 09093 (April 1960)

[10] Kivel, B , ' Radiation from hot air and its effect on stagnation-point heating," J Aerospace Sci **28,** 96–102 (1961)

[11] Page, W A , "Shock-layer radiation of blunt bodies traveling at lunar return entry velocities," IAS Paper 63-41 (1963)

[12] Canning, T N and Page, W A , "Measurements of radiation from the flow fields of bodies flying at speeds up to 13 4 kilometers per second, ' AGARD Fluid Mechanics Panel, Brussels (April 1962)

[13] Howe, J T , Viegas, J R , and Sheaffer, Y S , "Study of the nonequilibrium flow field behind normal shock waves in carbon dioxide, NASA TN D 1885 (June 1963)

[14] Spiegel, J M and Horton, T E , private communication, Jet Propulsion Lab , Calif Inst Tech (June and December 1963)

[15] Bennett, R G and Dalby, F W , "Experimental oscillator strength of the violet system of CN," J Chem Phys **36,** 399 (1962)

[16] Gruszczynski, J S and Warren W R , Jr , "Experimental heat transfer studies of hypervelocity flight in planetary atmospheres," AIAA Paper 63 450 (1963)

[17] Fairbairn, A , "The spectrum of shock-heated gases simulating the Venus atmosphere," AIAA Paper 63-454 (1963)

[18] Craig, R A and Davy, W C , "Thermal radiation from ablation products injected into a hypersonic shock layer," NASA TN D-1978 (September 1963)

[19] Steinberg, M , Maiden, C J , Leak, W R , and Hansen, C F , "Preliminary studies of the effects of ablation contaminants on radiation," General Motors Defense Res I ab Rept TR62-209H (December 1962)

[20] Browne, W G , "Thermodynamic properties of the Venusian atmosphere," General Electric Missile and Space Vehicle Div , Advance Aerospace Phys Tech Memo 13, Part II (June 1962)