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by Henry T. Woodward

Ames Research Center
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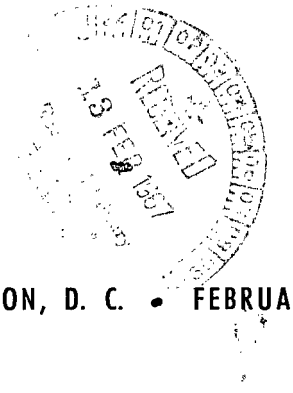

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PREDICTIONS OF SHOCK-LAYER RADIATION FROM MOLECULAR BAND SYSTEMS IN PROPOSED PLANETARY ATMOSPHERES

By Henry T. Woodward
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SUMMARY

Concentrations of radiating molecules and radiation from a number of band systems are presented for equilibrium shock-layer temperatures and densities of vehicles entering proposed Martian and Venusian atmospheres. The atmospheres selected consist of various proportions of CO_2, N_2, and A. Charts are also presented which relate these equilibrium shock-layer properties to flight velocity and ambient density through the normal shock conservation equations. These data can be used to estimate stagnation-point radiative heat transfer for entry trajectories. Estimates for a few selected flight conditions are discussed and compared.

INTRODUCTION

There is increasing interest in the radiative heating of vehicles entering the atmospheres of Mars and Venus. One constituent of these atmospheres, CO_2, has been identified, but its abundance, as well as the nature and abundance of other gases, is still uncertain. In addition to CO_2, proposed atmospheres usually consist of various proportions of N_2 and A (refs. 1-5).

Seven mixtures intended to cover the range of uncertainty in these proportions are considered in the present report. The first four include a more likely range for the Martian atmosphere, since latest evidence indicates that CO_2 is at least a major constituent (ref. 4). The mole fraction composition of the seven mixtures considered in the present study is given in the following table:

CO_2	N_2	A
0.50	0.50	0
.50	.30	.20
.50	0	.50
1.00	0	0
0	1.00	0
.25	.75	0
.75	.25	0

To include a range of possible shock-layer conditions caused by uncertainties in the density of the Martian and Venusian atmospheres, temperatures from 4,000° to 12,000° K and density ratios from 10^{-5} to 1 are considered for each mixture. The radiative intensity for 10 of the more well-known band systems considered to be major radiative contributors and the concentration of radiating molecules were then calculated for these conditions. Normal shock properties were also calculated to relate these shock-layer properties to flight conditions. The assistance of Dr. Victor H. Reis in calculating the effects of self-absorption for the CN violet band system is gratefully acknowledged.

SYMBOLS

B_e	rotational constant, cm^{-1}
B_v	rotational parameter that varies with vibrational level, cm^{-1}
B_λ	Planck black-body function, W/cm^2-sr-μ
c	velocity of light, cm/sec
E_v	vibrational energy, cm^{-1}
$E_3(\tau)$	function of τ used in self-absorption expression (eq. (12))
e	electronic charge, esu
$F''_{el,T}$	fractional population of the electronic state
f^{abs}_{el}	electronic absorption oscillator strength for the band system (f number)
h	Planck constant, erg-sec
I	total intensity, W/cm^3
I_p	total intensity per particle, W/particle
I_{p_λ}	spectral intensity per particle, W/μ particle
I_λ	spectral intensity, W/cm^3-μ
K_λ	spectral absorption coefficient, cm^{-1}
k	Boltzmann constant, erg/deg
m	mass of electron, g
n_p	number density of radiating species, cm^{-3}

Q_v	vibrational partition function
$q_{v',v''}$	Franck-Condon factor
$\dot{q}$	total heating rate, W/cm^2
$\dot{q}_\lambda$	spectral heating rate, $W/cm^2-\mu$
R	ratio of total self-absorbed heating rate to optically thin rate
T	temperature, ^oK
T_e	electronic energy, cm^{-1}
V	flight velocity, km/sec
v	vibrational quantum number
v''_M	maximum vibrational quantum number (eqs. (6) and (7))
α_e	vibration-rotation interaction constant, cm^{-1}
δ	shock standoff distance, cm
λ	wavelength, μ
ν	wave number, cm^{-1}
$\nu^o_{v',v''}$	band-head wave number, cm^{-1}
ρ	density, g/cm^3
ρ_o	density of air at 1 atm and 273^o K, 1.293×10^{-3} g/cm^3
ω_e, $\omega_e x_e$, $\omega_e y_e$, $\omega_e z_e$	vibrational constants, cm^{-1}

Subscripts

OT	optically thin
SA	self-absorbed
1	conditions ahead of shock wave
2	conditions behind shock wave

Superscripts

(') upper electronic state

(") lower electronic state

CALCULATIONS

Computer programs developed at Ames Research Center (ref. 6)[1] were used to calculate the concentrations of radiating molecules and other equilibrium thermodynamic shock-layer properties for atmospheres, temperatures, and densities of interest. These properties were then related to flight velocity and ambient density by solving the normal shock conservation equations. Number densities of radiating molecules are given in tables I through VII, and temperatures and densities behind normal shock waves are plotted in figures 1 to 7 for an ambient temperature of 300° K.

Calculations of the spectral intensities of the CN violet, CN red, CO fourth positive, C_2 swan, NO beta, NO gamma, N_2 first positive, N_2 second positive, N_2^+ first negative, and O_2 Schumann-Runge band systems used the "smeared line" model given by Williams and Treanor (ref. 8). The fundamental assumption of this model is that the density of rotational lines is so great that the distribution of their intensities may be regarded as continuous. This model gives a reasonably accurate representation of the gross features of band systems; other examples of its use are given in references 9 and 10.

From equation (7) of reference 8, the spectral intensity is

$$I_\lambda = 1.19\times10^{-16}\,\frac{\pi e^2}{mc^2}\,\frac{n_p f''^{abs}_{el}\,F''_{el,T}\,B''_e}{k\,\nu^\circ_{oo}\,T\,Q''_v}\,\frac{\nu^6}{e^{\nu/kT}-1}\sum\frac{q_{v'v''}}{|B'_e - B''_e|}\,e^{\dfrac{-\left[\frac{B''_e}{B'_e - B''_e}\,(\nu - \nu^\circ_{v'v''}) + E''_v\right]}{kT}}, \quad W/cm^3\text{-}\mu\text{-}sr \tag{1}$$

where the summation is such that $\nu^\circ_{v',v''} \leq \nu$ for bands degraded to shorter wavelengths and $\nu^\circ_{v',v''} \geq \nu$ for bands degraded to longer wavelengths. Williams and Treanor (ref. 8) stated that it was more exact to use B_v in place of B_e in that part of equation (1) included in the summation, where

$$B_v = B_e - \alpha_e\left(v + \frac{1}{2}\right), \quad cm^{-1} \tag{2}$$

[1]The CN radical is an important radiator, but the correct values of calculated CN concentrations are uncertain, primarily because of the wide range of values of heat of dissociation reported in the literature (from 7.5 to 8.5 eV), none of which is clearly better than any other (ref. 7). The value used here is approximately 8.2 eV.

They also indicated later in a private communication that the induced emission factor $1 - e^{-hc\nu/kT}$, as well as the factor hc, had been inadvertently omitted. After these corrections and modifications are made, the expression is multiplied by 4π to obtain the radiation in all directions (4π sr) and divided by n_p. The equation, as evaluated in this report, then becomes

$$I_{p_\lambda} = 1.9\times10^{-27} \frac{f^{abs}_{e\,l}\, F''_{e\,l,T}\, B''_e}{\nu^o_{oo}\, T\, Q''_v}\, \nu^8 e^{-\frac{hc\nu}{kT}} \sum \frac{q_{v'v''}}{|B'_v - B''_v|}\, e^{\frac{-hc\left[\frac{B'_v}{B'_v - B''_v}(\nu - \nu^o_{v'v''}) + E''_v\right]}{kT}}, \quad W/\mu \text{ particle} \tag{3}$$

where

$$E_v = \omega_e\left(v + \frac{1}{2}\right) - \omega_e x_e\left(v + \frac{1}{2}\right)^2 + \omega_e y_e\left(v + \frac{1}{2}\right)^3 - \omega_e z_e\left(v + \frac{1}{2}\right)^4, \quad cm^{-1} \tag{4}$$

$$\nu^o_{v'v''} = T'_e - T''_e + E'_v - E''_v, \quad cm^{-1} \tag{5}$$

$$Q''_v = \sum_{v''=o}^{v''_M} e^{\frac{-hcE''_v}{kT}} \tag{6}$$

and v''_M is the smallest value for which

$$\frac{e^{\frac{-hcE''_v}{kT}}}{\sum_{v''=o}^{v''_M} e^{\frac{-hcE''_v}{kT}}} \leq 0.001 \tag{7}$$

The values of T_e, B_e, ω_e, $\omega_e x_e$, $\omega_e y_e$, $\omega_e z_e$, and α_e were taken from Herzberg (ref. 11); the fraction of molecules in the lower electronic state, $F''_{e\,l,T}$, was computed by formulas obtained from Gilmore (ref. 12), and the vibrational quantum numbers for the band-head transitions considered were those listed by Wallace (refs. 13, 14). The values and sources of the band-system electronic-absorption oscillator strengths (f numbers) used, and the sources of the Franck-Condon factors are given in table VIII. Thus, the spectral intensity per particle, I_{p_λ}, of each band system was calculated from equation (3) and plotted for five temperatures in figures 8 to 17. The total intensity per particle, I_p, of each band system was obtained by integrating the spectral

intensity with respect to wavelength over the spectral range of the band system. Values of I_p and the spectral ranges used in the calculations are listed in table IX.[2]

DISCUSSION

These tables and graphs can be used to estimate stagnation-point radiative heating along proposed planetary entry trajectories. The procedure will be described and sample calculations of radiative heating at two points of a proposed trajectory through the first five atmospheres in the table on page 1 will be discussed and compared.

The temperature and density behind a normal shock wave can be determined from figures 1 to 7 as a function of flight velocity and ambient density for a particular atmosphere, and should be only slightly affected by ambient temperatures different from 300° K. These shock-layer conditions are then used to interpolate for n_p, the concentration of molecules, in tables I to VII. Interpolation in figures 8 to 17 or table IX using the shock-layer temperature gives I_{p_λ} and I_p, respectively. The spectral intensity of each band system is then

$$I_\lambda = n_p I_{p_\lambda} , \qquad W/cm^3-\mu \tag{8}$$

Similarly, the total intensity of each band system is

$$I = n_p I_p , \qquad W/cm^3 \tag{9}$$

At the stagnation point of a blunt body, the spectral radiative heating rate for an optically thin gas in thermochemical equilibrium is given by the plane-layer approximation (ref. 15) as

$$\dot{q}_{\lambda_{OT}} \approx \sum \frac{I_\lambda \delta}{2} , \qquad W/cm^2-\mu \tag{10}$$

and, similarly, the total rate is

$$\dot{q}_{OT} \approx \sum \frac{I\delta}{2} , \qquad W/cm^2 \tag{11}$$

where the summation includes all band systems and δ is the shock-wave standoff distance.

---

[2]Since the f number is considered constant over the entire band system in the method expressed by equation (3), the effect of a better f number on the given values of I_{p_λ} and I_p can be obtained by simply multiplying the given values by the ratio of the new f number to the given f number.

At the first point of an example trajectory, $V_1 = 6.5$ km/sec and $\rho_1/\rho_o = 10^{-4}$. In an atmosphere of 50 percent CO_2 and 50 percent N_2, $T_2 = 5600^\circ$ K and $\rho_2/\rho_o = 1.775 \times 10^{-3}$. Figure 18 is a plot of equation (8) for these conditions showing the spectral distribution and intensity of the band systems. The total heating rate, obtained by evaluating equation (11), is shown in figure 19. In 50 percent CO_2 and 50 percent N_2, most of the radiation comes from the CN(V), CN(R), and CO(4+) band systems; other contributions are smaller by factors of 100 to 1000. In 50 percent CO_2, 30 percent N_2, and 20 percent A, the shock-layer temperature is about 200° higher (5830° K), and the total radiation is somewhat higher. In 50 percent CO_2 and 50 percent A, the only contributions come from CO(4+), C_2(S), and O_2(S-R), but the latter two band systems are still negligible compared to CO(4+). Moreover, although the shock-layer temperature is about 600° higher (6450° K), the absence of CN(V) and CN(R) results in reduced total radiation. In 100 percent CO_2, the shock-layer temperature is about 800° lower (5650° K), and the total radiation, which again is from the CO(4+), C_2(S), and O_2(S-R) systems, is the lowest of the four gas mixtures considered thus far, but still more than 1/3 that from the highest. In 100 percent N_2, the shock-layer temperature is about 200° higher (5870° K), but the only contributions come from N_2(1+), N_2(2+), and N_2^+(1-). The total radiation in this case is about a factor of 100 lower than that from any of the previous four gas mixtures.

At the second point of the proposed trajectory, $V_1 = 5.8$ km/sec and $\rho_1/\rho_o = 10^{-3}$. The total radiation from the first three gas mixtures and 100 percent N_2 is about a factor of 10 higher than at the previous trajectory point. In 100 percent CO_2, however, the total radiation is about a factor of 10 lower, mainly because of a shock-layer temperature which is about 1200° lower (4400° K) than at the previous point.

Experimental evidence supporting similar predictions is discussed in reference 16. It should be noted that there are other sources of radiation, such as continua and atomic lines, that contribute importantly at high temperatures. In fact, continuum and line radiation are expected to be dominant above about 11,000° K (ref. 16).

An expression that accounts for self-absorption and is shown to be a good approximation for the stagnation-point radiative heating of a blunt body is given by Kennet and Strack (ref. 17) and Strack (ref. 18).

$$\dot{q}_{\lambda_{SA}} \approx \pi B_\lambda [1 - 2E_3(\tau)] \ , \qquad W/cm^2\text{-}\mu \tag{12}$$

where B_λ is the Planck black-body function, values of $E_3(\tau)$ tabulated by Kourganoff (ref. 19) are plotted in figure 20 as a function of τ, and

$$\tau = K_\lambda \delta \tag{13}$$

where

$$K_\lambda = \frac{I_\lambda}{4\pi B_\lambda} \ , \qquad cm^{-1} \tag{14}$$

is the spectral absorption coefficient. Hence, if differences between values from equations (10) and (12) are appreciable in a particular spectral region, the more realistic value of $\dot{q}_{SA}$ can be obtained by replacing the optically thin contribution indicated in equation (11) by the integral of equation (12) in this region. This procedure shows that radiation from the CN(V) and the CO(4+) band systems can be reduced by self-absorption. The ratio

$$R = \frac{\int_0^\infty \dot{q}_{\lambda_{SA}} \, d\lambda}{\int_0^\infty \dot{q}_{\lambda_{OT}} \, d\lambda} = \frac{\dot{q}_{SA}}{\dot{q}_{OT}} \tag{15}$$

for these systems is plotted as a function of temperature and density in figures 21 and 22 for a mixture of 50 percent CO_2 and 50 percent N_2, and shock-wave standoff distances of 1 and 20 cm. At higher shock-layer densities, most of the radiation is self-absorbed.

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National Aeronautics and Space Administration
Moffett Field, Calif., Oct. 3, 1966
129-01-08-17-21

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TABLE I.- NUMBER DENSITY, MOLECULES/CM^3: 50 PERCENT CO_2 - 50 PERCENT N_2

T_2, °K	$\log_{10} \rho_2/\rho_0$	N_2	N_2^+	CO	O_2	C_2	CN	NO
4,000	-5	9.629 +13	7.304 +5	1.079 +14	2.791 +9	9.651 +5	3.178 +10	1.543 +11
	-4	1.040 +15	1.395 +6	1.081 +15	2.757 +11	9.812 +5	1.053 +11	5.042 +12
	-3	1.061 +16	2.539 +6	1.081 +16	2.673 +13	1.011 +6	3.415 +11	1.586 +14
	-2	1.054 +17	4.670 +6	1.074 +17	2.294 +15	1.163 +6	1.154 +12	4.630 +15
	-1	1.029 +18	9.684 +6	1.029 +18	1.153 +17	2.126 +6	4.875 +12	1.025 +17
	0	1.011 +19	2.571 +7	8.840 +18	2.199 +18	8.228 +6	3.006 +13	1.404 +18
5,000	-5	1.930 +13	3.172 +7	5.449 +13	3.443 +8	1.263 +9	4.532 +11	4.124 +10
	-4	5.884 +14	5.325 +8	9.518 +14	1.924 +10	6.894 +9	5.846 +12	1.702 +12
	-3	8.870 +15	2.402 +9	1.063 +16	1.572 +12	1.053 +10	2.805 +13	5.974 +13
	-2	1.007 +17	4.993 +9	1.078 +17	1.481 +14	1.149 +10	9.876 +13	1.954 +15
	-1	1.031 +18	9.375 +9	1.077 +18	1.298 +16	1.307 +10	3.371 +14	5.854 +16
	0	1.005 +19	1.871 +10	1.050 +19	7.584 +17	2.129 +10	1.343 +15	1.397 +18
6,000	-5	6.547 +11	4.582 +7	1.877 +12	8.959 +7	4.374 +8	4.592 +10	5.481 +9
	-4	5.903 +13	1.369 +9	1.586 +14	7.829 +9	3.574 +10	3.942 +12	4.866 +11
	-3	3.207 +15	3.179 +10	6.128 +15	4.667 +11	8.951 +11	1.454 +14	2.769 +13
	-2	7.142 +16	3.194 +11	9.729 +16	2.710 +13	3.886 +12	1.430 +15	9.958 +14
	-1	9.336 +17	9.465 +11	1.063 +18	2.197 +15	5.724 +12	6.274 +15	3.242 +16
	0	9.911 +18	1.898 +12	1.072 +19	1.758 +17	7.273 +12	2.304 +16	9.448 +17
7,000	-5	4.367 +10	6.421 +7	6.848 +10	2.336 +7	5.041 +7	3.884 +9	9.217 +8
	-4	4.371 +12	1.833 +9	8.553 +12	2.338 +9	7.855 +9	4.851 +11	9.226 +10
	-3	4.071 +14	5.392 +10	8.242 +14	2.184 +11	7.812 +11	4.668 +13	8.603 +12
	-2	2.513 +16	1.266 +12	4.359 +16	1.496 +13	3.189 +13	2.344 +15	5.595 +14
	-1	6.422 +17	1.399 +13	8.786 +17	8.033 +14	2.413 +14	3.259 +16	2.073 +16
	0	8.873 +18	4.877 +13	1.038 +19	5.526 +16	4.900 +14	1.726 +17	6.390 +17
8,000	-5	5.107 +9	9.149 +7	3.281 +9	7.938 +6	3.586 +6	3.475 +8	2.196 +8
	-4	5.539 +11	2.365 +9	6.693 +11	8.476 +8	1.397 +9	7.143 +10	2.363 +10
	-3	5.586 +13	6.786 +10	8.525 +13	8.540 +10	2.250 +11	9.103 +12	2.382 +12
	-2	5.100 +15	1.953 +12	8.236 +15	7.978 +12	2.248 +13	8.694 +14	2.200 +14
	-1	2.863 +17	4.093 +13	4.294 +17	5.458 +14	8.930 +14	4.106 +16	1.364 +16
	0	6.611 +18	3.675 +14	8.590 +18	2.882 +16	6.768 +15	5.431 +17	4.761 +17
9,000	-5	6.430 +8	8.693 +7	1.790 +8	2.628 +6	2.033 +5	2.906 +7	5.136 +7
	-4	9.884 +10	2.875 +9	6.543 +10	3.618 +8	1.974 +8	1.123 +10	7.472 +9
	-3	1.091 +13	8.030 +10	1.195 +13	3.885 +10	6.129 +10	2.078 +12	8.133 +11
	-2	1.095 +15	2.354 +12	1.445 +15	3.902 +12	8.923 +12	2.512 +14	8.166 +13
	-1	9.174 +16	6.369 +13	1.276 +17	3.493 +14	7.770 +14	2.146 +16	7.073 +15
	0	3.903 +18	1.026 +15	5.258 +18	2.164 +16	2.131 +16	7.331 +17	3.631 +17
10,000	-5	5.401 +7	3.820 +7	1.092 +7	5.973 +5	1.463 +4	2.248 +6	7.890 +6
	-4	1.876 +10	2.662 +9	7.234 +9	1.546 +8	2.481 +7	1.725 +9	2.365 +9
	-3	2.698 +12	8.883 +10	2.054 +12	1.983 +10	1.558 +10	5.186 +11	3.214 +11
	-2	2.934 +14	2.626 +12	3.148 +14	2.098 +12	3.462 +12	8.060 +13	3.446 +13
	-1	2.834 +16	7.687 +13	3.450 +16	2.062 +14	4.230 +14	8.755 +15	3.358 +15
	0	1.888 +18	1.735 +15	2.414 +18	1.643 +16	2.600 +16	5.603 +17	2.446 +17
11,000	-5	2.669 +6	8.618 +6	5.839 +5	7.345 +4	1.144 +3	1.394 +5	6.692 +5
	-4	2.959 +9	1.588 +9	8.762 +8	5.540 +7	3.415 +6	2.535 +8	6.119 +8
	-3	7.312 +11	8.503 +10	3.982 +11	1.048 +10	3.730 +9	1.317 +11	1.323 +11
	-2	9.379 +13	2.772 +12	8.216 +13	1.230 +12	1.353 +12	2.841 +13	1.623 +13
	-1	9.803 +15	8.397 +13	1.055 +16	1.267 +14	2.165 +14	3.674 +15	1.684 +15
	0	8.292 +17	2.253 +15	9.733 +17	1.161 +16	2.010 +16	3.256 +17	1.483 +17
12,000	-5	1.107 +5	1.478 +6	2.974 +4	6.094 +3	9.805 +1	8.293 +3	4.201 +4
	-4	3.495 +8	6.210 +8	1.034 +8	1.436 +7	5.028 +5	3.337 +7	1.146 +8
	-3	1.914 +11	6.540 +10	8.383 +10	5.268 +9	9.013 +8	3.306 +10	5.136 +10
	-2	3.335 +13	2.725 +12	2.426 +13	7.568 +11	5.253 +11	1.054 +13	8.126 +12
	-1	3.844 +15	8.717 +13	3.717 +15	8.263 +13	1.129 +14	1.659 +15	9.115 +14
	0	3.677 +17	2.547 +15	4.000 +17	8.111 +15	1.333 +16	1.762 +17	8.833 +16

Note: A group of digits followed by +n indicates that the decimal point should be n places to the right of the first digit.

TABLE II.- NUMBER DENSITY, MOLECULES/CM^3: 50 PERCENT CO_2 - 30 PERCENT N_2 - 20 PERCENT A

T_2, °K	$\log_{10} \rho_2/\rho_o$	N_2	N_2^+	CO	O_2	C_2	CN	NO
4,000	-5	5.213 +13	4.738 +5	1.012 +14	2.457 +9	9.640 +5	2.337 +10	1.066 +11
	-4	5.779 +14	9.257 +5	1.014 +15	2.431 +11	9.788 +5	7.840 +10	3.529 +12
	-3	5.937 +15	1.693 +6	1.013 +16	2.370 +13	1.003 +6	2.544 +11	1.117 +14
	-2	5.892 +16	3.095 +6	1.007 +17	2.073 +15	1.133 +6	8.518 +11	3.290 +15
	-1	5.706 +17	6.318 +6	9.663 +17	1.085 +17	1.992 +6	3.514 +12	7.409 +16
	0	5.569 +18	1.655 +7	8.311 +18	2.142 +18	7.466 +6	2.125 +13	1.028 +18
5,000	-5	7.075 +12	1.190 +7	4.978 +13	3.082 +8	1.177 +9	2.649 +11	2.362 +10
	-4	2.729 +14	2.624 +8	8.878 +14	1.708 +10	6.752 +9	3.940 +12	1.092 +12
	-3	4.675 +15	1.502 +9	9.970 +15	1.388 +12	1.049 +10	2.032 +13	4.075 +13
	-2	5.538 +16	3.280 +9	1.012 +17	1.315 +14	1.139 +10	7.290 +13	1.366 +15
	-1	5.724 +17	6.175 +9	1.010 +18	1.177 +16	1.269 +10	2.474 +14	4.153 +16
	0	5.532 +18	1.211 +10	9.857 +18	7.216 +17	1.971 +10	9.585 +14	1.011 +18
6,000	-5	2.084 +11	1.511 +7	1.650 +12	7.889 +7	3.839 +8	2.428 +10	2.902 +9
	-4	1.959 +13	4.687 +8	1.414 +14	6.942 +9	3.204 +10	2.150 +12	2.640 +11
	-3	1.280 +15	1.311 +10	5.636 +15	4.175 +11	8.465 +11	8.935 +13	1.655 +13
	-2	3.512 +16	1.759 +11	9.106 +16	2.405 +13	3.837 +12	9.963 +14	6.578 +14
	-1	5.009 +17	6.051 +11	9.978 +17	1.962 +15	5.646 +12	4.564 +15	2.244 +16
	0	5.431 +18	1.231 +12	1.006 +19	1.623 +17	6.940 +12	1.666 +16	6.719 +17
7,000	-5	1.382 +10	2.126 +7	5.945 +10	2.054 +7	4.320 +7	2.023 +9	4.862 +8
	-4	1.389 +12	6.056 +8	7.499 +12	2.058 +9	6.862 +9	2.556 +11	4.878 +10
	-3	1.332 +14	1.829 +10	7.305 +14	1.930 +11	6.944 +11	2.518 +13	4.626 +12
	-2	9.597 +15	5.010 +11	3.984 +16	1.336 +13	2.982 +13	1.400 +15	3.268 +14
	-1	3.059 +17	7.347 +12	8.229 +17	7.154 +14	2.377 +14	2.232 +16	1.350 +16
	0	4.686 +18	3.051 +13	9.765 +18	4.998 +16	4.791 +14	1.240 +17	4.416 +17
8,000	-5	1.605 +9	3.086 +7	2.747 +9	6.938 +6	2.874 +6	1.744 +8	1.151 +8
	-4	1.752 +11	7.870 +8	5.793 +11	7.447 +8	1.191 +9	3.710 +10	1.246 +10
	-3	1.776 +13	2.254 +10	7.470 +13	7.514 +10	1.963 +11	4.795 +12	1.260 +12
	-2	1.683 +15	6.708 +11	7.311 +15	7.055 +12	2.003 +13	4.714 +14	1.188 +14
	-1	1.119 +17	1.673 +13	3.948 +17	4.879 +14	8.444 +14	2.496 +16	8.061 +15
	0	3.179 +18	1.985 +14	8.092 +18	2.580 +16	6.710 +15	3.751 +17	3.124 +17
9,000	-5	1.933 +8	2.892 +7	1.413 +8	2.222 +6	1.499 +5	1.368 +7	2.589 +7
	-4	3.100 +10	9.691 +8	5.496 +10	3.160 +8	1.595 +8	5.651 +9	3.910 +9
	-3	3.451 +12	2.681 +10	1.035 +13	3.413 +10	5.240 +10	1.081 +12	4.288 +11
	-2	3.496 +14	7.884 +11	1.268 +15	3.435 +12	7.808 +12	1.328 +14	4.330 +13
	-1	3.126 +16	2.268 +13	1.143 +17	3.100 +14	7.029 +14	1.191 +16	3.889 +15
	0	1.629 +18	4.562 +14	4.913 +18	1.940 +16	2.075 +16	4.674 +17	2.222 +17
10,000	-5	1.487 +7	1.183 +7	8.107 +6	4.683 +5	1.029 +4	9.890 +5	3.665 +6
	-4	5.694 +9	8.877 +8	5.820 +9	1.319 +8	1.881 +7	8.277 +8	1.204 +9
	-3	8.473 +11	2.988 +10	1.745 +12	1.735 +10	1.286 +10	2.640 +11	1.684 +11
	-2	9.295 +13	8.793 +11	2.740 +14	1.844 +12	2.985 +12	4.213 +13	1.818 +13
	-1	9.181 +15	2.619 +13	3.046 +16	1.819 +14	3.737 +14	4.685 +15	1.795 +15
	0	6.915 +17	6.686 +14	2.212 +18	1.469 +16	2.440 +16	3.285 +17	1.400 +17
11,000	-5	6.765 +5	2.491 +6	4.078 +5	5.271 +4	7.776 +2	5.784 +4	2.854 +5
	-4	8.458 +8	5.054 +8	6.737 +8	4.511 +7	2.480 +6	1.155 +8	2.952 +8
	-3	2.253 +11	2.847 +10	3.290 +11	9.052 +9	2.947 +9	6.499 +10	6.826 +10
	-2	2.955 +13	9.309 +11	7.071 +13	1.078 +12	1.143 +12	1.466 +13	8.528 +12
	-1	3.125 +15	2.829 +13	9.242 +15	1.115 +14	1.888 +14	1.937 +15	8.922 +14
	0	2.808 +17	8.036 +14	8.747 +17	1.032 +16	1.826 +16	1.806 +17	8.137 +16
12,000	-5	2.681 +4	4.121 +5	1.997 +4	4.135 +3	6.519 +1	3.328 +3	1.703 +4
	-4	9.323 +7	1.866 +8	7.558 +7	1.094 +7	3.530 +5	1.444 +7	5.165 +7
	-3	5.699 +10	2.138 +10	6.715 +10	4.443 +9	6.857 +8	1.574 +10	2.574 +10
	-2	1.041 +13	9.138 +11	2.056 +13	6.596 +11	4.330 +11	5.343 +12	4.238 +12
	-1	1.217 +15	2.930 +13	3.234 +15	7.258 +13	9.734 +13	8.663 +14	4.806 +14
	0	1.200 +17	8.780 +14	3.550 +17	7.176 +15	1.187 +16	9.497 +16	4.745 +16

See note on page 11.

TABLE III.- NUMBER DENSITY, MOLECULES/CM^3: 50 PERCENT CO_2 - 50 PERCENT A

T_2, °K	$\log_{10} \rho_2/\rho_0$	CO	O_2	C_2	T_2, °K	$\log_{10} \rho_2/\rho_0$	CO	O_2	C_2
4,000	-5	9.253 +13	2.061 +9	9.619 +5	9,000	-5	9.864 +7	1.730 +6	9.378 +4
	-4	9.275 +14	2.049 +11	9.721 +5		-4	4.271 +10	2.613 +8	1.164 +8
	-3	9.271 +15	2.029 +13	9.807 +5		-3	8.468 +12	2.850 +10	4.197 +10
	-2	9.218 +16	1.863 +15	1.056 +6		-2	1.057 +15	2.878 +12	6.476 +12
	-1	8.842 +17	1.070 +17	1.692 +6		-1	9.805 +16	2.625 +14	6.109 +14
	0	7.569 +18	2.248 +18	5.900 +6		0	4.531 +18	1.666 +16	2.055 +16
5,000	-5	4.387 +13	2.642 +8	1.066 +9	10,000	-5	5.130 +6	3.213 +5	6.002 +3
	-4	8.067 +14	1.448 +10	6.581 +9		-4	4.198 +9	1.047 +8	1.234 +7
	-3	9.125 +15	1.170 +12	1.042 +10		-3	1.381 +12	1.438 +10	9.718 +9
	-2	9.259 +16	1.130 +14	1.110 +10		-2	2.256 +14	1.540 +12	2.421 +12
	-1	9.244 +17	1.074 +16	1.165 +10		-1	2.560 +16	1.529 +14	3.141 +14
	0	9.013 +18	7.449 +17	1.596 +10		0	1.966 +18	1.259 +16	2.249 +16
6,000	-5	1.379 +12	6.610 +7	3.202 +8	11,000	-5	2.358 +5	3.164 +4	4.330 +2
	-4	1.204 +14	5.871 +9	2.749 +10		-4	4.513 +8	3.300 +7	1.521 +6
	-3	5.021 +15	3.573 +11	7.851 +11		-3	2.483 +11	7.344 +9	2.069 +9
	-2	8.343 +16	2.033 +13	3.810 +12		-2	5.714 +13	8.965 +11	8.975 +11
	-1	9.161 +17	1.706 +15	5.475 +12		-1	7.678 +15	9.336 +13	1.556 +14
	0	9.219 +18	1.556 +17	6.077 +12		0	7.537 +17	8.765 +15	1.597 +16
7,000	-5	4.877 +10	1.717 +7	3.478 +7	12,000	-5	1.093 +4	2.294 +3	3.521 +1
	-4	6.244 +12	1.723 +9	5.683 +9		-4	4.680 +7	7.184 +6	2.060 +5
	-3	6.173 +14	1.625 +11	5.889 +11		-3	4.814 +10	3.455 +9	4.532 +8
	-2	3.520 +16	1.142 +13	2.725 +13		-2	1.620 +13	5.435 +11	3.261 +11
	-1	7.583 +17	6.069 +14	2.379 +14		-1	2.658 +15	6.059 +13	7.879 +13
	0	9.030 +18	4.476 +16	4.575 +14		0	3.002 +17	6.050 +15	1.007 +16
8,000	-5	2.125 +9	5.746 +6	2.078 +6					
	-4	4.729 +11	6.222 +8	9.502 +8					
	-3	6.213 +13	6.291 +10	1.622 +11					
	-2	6.191 +15	5.944 +12	1.705 +13					
	-1	3.528 +17	4.174 +14	7.883 +14					
	0	7.579 +18	2.209 +16	6.875 +15					

See note on page 11.

TABLE IV.- NUMBER DENSITY, MOLECULES/CM^3: 100 PERCENT CO_2

T_2, °K	$\log_{10} \rho_2/\rho_0$	CO	O_2	C_2	T_2, °K	$\log_{10} \rho_2/\rho_0$	CO	O_2	C_2
4,000	-5	1.767 +14	7.479 +9	9.669 +5	9,000	-5	5.417 +8	7.343 +6	6.666 +5
	-4	1.769 +15	7.446 +11	9.733 +5		-4	1.984 +11	9.865 +8	6.655 +8
	-3	1.768 +16	7.317 +13	9.885 +5		-3	3.370 +13	1.045 +11	1.813 +11
	-2	1.749 +17	6.276 +15	1.128 +6		-2	3.897 +15	1.038 +13	2.440 +13
	-1	1.639 +18	2.788 +17	2.232 +6		-1	3.171 +17	8.826 +14	1.900 +15
	0	1.340 +19	4.523 +18	9.197 +6		0	1.102 +19	5.012 +6	4.045 +16
5,000	-5	1.079 +14	7.970 +8	2.136 +9	10,000	-5	2.973 +7	1.617 +6	4.006 +4
	-4	1.635 +15	4.774 +10	8.194 +9		-4	2.148 +10	4.277 +8	7.906 +7
	-3	1.754 +16	4.190 +12	1.075 +10		-3	5.979 +12	5.381 +10	4.869 +10
	-2	1.767 +17	4.086 +14	1.119 +10		-2	8.698 +14	5.631 +12	9.846 +12
	-1	1.758 +18	3.731 +16	1.213 +10		-1	9.144 +16	5.437 +14	1.127 +15
	0	1.687 +19	2.107 +18	1.977 +10		0	5.745 +18	4.015 +16	6.024 +16
6,000	-5	5.014 +12	2.374 +8	1.179 +9	11,000	-5	1.517 +6	1.915 +5	2.960 +3
	-4	3.798 +14	1.947 +10	8.243 +10		-4	2.416 +9	1.508 +8	9.537 +6
	-3	1.190 +16	1.077 +12	1.462 +12		-3	1.160 +12	2.871 +10	1.155 +10
	-2	1.668 +17	6.823 +13	4.535 +12		-2	2.310 +14	3.319 +12	3.963 +12
	-1	1.757 +18	6.092 +15	5.636 +12		-1	2.860 +16	3.386 +14	5.954 +14
	0	1.752 +19	5.301 +17	6.443 +12		0	2.500 +18	2.992 +16	5.148 +16
7,000	-5	1.964 +11	6.270 +7	1.544 +8	12,000	-5	7.666 +4	1.573 +4	2.524 +2
	-4	2.325 +13	6.235 +9	2.177 +10		-4	2.708 +8	3.781 +7	1.311 +6
	-3	2.087 +15	5.605 +11	1.951 +12		-3	2.352 +11	1.440 +10	2.595 +9
	-2	9.147 +16	3.480 +13	6.037 +13		-2	6.872 +13	2.055 +12	1.553 +12
	-1	1.573 +18	1.945 +15	3.195 +14		-1	1.019 +16	2.221 +14	3.160 +14
	0	1.741 +19	1.562 +17	4.871 +14		0	1.063 +18	2.144 +16	3.559 +16
8,000	-5	1.034 +10	2.166 +7	1.305 +7					
	-4	1.920 +12	2.279 +9	4.275 +9					
	-3	2.320 +14	2.279 +11	6.246 +11					
	-2	2.094 +16	2.050 +13	5.652 +13					
	-1	9.158 +17	1.271 +15	1.744 +15					
	0	1.571 +19	7.045 +16	9.264 +15					

See note on page 11.

TABLE V.- NUMBER DENSITY, MOLECULES/CM^3: 100 PERCENT N_2

T_2, °K	$\log_{10} \rho_2/\rho_0$	N_2	N_2^+	T_2, °K	$\log_{10} \rho_2/\rho_0$	N_2	N_2^+
4,000	-5	2.588 +14	6.689 +7	9,000	-5	3.864 +9	6.258 +8
	-4	2.718 +15	3.105 +8		-4	6.066 +11	2.776 +10
	-3	2.761 +16	1.202 +9		-3	6.971 +13	9.739 +11
	-2	2.774 +17	4.129 +9		-2	6.967 +15	3.071 +13
	-1	2.778 +18	1.344 +10		-1	4.999 +17	7.424 +14
	0	2.780 +19	4.292 +10		0	1.524 +19	8.804 +15
5,000	-5	8.842 +13	1.314 +9	10,000	-5	3.501 +8	2.518 +8
	-4	1.901 +15	1.260 +10		-4	1.142 +11	1.934 +10
	-3	2.464 +16	7.677 +10		-3	1.685 +13	8.182 +11
	-2	2.676 +17	3.574 +11		-2	1.883 +15	2.810 +13
	-1	2.747 +18	1.367 +12		-1	1.742 +17	8.320 +14
	0	2.770 +19	4.661 +12		0	9.086 +18	1.535 +16
6,000	-5	4.234 +12	1.630 +9	11,000	-5	1.845 +7	5.800 +7
	-4	3.380 +14	4.331 +10		-4	1.895 +10	1.052 +10
	-3	1.279 +16	6.424 +11		-3	4.520 +12	6.387 +11
	-2	2.163 +17	4.884 +12		-2	5.962 +14	2.485 +13
	-1	2.568 +18	2.512 +13		-1	6.251 +16	8.115 +14
	0	2.711 +19	1.011 +14		0	4.656 +18	2.003 +16
7,000	-5	2.808 +11	1.304 +9	12,000	-5	7.756 +5	1.004 +7
	-4	2.831 +13	4.145 +10		-4	2.381 +9	4.141 +9
	-3	2.427 +15	1.162 +12		-3	1.209 +12	4.429 +11
	-2	1.085 +17	1.948 +13		-2	2.102 +14	2.121 +13
	-1	2.045 +18	1.584 +14		-1	2.468 +16	7.552 +14
	0	2.522 +19	8.182 +14		0	2.242 +18	2.191 +16
8,000	-5	3.109 +10	9.992 +8				
	-4	3.534 +12	3.478 +10				
	-3	3.597 +14	1.113 +12				
	-2	2.981 +16	3.032 +13				
	-1	1.205 +18	4.631 +14				
	0	2.120 +19	3.425 +15				

See note on page 11.

TABLE VI.- NUMBER DENSITY, MOLECULES/CM^3: 25 PERCENT CO_2 - 75 PERCENT N_2

T_2, °K	$\log_{10} \rho_2/\rho_0$	N_2	N_2^+	CO	O_2	C_2	CN	NO
4,000	-5	1.669 +14	1.467 +6	6.054 +13	8.860 +8	9.576 +5	4.168 +10	1.145 +11
	-4	1.772 +15	2.775 +6	6.079 +14	8.708 +10	9.824 +5	1.375 +11	3.699 +12
	-3	1.803 +16	5.043 +6	6.079 +15	8.424 +12	1.016 +6	4.461 +11	1.160 +14
	-2	1.803 +17	9.270 +6	6.058 +16	7.380 +14	1.151 +6	1.502 +12	3.434 +15
	-1	1.782 +18	1.876 +7	5.899 +17	4.257 +16	1.893 +6	6.054 +12	8.200 +16
	0	1.762 +19	4.754 +7	5.288 +18	9.969 +17	6.493 +6	3.526 +13	1.248 +18
5,000	-5	4.578 +13	8.944 +7	2.315 +13	1.276 +8	6.150 +8	4.871 +11	3.866 +10
	-4	1.140 +15	1.114 +9	4.936 +14	6.847 +9	5.208 +9	7.072 +12	1.413 +12
	-3	1.568 +16	4.831 +9	5.898 +15	5.090 +11	1.000 +10	3.636 +13	4.520 +13
	-2	1.733 +17	1.001 +10	6.053 +16	4.668 +13	1.149 +10	1.295 +14	1.439 +15
	-1	1.776 +18	1.883 +10	6.063 +17	4.073 +15	1.321 +10	4.447 +14	4.303 +16
	0	1.763 +19	3.746 +10	5.978 +18	2.548 +17	2.053 +10	1.746 +15	1.072 +18
6,000	-5	1.849 +12	1.713 +8	5.881 +11	2.855 +7	1.348 +8	4.284 +10	5.200 +9
	-4	1.573 +14	4.665 +9	5.465 +13	2.630 +9	1.264 +10	3.826 +12	4.603 +11
	-3	7.027 +15	8.084 +10	2.678 +15	1.745 +11	4.573 +11	1.539 +14	2.506 +13
	-2	1.328 +17	6.476 +11	5.082 +16	9.545 +12	3.010 +12	1.716 +15	8.059 +14
	-1	1.638 +18	1.910 +12	5.888 +17	7.051 +14	5.471 +12	8.126 +15	2.433 +16
	0	1.733 +19	3.861 +12	6.021 +18	5.478 +16	7.363 +12	3.066 +16	6.974 +17
7,000	-5	1.238 +11	2.429 +8	1.974 +10	7.364 +6	1.329 +7	3.357 +9	8.711 +8
	-4	1.237 +13	6.783 +9	2.634 +12	7.415 +8	2.350 +9	4.463 +11	8.739 +10
	-3	1.107 +15	1.876 +11	2.706 +14	7.130 +10	2.578 +11	4.422 +13	8.106 +12
	-2	5.760 +16	3.449 +12	1.734 +16	5.437 +12	1.389 +13	2.341 +15	5.106 +14
	-1	1.228 +18	2.916 +13	4.332 +17	2.953 +14	1.596 +14	3.664 +16	1.737 +16
	0	1.584 +19	9.872 +13	5.631 +18	1.815 +16	4.386 +14	2.182 +17	4.894 +17
8,000	-5	1.416 +10	3.171 +8	8.840 +8	2.458 +6	8.404 +5	2.801 +8	2.035 +8
	-4	1.564 +12	8.571 +9	1.944 +11	2.666 +8	3.747 +8	6.217 +10	2.228 +10
	-3	1.577 +14	2.438 +11	2.628 +13	2.706 +10	6.747 +10	8.375 +12	2.253 +12
	-2	1.373 +16	6.572 +12	2.697 +15	2.602 +12	7.389 +12	8.179 +14	2.062 +14
	-1	6.456 +17	1.078 +14	1.687 +17	1.978 +14	3.804 +14	4.024 +16	1.233 +16
	0	1.264 +19	7.629 +14	4.151 +18	1.062 +16	4.288 +15	5.979 +17	3.998 +17
9,000	-5	1.758 +9	2.575 +8	5.199 +7	8.059 +5	5.595 +4	2.521 +7	4.702 +7
	-4	2.743 +11	9.530 +9	1.843 +10	1.124 +8	5.044 +7	9.456 +9	6.937 +9
	-3	3.077 +13	2.789 +11	3.558 +12	1.222 +10	1.727 +10	1.853 +12	7.663 +11
	-2	3.072 +15	8.125 +12	4.504 +14	1.239 +12	2.731 +12	2.328 +14	7.707 +13
	-1	2.385 +17	1.997 +14	4.267 +16	1.156 +14	2.628 +14	2.012 +16	6.559 +15
	0	8.396 +18	2.474 +15	2.137 +18	7.960 +15	9.565 +15	7.204 +17	3.230 +17
10,000	-5	1.524 +8	1.086 +8	3.418 +6	1.876 +5	4.563 +3	2.109 +6	7.429 +6
	-4	5.158 +10	7.912 +9	2.126 +9	4.771 +7	6.944 +6	1.514 +9	2.179 +9
	-3	7.532 +12	2.885 +11	6.008 +11	6.192 +9	4.272 +9	4.537 +11	3.000 +11
	-2	8.274 +14	8.806 +12	9.614 +13	6.613 +11	1.024 +12	7.362 +13	3.250 +13
	-1	7.820 +16	2.521 +14	1.094 +16	6.588 +13	1.331 +14	8.158 +15	3.153 +15
	0	4.586 +18	4.854 +15	8.475 +17	5.615 +15	9.374 +15	5.244 +17	2.229 +17
11,000	-5	7.752 +6	2.473 +7	1.886 +5	2.366 +4	3.704 +2	1.351 +5	6.473 +5
	-4	8.306 +9	4.527 +9	2.720 +8	1.734 +7	1.052 +6	2.357 +8	5.736 +8
	-3	2.025 +12	2.562 +11	1.182 +11	3.255 +9	1.059 +9	1.168 +11	1.227 +11
	-2	2.634 +14	8.880 +12	2.482 +13	3.859 +11	3.933 +11	2.567 +13	1.524 +13
	-1	2.752 +16	2.723 +14	3.287 +15	4.008 +13	6.643 +13	3.410 +15	1.587 +15
	0	2.187 +18	6.812 +15	3.176 +17	3.781 +15	6.574 +15	3.024 +17	1.374 +17
12,000	-5	3.234 +5	4.259 +6	9.654 +3	1.976 +3	3.186 +1	8.081 +3	4.089 +4
	-4	1.009 +9	1.775 +9	3.318 +7	4.594 +6	1.619 +5	3.217 +7	1.101 +8
	-3	5.340 +11	1.883 +11	2.571 +10	1.644 +9	2.717 +8	3.032 +10	4.792 +10
	-2	9.320 +13	8.313 +12	7.332 +12	2.367 +11	1.535 +11	9.520 +12	7.597 +12
	-1	1.083 +16	2.750 +14	1.149 +15	2.604 +13	3.427 +13	1.533 +15	8.588 +14
	0	1.010 +18	7.867 +15	1.270 +17	2.588 +15	4.209 +15	1.641 +17	8.270 +16

See note on page 11.

TABLE VII.- NUMBER DENSITY, MOLECULES/CM^3: 75 PERCENT CO_2 - 25 PERCENT N_2

T_2, °K	$\log_{10} \rho_2/\rho_0$	N_2	N_2^+	CO	O_2	C_2	CN	NO
4,000	-5	4.092 +13	3.301 +5	1.457 +14	5.084 +9	9.671 +5	2.074 +10	1.358 +11
	-4	4.587 +14	6.488 +5	1.460 +15	5.039 +11	9.789 +5	6.985 +10	4.526 +12
	-3	4.713 +15	1.187 +6	1.458 +16	4.900 +13	1.005 +6	2.269 +11	1.431 +14
	-2	4.634 +16	2.172 +6	1.446 +17	4.159 +15	1.164 +6	7.656 +11	4.133 +15
	-1	4.425 +17	4.526 +6	1.370 +18	1.922 +17	2.260 +6	3.296 +12	8.682 +16
	0	4.303 +18	1.224 +7	1.146 +19	3.306 +18	9.199 +6	2.074 +13	1.123 +18
5,000	-5	4.719 +12	7.186 +6	8.303 +13	5.745 +8	1.757 +9	2.643 +11	2.634 +10
	-4	1.994 +14	1.829 +8	1.326 +15	3.339 +10	7.703 +9	3.597 +12	1.305 +12
	-3	3.618 +15	1.046 +9	1.443 +16	2.848 +12	1.070 +10	1.806 +13	5.136 +13
	-2	4.355 +16	2.284 +9	1.457 +17	2.723 +14	1.141 +10	6.471 +13	1.742 +15
	-1	4.468 +17	4.289 +9	1.452 +18	2.406 +16	1.283 +10	2.198 +14	5.246 +16
	0	4.221 +18	8.448 +9	1.404 +19	1.352 +18	2.136 +10	8.716 +14	1.208 +18
6,000	-5	1.335 +11	8.064 +6	3.420 +12	1.623 +8	8.018 +8	2.807 +10	3.331 +9
	-4	1.267 +13	2.598 +8	2.713 +14	1.368 +10	5.988 +10	2.364 +12	2.980 +11
	-3	8.780 +14	8.228 +9	9.219 +15	7.770 +11	1.217 +12	8.871 +13	1.870 +13
	-2	2.627 +16	1.232 +11	1.352 +17	4.738 +13	4.291 +12	9.112 +14	7.986 +14
	-1	3.876 +17	4.184 +11	1.443 +18	4.031 +15	5.750 +12	4.052 +15	2.829 +16
	0	4.167 +18	8.451 +11	1.446 +19	3.305 +17	7.043 +12	1.470 +16	8.400 +17
7,000	-5	8.863 +9	1.114 +7	1.303 +11	4.264 +7	9.999 +7	2.464 +9	5.610 +8
	-4	8.894 +11	3.228 +8	1.575 +13	4.252 +9	1.464 +10	2.987 +11	5.612 +10
	-3	8.576 +13	9.992 +9	1.456 +15	3.886 +11	1.370 +12	2.838 +13	5.268 +12
	-2	6.448 +15	3.018 +11	6.879 +16	2.508 +13	4.738 +13	1.447 +15	3.670 +14
	-1	2.243 +17	5.063 +12	1.253 +18	1.371 +15	2.875 +14	2.102 +16	1.600 +16
	0	3.563 +18	2.096 +13	1.422 +19	1.014 +17	5.002 +14	1.105 +17	5.486 +17
8,000	-5	1.049 +9	1.625 +7	6.595 +9	1.464 +7	7.856 +6	2.331 +8	1.352 +8
	-4	1.126 +11	4.165 +8	1.273 +12	1.549 +9	2.767 +9	4.533 +10	1.441 +10
	-3	1.138 +13	1.209 +10	1.570 +14	1.554 +11	4.197 +11	5.612 +12	1.451 +12
	-2	1.084 +15	3.685 +11	1.458 +16	1.421 +13	3.958 +13	5.319 +14	1.354 +14
	-1	7.532 +16	1.015 +13	6.835 +17	9.159 +14	1.348 +15	2.588 +16	9.060 +15
	0	2.317 +18	1.359 +14	1.238 +19	4.926 +16	8.230 +15	3.546 +17	3.685 +17
9,000	-5	1.343 +8	1.702 +7	3.491 +8	4.905 +6	4.144 +5	1.897 +7	3.207 +7
	-4	2.032 +10	5.238 +8	1.284 +11	6.666 +8	4.124 +8	7.359 +9	4.599 +9
	-3	2.221 +12	1.442 +10	2.248 +13	7.099 +10	1.188 +11	1.306 +12	4.961 +11
	-2	2.242 +14	4.276 +11	2.647 +15	7.088 +12	1.649 +13	1.546 +14	4.980 +13
	-1	2.020 +16	1.270 +13	2.229 +17	6.160 +14	1.345 +15	1.325 +16	4.407 +15
	0	1.110 +18	2.864 +14	8.255 +18	3.615 +16	3.145 +16	4.749 +17	2.502 +17
10,000	-5	1.102 +7	7.744 +6	2.008 +7	1.095 +6	2.699 +4	1.379 +6	4.826 +6
	-4	3.900 +9	5.202 +8	1.397 +10	2.870 +8	4.981 +7	1.115 +9	1.470 +9
	-3	5.531 +11	1.642 +10	3.933 +12	3.643 +10	3.112 +10	3.318 +11	1.972 +11
	-2	5.978 +13	4.803 +11	5.849 +14	3.829 +12	6.546 +12	5.003 +13	2.102 +13
	-1	5.888 +15	1.443 +13	6.256 +16	3.726 +14	7.696 +14	5.383 +15	2.058 +15
	0	4.498 +17	3.882 +14	4.104 +18	2.840 +16	4.346 +16	3.536 +17	1.570 +17
11,000	-5	5.320 +5	1.734 +6	1.047 +6	1.319 +5	2.046 +3	8.322 +4	4.004 +5
	-4	6.064 +8	3.214 +8	1.622 +9	1.019 +8	6.368 +6	1.567 +8	3.756 +8
	-3	1.511 +11	1.647 +10	7.611 +11	1.935 +10	7.378 +9	8.421 +10	8.171 +10
	-2	1.916 +13	5.179 +11	1.542 +14	2.252 +12	2.601 +12	1.780 +13	9.927 +12
	-1	2.006 +15	1.568 +13	1.938 +16	2.307 +14	4.011 +14	2.263 +15	1.028 +15
	0	1.799 +17	4.531 +14	1.733 +18	2.071 +16	3.572 +16	2.022 +17	9.225 +16
12,000	-5	2.196 +4	2.964 +5	5.308 +4	1.089 +4	1.749 +2	4.933 +3	2.501 +4
	-4	7.000 +7	1.253 +8	1.862 +8	2.594 +7	9.031 +5	2.001 +7	6.892 +7
	-3	3.939 +10	1.312 +10	1.567 +11	9.710 +9	1.709 +9	2.066 +10	3.163 +10
	-2	6.842 +12	5.239 +11	4.566 +13	1.390 +12	1.013 +12	6.628 +12	4.989 +12
	-1	7.842 +14	1.647 +13	6.870 +15	1.509 +14	2.113 +14	1.025 +15	5.565 +14
	0	7.670 +16	4.944 +14	7.261 +17	1.468 +16	2.427 +16	1.086 +17	5.427 +16

See note on page 11.

TABLE VIII.- VALUES AND REFERENCES FOR f NUMBERS AND FRANCK-CONDON FACTORS USED IN CALCULATIONS

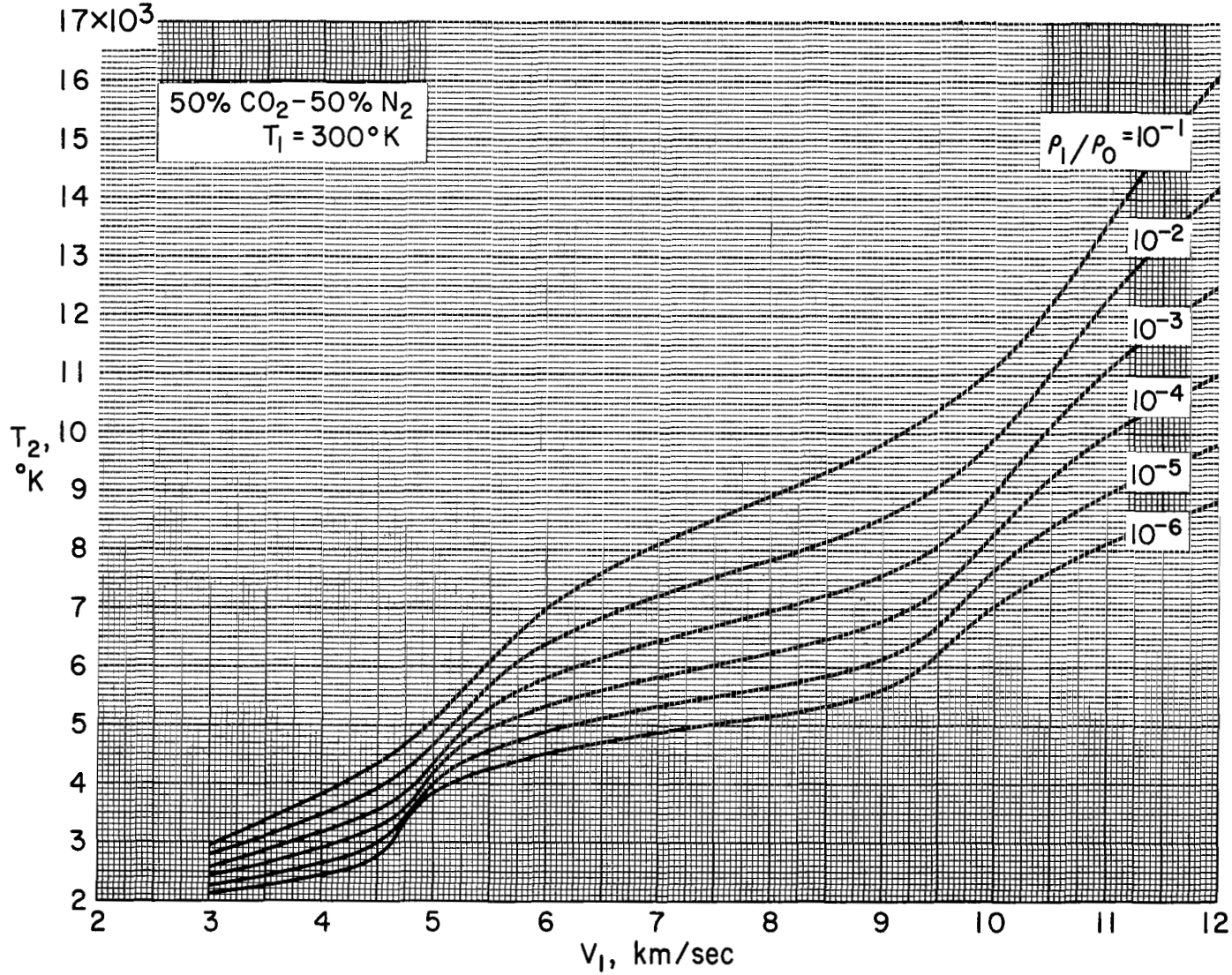
Band system	f number		Franck-Condon factors
	Value	Reference	Reference
CN(V)	0.020[a]	7	20
CN(R)	.007	21	20
CO(4+)	.15	22	23
C_2(S)	.034	24	25
NO(β)	.0015	26	27
NO(γ)	.0024	26	27
N_2(1+)	.0034	28	29
N_2(2+)	.057	30	29
N_2^+(1-)	.053	30	29
O_2(S-R)	.16	31	23

[a]The CN concentrations used to deduce this f value are from the same source as those given in tables I to VII.

TABLE IX.- TOTAL INTENSITY, W/PARTICLE

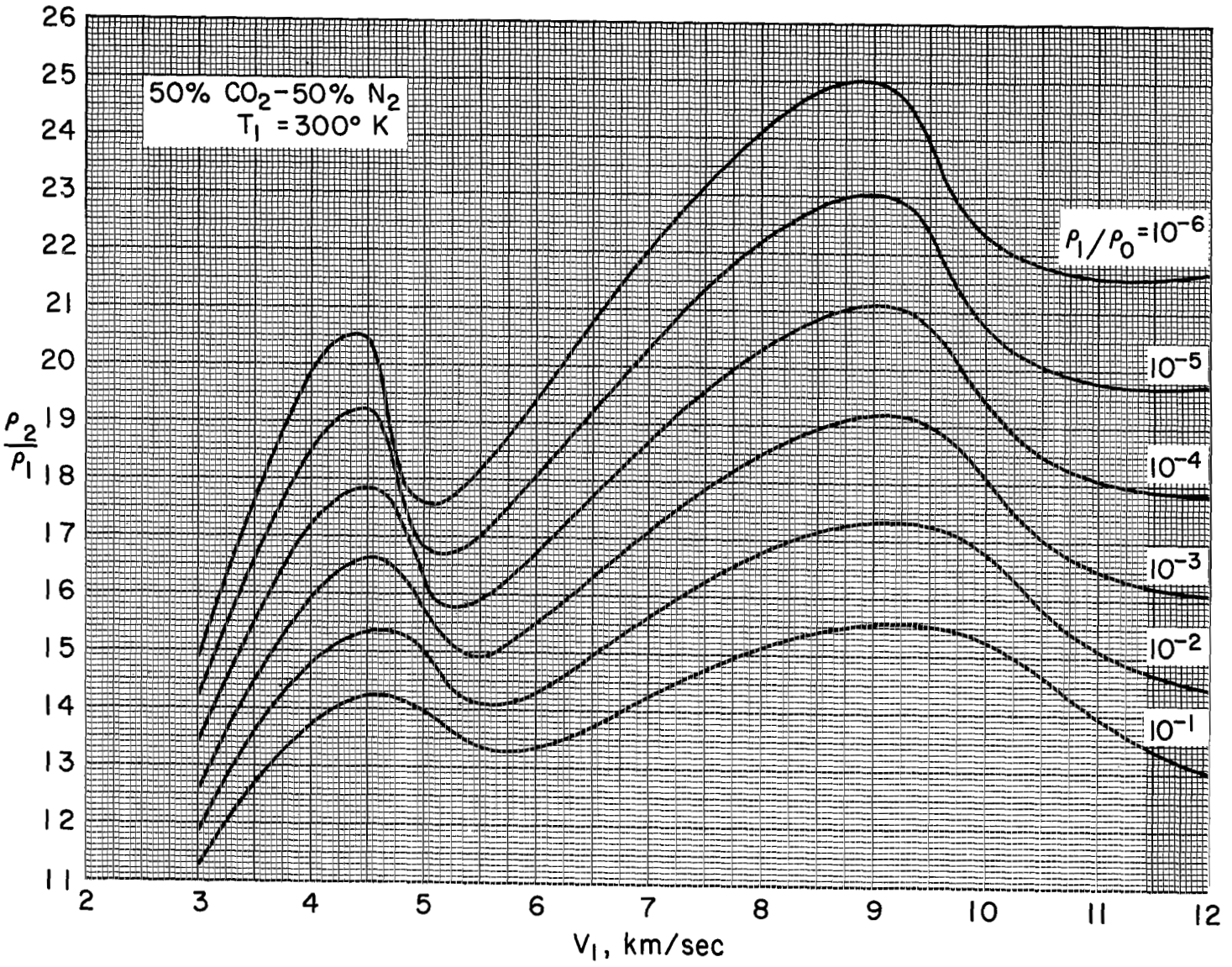
T_2, °K / Band system	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000	Spectral range, μ
CN(V)	3.60 -16	2.07 -15	6.36 -15	1.36 -14	2.35 -14	3.50 -14	4.75 -14	6.00 -14	7.23 -14	0.3473 -0.4600
CN(R)	2.27 -15	4.16 -15	6.03 -15	7.70 -15	9.08 -15	1.02 -14	1.10 -14	1.17 -14	1.21 -14	.4331 -1.6111
CO(4+)	4.68 -20	4.88 -18	1.06 -16	9.44 -16	4.80 -15	1.67 -14	4.46 -14	9.84 -14	1.86 -13	.1161 -.2913
C_2(S)	2.03 -15	7.68 -15	1.80 -14	3.23 -14	4.89 -14	6.63 -14	8.32 -14	9.86 -14	1.12 -13	.4258 -.6670
NO(β)	6.70 -20	1.70 -18	1.45 -17	6.55 -17	2.00 -16	4.71 -16	9.20 -16	1.57 -15	2.42 -15	.1588 -.6631
NO(γ)	2.01 -19	4.80 -18	3.96 -17	1.78 -16	5.48 -16	1.31 -15	2.61 -15	4.57 -15	7.24 -15	.1414 -.3451
N_2(1+)	9.51 -23	8.57 -21	1.77 -19	1.55 -18	7.93 -18	2.79 -17	7.87 -17	1.83 -16	3.69 -16	.4642 -1.2463
N_2(2+)	1.50 -24	9.30 -22	6.65 -20	1.39 -18	1.35 -17	7.76 -17	3.11 -16	9.63 -16	2.43 -15	.2583 -.5452
N_2^+(1-)	9.10 -16	5.26 -15	1.62 -14	3.47 -14	5.99 -14	8.96 -14	1.22 -13	1.54 -13	1.86 -13	.2971 -.5860
O_2(S-R)	1.71 -18	5.21 -17	4.81 -16	2.25 -15	6.91 -15	1.60 -14	3.06 -14	5.06 -14	7.54 -14	.1759 -.4668

Note: A group of digits followed by -n indicates that the decimal point should be n places to the left of the first digit.



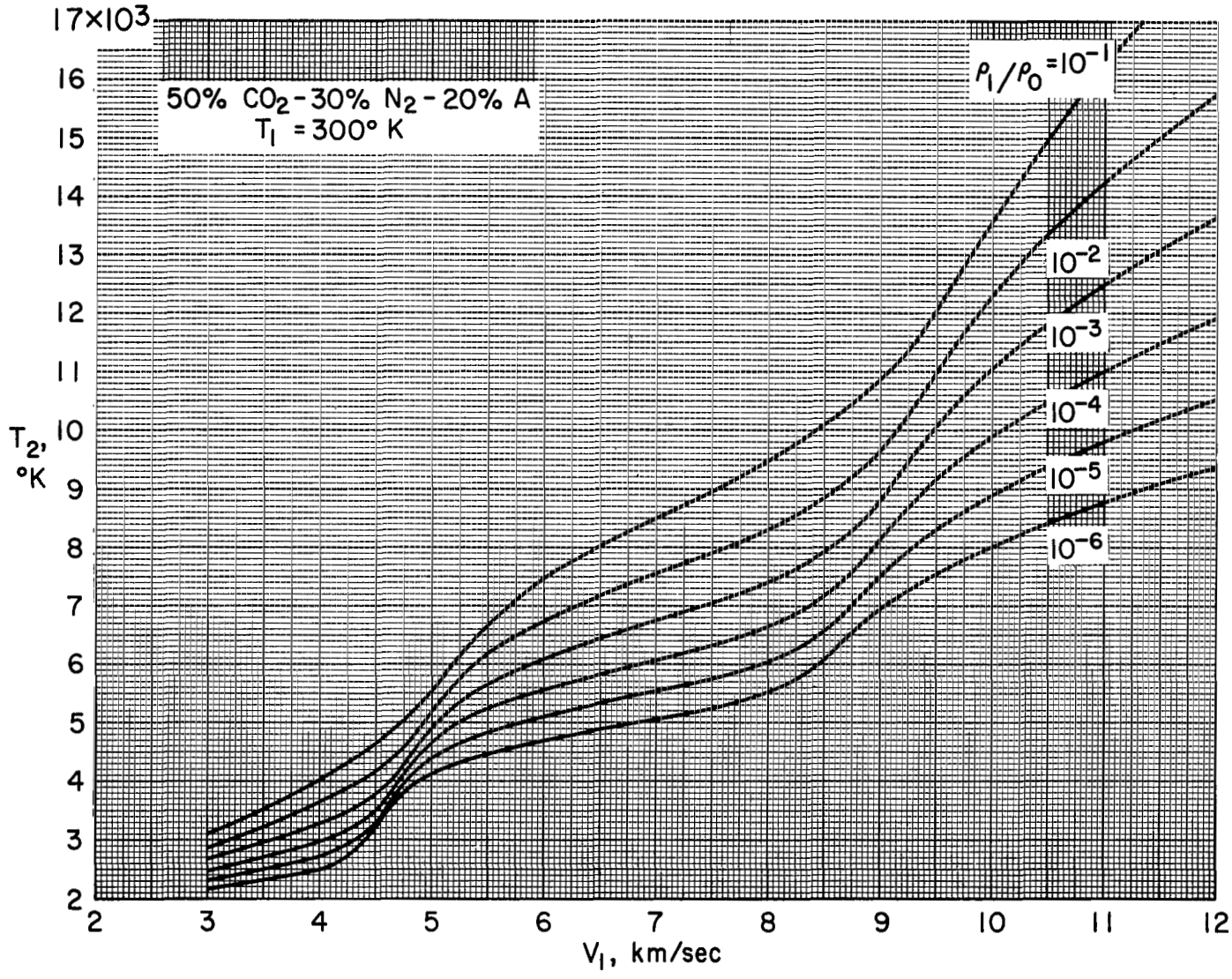
(a) Temperature.

Figure 1.- Equilibrium gas properties behind normal shock waves in 0.5 CO_2-0.5 N_2 mixture; $T_1 = 300^{\circ}$ K.



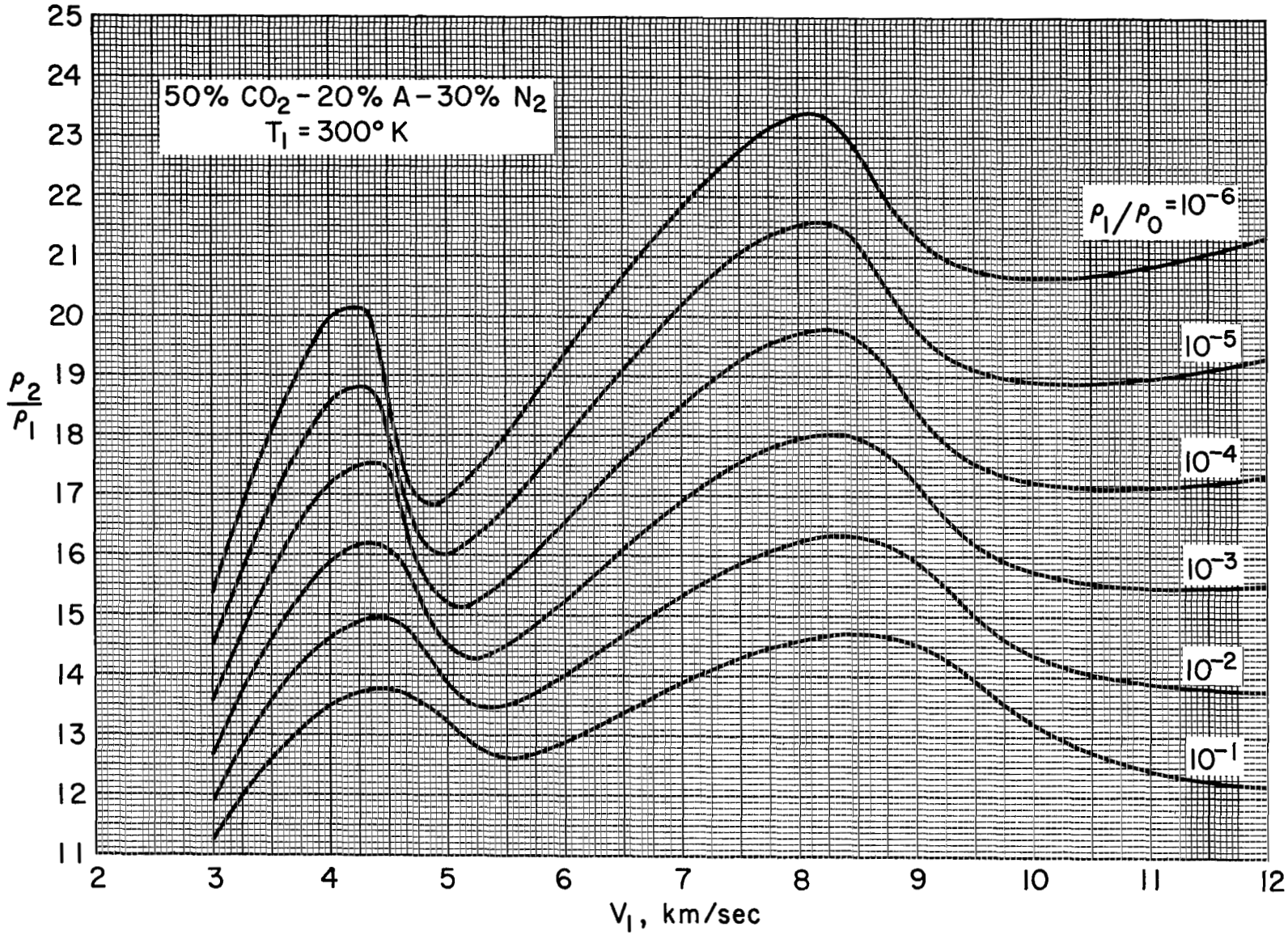
(b) Density ratio across normal shock.

Figure 1.- Concluded.



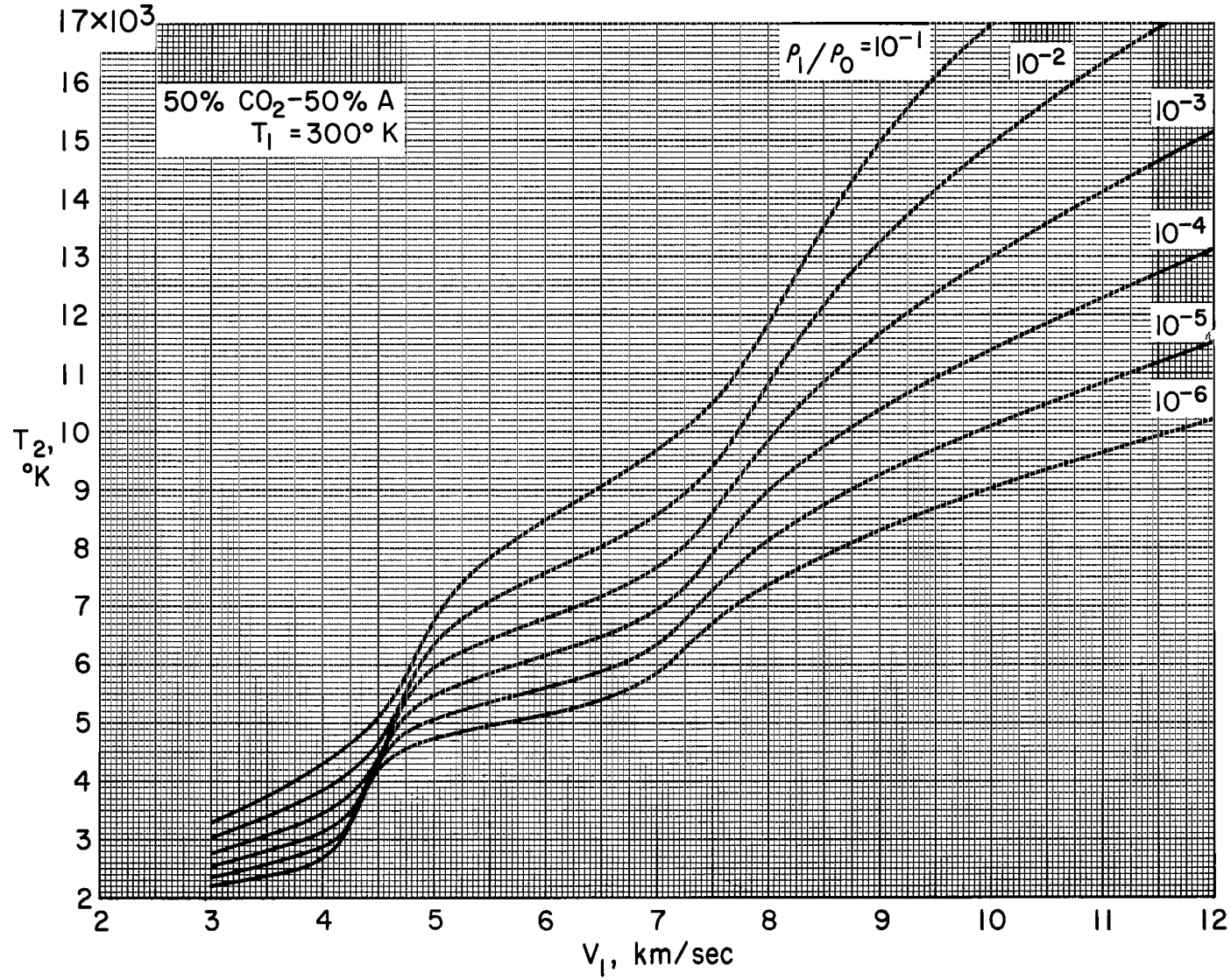
(a) Temperature.

Figure 2.- Equilibrium gas properties behind normal shock waves in 0.5 CO_2-0.3 N_2-0.2 A mixture; T_1 = 300° K.



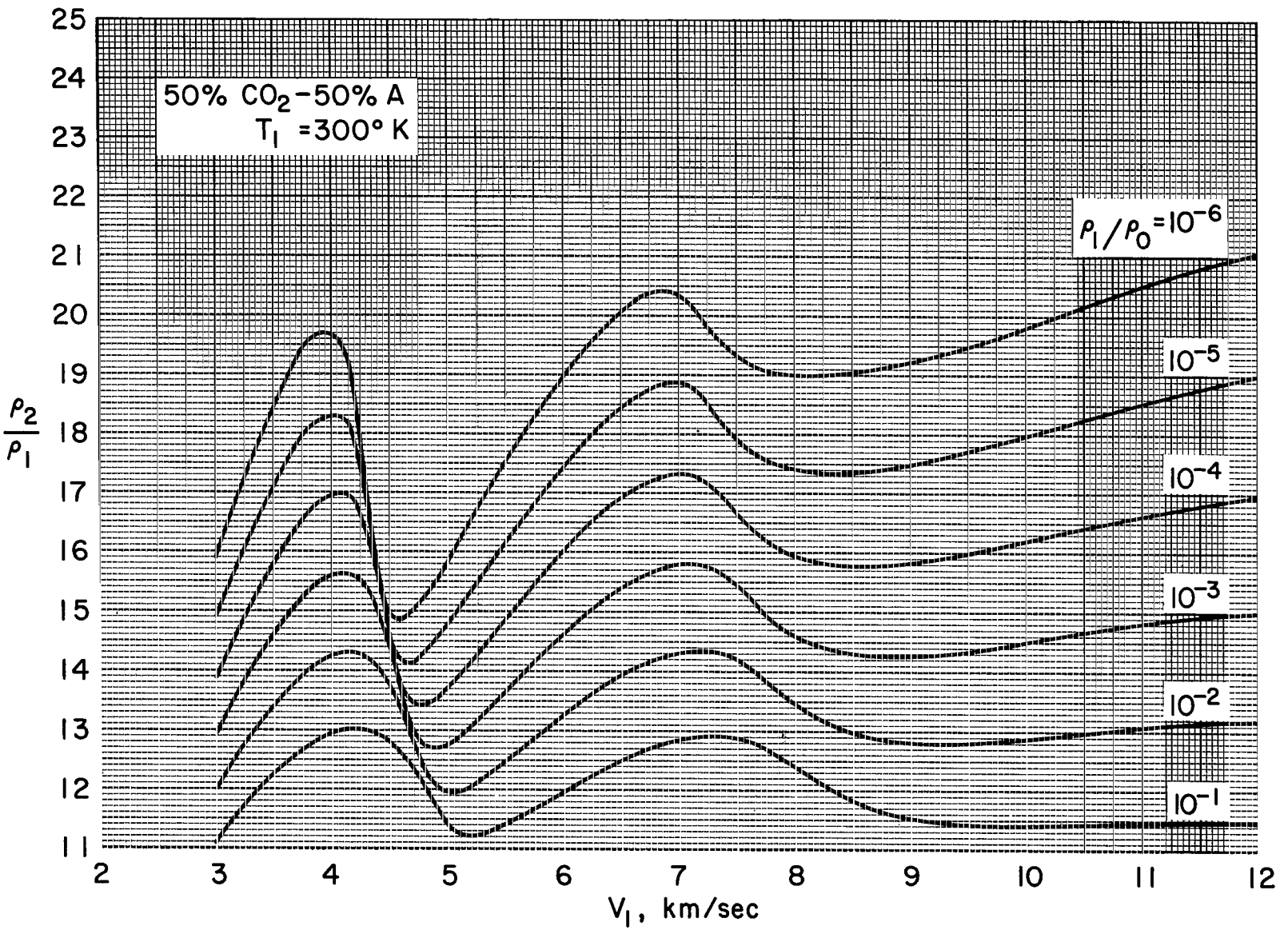
(b) Density ratio across normal shock.

Figure 2.- Concluded.



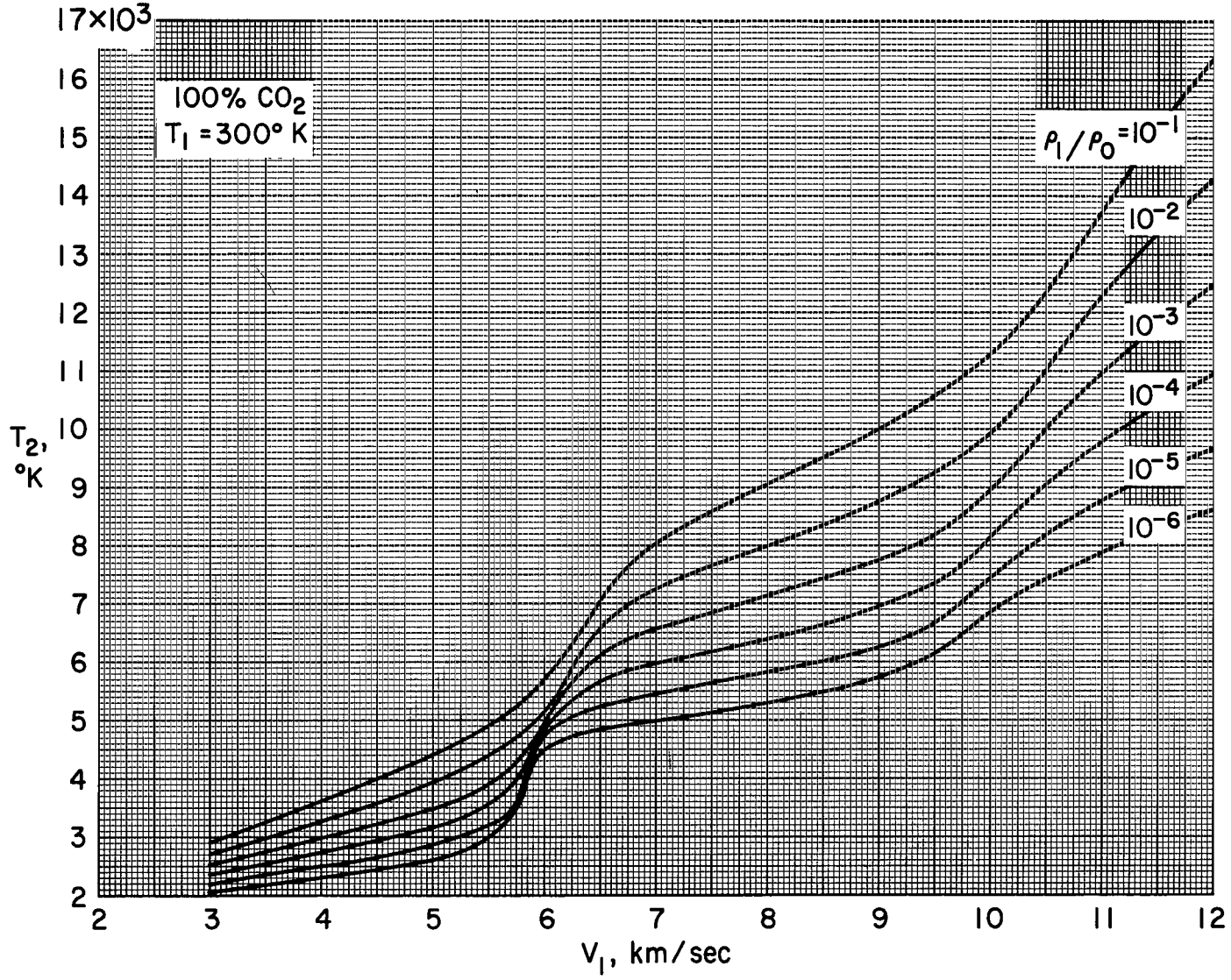
(a) Temperature.

Figure 3.- Equilibrium gas properties behind normal shock waves in 0.5 CO_2-0.5 A mixture; T_1 = 300° K.



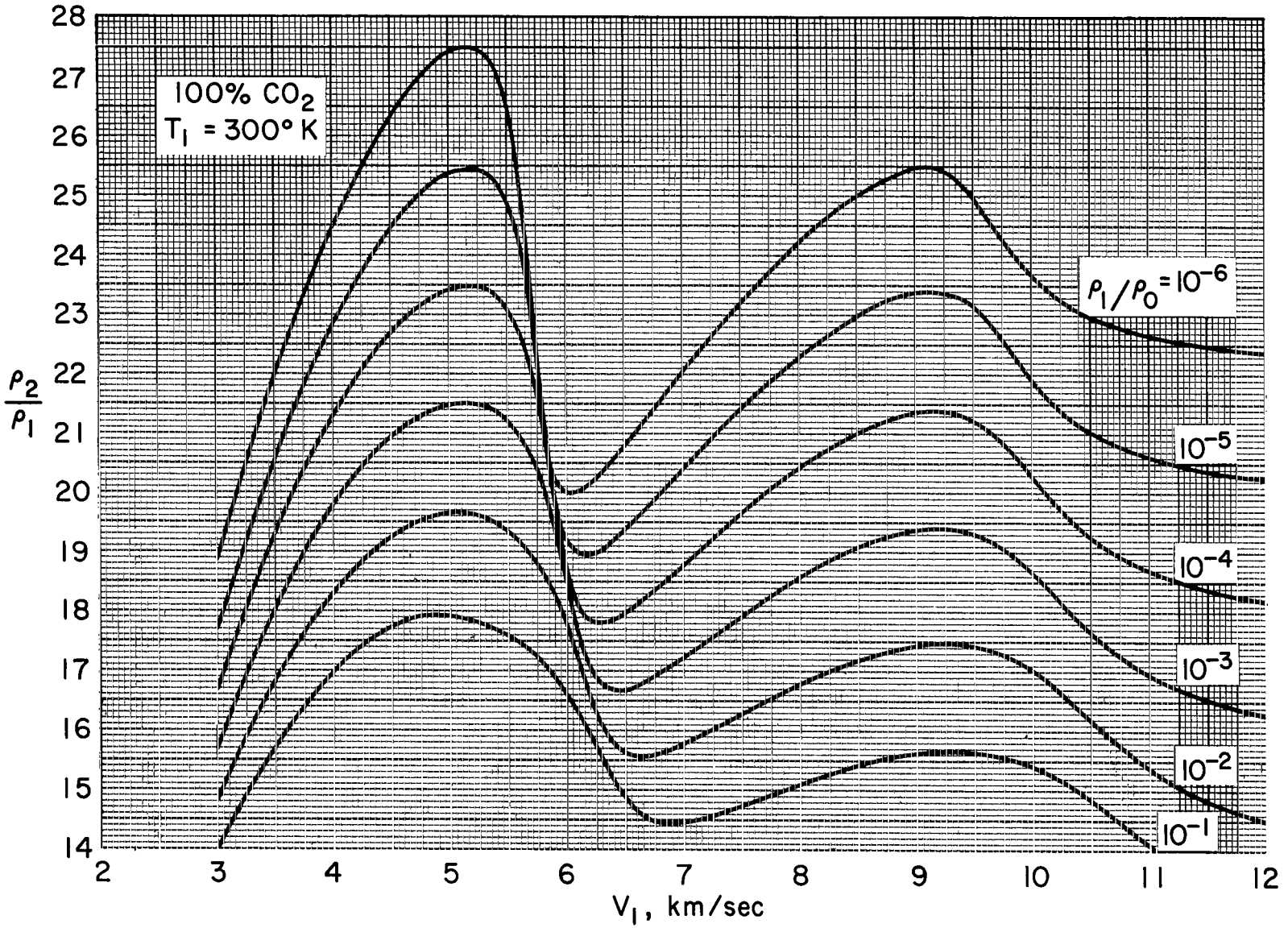
(b) Density ratio across normal shock.

Figure 3.- Concluded.



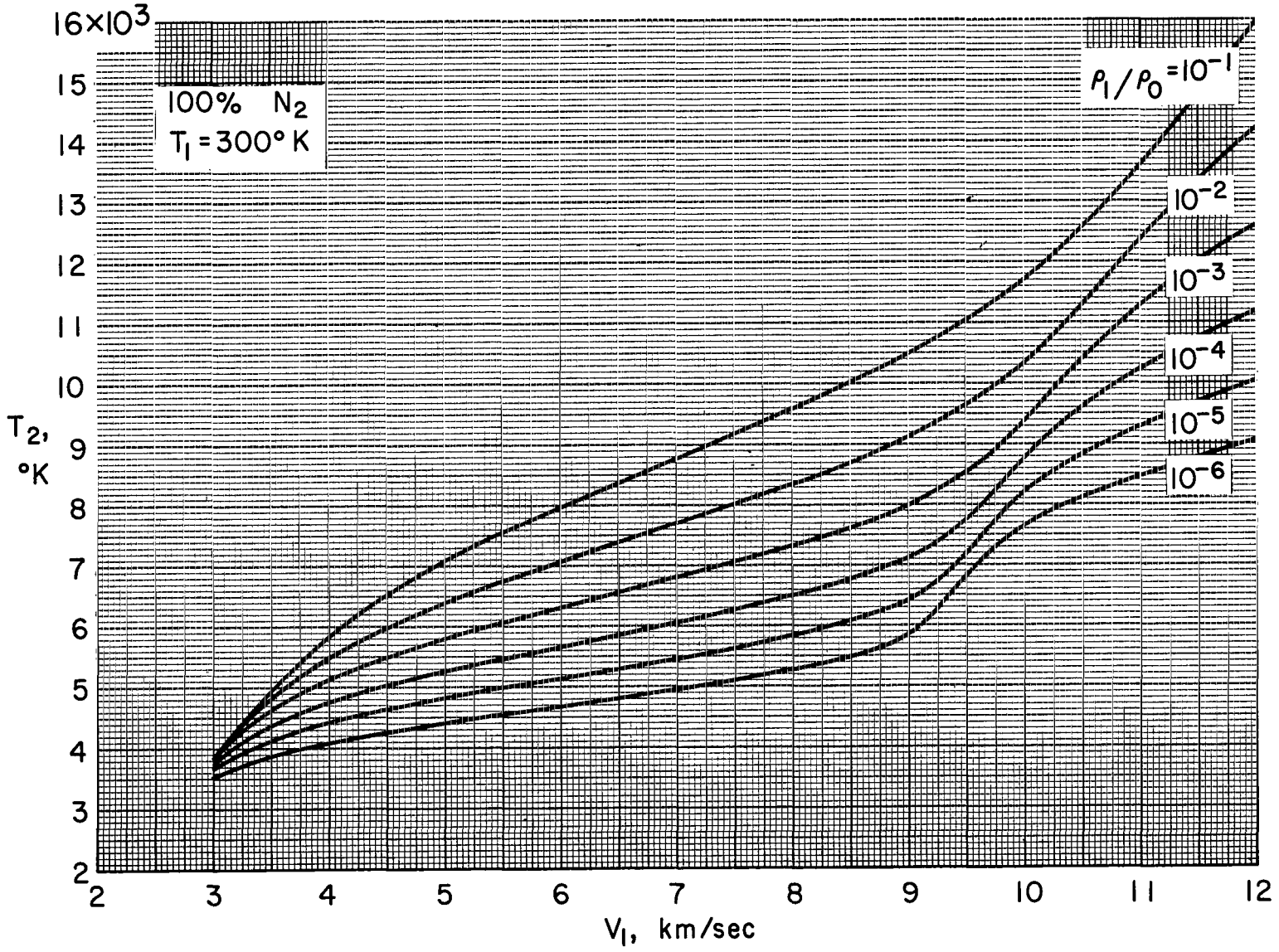
(a) Temperature.

Figure 4.- Equilibrium gas properties behind normal shock waves in 1.0 CO_2; T_1 = 300° K.



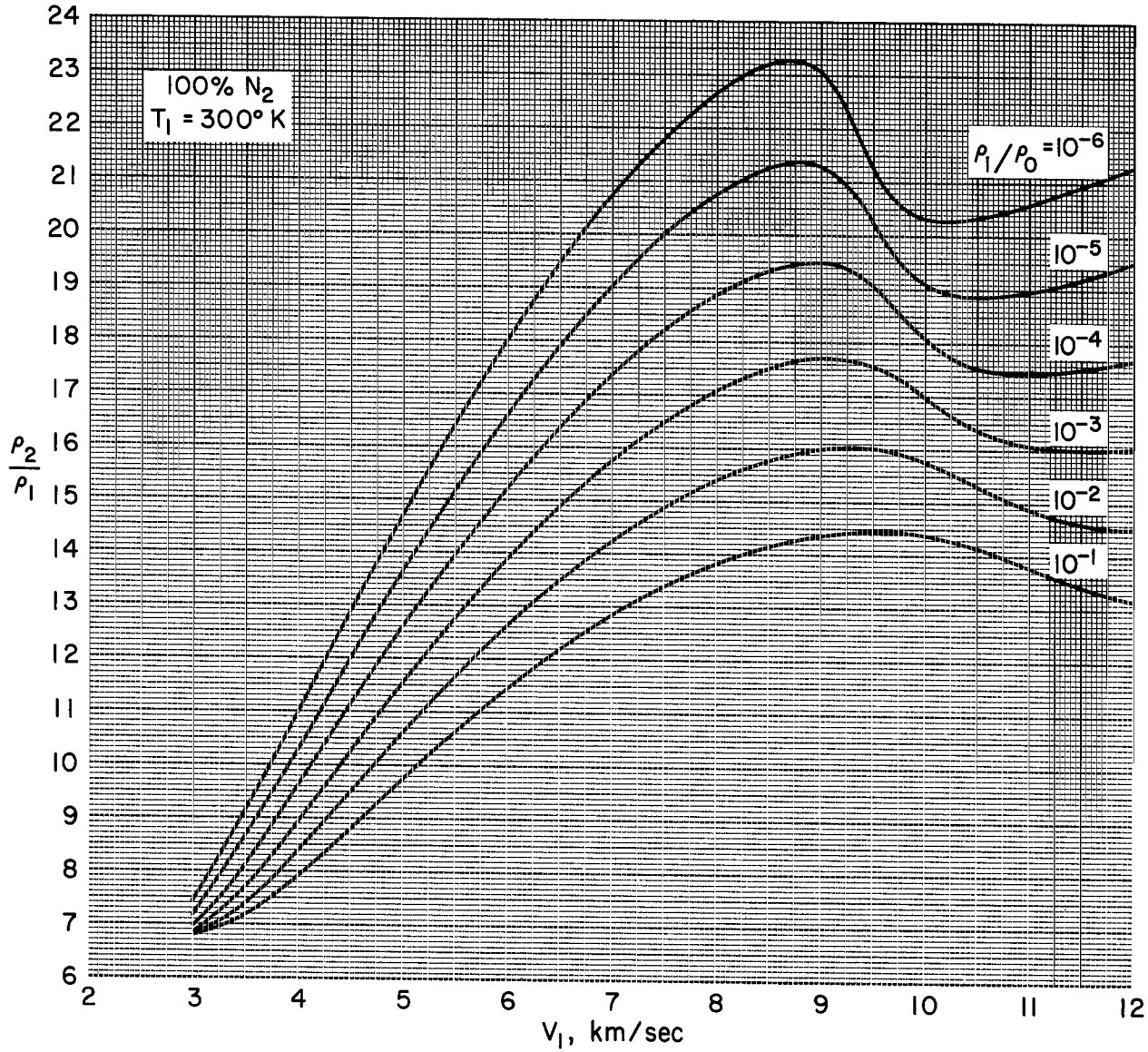
(b) Density ratio across normal shock.

Figure 4.- Concluded.



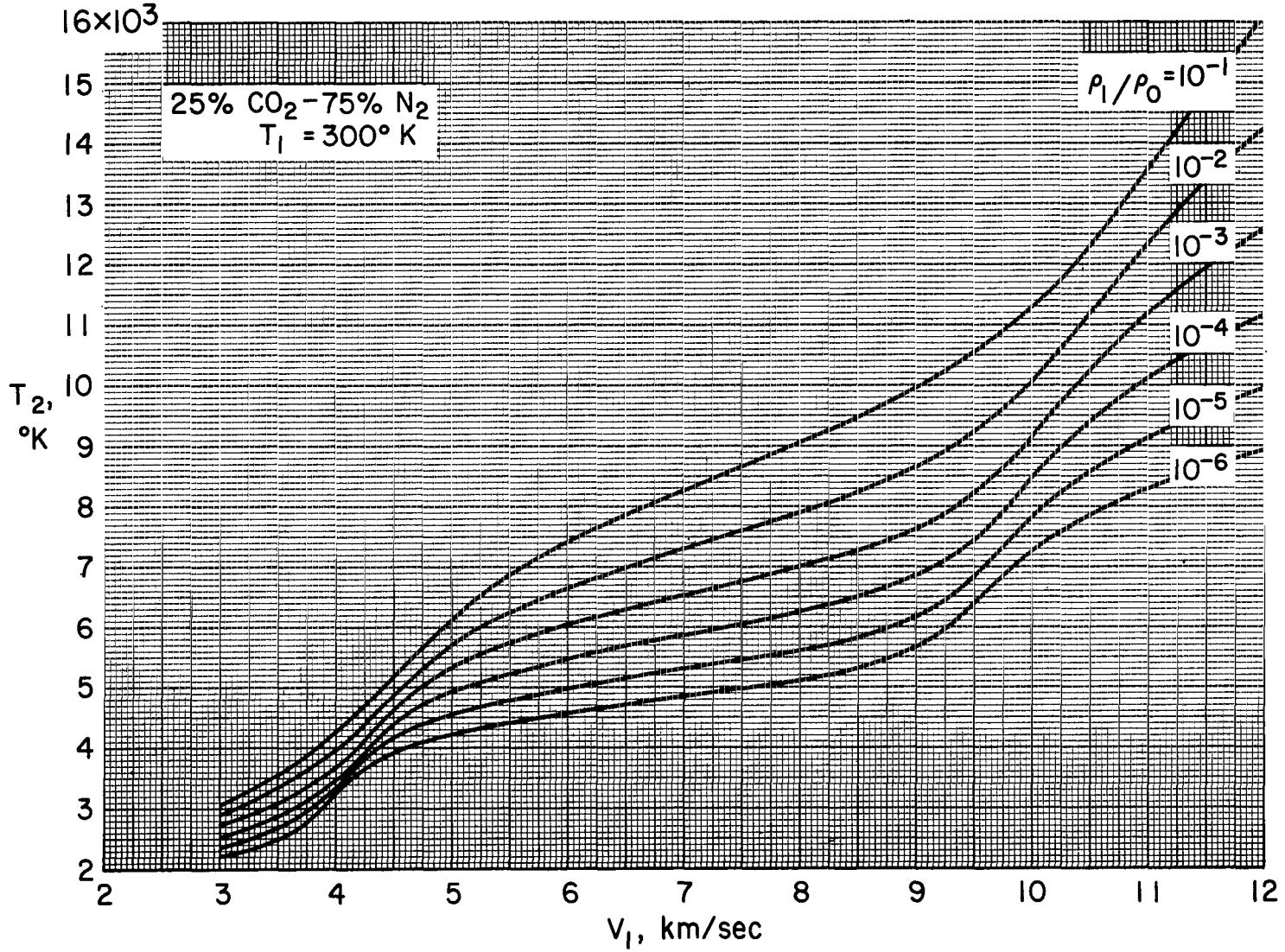
(a) Temperature.

Figure 5.- Equilibrium gas properties behind normal shock waves in 1.0 N_2; T_1 = 300° K.



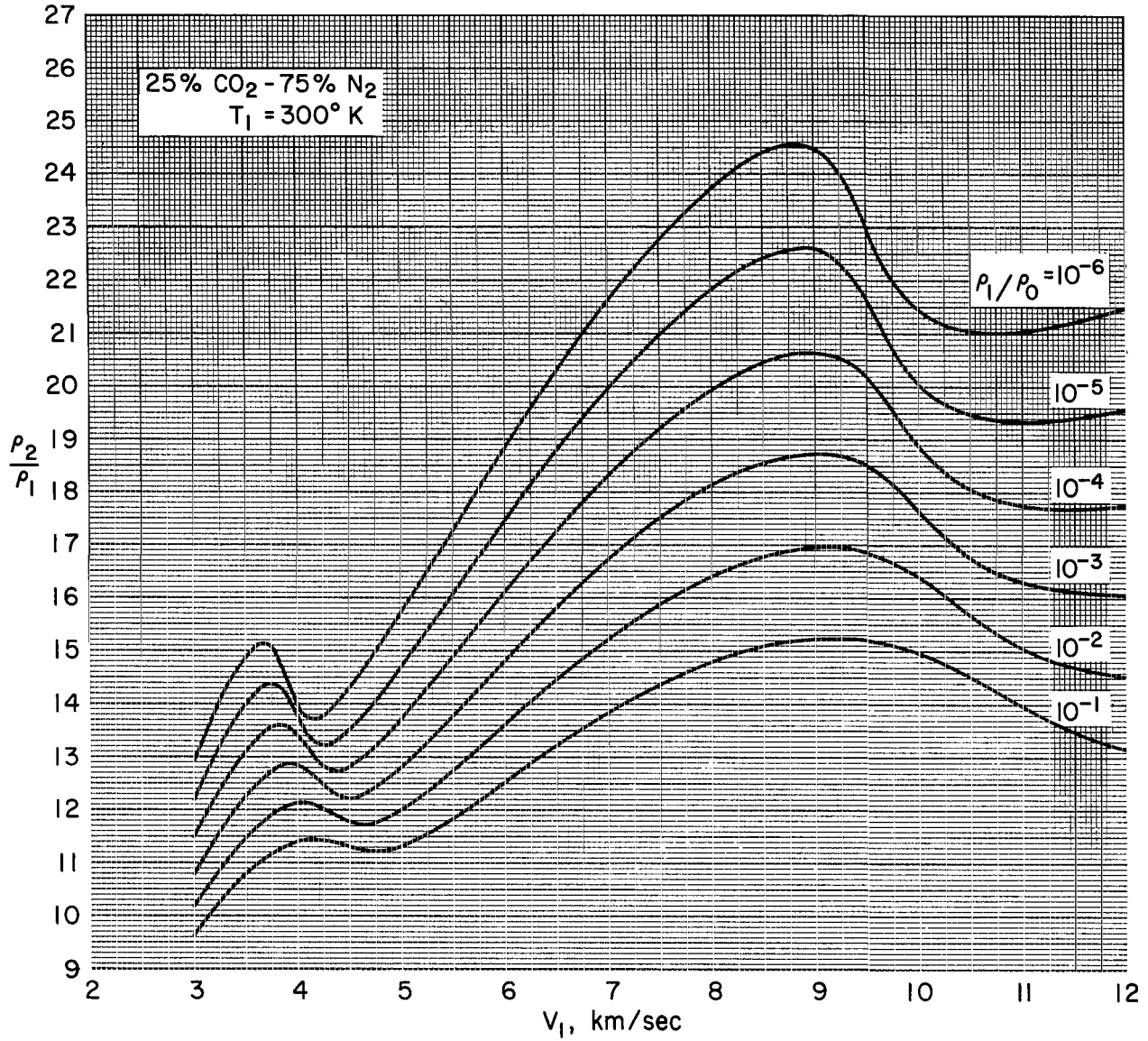
(b) Density ratio across normal shock.

Figure 5.- Concluded.



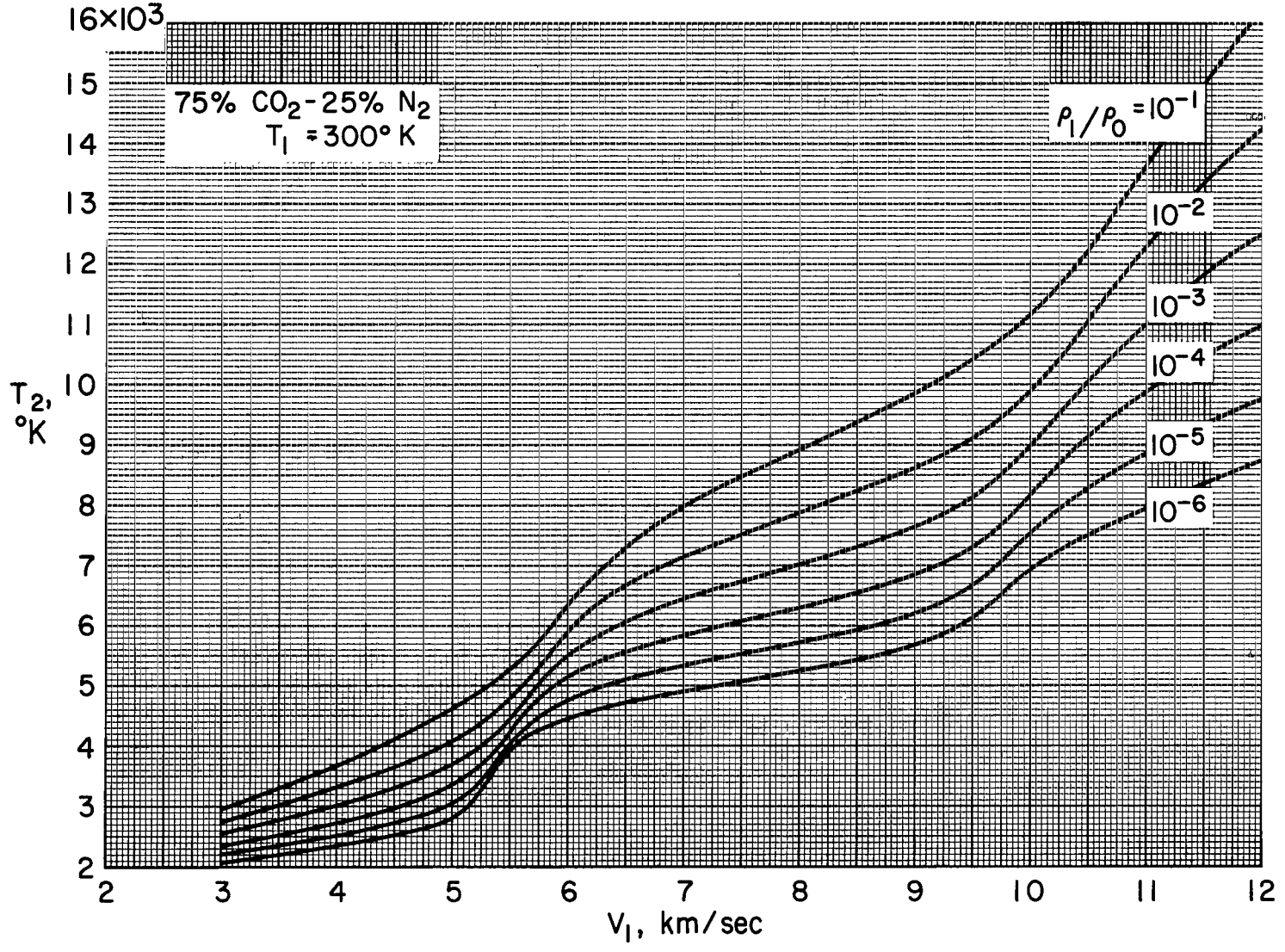
(a) Temperature.

Figure 6.- Equilibrium gas properties behind normal shock waves in 0.25 CO_2-0.75 N_2 mixture; $T_1 = 300^\circ$ K.



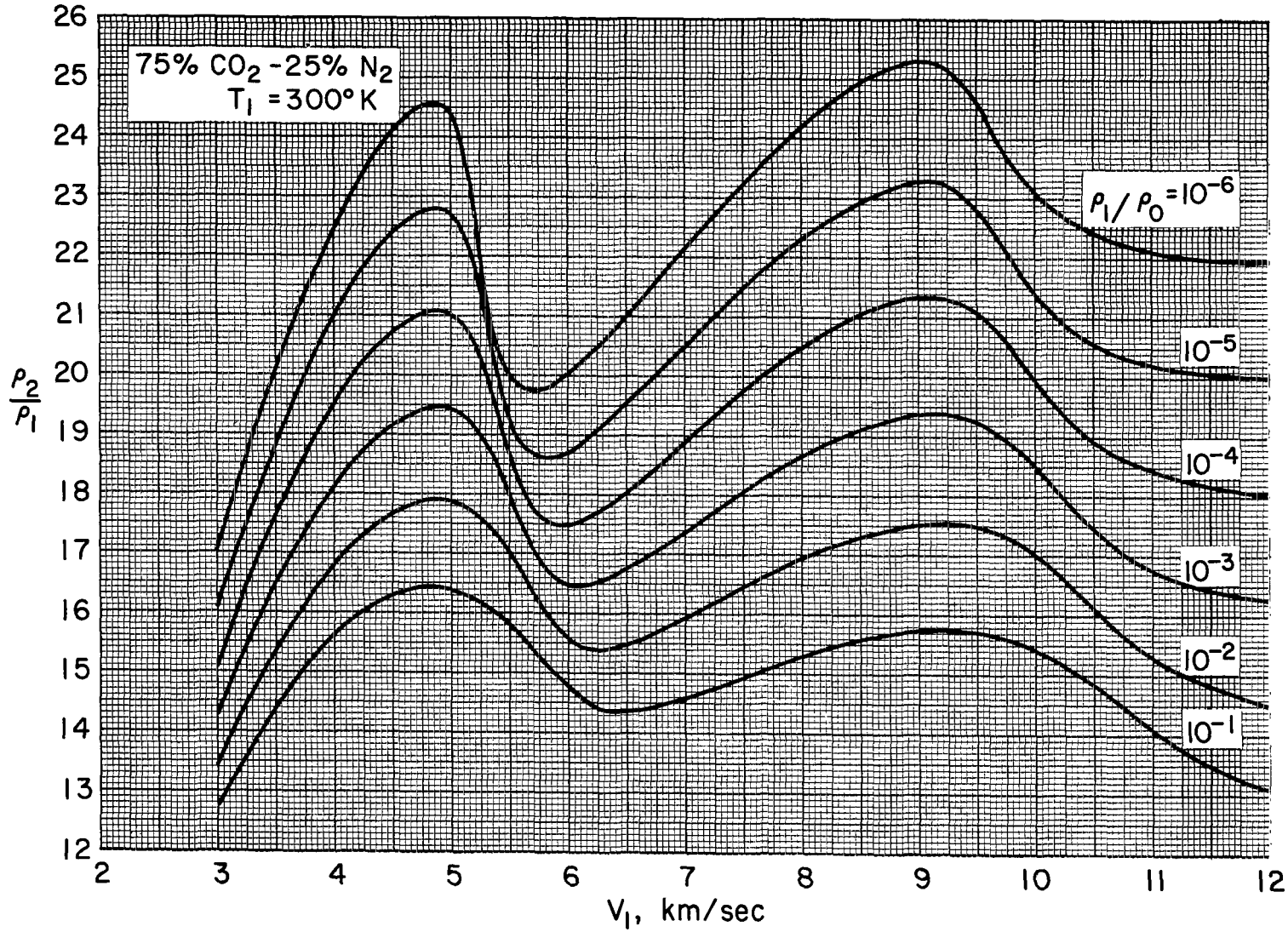
(b) Density ratio across normal shock.

Figure 6.- Concluded.



(a) Temperature.

Figure 7.- Equilibrium gas properties behind normal shock waves in 0.75 CO_2-0.25 N_2 mixture; T_1 = 300° K.



(b) Density ratio across normal shock.

Figure 7.- Concluded.

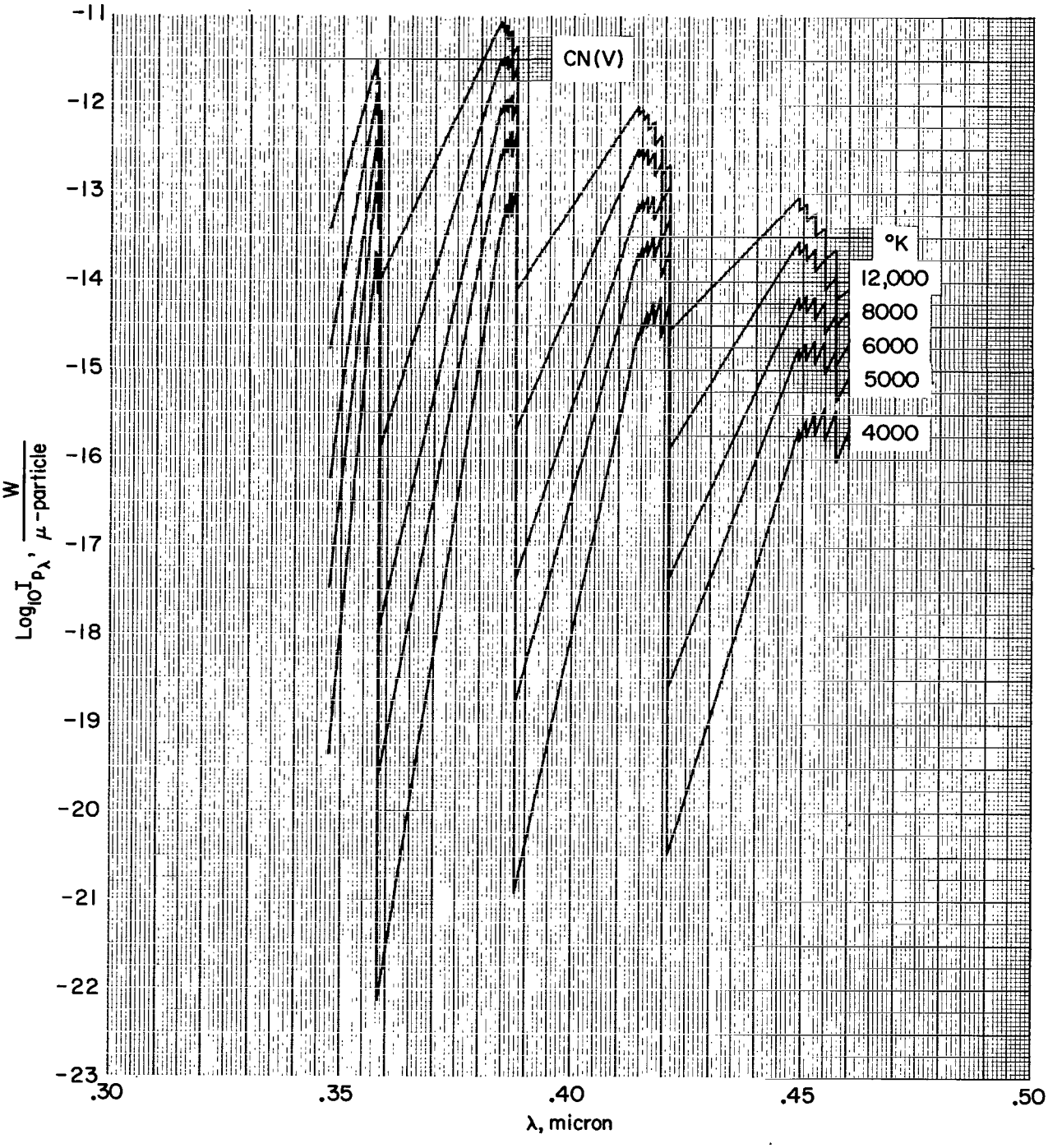


Figure 8.- Spectral intensity per particle for CN(V) band system.

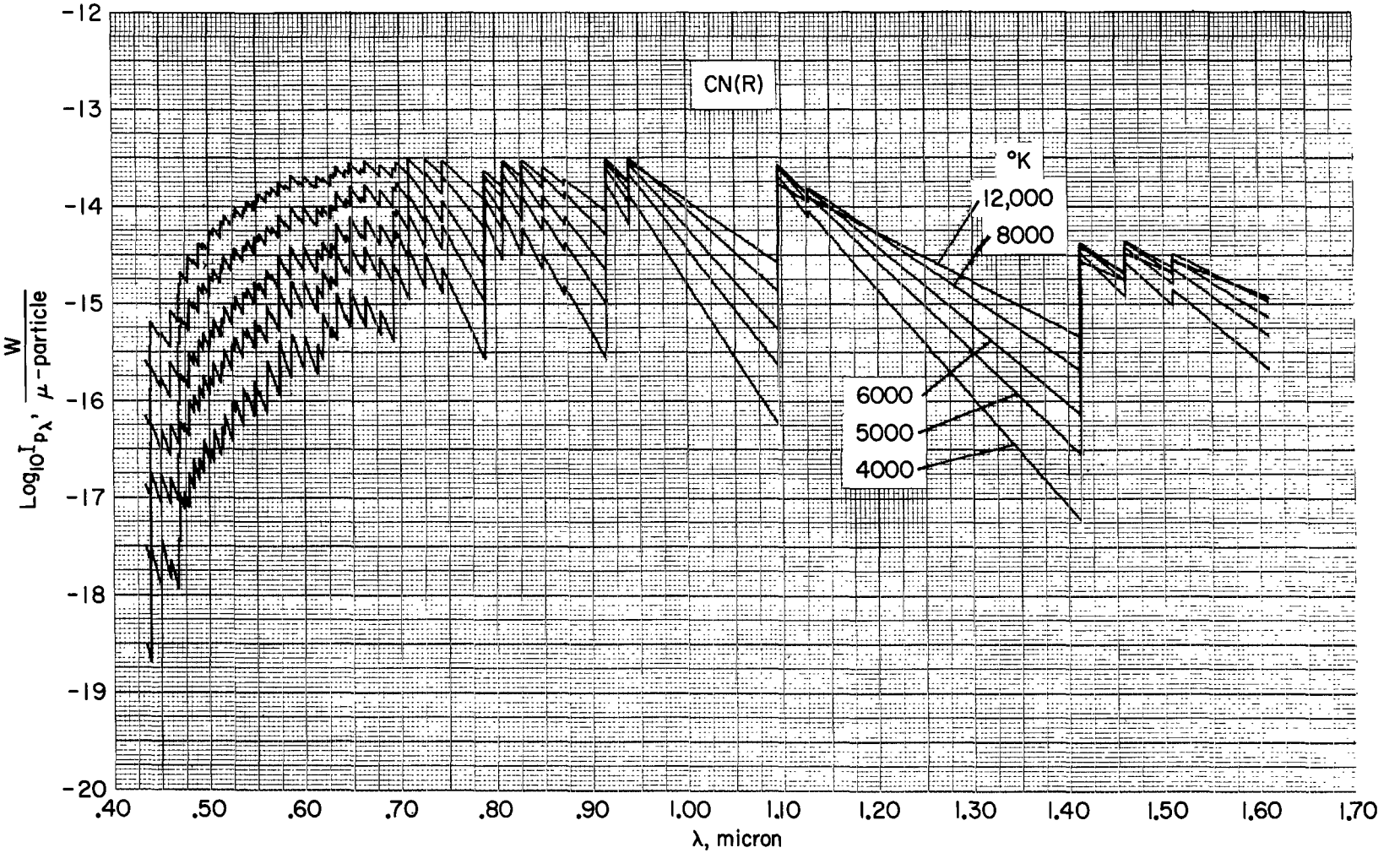


Figure 9.- Spectral intensity per particle for CN(R) band system.

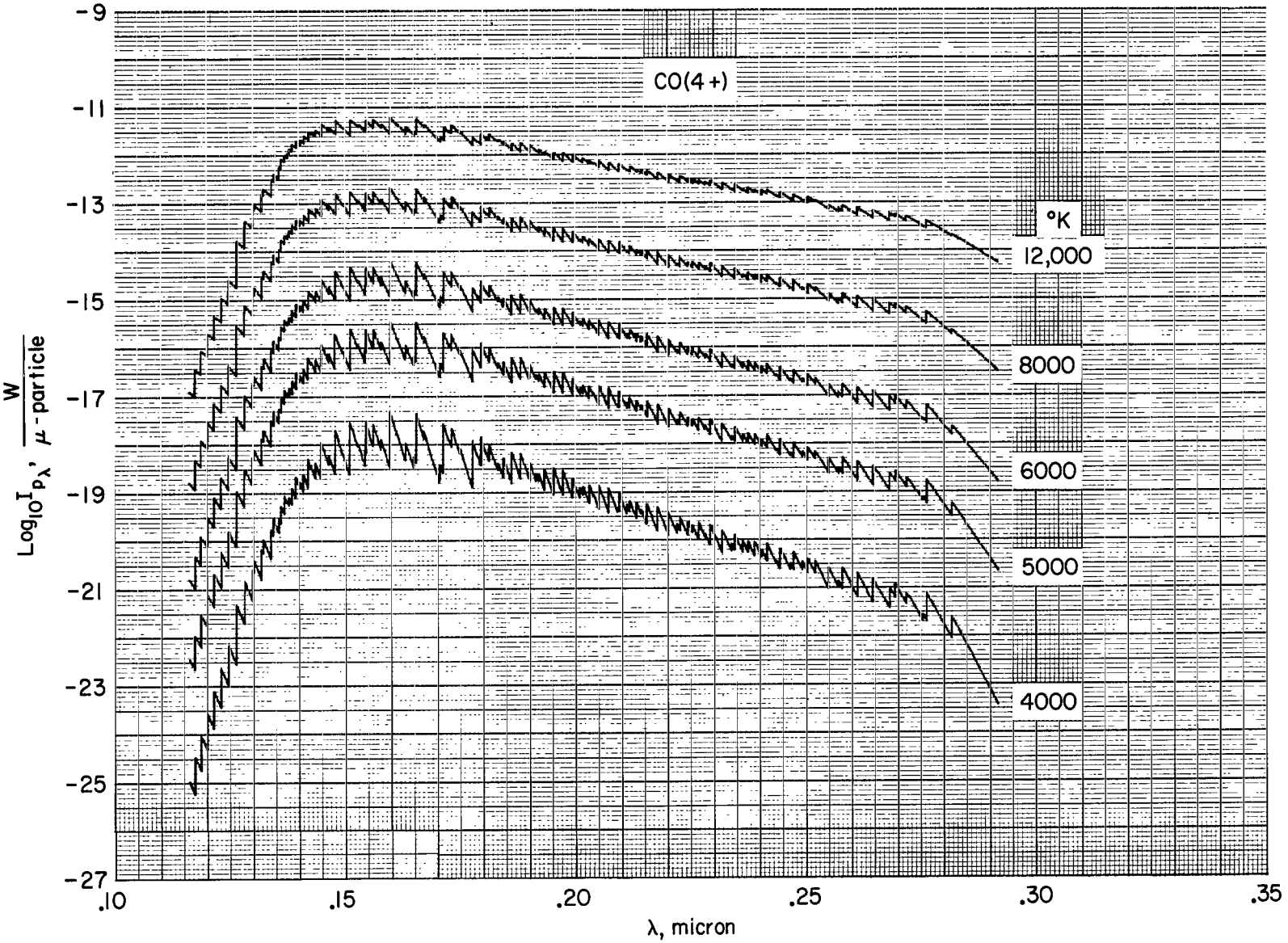


Figure 10.- Spectral intensity per particle for CO(4+) band system.

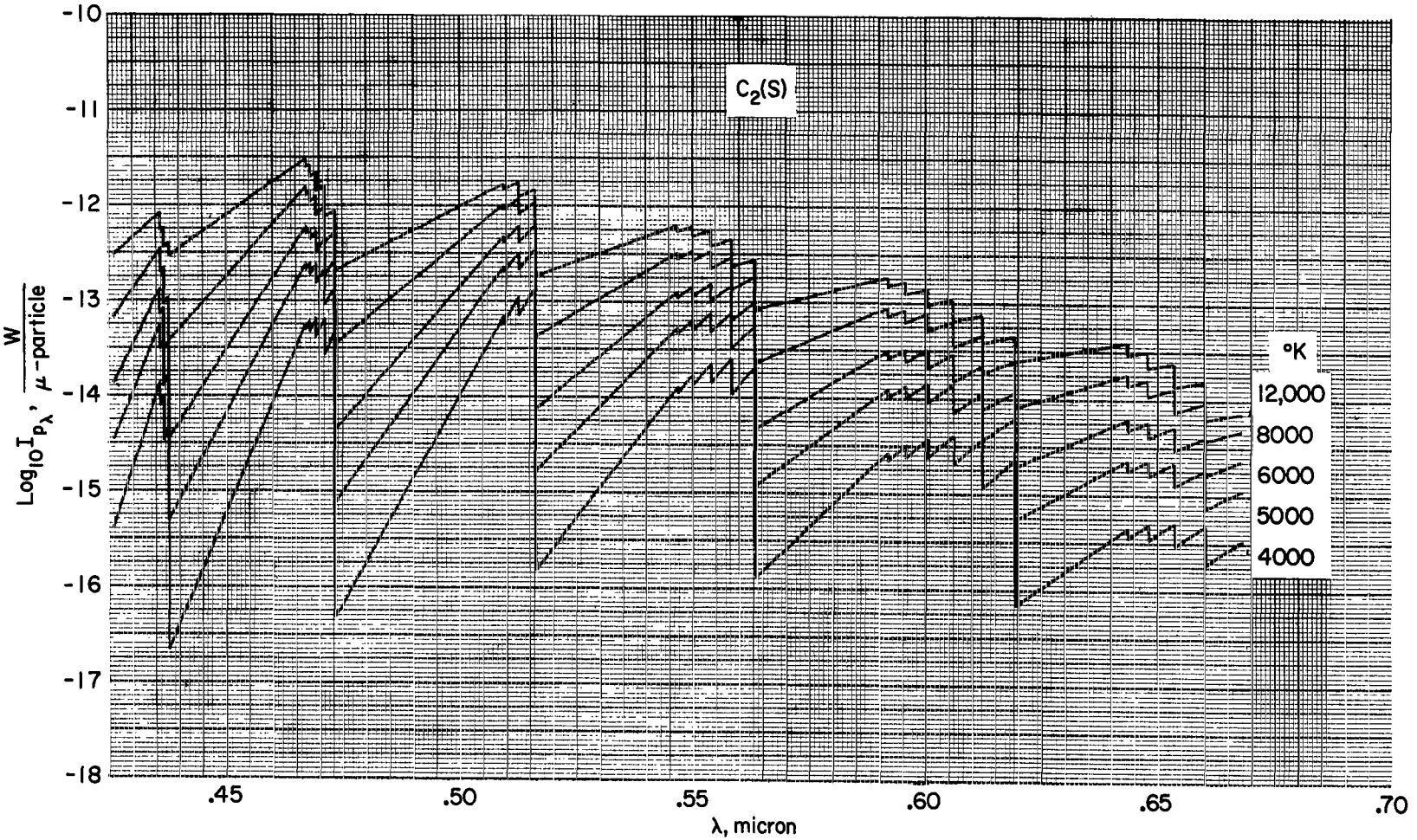


Figure 11.- Spectral intensity per particle for $C_2(S)$ band system.

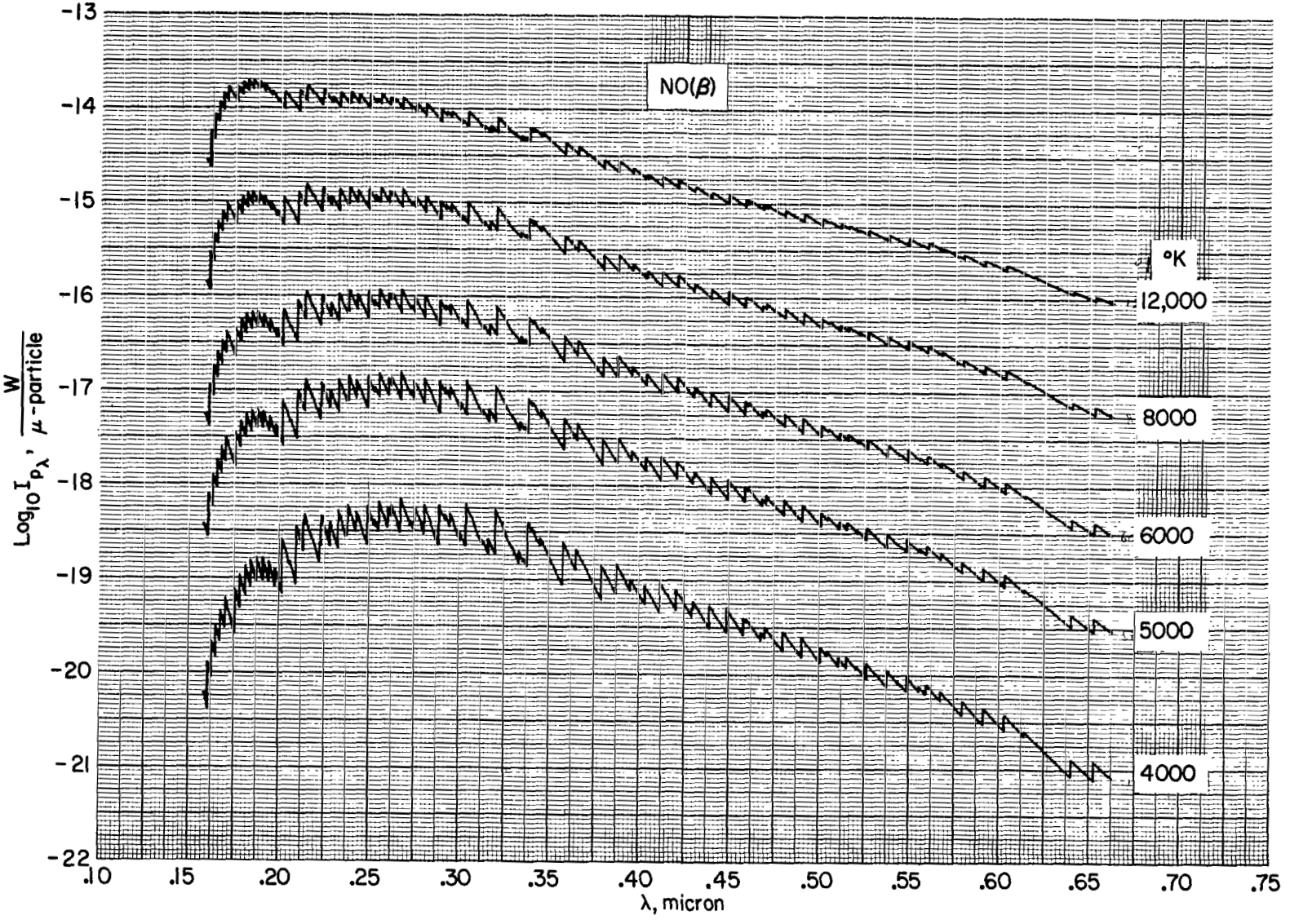


Figure 12.- Spectral intensity per particle for NO(β) band system.

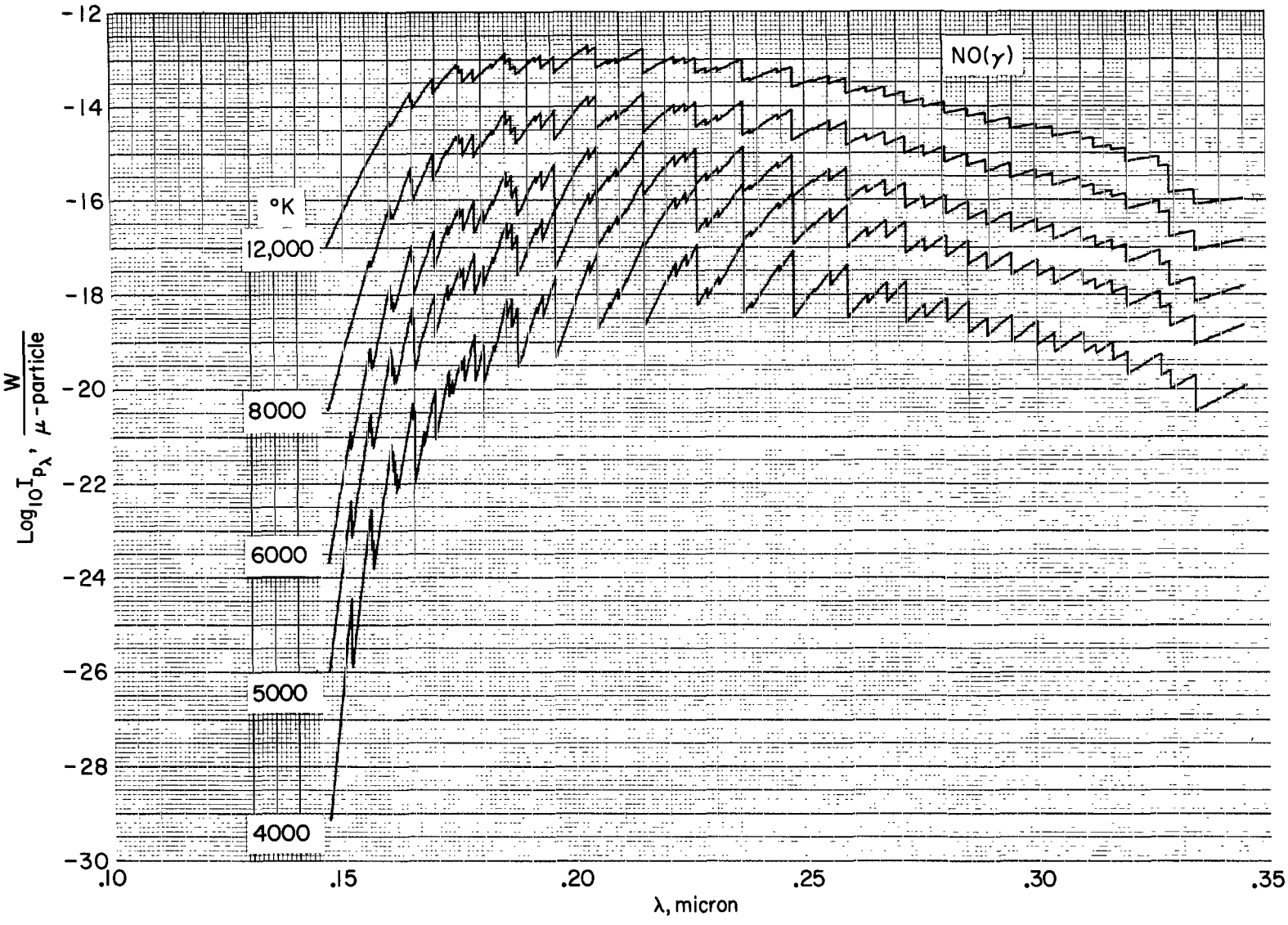


Figure 13.- Spectral intensity per particle for NO(γ) band system.

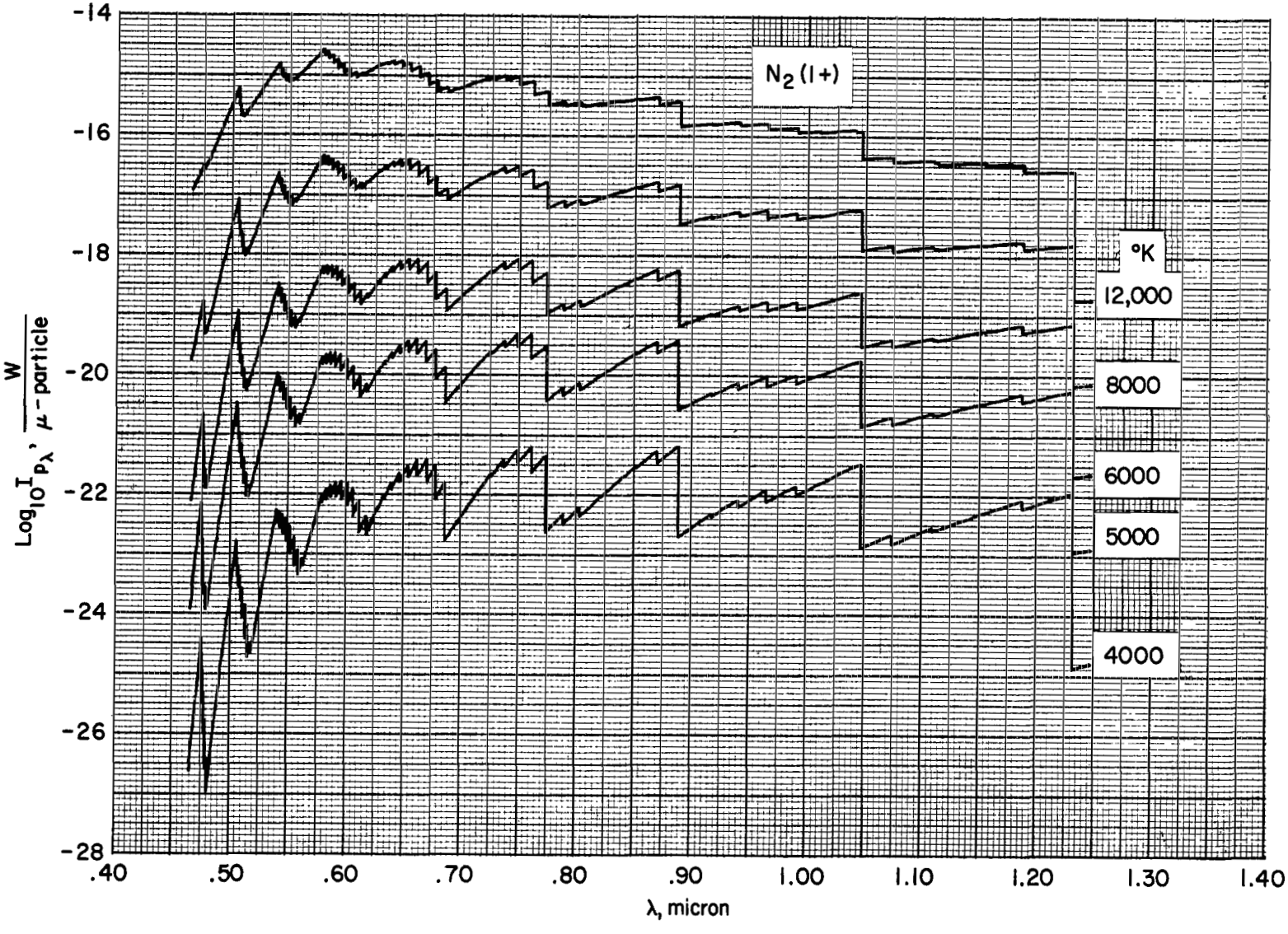


Figure 14.- Spectral intensity per particle for N_2(1+) band system.

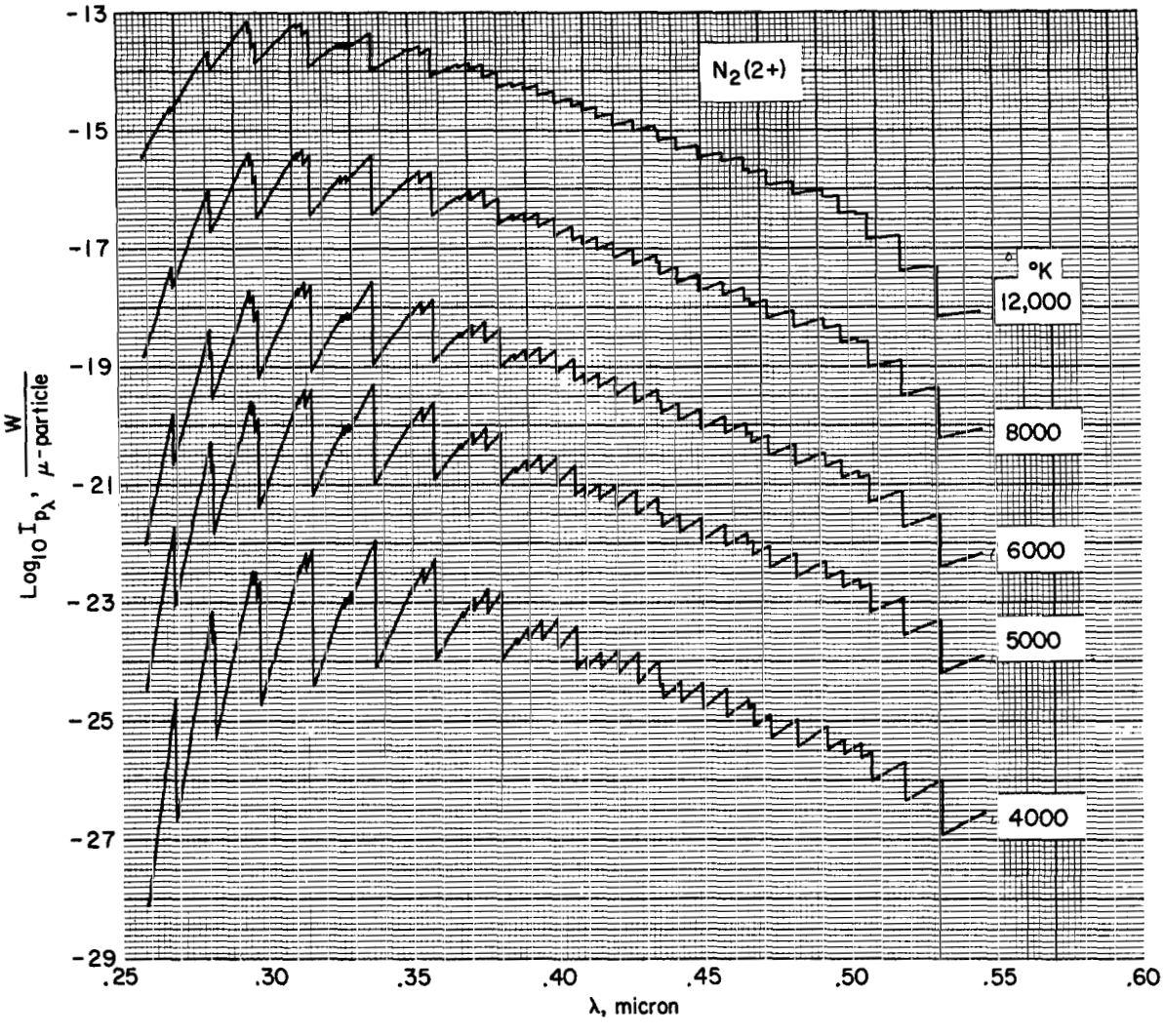


Figure 15.- Spectral intensity per particle for $N_2(2+)$ band system.

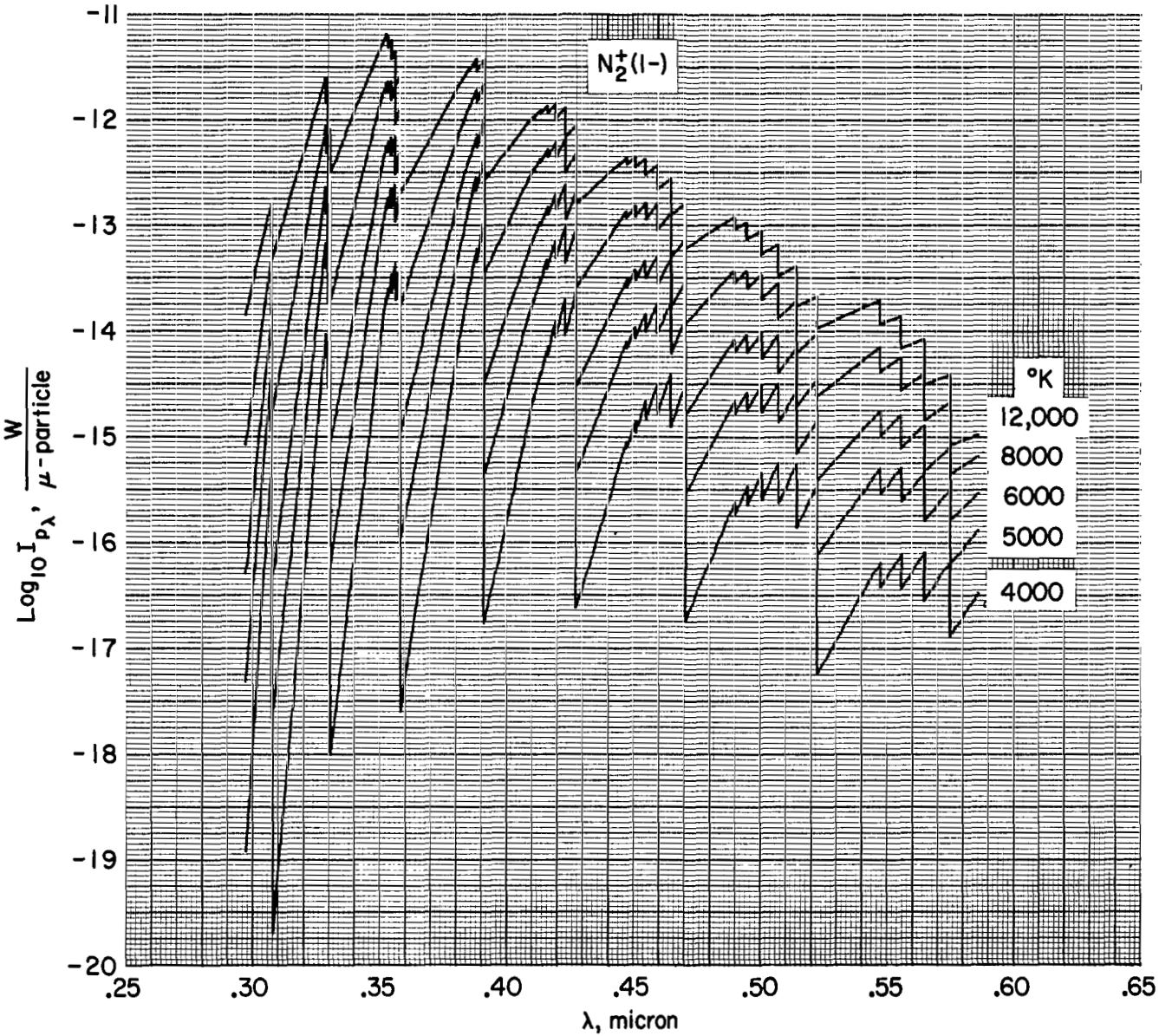


Figure 16.- Spectral intensity per particle for $N_2^+(1-)$ band system.

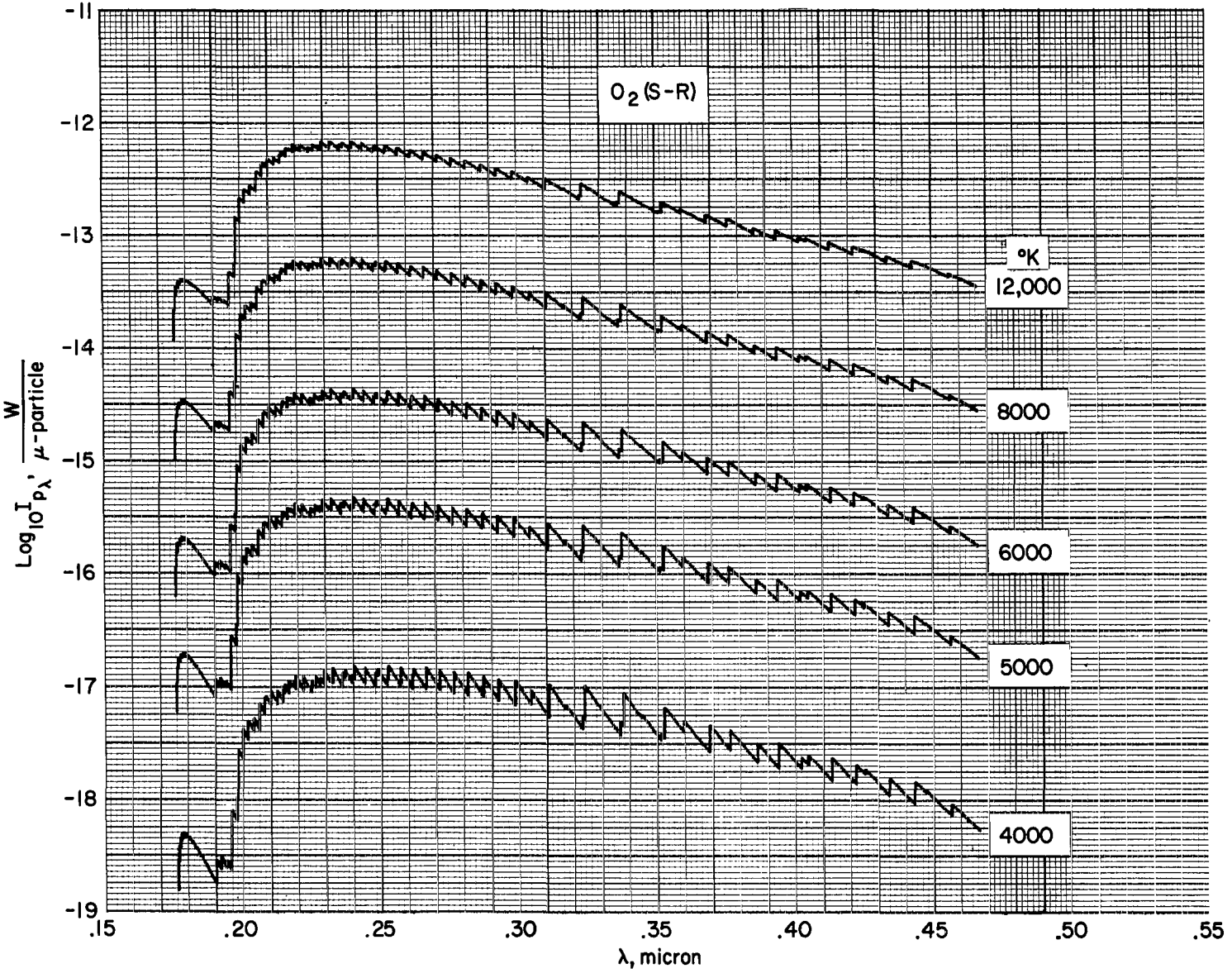


Figure 17.- Spectral intensity per particle for O_2(S-R) band system.

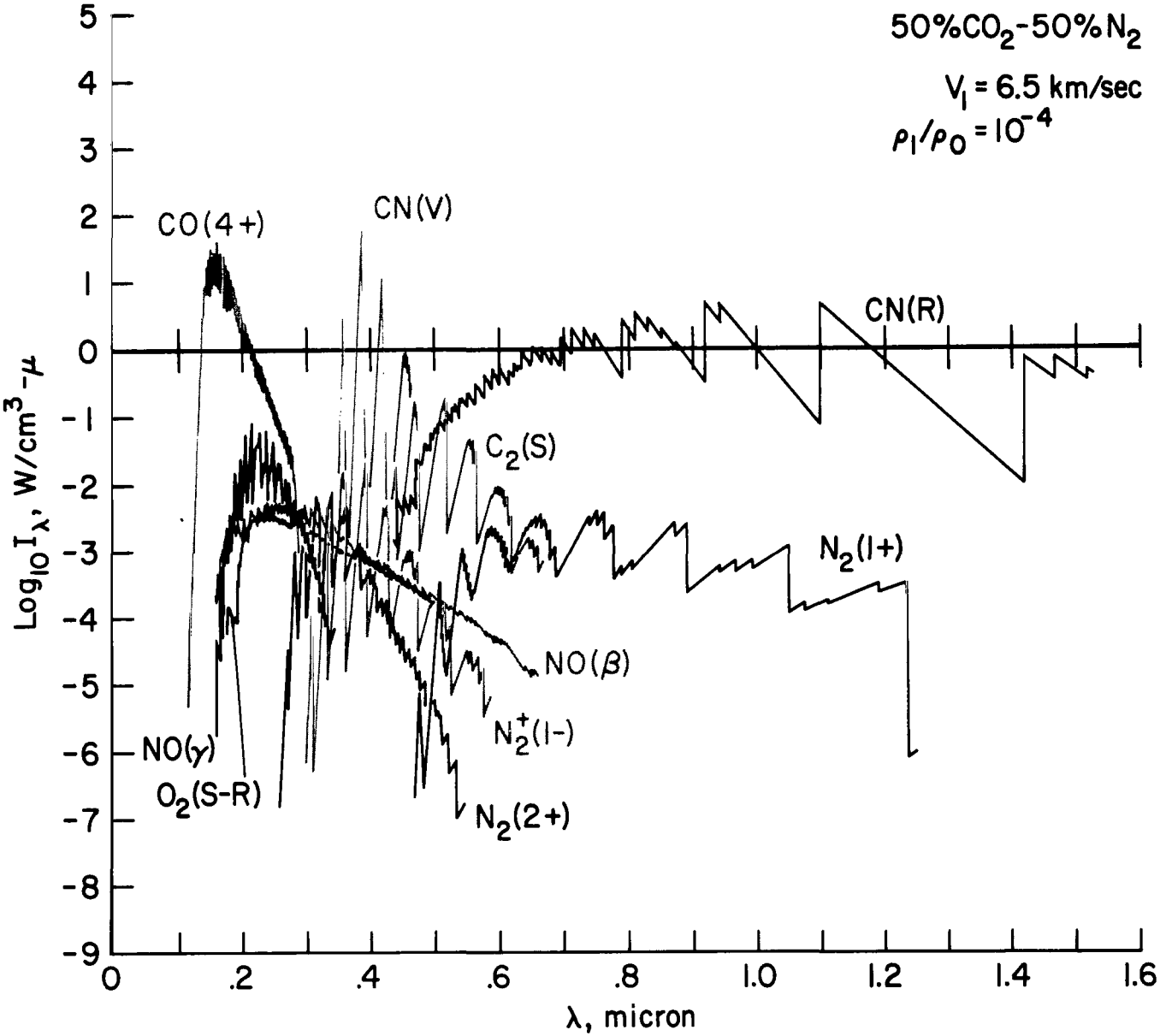


Figure 18.- Spectral intensity at $V_1 = 6.5$ km/sec and $\rho_1/\rho_0 = 10^{-4}$.

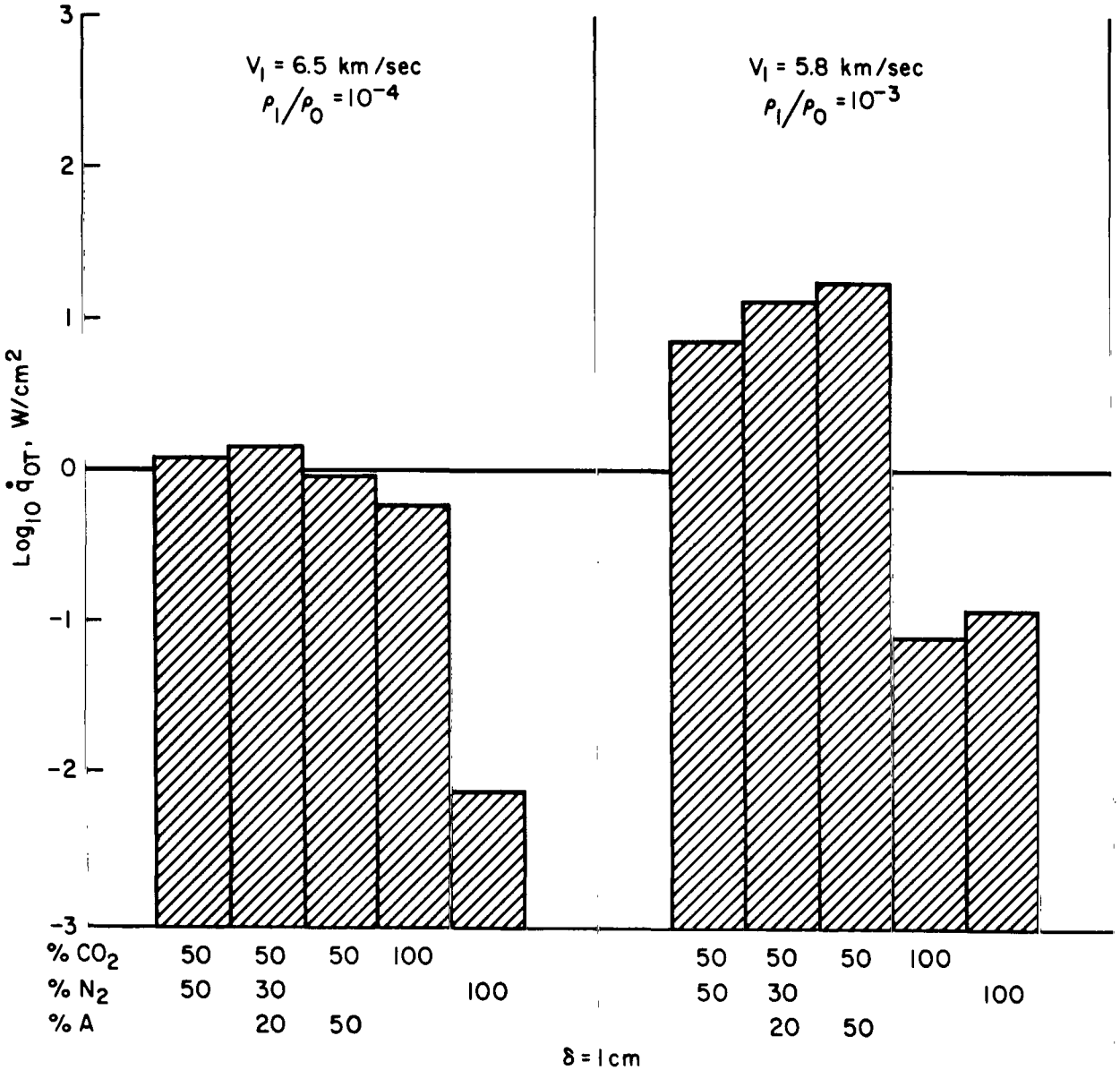


Figure 19.- Comparison of total heat-transfer rate in different gas mixtures.

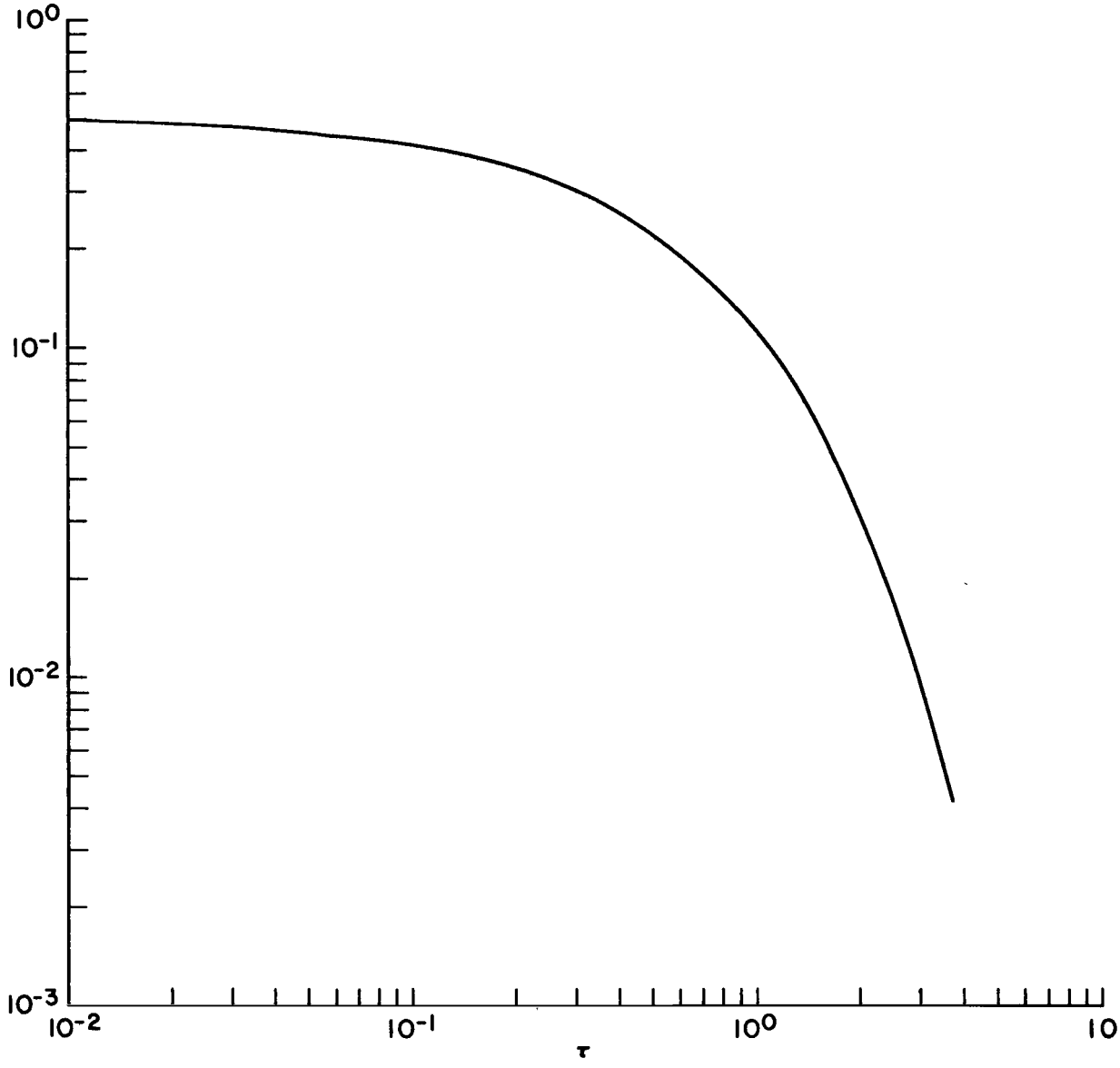


Figure 20.- Values of the function $E_3(\tau)$ in equation (12).

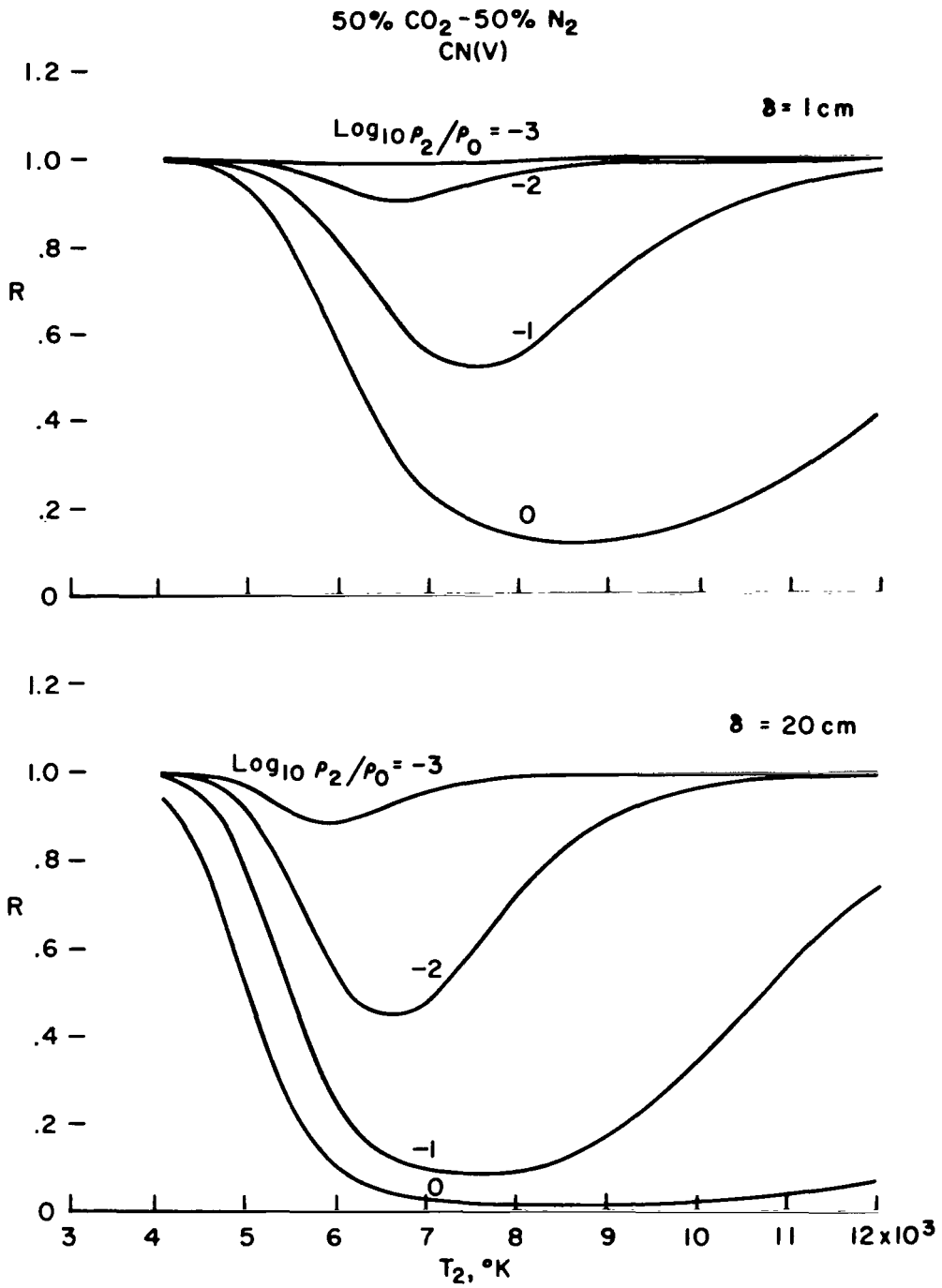


Figure 21.- Effect of self-absorption for CN violet band system.

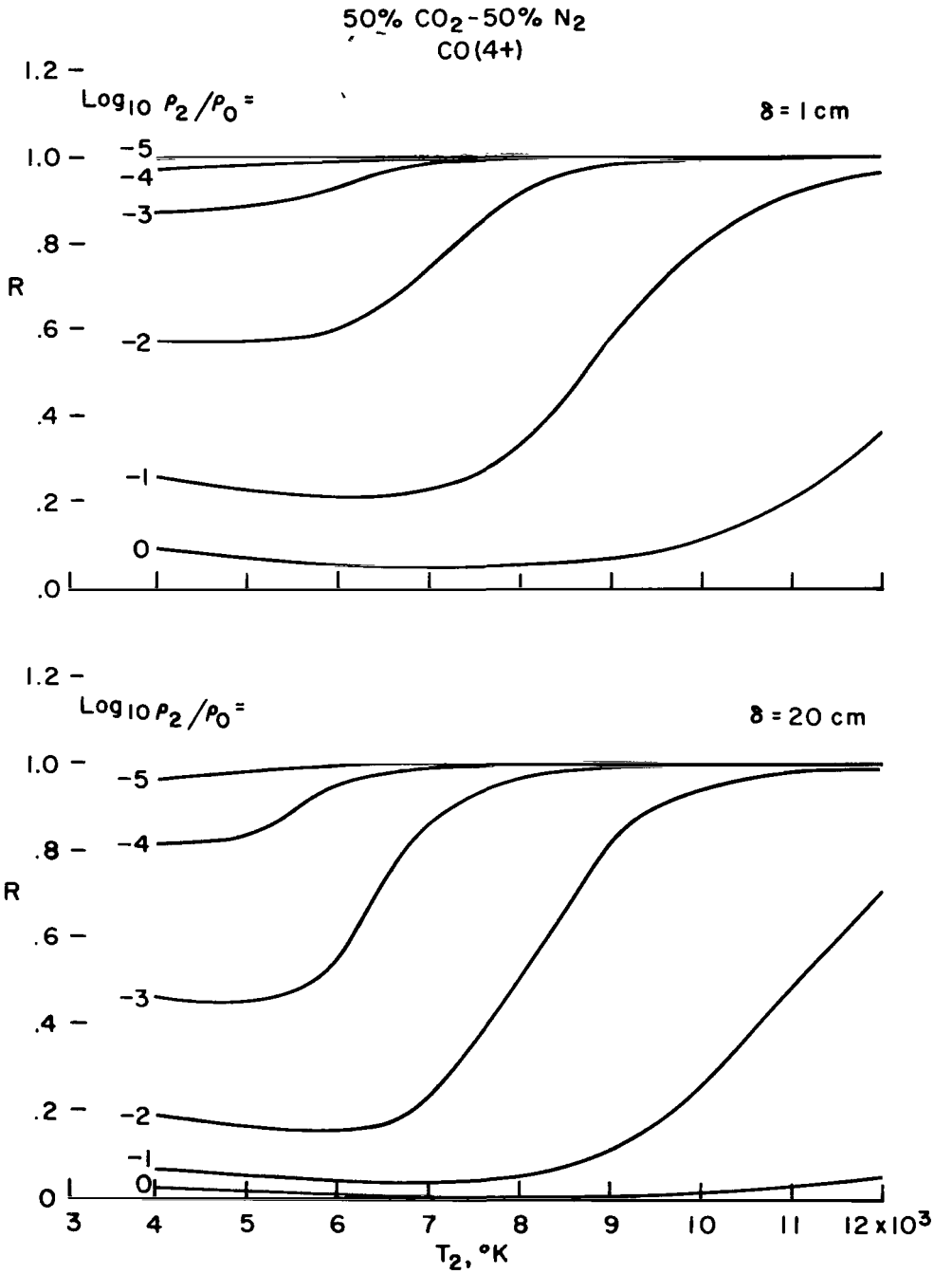


Figure 22.- Effect of self-absorption for CO fourth positive band system.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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