UNCLASSIFIED

AD 400939

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION ALEXANDRIA, VIRGINIA

UNCLASSIFIED

NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

63-3-1

SSD-TDR-62-127-VOLUME III

400959

400959 CATALOGED BY ASTIA AS AD NO. ____

INFRARED TRANSMISSION STUDIES FINAL REPORT, VOLUME III

THE INFRARED ABSORPTION OF CARBON DIOXIDE

31 JANUARY 1963

PREPARED FOR

HEADQUARTERS
SPACE SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

Best
Available
Copy

SSD-TDR-62-127 - Volume III

INFRARED TRANSMISSION STUDIES

FINAL REPORT, VOLUME III

THE INFRARED ABSORPTION OF CARBON DIOXIDE

V. R. Stull
P. J. Wyatt
G. N. Plass

Contract No. AF 04(695)-96
Project No. 4479-730F
Task No. 447904

as an extension to

Contract No. AF 19(604)-7479

31 January 1963

Prepared for

SPACE SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
Los Angeles, California

as an extension to work sponsored by

GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
Office of Aerospace Research
United States Air Force
Bedford, Massachusetts

AERONUTRONIC DIVISION
FORD MOTOR COMPANY
Newport Beach, California

ABSTRACT

The infrared absorption of carbon dioxide has been calculated over a wide range of path length, pressure, and temperature from 500 to 10,000 cm^{-1}. The results are presented in extensive tables which give the transmission over intervals of 5 cm^{-1} and also averaged over larger intervals. The calculated data representing the intensity, position, and number of spectral lines in a given frequency interval is tabulated in a form which is useful for further transmission calculations. All lines from all isotopic species having an intensity greater than 10^{-8} of the strongest line in an absorption region were included in the calculation. The transmission values were calculated from the quasi-random model which simulates the actual frequency and intensity distributions of spectral lines better than previous models.

CONTENTS

SECTION		PAGE
1	INTRODUCTION	1-1
2	MOLECULAR STRUCTURE OF CARBON DIOXIDE	2-1
	2.1 Vibrational Analysis	2-1
	2.2 Infrared Bands	2-7
	2.3 Structure of Vibrational Bands; Individual Lines	2-11
	2.4 Relative Intensity of Vibrational Bands	2-16
3	CALCULATION OF TRANSMISSION TABLES	3-1
	3.1 Introduction	3-1
	3.2 Calculation of Normalization Constants	3-4
	3.3 Calculation of Spectral Transmission	3-5
	3.4 Use of Appendices	3-8

APPENDIX		
A	THE VIBRATIONAL ENERGY LEVELS FOR THE EIGHT MAJOR ISOTOPIC SPECIES OF CARBON DIOXIDE	A-1
B	THE COEFFICIENTS ξ_o AND n FOR THE TOP FIVE INTENSITY DECADES	B-1
C	CARBON DIOXIDE TRANSMISSIONS BASED ON THE BENEDICT LINE SHAPE	C-1
D	CARBON DIOXIDE TRANSMISSIONS BASED ON THE LORENTZ LINE SHAPE AT 1.0 ATMOSPHERE PRESSURE	D-1
E	CARBON DIOXIDE TRANSMISSIONS AVERAGED OVER 20 cm^{-1} WITH ENTRIES EVERY 10 cm^{-1}	E-1

CONTENTS (Cont'd)

APPENDIX		PAGE
F	CARBON DIOXIDE TRANSMISSIONS AVERAGED OVER 50 cm^{-1} WITH ENTRIES EVERY 25 cm^{-1}	F-1
G	CARBON DIOXIDE TRANSMISSIONS AVERAGED OVER 100 cm^{-1} WITH ENTRIES EVERY 50 cm^{-1}	G-1

ILLUSTRATIONS

FIGURE		PAGE
3-1	COMPARISON OF THEORETICAL RESULTS WITH THE EXPERIMENTAL MEASUREMENTS OF BURCH, GRYVNAK AND WILLIAMS[8] FOR THE 15 μ BAND	3-10
3-2	COMPARISON OF THEORETICAL RESULTS WITH THE EXPERIMENTAL MEASUREMENTS OF BURCH, GRYVNAK AND WILLIAMS[8] FOR THE 4.3 μ BAND	3-11
3-3	COMPARISON OF THEORETICAL RESULTS WITH THE EXPERIMENTAL MEASUREMENTS OF BURCH, GRYVNAK AND WILLIAMS[8] FOR THE 2.7 μ BAND	3-12

TABLES

TABLE		PAGE
1	VIBRATIONAL CONSTANTS	2-3
2	FERMI RESONANCE CONSTANTS	2-6
3	FERMI RESONANCE CONSTANTS	2-6
4	GROUPS OF INFRARED-ACTIVE CO_2 TRANSITIONS	2-8
5	ROTATIONAL CONSTANTS FOR $C^{12}O_2^{16}$	2-12
6	RELATIVE INTENSITIES OF 15 μ CO_2 BANDS	2-18
7	RELATIVE INTENSITIES OF PARALLEL BANDS ($\Delta \ell = 0$) IN FERMI RESONANCE	2-20
8	RELATIVE INTENSITIES OF PERPENDICULAR BANDS ($\Delta \ell = \pm 1$) IN FERMI RESONANCE	2-21
9	NORMALIZATION CONSTANTS	3-6

SECTION 1

INTRODUCTION

The amount of infrared radiation which is transmitted through the earth's atmosphere is determined largely by the behavior of two molecules: carbon dioxide and water vapor. In this report a method is described for the calculation of the spectral transmission of carbon dioxide over a wide range of infrared frequencies. The results which were calculated on high speed digital computers are presented in the form of extensive tables. A companion report (SSD-TDR-62-127 - Volume II) presents similar data for water vapor.

The most extensive transmission tables which have previously been calculated are those of Ballard, Larmore, and Passman[1]. Their tables cover a wavelength range from 0.3 to 7.0 μ at intervals of 0.1 μ. The results are for one temperature (300°K) and one pressure (1 atmosphere). They assumed that the transmission is given by the Elsasser model. In particular, they used the error function approximation for the Elsasser model which is of limited accuracy at the higher pressures and shorter path lengths. Furthermore, the Elsasser model sometimes provides a poor representation of the transmission of the carbon dioxide spectrum mainly because of the variation in line intensity from one line to the next.[2]

Tables of carbon dioxide transmission are presented in this report for the frequency range from 500 cm^{-1} (20 microns) to 10,000 cm^{-1}

---

[1] S. S. Ballard, L. Larmore, S. Passman, Fundamentals of Infrared for Military Application, The Rand Corporation, R-297, March 31, 1956 (C).

[2] V. R. Stull, P. J. Wyatt and G. N. Plass, Bull. Amer. Phys. Soc. 6, 336 (1961); J. Opt. Soc. Amer. 52, 1209 (1962).

(1 μ) at intervals of 2.5 cm^{-1} for three temperatures (300, 250, 200°K), seven pressures (1.00, 0.50, 0.20, 0.10, 0.005, 0.002, 0.001 atm), and for fifteen amounts of CO_2 between 0.2 and 10,000 atm. cm. These temperatures and pressures cover the range of values which occur in the earth's atmosphere at altitudes where thermal equilibrium occurs. At higher altitudes calculations which assume equilibrium are invalid. However, this is not a serious limitation since for most paths almost all of the absorption of infrared by carbon dioxide occurs below these altitudes.

These calculations were carried out using the quasi-random model which is capable of representing the spectral transmission of molecular gases quite accurately. A detailed description of this model is given in SSD-TRD-62-127 - Volume II.

In Section 2 the molecular structure of CO_2 is described together with the rotational and vibrational motions. The intensities and frequencies of the spectral lines are described. In Section 3 the details of the calculation of the transmission tables are described.

SECTION 2

MOLECULAR STRUCTURE OF CARBON DIOXIDE

2.1 VIBRATIONAL ANALYSIS

Carbon dioxide is a linear triatomic molecule whose vibrational energy levels are given by[3]

$$G(v_1,v_2,v_3;\ell) = \sum_{i=1}^{3} \omega_i\,(v_i+\tfrac{1}{2}d_i) + \sum_{i=1}^{3}\sum_{j\geq i} x_{ij}(v_i+\tfrac{1}{2}d_i)(v_j+\tfrac{1}{2}d_j) + \sum_{i=1}^{3}\sum_{j\geq i}\sum_{k\geq j} Y_{ijk}(v_i+\tfrac{1}{2}d_i)(v_j+\tfrac{1}{2}d_j)(v_k+\tfrac{1}{2}d_k) + \ldots + g_{22}\,\ell^2 \qquad (1)$$

where v_1, v_2, v_3 are the vibrational quantum numbers, d_i are the vibrational degeneracy indices which for triatomic linear molecules have the values $d_1 = d_3 = 1$, $d_2 = 2$, ℓ is the quantum number representing the angular momentum associated with the degenerate vibrational mode about the symmetry axis of the molecule and can assume the values v_2, v_2-2, $v_2 - 4$, ...,1 or 0 depending on whether v_2 is odd or even. The coefficients ω_i, x_{ij}, Y_{ijk}, g_{22} can be expressed in terms of the potential constants for the molecule. However, they are usually determined directly by fitting Eq. (1) to a series of measurements of vibrational energy levels.

---

[3] G. Herzberg, Infrared and Raman Spectra, D. Van Nostrand Co., Inc., Princeton, 1945.

For lower order energy levels (small values of v_1, v_2, v_3), it is usually sufficient to retain terms to second order in v_i in Eq. (1) in order to determine the energy accurately.[3] However, Courtoy[4] has shown that the inclusion of third order terms in Eq. (1) determines the vibrational energy to within 1 cm^{-1} for nearly all values of the quantum numbers v_i which are of interest. The best values of the vibrational constants as determined by Courtoy[4] are given in Table I.

The vibrational constants are in general different for each isotopic species. The constants given in Table I for symmetric isotopic species such as $C^{13}O_2^{16}$ and $C^{12}O_2^{18}$ were determined from those for $C^{12}O_2^{16}$ by means of these relationships given, for example, by Herzberg:[3]

$$\frac{\omega_1^{(i)}}{\omega_1} = \left[\frac{m(0)}{m(0)^{(i)}}\right]^{\frac{1}{2}} = \rho_1 , \tag{2}$$

$$\frac{\omega_2^{(i)}}{\omega_2} = \frac{\omega_3^{(i)}}{\omega_3} = \left[\frac{m(0)\left(1 + \frac{2m(0)^{(i)}}{m(C)^{(i)}}\right)}{m(0)^{(i)}\left(1 + \frac{2m(0)}{m(C)}\right)}\right]^{\frac{1}{2}} = \rho_2 = \rho_3 \tag{3}$$

$$x_{ij}^{(i)} = x_{ij}\,\rho_i\,\rho_j , \tag{4}$$

$$Y_{ijk}^{(i)} = Y_{ijk}\,\rho_i\,\rho_j\,\rho_k , \tag{5}$$

where m(0) and m(C) are the masses of the oxygen and carbon atoms respectively. No such relationships exist for species such as $C^{12}O^{16}O^{18}$

[4] C. P. Courtoy, Ann. de la Soc. Sci. de Bruxelles, 63 (March 27, 1959).

TABLE 1

VIBRATIONAL CONSTANTS

Constant \ Species	$C^{12}O_2^{16}$	$C^{13}O_2^{16}$	$C^{12}O^{16}O^{18}$	$C^{13}O^{16}O^{18}$	$C^{12}O_2^{18}$
ω_1 (cm^{-1})	1354.91	1354.91	1316.08	1316.08	1277.25
ω_2	673.00	653.83	667.83	648.53	662.66
ω_3	2396.49	2328.22	2378.07	2309.34	2359.66
x_{11}	- 3.75	- 3.74	- 3.54	- 3.54	- 3.33
x_{22}	- .63	- .64	- .62	- .63	- .61
x_{33}	-12.63	-11.85	-12.43	-11.66	-12.24
x_{12}	3.65	3.50	3.52	3.37	3.39
x_{13}	-19.37	-18.89	-18.67	-18.20	-17.98
x_{23}	-12.53	-11.75	-12.34	-11.56	-12.15
y_{111}	.13	.13	.13	.13	.13
y_{222}	.01	.01	.01	.01	.01
y_{333}	.015	.015	.015	.015	.015
y_{112}	- .08	- .08	- .08	- .08	- .08
y_{122}	- .07	- .07	- .07	- .07	- .07
y_{133}	.07	.07	.07	.07	.07
y_{113}	.00	.00	.00	.00	.00
y_{223}	.00	.00	.00	.00	.00
y_{233}	.01	.01	.01	.01	.01
y_{123}	.02	.02	.02	.02	.02
g_{22}	.775	.790	.770	.770	.780

which have a different symmetry than that of the main species. However, when the mass difference between isotopes is small, as is the case for CO_2, the constants for the asymmetric species can be determined by interpolation between the main species and the corresponding symmetric isotopic species. For example, the constants for $C^{12}O^{16}O^{18}$ can be obtained by interpolating linearly between $C^{12}O_2^{16}$ and $C^{12}O_2^{18}$. It turns out that Eqs. (2), (3), (4) and (5) and linear interpolation obtain good agreement with all the measurements which Courtoy[4] has made. Thus, this method can be used with confidence to calculate the vibrational constants for isotopic species of CO_2 for which no measurements exist.

In polyatomic molecules it may happen that two or more vibrational levels corresponding to different vibrational modes (or combinations of modes) may have nearly the same energy and be of the same symmetry type. This accidental degeneracy or Fermi resonance perturbs the participating vibrational levels and produces states which are mixtures of the initial states with energies different from the initial energies. This shift of the levels is greater when the unperturbed energy levels are closer to each other.

For CO_2, $G(0,2,0;0) \approx G(1,0,0;0)$ and the corresponding levels are of the same symmetry type. From this it is clear that a level $(v_1,v_2,v_3;\ell)$ will be in Fermi resonance with the level $(v_1-1,\ v_2+2,\ v_3;\ell)$. This means that for each set $(v_3;\ell)$ there are $\left[v_1+\frac{1}{2}(v_2-\ell)+1\right]$ levels in resonance. The magnitude of the energy level shifts can be calculated by first order perturbation theory. The diagonal elements of the energy matrix are computed from Eq. (1). The final values of the vibrational energy are the eigenvalues of the matrix whose off-diagonal elements have been shown by Amat and Goldsmith[5] to be

$$W^{v_1,v_2,v_3;\ell}_{v_1',v_2',v_3';\ell'} = \frac{1}{2}\left[W_o - \lambda_1 v_1 - \lambda_2 v_2 - \lambda_3 v_3 - \lambda_\ell \ell\right]\left[(v_2+2)^2 - \ell^2\right]^{\frac{1}{2}} v_1^{\frac{1}{2}}$$

$$\text{if } v_1' = v_1-1;\ v_2' = v_2+2;\ v_3' = v_3;\ \ell' = \ell, \qquad (6)$$

$$= 0 \text{ otherwise}$$

---

[5] G. Amat and M. Goldsmith, J. Chem. Phys. 23, 1171 (1955).

Courtoy[6,4] has determined the constants in Eq. (6) experimentally. His results are given in Table 2. The Fermi constants for other isotopic species can be determined by extrapolation and interpolation of the values given in Table 2. Fermi constants determined in this way are given in Table 3 for four species which have relatively significant abundances.

Of the twelve isotopic species of carbon dioxide, eight occur in sufficient abundance to be considered in the present study. These species and their relative abundances are: $C^{12}O_2^{16}$ (1.00), $C^{13}O_2^{16}$ (1.12×10^{-2}), $C^{12}O^{16}O^{18}$ (4.0×10^{-3}), $C^{12}O^{16}O^{17}$ (8.0×10^{-4}), $C^{13}O^{16}O^{18}$ (4.5×10^{-5}), $C^{13}O^{16}O^{17}$ (8.9×10^{-6}), $C^{12}O_2^{18}$ (4.1×10^{-6}), and $C^{12}O^{17}O^{18}$ (1.6×10^{-6}).

The most extensive previous calculations of the vibrational energy levels of CO_2 have been made by Courtoy.[4,6] He has tabulated the energies of 74 levels of species $C^{12}O_2^{16}$, 48 levels of $C^{13}O_2^{16}$ and 9 levels of both $C^{12}O^{16}O^{18}$ and $C^{13}O^{16}O^{18}$. In the present study it is necessary that the vibrational energies be known for all energy levels up to the levels (12,0,0;0), (0,24,0;24) and (0,0,6;0), at least for the main species $C^{12}O_2^{16}$. This results in a total of over 1800 energy levels. The calculation of these energies has been carried out using an IBM 709 computer. Since it was convenient to do so all of these levels were calculated for all eight isotopic species.

The calculation necessary to obtain these values consists first in evaluating the unperturbed energies using Eq. (1) and the off-diagonal matrix elements using Eq. (6), and finally diagonalizing the resultant energy matrix. In the usual manner the energy matrix is broken up into submatrices which are in turn diagonalized. This last phase of the program is a formidable computation in itself for it involves the diagonalization of the submatrices which may be as large as 13 x 13. For the calculations which have been carried out, an eigenvalue routine written by Dr. George Baker of the Los Alamos Scientific Laboratory was used. This method consists of first calculating the first n matrix powers (using double precision arithmetic

---

[6] C. P. Courtoy, Can. J. Phys. 35, 608 (1957).

TABLE 2

FERMI RESONANCE CONSTANTS

Species / Constant	$C^{12}O_2^{16}$	$C^{13}O_2^{16}$	$C^{12}O^{16}O^{18}$	$C^{13}O^{16}O^{18}$
W_0 (cm-1)	51.31	46.52	52.50	47.80
λ_1 "	.15	.10	.10	.09
λ_2 "	.41	.37	.40	.36
λ_3 "	.78	.74	.75	.74
λ_ℓ	0	0	0	0

TABLE 3

FERMI RESONANCE CONSTANTS

Species / Constant	$C^{12}O^{16}O^{17}$	$C^{13}O^{16}O^{17}$	$C^{12}O_2^{18}$	$C^{12}O^{17}O^{18}$
W_0 (cm^{-1})	51.91	47.66	53.69	53.09
λ_1 "	.13	.10	.05	.08
λ_2 "	.41	.37	.39	.40
λ_3 "	.77	.74	.72	.74
λ_ℓ	0	0	0	0

in order to minimize round off difficulties) and their traces. Then by means of Newton's identities, the traces are used to calculate the coefficients of the characteristic polynomial. The roots of this characteristic polynomial are then obtained. The final tabulation of the perturbed energy levels comprises the most extensive known to date and is almost fifty times the size of Courtoy's.

The calculated vibrational energy levels agree to five significant figures with the measurements of Courtoy.[4,6] The results including more than 1800 energy levels for each of the eight isotopic species are tabulated in Appendix A.

2.2 INFRARED BANDS

In the present study the spectral region considered is from 500 to 10,000 cm^{-1}. The lower limit is chosen so as to include the 15μ CO_2 band, but to exclude all the stronger lines of the purely rotational H_2O spectrum. Within this limitation only certain of the vibrational transitions of CO_2 need be considered. The frequencies of the fundamental vibrational modes of CO_2 have values such that a transition corresponding to a unit change in v_3 has approximately the same energy as a change of 2 units in v_1 and a change of 4 units in v_2. This point is useful in cataloging the vibrational transitions of CO_2, since any transition can be imagined as corresponding to some integral multiple of Δv_2. Thus the transitions which are effective in the spectral region of interest can be divided in 22 separate groups, each group (with 2 exceptions) corresponding to a different integral multiple of Δv_2. This is illustrated in Table 4.

In general the vibrational transitions active in the infrared are dipole transitions determined by the selection rules,[3]

1) $\Delta \ell = 0$, v_2-even, v_3-odd

2) $\Delta \ell = \pm 1$, v_2-odd, v_3-even

for symmetric species such as $C^{13}O_2^{18}$ and

1) $\Delta \ell = 0$

2) $\Delta \ell = \pm 1$

for asymmetric species such as $C^{12}O^{16}O^{18}$. It is clear that there is a

TABLE 4

GROUPS OF INFRARED-ACTIVE CO_2 TRANSITIONS

Group No.	Multiple of Δv_2	Primary Transition	Frequency (cm^{-1})	Wavelength (μ)	No. of Sym. Species Transitions	No. of Asym. Species Transitions
1	1	(000,0) → (010,1)	667.	15.0	24	26
2+	2	(100,0) → (001,0)	961.	10.4	2	2
3+	2	(020,0) → (001,0)	1064.	9.4	2	22
4*	3	(000,0) → (030,1)	1933.	5.2	16	27
5*	3	(000,0) → (110,1)	2077.	4.8	21	21
6	4	(000,0) → (001,0)	2349.	4.3	12	40
7#	5	(000,0) → (050,1)	3181.	3.1	29	73
8#	6	(000,0) → (021,0)	3613.	2.8	20	60
9#	7	(000,0) → (070,1)	4416.	2.3	42	100
10#	8	(000,0) → (041,0)	4854.	2.1	28	84
11#	9	(000,0) → (090,1)	5639.	1.8	68	142
12#	10	(000,0) → (061,0)	6076.	1.6	40	112
13#	11	(000,0) → (0 11 0,1)	6851.	1.5	88	188
14#	12	(000,0) → (081,0)	7284.	1.4	56	144
15#	13	(000,0) → (0 13 0,1)	8054.	1.24	102	231
16#	14	(000,0) → (0 10 1,0)	8481.	1.18	72	180
17#	15	(000,0) → (0 15 0,1)	9249.	1.08	118	296
18#	16	(000,0) → (0 12 1,0)	9668.	1.03	88	220

TABLE 4 (Continued)

Group No.	Multiple of Δv_2	Primary Transition	Frequency (cm^{-1})	Wavelength (μ)	No. of Sym. Species Transitions	No. of Asym. Species Transitions
19#	17	(000,0) → (0 12 0,1)	10437.	.96	157	356
20#	18	(000,0) → (0 14 1,0)	10846.	.92	108	264
21#	19	(000,0) → (0 19 0,1)	11620.	.86	218	440
22#	20	(000,0) → (0 16 1,0)	12018.	.83	132	308

+ Groups 2 ard 3 both correspond to 2 units of Δv_2. They are separated because experimentally they are resolved and measured separately. In addition it is to be noted that the ground state transition (000,0) → (020,0) corresponding to two units of Δv_2 is forbidden by the selection rules for the main isotopic species which is symmetric. Thus it is not listed as a primary transition even though it occurs for the rarer asymmetric species.

* Groups 4 and 5 correspond to the 3 units of Δv_2. They are separated because they are resolved experimentally.

These groups list only one primary transition. However, there are other ground state transitions in Fermi resonance with the one listed which might equally well have been listed. For example, group 14 actually has a primary quintuplet (000,0) → (081,0), (161,0), (241,0), (321,0), (401,0) in addition to the transition (000,0) → (003,0). There will of course be additional ground state transitions for the asymmetric species.

very large number of sets ($\Delta v_1, \Delta v_2, \Delta v_3$) consistent with these selection rules, especially for the higher frequency groups of transitions. In the present study all of the sets for each of the 22 groups were determined by programming the selection rules for the IBM 709 computer.

The next phase of this study was a determination of all of the pairs of levels and the corresponding transition frequencies from the previously obtained energy tables for each of the sets ($\Delta v_1, \Delta v_2, \Delta v_3$). With no further restriction there would obviously be an extremely large number of transitions. The intensity of a given transition is proportional to the population of the initial state. In thermal equilibrium this population is proportional to the Boltzmann factor, exp (-G/kT). In the present study only temperatures of 300°K and lower are of interest. At these temperatures levels with energies greater than or equal to that of the state (001,0) are negligibly populated. Thus the only transitions included were those with one of the following eight initial states: (000,0), (010,1), (020,0), (020,2), (100,0), (030,1), (030,3) and (110,1). Even with this limitation a large number of transitions remain. The number of transitions in each group for symmetric and asymmetric molecular species are given in columns 6 and 7, respectively, of Table 4.

Attention should be called to transition groups 7, 9, 11, 13, 15, 17, 19 and 21. There is no mention of these transitions in the literature. Apparently they are too weak to have been observed experimentally.[7,8] However, they are allowed by the selection rules and should be included in the spectrum. These transitions fall into a regular progression behind groups 1 and 4 and as Herzberg[3] points out such progressions show a regular falling off in intensity. A comparison of the measured intensities of the transitions of group 1 and those of group 4 would lead one to expect that the transitions of groups 7, 9, etc. have very low intensities. Thus they would be difficult to observe. The actual intensities of these transitions will be considered in section 2.4.

---

[7] J. N. Howard, D. E. Burch, D. Williams; Sci. Rep. #1, AF 19(604)-516 The Ohio State University, Dec. 1954.

[8] D. E. Burch, D. Gryvnak, D. Williams, Sci. Rep. #2, AF 19(604)-2633, The Ohio State University, Jan. 1961.

2.3 STRUCTURE OF VIBRATIONAL BANDS; INDIVIDUAL LINES

For each vibrational energy state of a molecule there are a number of rotational energy states. Thus a given vibrational transition can occur in combination with any one of a number of rotational transitions. The rotational transitions form a line spectrum which constitutes the structure of the vibrational band.

The rotational energy of a linear molecule is given by

$$F_v(j) = B_v j(j+1) \tag{7}$$

where

$$B_v = B_e - \sum_{i=1}^{3} \alpha_i (v_i + \tfrac{1}{2} d_i). \tag{8}$$

The quantum number j corresponds to the total angular momentum of the molecule and in general j takes on the values ℓ, $\ell + 1$, $\ell + 2$ ..... However, for a molecule such as CO_2 j can only take on the values 0,2,4 ... when $\ell = 0$. This result arises in the following way. For a molecule in the symmetry class corresponding to the symmetric species of CO_2 the rotational levels are alternatively symmetric and antisymmetric.[3] The ratio of the statistical weights of the antisymmetric and symmetric states is given by $(s/(s+1))$,[9] where s is the spin of the two identical nuclei in the molecule. Since the spin of O^{16} and O^{18} are zero the statistical weight of the antisymmetric rotational levels of the molecules $C^{12}O_2^{16}$, $C^{13}O_2^{16}$ and $C^{12}O_2^{18}$ vanish. Thus only every other rotational level occurs for these molecules. However, when the quantum number $\ell > 0$, each rotational level is doubly degenerate; the pair of states corresponds to the values $+\ell$ and $-\ell$ for the component of angular momentum about the symmetry axis. Thus the absence of alternative levels does not manifest itself and j can take on all values $\geq \ell$. It should be noted that there is no such alternation for asymmetric molecules such as $C^{12}O^{16}O^{18}$. For such species the quantum number $j = \ell, \ell + 1, \ell + 2$ ... for all values of ℓ.

---

[9] L. I. Schiff, Quantum Mechanics, McGraw-Hill, New York (1949).

Equation (7) does not include second and higher order terms in the rotational energy. These terms are negligible for CO_2 because the coefficient of the second order term ($D_v\ j^2(j+1)^2$) has been found to be $< 5 \times 10^{-7}\ B_v$.[10] Thus even for $j \sim 100$ which is the maximum value considered in the present study the first order term dominates. Higher rotational states do not have to be considered since the populations are too small in thermal equilibrium for spectral lines arising from these states to lie in the intensity range considered here. Values of the rotational constants B_e, α_i have been determined by Benedict, et al[10] from the experimental measurements and are listed in Table 5. For the other isotopic species the relations[3]

$$B_e^{(i)} = B_e(\rho_1 \rho_2 \rho_3)^{2/3}\ , \tag{9}$$

$$\alpha_j^{(i)} = \alpha_j(\rho_j)^3 \tag{10}$$

can be used, where the ρ_j are defined in Eqs. (2) and (3).

TABLE 5

ROTATIONAL CONSTANTS FOR $C^{12}O_2^{16}$

B_e	α_1	α_2	α_3
.3925	.00058	- .00045	.00307

An individual spectral line in a vibration-rotation spectrum can be completely described by as few as three parameters. These are the frequency, intensity, and a line shape parameter. In the simplest description, this latter parameter is taken to be the same for all the lines of a given molecule. Thus, each line requires only two descriptive parameters.

[10] W. S. Benedict, R. Herman, S. Silverman, J. Chem. Phys. 19, 1325 (1951).

The frequency of a given spectral line is simply proportional to the difference between the total energy (in the present case vibrational plus rotational energy) of the initial and final states of the corresponding transition. The line strength or intensity parameter is usually taken to be integrated intensity, which is given by[11]

$$S_{v,\ell,j}^{v',\ell',j'} = \frac{8\pi^3}{3hc}\ \omega_{v,\ell,j}^{v',\ell',j'}\ \frac{N}{Qp}\ \exp\left(-\frac{hc[G(v,\ell) + F_v(j)]}{kT}\right) \cdot$$

$$\cdot \left|M_{v\,\ell\,j}^{v'\ell'j'}\right|^2 s(j,\ell)\left[1 - \exp\left(-\frac{hc\omega_{vj\ell}^{v'j'\ell'}}{kT}\right)\right], \qquad (11)$$

where $\omega_{v,j,\ell}^{v',j',\ell'}$ is the wavenumber of the line, N is the number of molecules per unit volume, Q is the partition function, p is the pressure, and $s(j,\ell)$ is the square of the pure rotational matrix element given by[3]

$$s(j,\ell) = \begin{cases} \dfrac{(j+1)^2 - \ell^2}{j+1}, & \Delta j = +1, \quad \Delta\ell = 0, \\ \dfrac{(2j+1)\,\ell^2}{j(j+1)}, & \Delta j = 0, \quad \Delta\ell = 0, \\ \dfrac{j^2 - \ell^2}{j}, & \Delta j = -1, \quad \Delta\ell = 0, \end{cases} \qquad (12)$$

[11] S. S. Penner and A. Thomson, Tech. Rep. No. 25, Contract No. Nonr-220(03), NR 015401, Guggenheim Jet Prop. Center, Calif. Inst. Tech.

and

$$s(j,\ell) = \begin{cases} \dfrac{(j+2\pm\ell)(j+1\pm\ell)}{2(j+1)}, & \Delta j = +1, \quad \Delta\ell = \pm 1, \\ \dfrac{(j+1\pm\ell)(j\pm\ell)(2j+1)}{2j(j+1)}, & \Delta j = 0, \quad \Delta\ell = \pm 1, \\ \dfrac{(j-1\pm\ell)(j\pm\ell)}{2j}, & \Delta j = -1, \quad \Delta\ell = \pm 1. \end{cases} \tag{13}$$

Equations (12) and (13) imply the well-known rotational selection rules governing the quantum number j, i.e. $\Delta j = 0, \pm 1$.

In Eq. (11) the amplitude $\left| M^{v',j',\ell'}_{v,j,\ell} \right|^2$ can be written as $\left(\left| R^{v',\ell'}_{v,\ell} \right|^2 f^{v',j',\ell'}_{v,j,\ell} \right)$ where $R^{v',\ell'}_{v,\ell}$ are the pure vibrational matrix elements of a non-rotating oscillator and $f^{v',j',\ell'}_{v,j,\ell}$ are correction factors which account for the interaction of vibration and rotation. For diatomic molecules at high temperatures it is known that this interaction may be significant.[12,13] However, the theory of polyatomic molecules is not sufficiently developed to permit a quantitative description of $f^{v',j',\ell'}_{v,j,\ell}$. It has been found that neglecting this interaction (i.e. assuming $f^{v',j',\ell'}_{v,j,\ell} = 1$) usually does not cause serious disagreement with experiment for $T \leq 300^{\circ}K$.

A useful parameter here is the band strength defined by

$$\alpha^{v',\ell'}_{v,\ell} = \sum_{jj'} S^{v',j',\ell'}_{v,j,\ell} = \frac{8\pi^3}{3hc} \frac{}{\omega}{}^{v',\ell'}_{v,\ell} \frac{N}{Qp} \exp\left[-\frac{hcG(v,\ell)}{kT} \right] \cdot \left| R^{v',\ell'}_{v,\ell} \right|^2 \sum_{jj'} s(j,\ell) \exp\left[-\frac{hcF_v(j)}{kT} \right], \tag{14}$$

[12] R. Herman and R. F. Wallis, J. Chem. Phys. 23, 675 (1955).

[13] V. R. Stull and C. N. Plass, J. Opt. Soc. Amer. 50, 1279 (1960).

which, if there were no overlapping of lines in the band, would be equal to the total band absorption. The mean frequency $\bar{\omega}_{v,\ell}^{v',\ell'}$ is defined by

$$\bar{\omega}_{v,\ell}^{v',\ell'} \sum_{jj'} s(j,\ell) \exp\left[-\frac{hcF_v(j)}{kT}\right] = \sum_{jj'} \omega_{v,\ell,j}^{v',\ell',j'} \exp\left[-\frac{hcF_v(j)}{kT}\right]$$

$$\cdot f_{v,\ell,j}^{v',\ell',j'} s(j,\ell) \left[1 - \exp\left(-\frac{hc\omega_{v,\ell,j}^{v',\ell',j'}}{kT}\right)\right]. \quad (15)$$

Since at infrared frequencies and ordinary temperatures

$$\left[1 - \exp\left(-\frac{hc\omega_{v,\ell,j}^{v',\ell',j'}}{kT}\right)\right] \cong \left[1 - \exp\left(-\frac{hc\omega_{v,\ell}^{v',\ell'}}{kT}\right)\right] \cong 1.$$

and since $f_{v,\ell,j}^{v',\ell',j'} \cong 1$, then

$$S_{v,\ell,j}^{v',\ell',j'} = C_{v,\ell}^{v',\ell'} \frac{\omega_{v,\ell,j}^{v',\ell',j'}}{\bar{\omega}_{v,\ell}^{v',\ell'}} \exp\left[-\frac{hcF_v(j)}{kT}\right] s(j,\ell), \quad (16)$$

where

$$C_{v,\ell}^{v',\ell'} = \frac{\alpha_{v,\ell}^{v',\ell'}}{\sum_{jj'} s(j,\ell) \exp\left[-\frac{hcF_v(j)}{kT}\right]} \quad (17)$$

and the denominator in this expression may be recognized as the rotational partition function Q_R.

From Eq. (17) and (14) it follows that amplitude $C_{v,\ell}^{v',\ell'}$ (i.e. the vibrational intensity) for any vibrational transition and

any temperature may be related to that of another transition at another temperature, so that

$$C_{v,\ell}^{v',\ell'}(T) = I_R\, C_{v^*,\ell^*}^{v^*,\ell'^*}(T_o)\, \frac{N(T)Q(T_o)}{N(T_o)Q(T)}\, \exp\left[\frac{hcG(v^*,\ell^*)}{kT_o} - \frac{hcG(v,\ell)}{kT}\right], \tag{18}$$

where I_R is the ratio $\left(\left| R_{v,\ell}^{v',\ell'} \right|^2 \Big/ \left| R_{v^*,\ell^*}^{v^{*\prime},\ell^{*\prime}} \right|^2 \right)$. Thus if $C_{v,\ell}^{v^*,\ell'}(T)$ is known for any one of the vibrational transitions included in one of the 22 groups described previously and if the ratios I_R are known for the group then the intensity of any individual line at any temperature may be calculated from Eqs. (18) and (16). It is to be noted that Eq. (18) equally well expresses the relationship between vibrational transitions belonging to different groups. However, it is only within a single group that the ratio I_R can be readily determined. The method used to determine the relative intensity ratio I_R will be discussed in section 2.4.

For CO_2, in calculations using Eq. (18) it may be assumed that $N(T) \sim (p/T)$ and that the partition function is given by[3]

$$Q(T) = \prod_{i=1}^{3} \left[1 - \exp\left(-\frac{\omega_i^o}{kT}\right)\right]^{-d_i} \left[\frac{kT}{hcB_e} + \frac{1}{3} + \frac{1}{15}\,\frac{hcB_e}{kT} + \frac{4}{315}\left(\frac{hcB_e}{kT}\right)^2 + \frac{1}{315}\left(\frac{hcB_e}{kT}\right)^3 + \cdots\right] \exp\left[-\frac{hcG(0,0)}{kT}\right], \tag{19}$$

where ω_i^o are the frequencies of the three fundamental vibrational modes. This expression neglects the interaction of vibration and rotation and assumes $B_v \approx B_e$. These assumptions are quite valid for $T \leq 300^oK$. These simplifications are implied by the suppression of subscripts and superscripts on Q in all of the above expressions.

2.4 RELATIVE INTENSITY OF VIBRATIONAL BANDS

The quantum mechanical expressions for the matrix elements $R_{v,\ell}^{v',\ell'}$ for polyatomic molecules such as CO_2 have never been calculated.

Thus, vibrational intensities must be obtained semi-empirically. Ideally, high resolution experimental data would give the intensity of each individual vibrational transition. However, only a small amount of such data is available. Yamamoto and Sasamori[14] summarize the measurements of Kostkowsky, Kaplan, Madden and Eggers[15,16,17,18] on the transitions in group 1 (15.0 μ region). This data includes most of the significant transitions and is quoted in terms of relative intensities in Table 6. Since only a sparse amount of such data is known to exist for the other groups of transitions[19] the relative intensities must be determined by a semi-qualitative method. If a pair of the transition groups is compared, it is found that there is a one-to-one correspondence between the transitions in each group (if those transitions are taken together which are in Fermi resonance with each other). Thus one would expect that the variation in intensity from transition to transition in one group would be approximately the same as for the corresponding transitions in another group. If it is assumed that this is the case then the relative intensities for the transitions in all of the groups can be derived from those of group 1 which are given in Table 6.

When Fermi resonance occurs this method gives only the total intensity of each resonating group. In addition the distribution of intensity over the member transitions must be determined. Courtoy[6] has calculated the matrix elements for a number of resonating groups in his treatment of the effect of Fermi resonance on the rotational constants. For parallel transitions ($\Delta \ell = 0$) the relative intensities are directly proportional to these matrix elements. Thus Courtoy's results give the intensities directly. For the perpendicular transitions ($\Delta \ell = \pm 1$) it is known that most of the intensity is concentrated

---

[14] G. Yamamoto and T. Sasamori, Sci. Rep. Tohuku Univ., Geophysics Series 5, 10, 37 (July 1958).

[15] L. D. Kaplan and D. F. Eggers, Jr., J. Chem. Phys. 25, 876 (1956).

[16] H. J. Kostkowsky, Contract No. 248(01) Johns Hopkins Univ. (1955).

[17] H. J. Kostkowsky and L. D. Kaplan, J. Chem. Phys. 26, 1252 (1957).

[18] R. P. Madden, Contract No. 248(01) Johns Hopkins Univ. (1957).

[19] S. S. Penner, "Quantitative Molecular Spectroscopy and Gas Emissivities", Addison-Wesley (1959), p. 310.

TABLE 6

RELATIVE INTENSITIES OF 15 μ CO_2 BANDS

Transition	$I_R = \left\| R_{v,\ell}^{v',\ell'} \right\|^2 / \left\| R_{000,0}^{010,1} \right\|^2$
000,0 → 010,1	1.000
010,1 → 020,2	.906
010,1 → 020,0	.539
010,1 → 100,0	.711
020,0 → 030,1	2.524
020,0 → 110,1	.[illegible]8
020,2 → 030,1	. 18
020,2 → 030,3	1.177
020,2 → 110,1	.194
100,0 → 110,1*	.080
100,0 → 030,1	.016
030,1 → 040,0*	.015
030,1 → 040,2*	.005
030,1 → 120,0	.695
030,1 → 120,2	.024
030,1 → 200,0*	2.800
030,3 → 040,2	.150
030,3 → 040,4*	1.050
030,3 → 120,2	.209
110,1 → 120,0*	.511
110,1 → 120,2*	.024
110,1 → 200,0*	2.000
110,1 → 040,0*	.011
110,1 → 040,2*	.005

*The relative intensities of these transitions were not given by Yamamoto and Sasamori[12] but were determined on the basis of the distribution of intensity within Fermi resonance groups which is discussed in section 2.4.

in the highest frequency member of a set of resonating transitions.[20,21] Taylor, Benedict and Strong[20] give estimates of the relative intensities of the members of particular resonating pairs and triplets. From these and Courtoy's calculations, which go as far as quintet groups, it has been possible to make estimates of the distribution of intensity in resonating groups up to order 13 by graphical extrapolation. These results are given in Tables 7 and 8. For example, if it is assumed that all sextets contain the same distribution of intensities, then all the necessary relative intensities can be determined. This method was used in the present calculations except for group 6 (4.3 μ) where according to Benedict[21] it is known that the "cross-over transitions" (e.g. 020,0 $\rightarrow$101,0) are orders of magnitude less intense than the corresponding "noncross-over transitions" (e.g. 020,0 $\rightarrow$021,0). The factor which was used in the present calculation is 10^{-4}.

Finally, the intensities for the transitions of each isotopic species must be multiplied by the relative abundance of the species. There are new transitions for the asymmetric isotopic species which do not occur in the symmetric isotopes. All of these transitions are very weak, because the replacement of O^{16} by O^{18}, for example, introduces only a slight mass asymmetry. The weighting factor which was used for these transitions was 10^{-5}.[21]

The above method has been used in the present study to determine all of the relative intensities of the transitions in each of the transition groups. This calculation was programmed for the 709 IBM computer and the extensive results have been tabulated, but are not included in this report.

When the relative intensities are known, there remains only one unknown parameter for each group as is seen from Eq. (18). This parameter or normalization constant is determined by comparing the calculated values of the total absorption for the transitions in a given group at particular values of pressure and CO_2 amount with measured values of the same quantity. Details of this method are given in section 3.2. However, measurements are not available for all 22 transition groups of interest. In fact, as previously mentioned, the absorption is too weak to have been detected for some of the groups. For these groups the following qualitative method is used to determine the intensities. An examination of the groups shows that they fall into

---

[20] J. H. Taylor, W. S. Benedict, and J. Strong, J. Chem. Phys. 20, 1884 (1952).

[21] W. S. Benedict, private communication (May 1962).

TABLE 7

RELATIVE INTENSITIES OF PARALLEL BANDS ($\Delta \ell = 0$) IN FERMI RESONANCE

Order	2	3	4	5	6	7	8	9	10	11	12	13
v_2 increasing ↓												6×10^{-14}
											5×10^{-12}	3×10^{-10}
										3×10^{-10}	1.2×10^{-8}	4×10^{-7}
									1.2×10^{-8}	4×10^{-7}	8×10^{-6}	1.2×10^{-4}
								4×10^{-7}	8×10^{-6}	1.2×10^{-4}	1.2×10^{-3}	.01
							8×10^{-6}	1.2×10^{-4}	1.2×10^{-3}	.01	.04	.04
						1.2×10^{-4}	1.2×10^{-3}	.01	.04	.20	.20	.20
					1.2×10^{-3}	.01	.04	.20	.42	.58	.42	.58
				.01	.04	.20	.42	.58	.48	.20	.48	.20
			.04	.20	.42	.58	.48	.20	.06	.01	.06	.01
		.25	.42	.58	.48	.20	.06	.01	1.2×10^{-3}	1.2×10^{-4}	1.2×10^{-3}	1.2×10^{-4}
	.40	.59	.48	.20	.06	.01	1.2×10^{-3}	1.2×10^{-4}	8×10^{-6}	4×10^{-7}	8×10^{-6}	4×10^{-7}
	.60	.16	.06	.01	1.2×10^{-3}	1.2×10^{-4}	8×10^{-6}	4×10^{-7}	1.2×10^{-8}	3×10^{-10}	1.2×10^{-8}	3×10^{-10}
											5×10^{-12}	6×10^{-14}

TABLE 8

RELATIVE INTENSITIES OF PERPENDICULAR BANDS ($\Delta \ell = \pm 1$) IN FERMI RESONANCE

Order	2	3	4	5	6	7	8	9	10	11	12	13
v_2 increasing ↓												
												10^{-12}
											10^{-11}	10^{-11}
										10^{-10}	10^{-10}	10^{-10}
									10^{-9}	10^{-9}	10^{-9}	10^{-9}
								10^{-8}	10^{-8}	10^{-8}	10^{-8}	10^{-8}
							10^{-7}	10^{-7}	10^{-7}	10^{-7}	10^{-7}	10^{-7}
						10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}
					10^{-5}	10^{-5}	10^{-5}	10^{-5}	10^{-5}	10^{-5}	10^{-5}	10^{-5}
				10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}
			10^{-3}	10^{-3}	10^{-3}	10^{-3}	10^{-3}	10^{-3}	10^{-3}	10^{-3}	10^{-3}	10^{-3}
		.01	.009	.01	.01	.01	10^{-2}	10^{-2}	10^{-2}	10^{-2}	10^{-2}	10^{-2}
	.17	.09	.11	.11	.11	.11	.11	.11	.11	.11	.11	.11
	.83	.90	.88	.88	.88	.88	.88	.88	.88	.88	.88	.88

harmonic sequences. For example the primary transitions of groups 1, 4, 7, 9, 11, 13, 15, 17, 19, 21 fall into a simple harmonic series. Similarly the primary transitions of groups 6, 8, 10, 12, 14, 16, 18, 20, 22 fall into another harmonic sequence. As indicated by Herzberg[3] there is a regular falling-off of intensity in such a sequence which is expected to be nearly the same for different sequences of the same molecule. Thus the following ratios for the constants C given by Eq. (18) are obtained when Fermi resonance is taken into account:

$$C_1 : C_4 + C_5 : 3C_7 : 4C_9 : 5C_{11} : 6C_{13} : 7C_{15} : 8C_{17} : 9C_{19} : 10C_{21}$$

$$:: C_6 : 2C_8 : 3C_{10} : 4C_{12} : 5C_{14} : 6C_{16} : 7C_{18} : 8C_{20} : 9C_{22},$$

where the subscript indicates the group to which the constants C_i belong. Measurements of the total absorption have been made for groups 1,2,3,4,5,6,8,10,12,14.[7,8] These results and the above relationship are used to determine the normalization constant for all 22 groups of transitions.

SECTION 3

CALCULATION OF TRANSMISSION TABLES

3.1 INTRODUCTION

In section 2.3 the equations are given for the calculation of the frequencies and intensities of all the vibration-rotation lines of carbon dioxide. Thus the transmission at any frequency ν can be calculated from the exact expression

$$T(\nu) = \exp\left(- \int_0^L w(x) \sum_{i=1}^{N} S_i(x) b_i(\nu,x) dx \right), \qquad (20)$$

where $w(x)$ is the mass of CO_2 per unit area per unit distance at the point x, $S_i(x)$ is the intensity of ith line given by Eq. (16), and $b_i(\nu,x)$ is the line shape factor normalized so that

$$\int_0^\infty b_i(\nu,x) d\nu = 1.$$

The summation in Eq. (20) is over the N lines which contribute to the absorption at ν. However extensive transmission calculations based on Eq. (20) are beyond the practical limits of even the fastest digital computers.

In the first place the intensity $S_i(x)$ is a function of the gas temperature along the path and the line shape factor $b_i(\nu,x)$ is a function of both the temperature and the pressure. For example, the Lorentz pressure broadened line shape, which has been found to be

an adequate description of the vibration-rotation lines of many gases in the pressure range, .01 - 1.0 atmospheres, is given by[22]

$$b_i(\nu,x) = b(\nu_i - \nu,x) = \frac{\alpha(x)}{\pi\left[(\nu - \nu_i)^2 + (\alpha(x))^2\right]} \qquad (21)$$

where the half-width of the line

$$\alpha(x) = \alpha_o(T_o)\left(\frac{T_o}{T}\right)^{\frac{1}{2}} \frac{P}{P_o}, \qquad (22)^{+}$$

where α_o, p_o, and T_o are some particular set of values for the half-width, pressure, and temperature.

The available experimental evidence indicates that the best line shape for CO_2 is the Benedict modification of the simple Lorentz line shape. A study of the absorption by an isolated spectral line showed that the intensity in the wings of the line decreased more rapidly than predicted by the Lorentz expression. The available data is described by the following empirical expression proposed by Benedict:

$$b(\nu) = \frac{\alpha/\pi}{(\nu - \nu_i)^2 + \alpha^2}, \quad |\nu - \nu_i| \leq d,$$

$$= \frac{A\alpha/\pi}{(\nu - \nu_i)^2 + \alpha^2} e^{-a|\nu - \nu_i|^b}, \quad |\nu - \nu_i| \geq d \qquad (23)$$

---

[22] A.C.G. Mitchell and M.W. Zemansky, "Resonance Radiation and Excited Atoms", the McMillan Co., New York (1934).

+ The quantity p in this expression is the effective broadening pressure. It is different from the total pressure because the CO_2 molecules themselves are more effective in broadening than the foreign gas molecules in collisions with CO_2 molecules. Thus p = total pressure + 0.3 partial pressure of CO_2. The derivation of this relationship is given by Burch.[8] In the present report, the symbol p and word pressure mean this effective broadening pressure.

where $a = 0.0675$, $b = 0.7$, $d = 2.5\ cm^{-1}$. The value of A is chosen to make the two forms continuous at $|\nu - \nu_i| = d = 2.5\ cm^{-1}$.

In order to determine the effect of the Benedict modification of the Lorentz line shape the transmission calculations were made with both line shapes. The results given in Appendices C, E, F and G were calculated with the Benedict modification of the Lorentz line shape. For purposes of comparison the results for the Lorentz line shape at one temperature and pressure are reproduced in Appendix D. A comparison of this table with the corresponding table in Appendix C indicates that the Benedict shape gives substantially less absorption in the window regions for the larger amounts of CO_2.

Only homogeneous paths along which the pressure and temperature are constant are considered in this report. In this case Eq. (20) reduces to

$$T(\nu) = \exp\left\{ - u \sum_{i=1}^{N} S_i\, b(\nu - \nu_i) \right\}, \qquad (24)$$

where

$$u = \int_0^L w(x)dx = wL.$$

Even with this simplification, transmission calculations using Eq. (24) are impractical. Not only does a single evaluation of $T(\nu)$ involve a summation over thousands of spectral lines but in a practical calculation this evaluation has to be made a very large number of times. In order to describe adequately the transmission over a frequency range, $T(\nu)$ must be calculated from Eq. (23) at frequencies which differ from each other by much less than the half-width α. In the present study the frequency range of interest is 500 to $10{,}000\ cm^{-1}$ and $\alpha_o(300^oK) = .06\ cm^{-1}$ at p = 1 atmosphere for CO_2.[23] Thus more than a million evaluations of Eq. (24) would be required for a given temperature, pressure and amount of gas. In addition a useful calculation must cover a range of temperatures, pressures, and amounts of gas which in general amount to several hundred different sets of these three quantities.

[23] L. D. Kaplan and D. F. Eggers, J. Chem. Phys. 25, 876 (1956).

Thus it is necessary to use a model in order to calculate the transmission. Such a model must be capable of evaluating the transmission at intervals large compared to the half-width and yet adequately describe its frequency dependence. The quasi-random model has been derived which fulfills this requirement.

Basic to the quasi-random model is the separation of the spectral lines into groups by the division of the spectrum into finite frequency intervals and the subsequent calculation of the effect of the lines within each interval separately. Clearly as this frequency interval is made smaller, the spectral lines are localized more closely around their actual positions. The main features of the quasi-random model are: (1) the use of small intervals to localize the position of the strong spectral lines; (2) the averaging of results for at least two different sets of intervals shifted with respect to each other in order to minimize the effects of lines which occur just inside or outside of a given interval; (3) the use of transmission equations which are valid for the actual number of spectral lines in the interval rather than the equations which are valid in the limit of an infinite number of lines; (4) the use of equations for the transmission of a spectral line over a finite interval rather than an infinite interval as is often used; (5) the absorption by the wings of spectral lines in adjacent intervals is taken into account; (6) the simulation of the intensity distribution by grouping the lines in a given frequency interval into subgroups defined by certain ranges of intensity. A more detailed description of the quasi-random model is given in SSD-TDR-62-127 - Volume II.

3.2 CALCULATION OF NORMALIZATION CONSTANTS

For the problem of normalization (section 2.4), the quantity to be calculated is the integrated transmission over a large spectral region corresponding to that covered by the vibrational bands in one of the groups listed in Table 4. For this purpose it is not necessary to employ the shifted intervals described in section 3.1 because the details of the spectral structure are not required. Thus the normalization was actually accomplished using a single set of intervals. The other features of the quasi-random model listed as 3 through 6 in section 3.1 were used in the normalization calculation.

The normalization calculation proceeded as follows. Measurements of the integrated transmission were available only for transition groups 1, 2, 3, 4, 5, 6, 8, 10, 12, and 14.[7,8] For each of these

groups the frequencies and intensities of the spectral lines of all of the vibrational bands in the group were calculated. The intensities were calculated for a range of values of the normalization constant which was taken to be $C_{o,o}^{v',\ell'}(300^{o}K)$, the vibrational intensity of the primary transition. Using the model described in the previous paragraph the transmission was calculated for a number of sets of values of pressure and amount of CO_2 for each assumed value of $C_{o,o}^{v',\ell'}(300^{o}K)$. The integrated transmission was calculated in each case using Simpson's rule. The correct value of $C_{o,o}^{v',\ell'}(300^{o}K)$ was determined by fitting the calculated results to the measured integrated transmissions for the corresponding pressures and amounts of gas by the method of least squares. This procedure was carried out for each of the 10 groups for which measurements were available. The resulting values of $C_{o,o}^{v',\ell'}(300^{o}K)$ were well defined. For the other 12 groups, for which measurements were not available, the method described in section 2.4 was used to obtain the normalization constant. The results for all 22 groups are listed in Table 9.

3.3 CALCULATION OF SPECTRAL TRANSMISSION

The final calculations of the spectral transmission of CO_2 can be divided into two parts. The first part began with the calculation of the intensities of all the spectral lines for all of the isotopes, using the data in Table 9 and Eqs. (18) and (16). As each line was generated it was retained only if its relative intensity was greater than 10^{-8} of the intensity of the strongest line in the transition group being considered. Thus the calculation of the rotational lines of a given vibrational band were terminated with that value of the quantum number j for which the intensity becomes less than 10^{-8} the intensity of the strongest line. The strongest line in each of the 22 groups had been previously determined.

When a particular line was retained it was grouped according to its frequency into the appropriate frequency interval. The width of these intervals was chosen as 5 cm^{-1} for CO_2. With this interval size and the shifting of the interval described later, the final transmission was obtained with as fine a structure as the resolving power of typical infrared instruments. An interval any smaller than 5 cm^{-1} would not be of sufficient practical value to justify the considerable extension of the calculations. As is explained in the detailed description of the quasi-random model in SSD-TDR-62-127

TABLE 9

NORMALIZATION CONSTANTS

Transition Group No.	$C^{v',\ell'}_{o,o}$ (300°K)
1	6.9×10^{-1}
2	2.0×10^{-2}
3	5.0×10^{-2}
4	6.3×10^{-5}
5	6.4×10^{-4}
6	9.8
7	7.0×10^{-7}
8	2.6×10^{-1}
9	7.0×10^{-10}
10	3.9×10^{-3}
11	7.0×10^{-13}
12	6.8×10^{-5}
13	7.0×10^{-16}
14	1.7×10^{-4}
15	7.0×10^{-19}
16	3.6×10^{-7}
17	7.0×10^{-22}
18	1.2×10^{-8}
19	7.0×10^{-25}
20	5.0×10^{-10}
21	7.0×10^{-28}
22	2.0×10^{-11}

-- Volume II, the lines within each frequency interval were further grouped according to their intensities. Each of these successive groups includes lines with intensities within an order of magnitude of each other. For the purposes of the quasi-random model each group is described by two parameters. These are the number of lines in each group, n, and

$$\xi_o = \frac{\sum_i S_i}{\pi n \alpha_o} \quad . \tag{25}$$

Furthermore, it has been found that only the five largest intensity groups need be retained for a given frequency interval, since any line with intensity outside this range contributes negligibly to the absorption. Accordingly, the first part of the transmission calculation generated 5 sets of the parameters ξ_o, and n for 5 cm^{-1} intervals from 500 to 10,000 cm^{-1}.

Concerning the displaced meshes, it has been found that one such set of intervals shifted by half the interval size (2.5 cm^{-1} for CO_2) is sufficient to calculate the average transmission on the basis of the quasi-random model (see SSD-TDR-62-127 -- Volume II). Thus sets of ξ_o and n were generated for 5 cm^{-1} intervals between 502.5 and 10,002.5 cm^{-1} as well as for a mesh displaced by 2.5 cm^{-1}. This calculation was performed for the temperatures 300°K, 250°K and 200°K, yielding six tables of ξ_o and n (Appendix B).

At a given temperature the pair of tables, shifted and unshifted, of ξ_o and n are sufficient to calculate the complete infrared transmission for any pressure and amount of CO_2. These tables contain all of the data required by the quasi-random model and no further recourse to the actual spectral lines is necessary.

The final part of the calculation was the determination of the spectral transmission by the quasi-random model using these values of ξ_o and n. At the temperatures 300°K, 250°K and 200°K this calculation was carried out for 7 pressures (1.00, 0.50, 0.20, 0.10, 0.05, 0.02, 0.01 atmospheres) and for each pressure for 15 different amounts of CO_2 (10000, 5000, 2000, 1000, 500, 200, 100, 50, 20, 10, 5, 2, 1, .5, .2 atm cm). These amounts do not correspond to the number of atm cm at the temperature considered; but are normalized to standard temperature, 273°K. Thus they are

obtained by multiplying the amount at temperature T by (273/T). When these normalized units are used, the variation of the transmission with temperature of a particular sample of gas can be obtained directly from values listed in the tables for the same value of u at each temperature. The calculation produced the transmission every 2.5 cm^{-1} over the entire frequency range of interest. The complete tables of these results are given in Appendix C.

Finally the transmissions given in the tables of Appendix C were integrated over three larger frequency intervals (20, 50 and 100 cm^{-1}) to produce an average transmission which corresponds with the results of measurements made with instruments having spectral resolutions of these three amounts. This illustrates how the previous results can be averaged over any larger spectral interval. These results are given in Appendix E, F and G.

3.4 USE OF APPENDICES

The seven appendices which follow this section represent the results of the present calculation.

Appendix A lists the vibrational energy levels in wave numbers of carbon dioxide for eight isotopic species. The levels of each isotopic species are labeled by v_1, ℓ, v_3, and v_2 - the latter quantum number (v_2) is indicated implicitly while the former are presented explicitly. The sets of energy levels (from left to right) following a particular v_1,ℓ, v_3 designation correspond to specific values of v_2, viz., $v_2 = \ell$, $\ell + 2$, $\ell + 4$, ... All levels whose energies are less than or equal to the $(v_1,v_2,v_3;1)$ levels (12,0,0;0), (0,24,0;24) and (0,0,6;0) are given. (See section 2.1 for a detailed explanation.) The ordering of the (v_1,ℓ,v_3) entries is based on letting v_1 go through its entire range (subject to the above maximum energy limitations) for each value of ℓ and v_3. These combinations of ℓ and v_3 in turn are generated by letting first ℓ and then v_3 run through their ranges in ascending order. To find, for example, the $(v_1,v_2,v_3;\ell)$ level corresponding to (1,4,3;2) one begins by locating the levels of $v_3 = 3$ in the third column. Next the $\ell = 2$ group are located from these v_3 entries and then the $v_1 = 1$ row or rows are found. Finally the $v_2 = 4$ energy level will correspond to the second energy level from the left (since these levels, as has already been mentioned, correspond to $v_2 = \ell$, $\ell + 2$, $\ell + 4$, ...).

Appendix B contains the coefficients ξ_o and n, (see Eq. (25)), for the top five intensity groups as a function of frequency. If

intensities more than eight orders of magnitude below the strongest group had been needed to provide five groups, one or more of the five groups are listed as identically equal to zero. A particular frequency entry which is in the first column corresponds to the center of an interval extending 2.5 cm^{-1} in both directions. The second, fourth, sixth, eighth, and tenth columns give the parameter ξ_o which is proportional to the average intensity for the lines in each intensity decade. The third, fifth, seventh, ninth, and eleventh columns give n, the number of lines in the intensity decade. Thus, subsequent transmission calculations are based upon those frequencies lying midway between mesh points implied by the coefficient tables. Two sets of coefficients are included for each temperature and correspond to two meshes displaced 2.5 cm^{-1} from each other. For identification purposes the meshes beginning at 505.0 cm^{-1} have been labeled "unshifted" while those starting at 507.5 cm^{-1} have been labeled "shifted". Again, note that the entries correspond to the frequencies at the center of two mesh points (e.g. the entries at 505.0 were calculated from the spectral lines lying between 502.5 and 507.5 cm^{-1}, etc.)

Appendix C lists, as a function of frequency and path thickness (u in atmosphere centimeters) for three temperatures at seven different pressures, the transmission calculated on the basis of the quasi-random model using the Benedict line shape.

Appendix D is included for comparison purposes. It presents the transmissions as in Appendix C at 300°K and 1 atmosphere pressure only. The tabulated transmissions were calculated on the basis of the Lorentz line shape rather than the Benedict modification which is used exclusively in Appendices C and E.

Appendices E, F and G list the transmissions averaged over 20, 50 and 100 cm^{-1} at intervals of 10, 25 and 50 cm^{-1} respectively for all the temperatures and pressures of Appendix C.

In Figs. 3-1 to 3-3 portions of the calculated CO_2 spectrum are compared with the experimental results of Burch, Gryvnak and Williams[8] for nearly equivalent pressures and gas amounts.

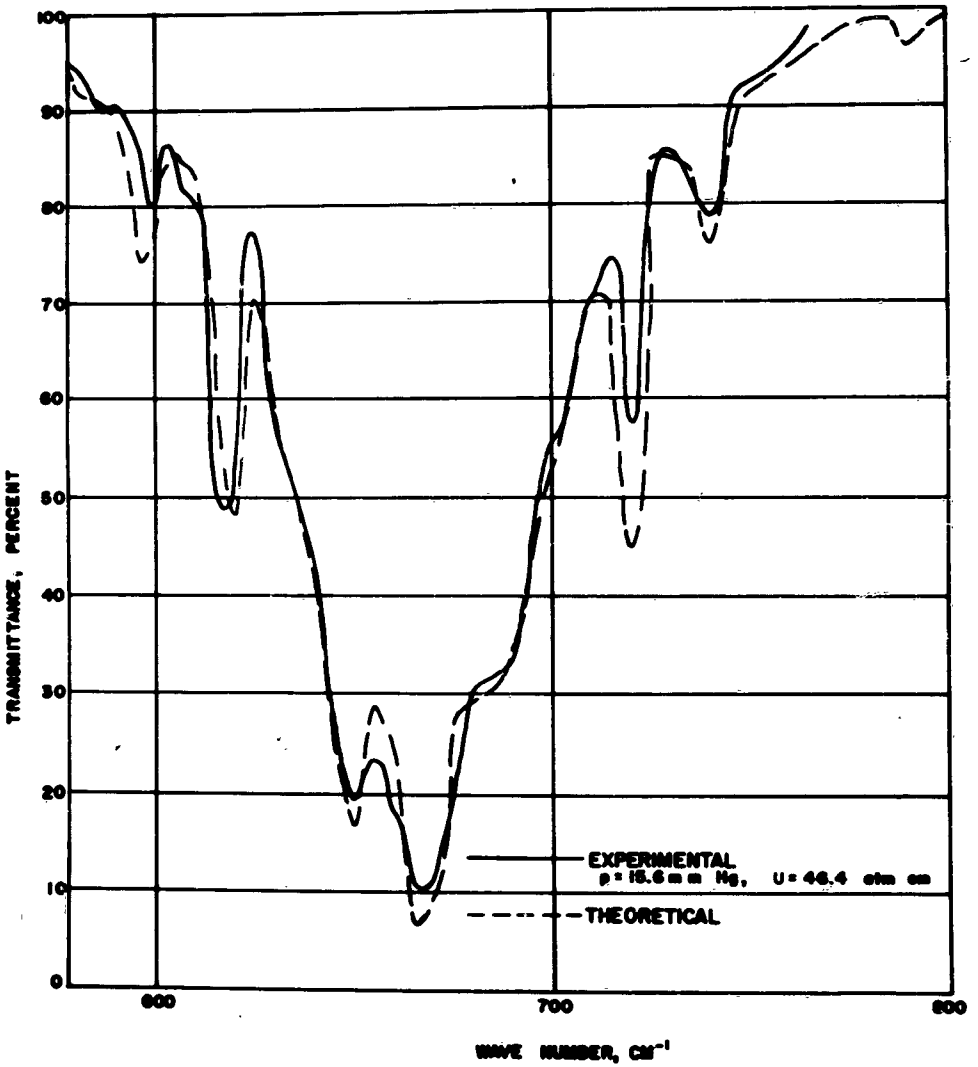


FIG. 3-1. COMPARISON OF THEORETICAL RESULTS WITH THE EXPERIMENTAL MEASUREMENTS OF BURCH, GRYVNAK AND WILLIAMS[8] FOR THE 15μ BAND

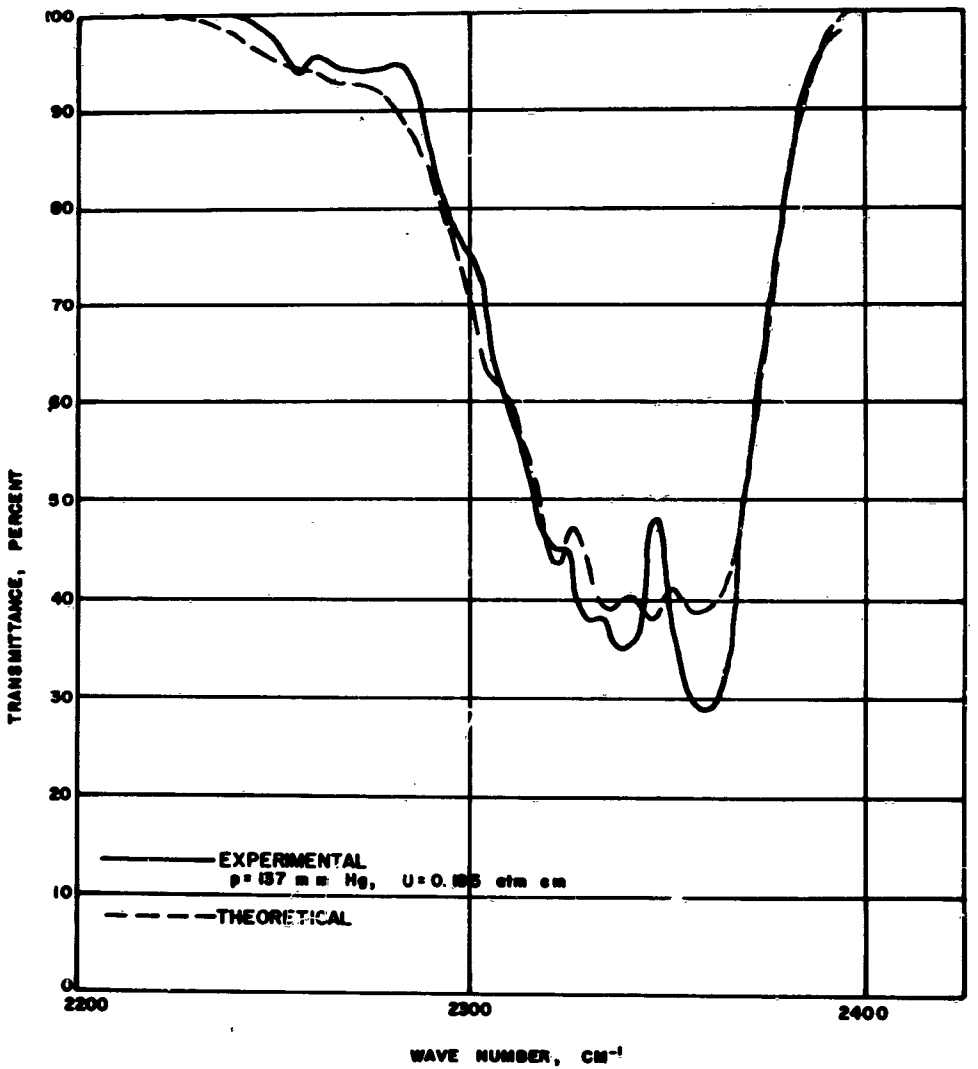


FIG. 3-2. COMPARISON OF THEORETICAL RESULTS WITH THE EXPERIMENTAL MEASUREMENTS OF BURCH, GRYVNAK AND WILLIAMS[8] FOR THE 4.3μ BAND

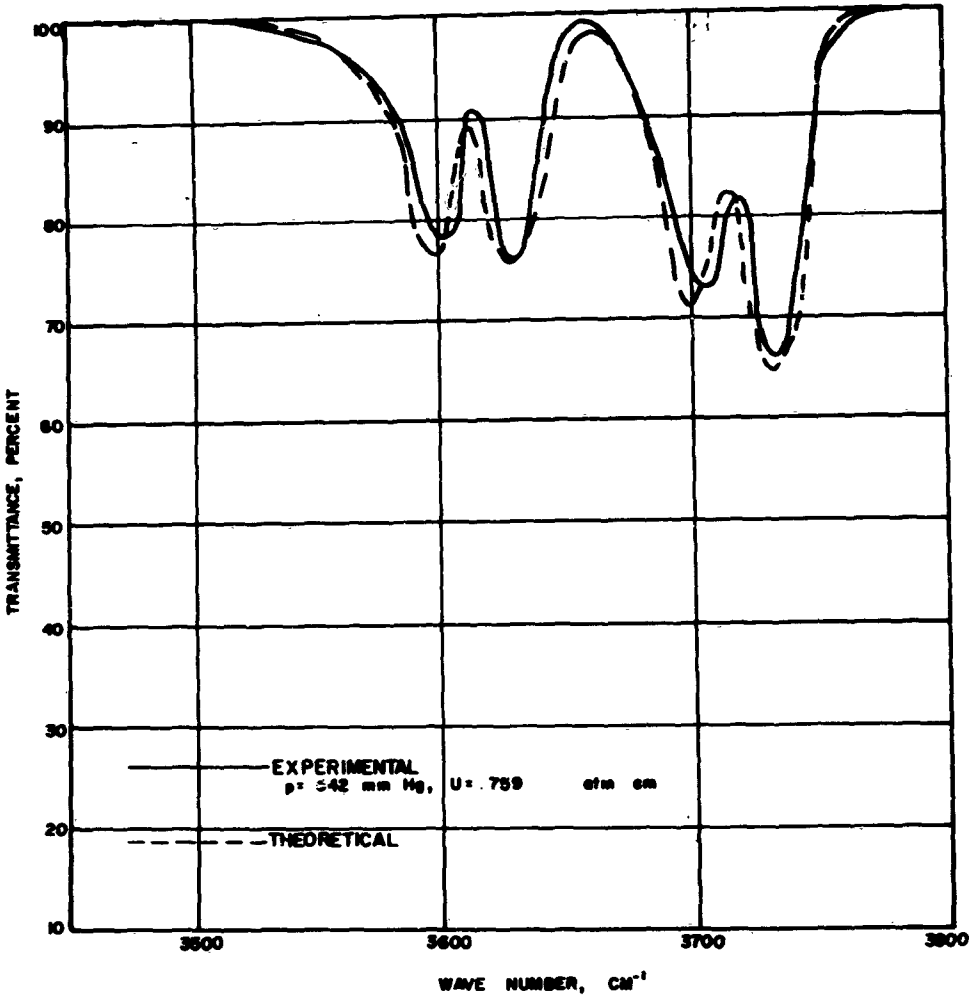
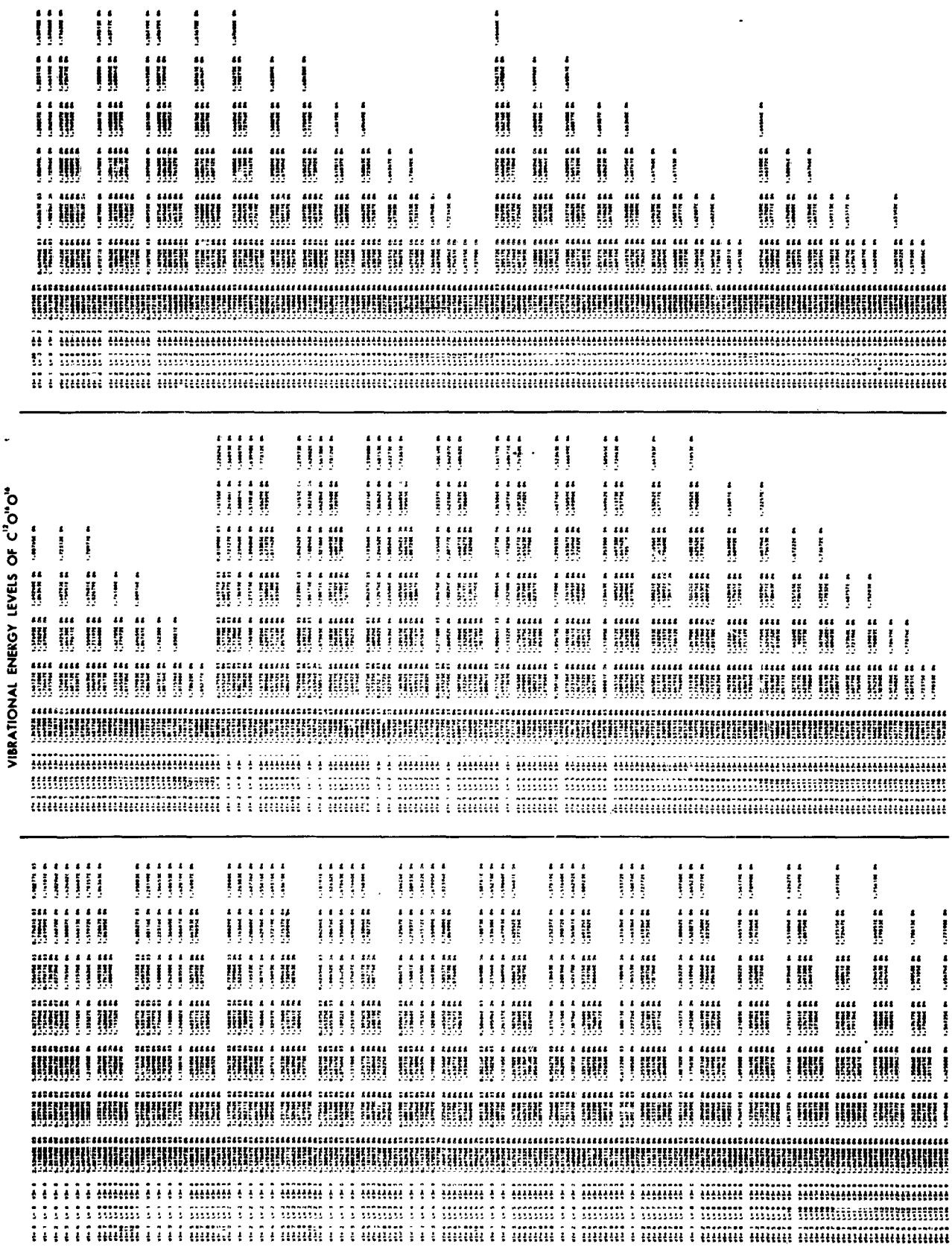
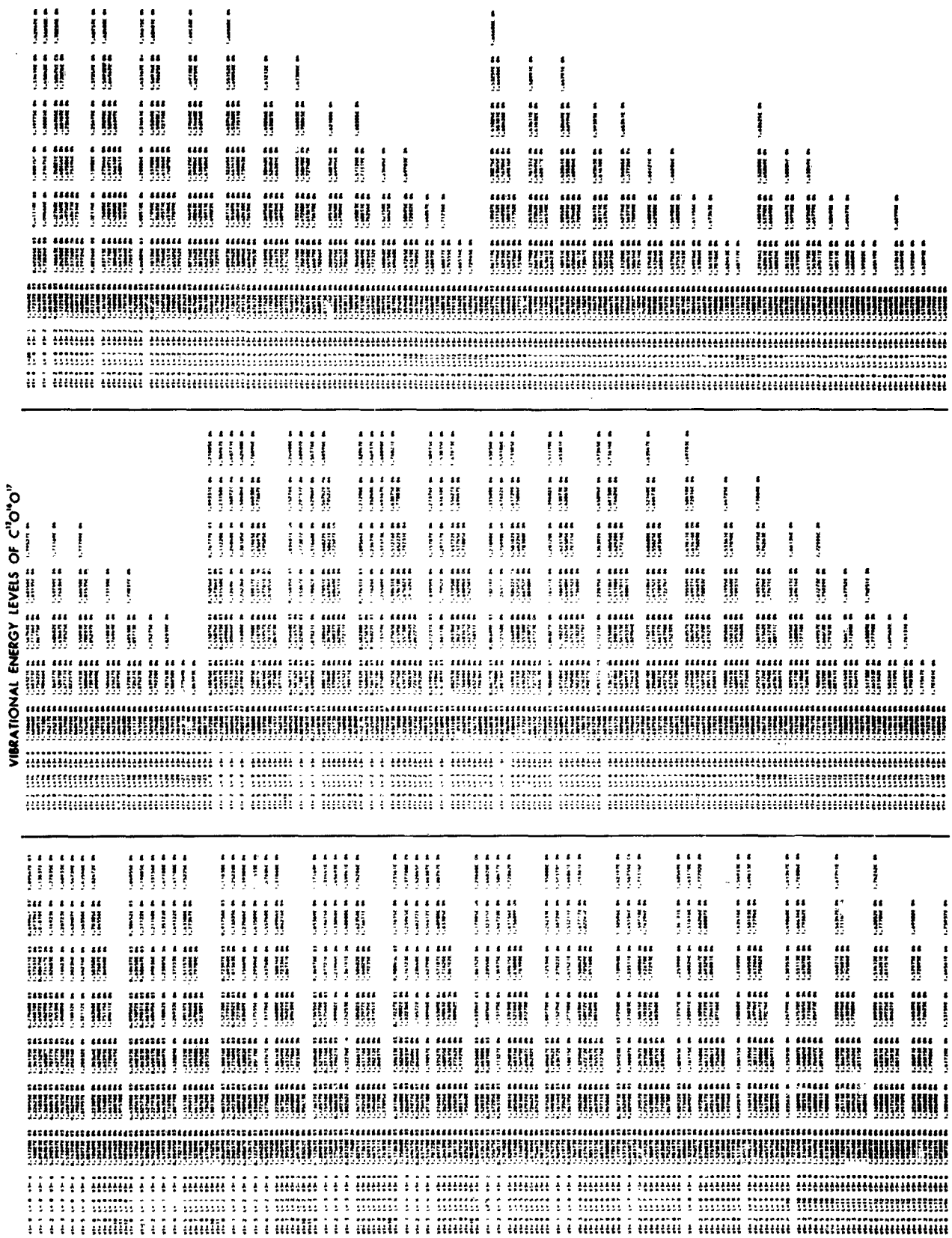


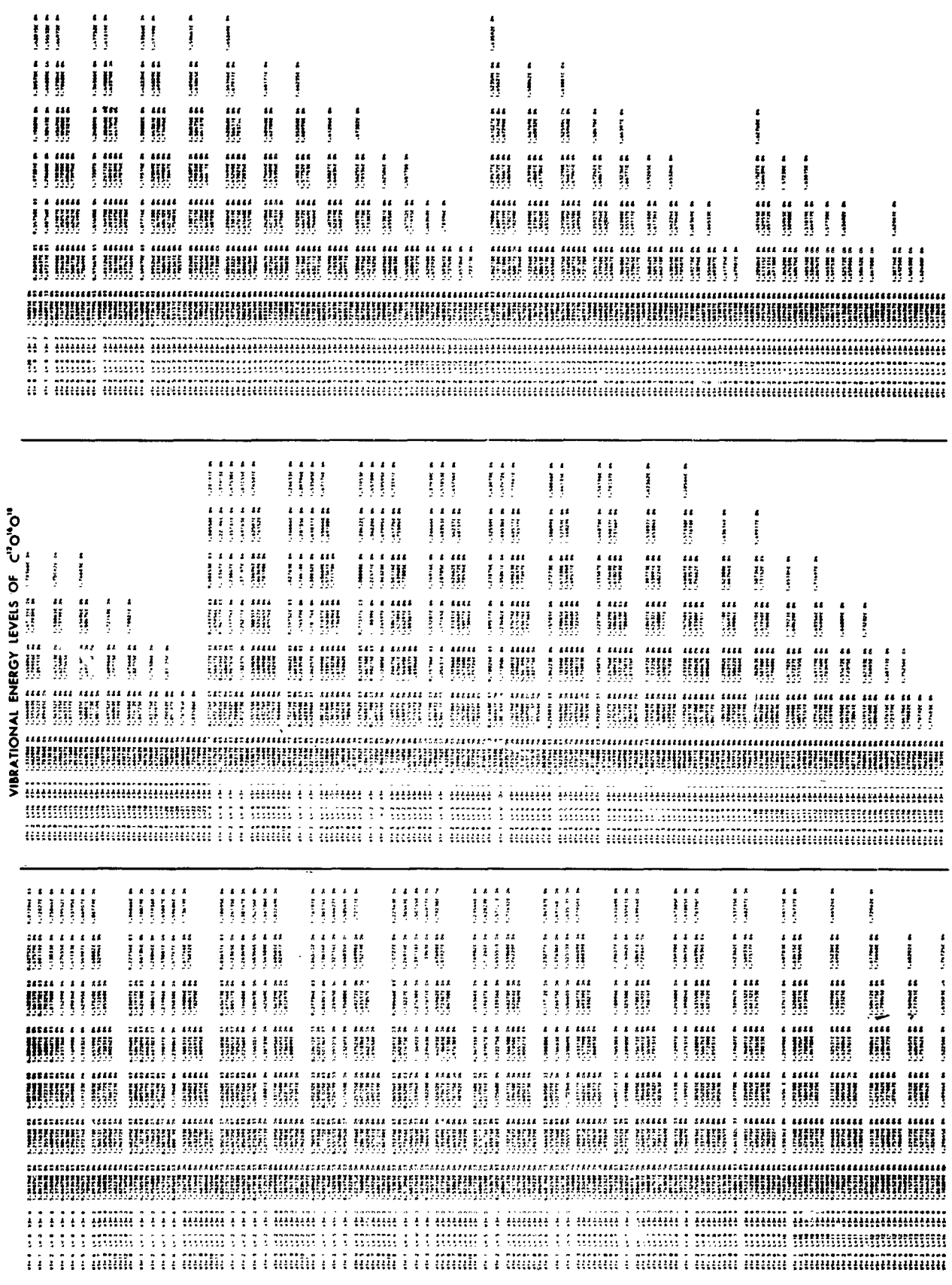
FIG. 3-3. COMPARISON OF THEORETICAL RESULTS WITH THE EXPERIMENTAL MEASUREMENTS OF BURCH, GRYVNAK AND WILLIAMS[8] FOR THE 2.7μ BAND

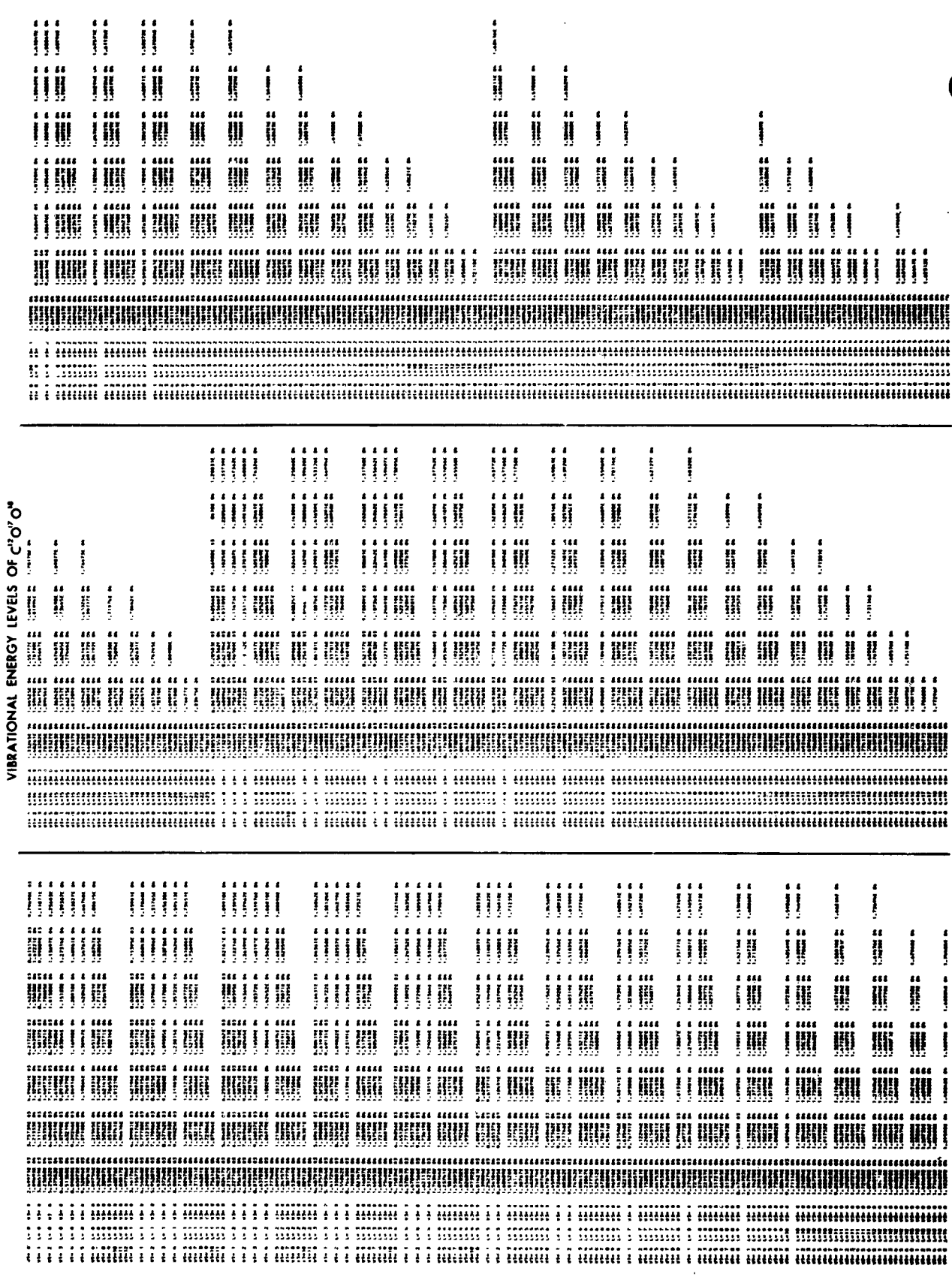
APPENDIX A

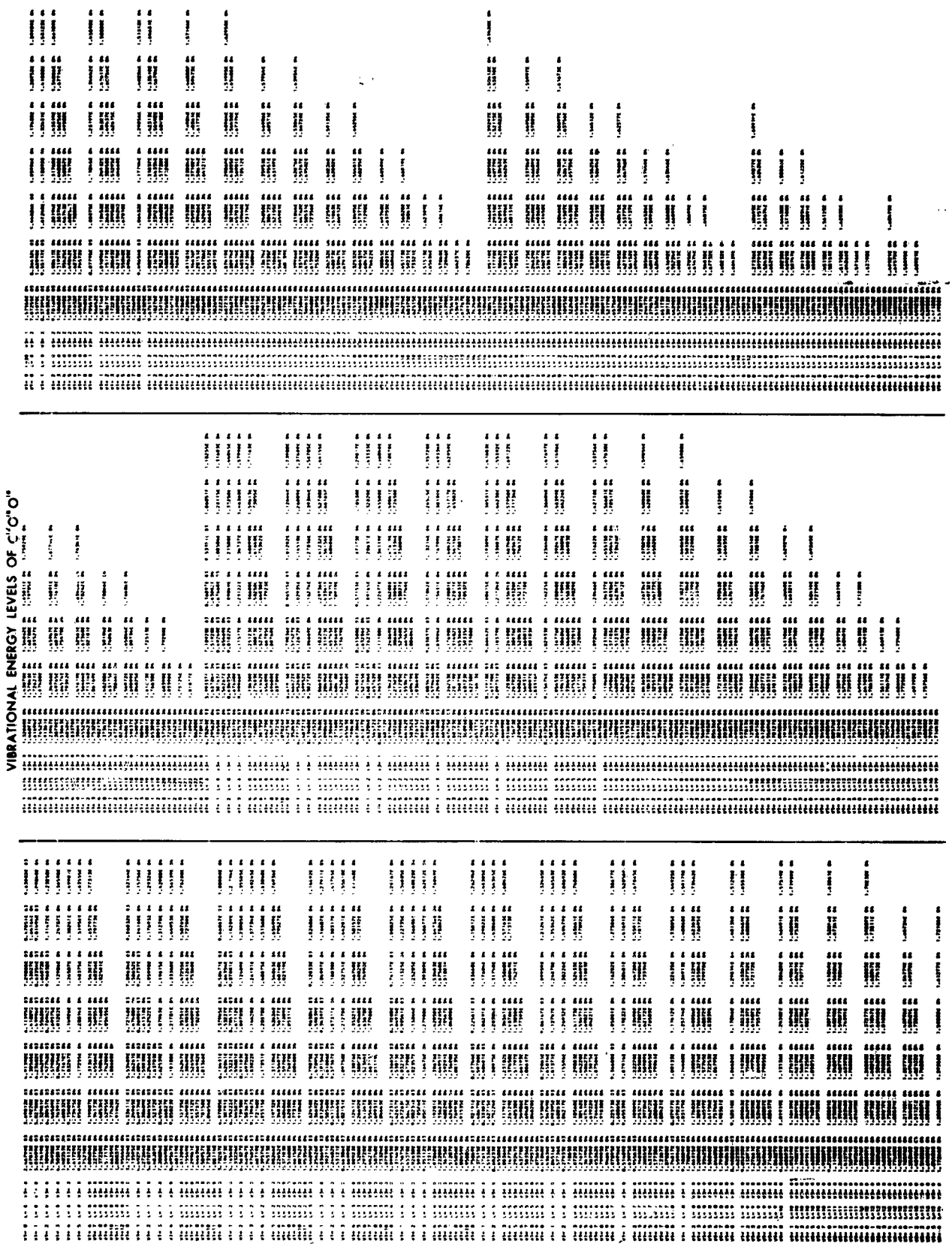
THE VIBRATIONAL ENERGY LEVELS FOR THE EIGHT MAJOR ISOTOPIC SPECIES OF CARBON DIOXIDE

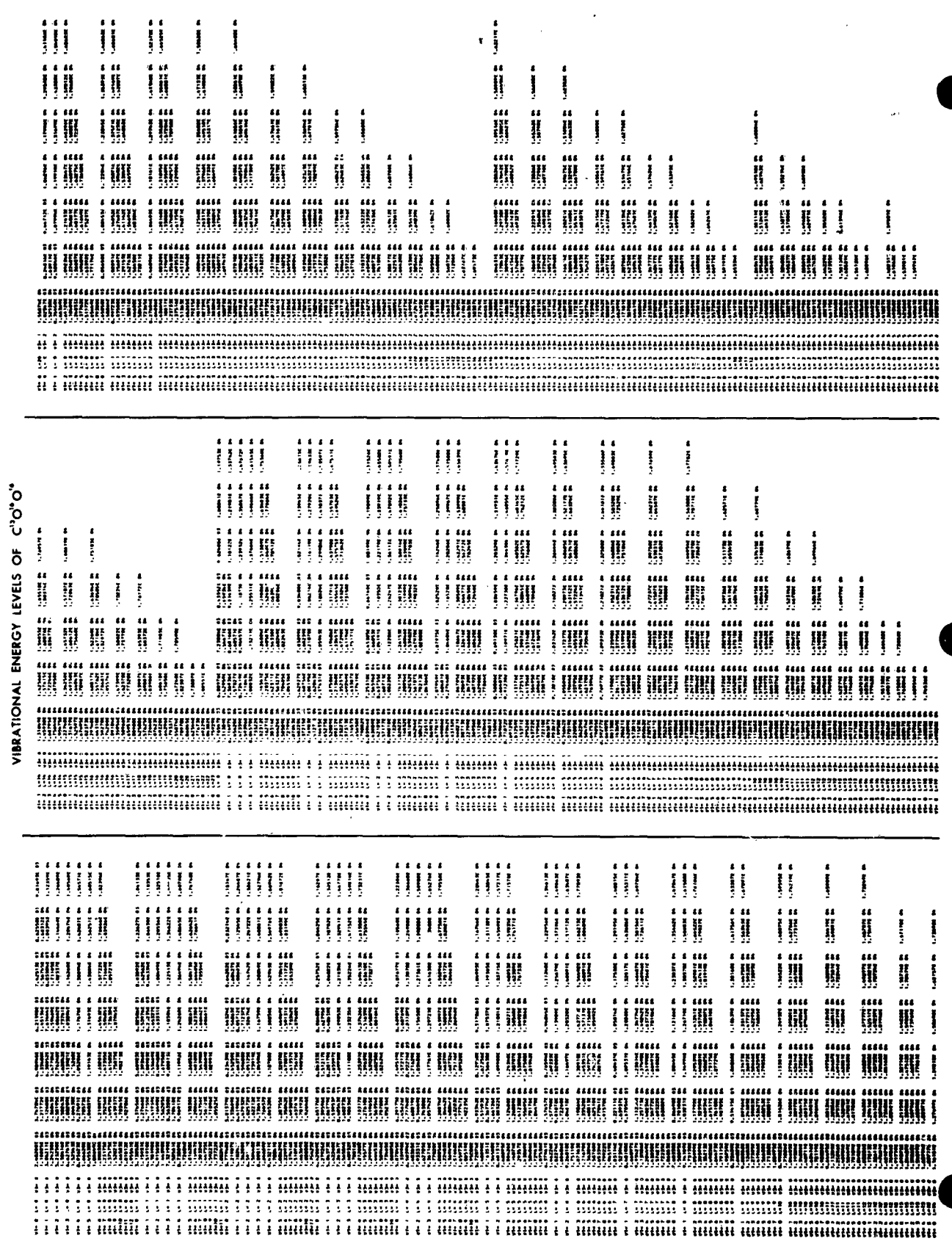

VIBRATIONAL ENERGY LEVELS OF $C^{12}O^{16}O^{18}$

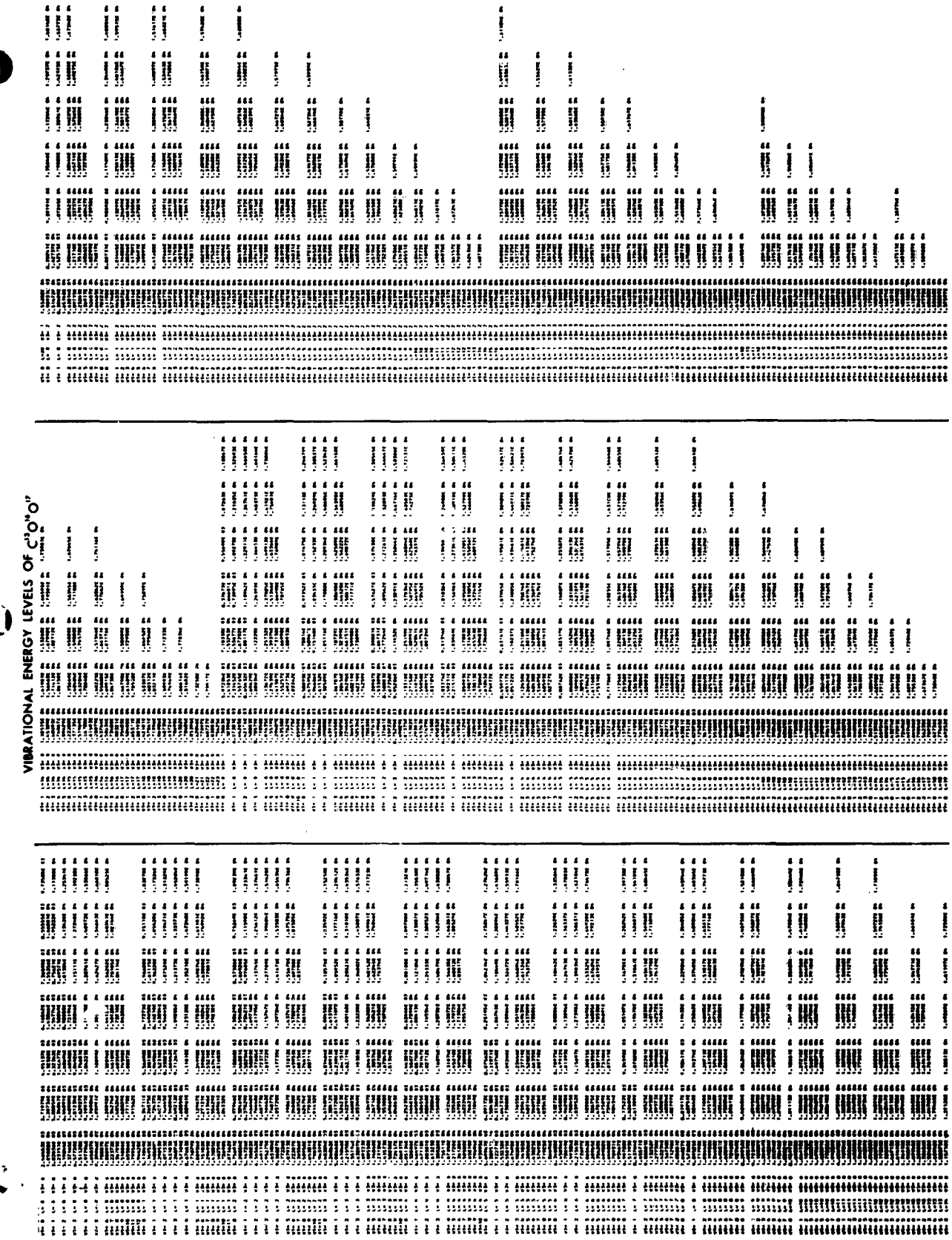

VIBRATIONAL ENERGY LEVELS OF C¹²O¹⁶O¹⁷

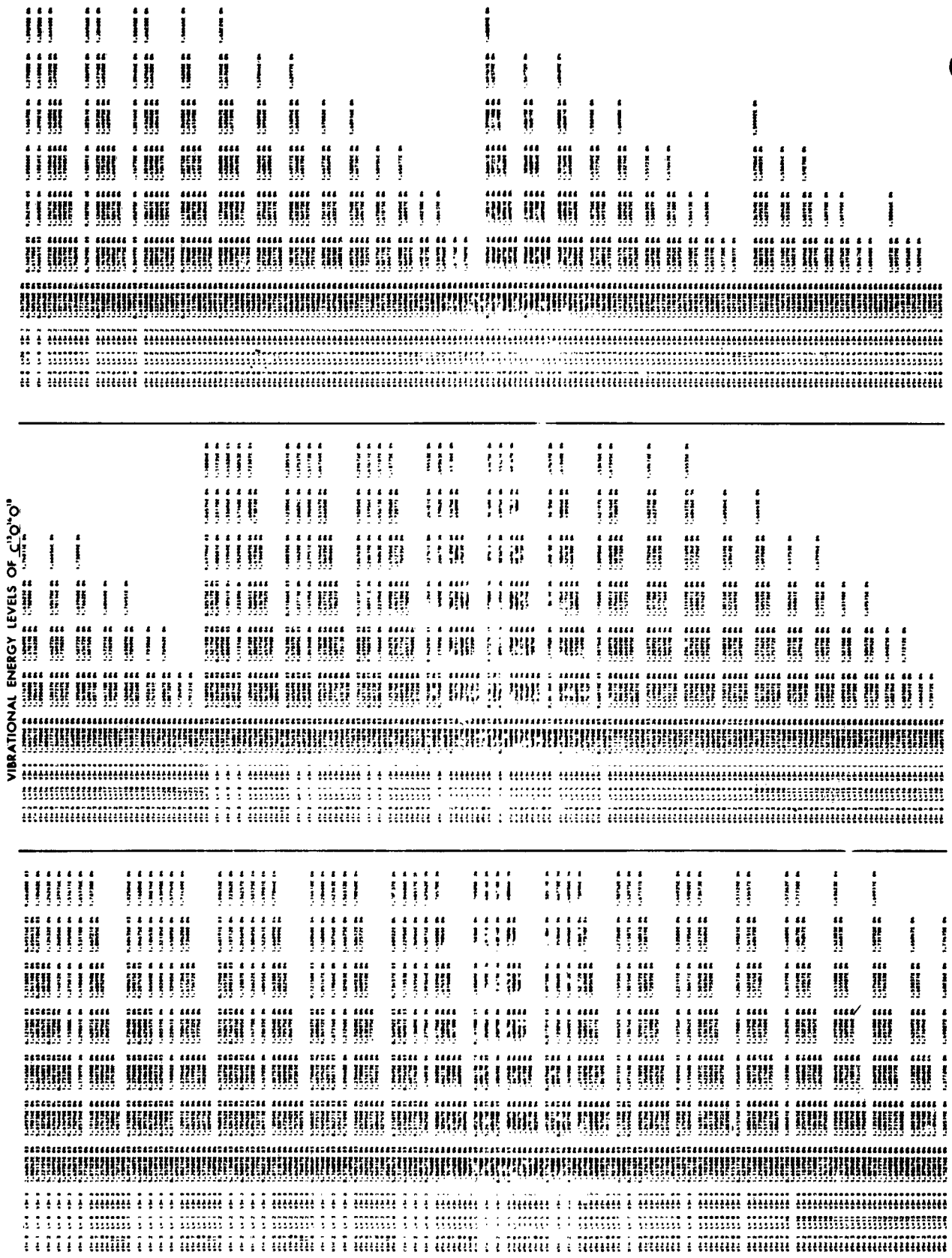

VIBRATIONAL ENERGY LEVELS OF $C^{13}O^{16}O^{18}$


VIBRATIONAL ENERGY LEVELS OF $C^{13}O^{17}O^{18}$


VIBRATIONAL ENERGY LEVELS OF C'2O'6O'8

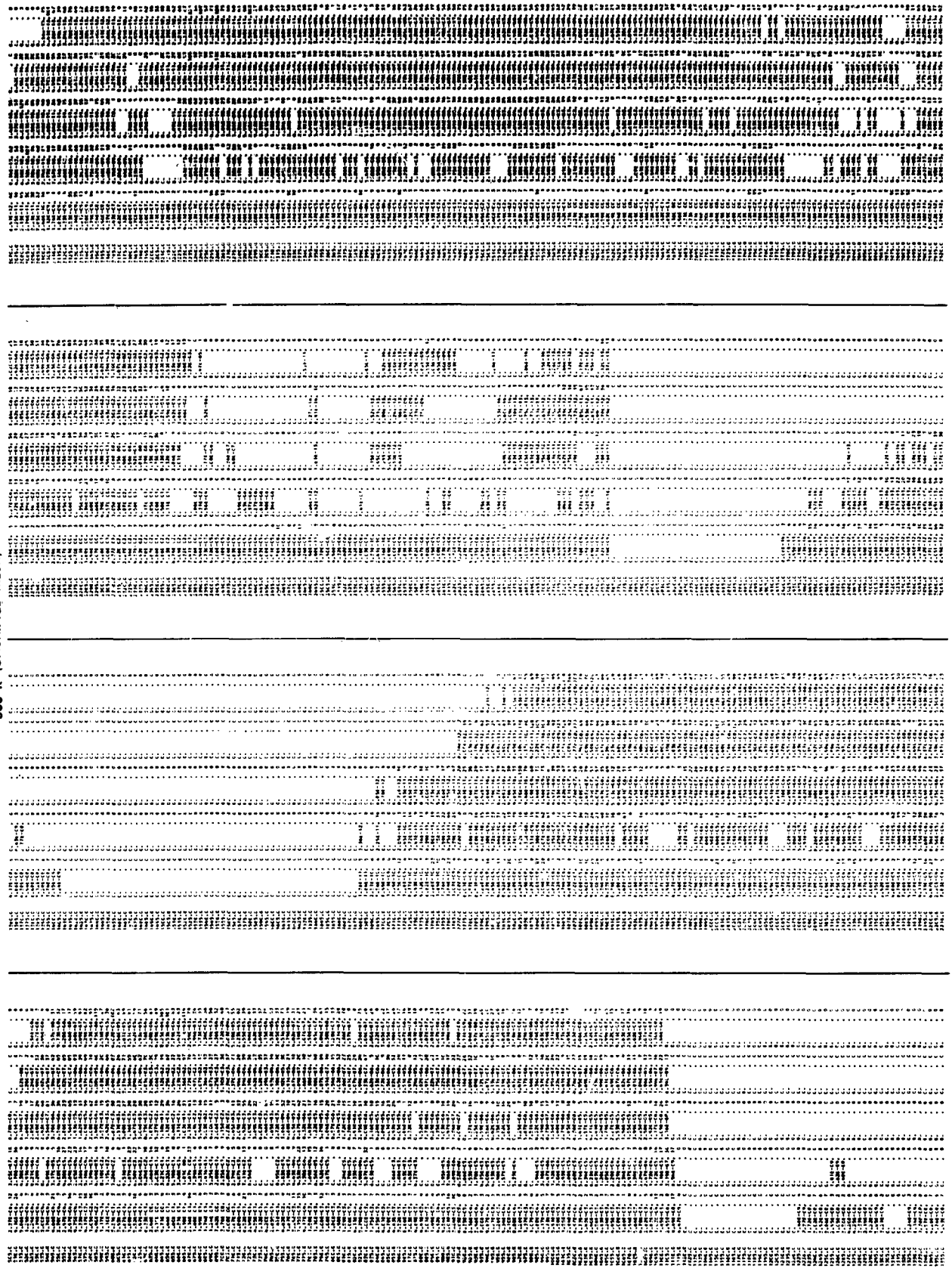

VIBRATIONAL ENERGY LEVELS OF C¹³O¹⁶O


VIBRATIONAL ENERGY LEVELS OF $C^{13}O^{16}O$

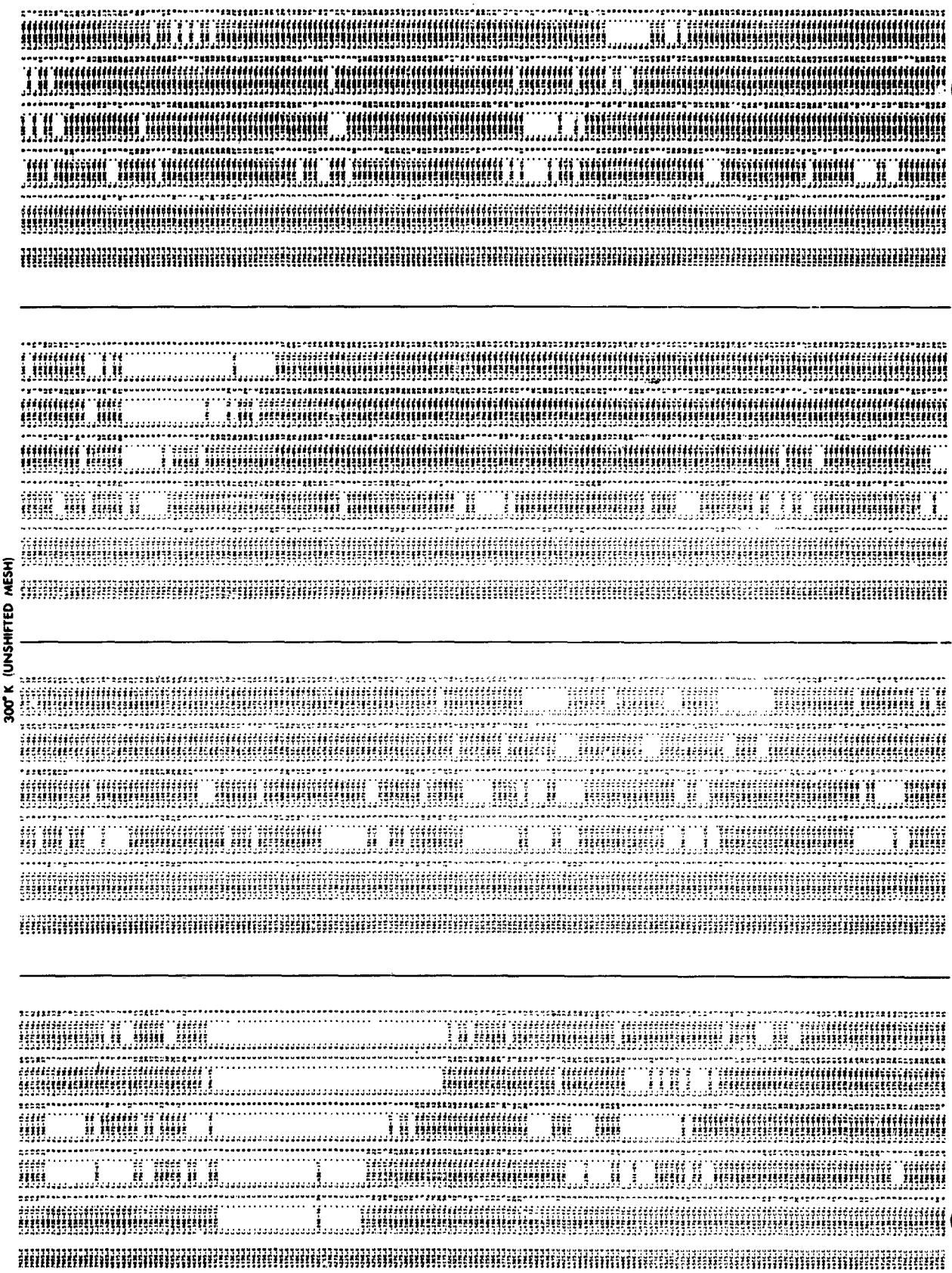

VIBRATIONAL ENERGY LEVELS OF $C^{13}O^{16}O$

APPENDIX B

THE COEFFICIENTS ξ_o AND n FOR THE TOP FIVE INTENSITY DECADES

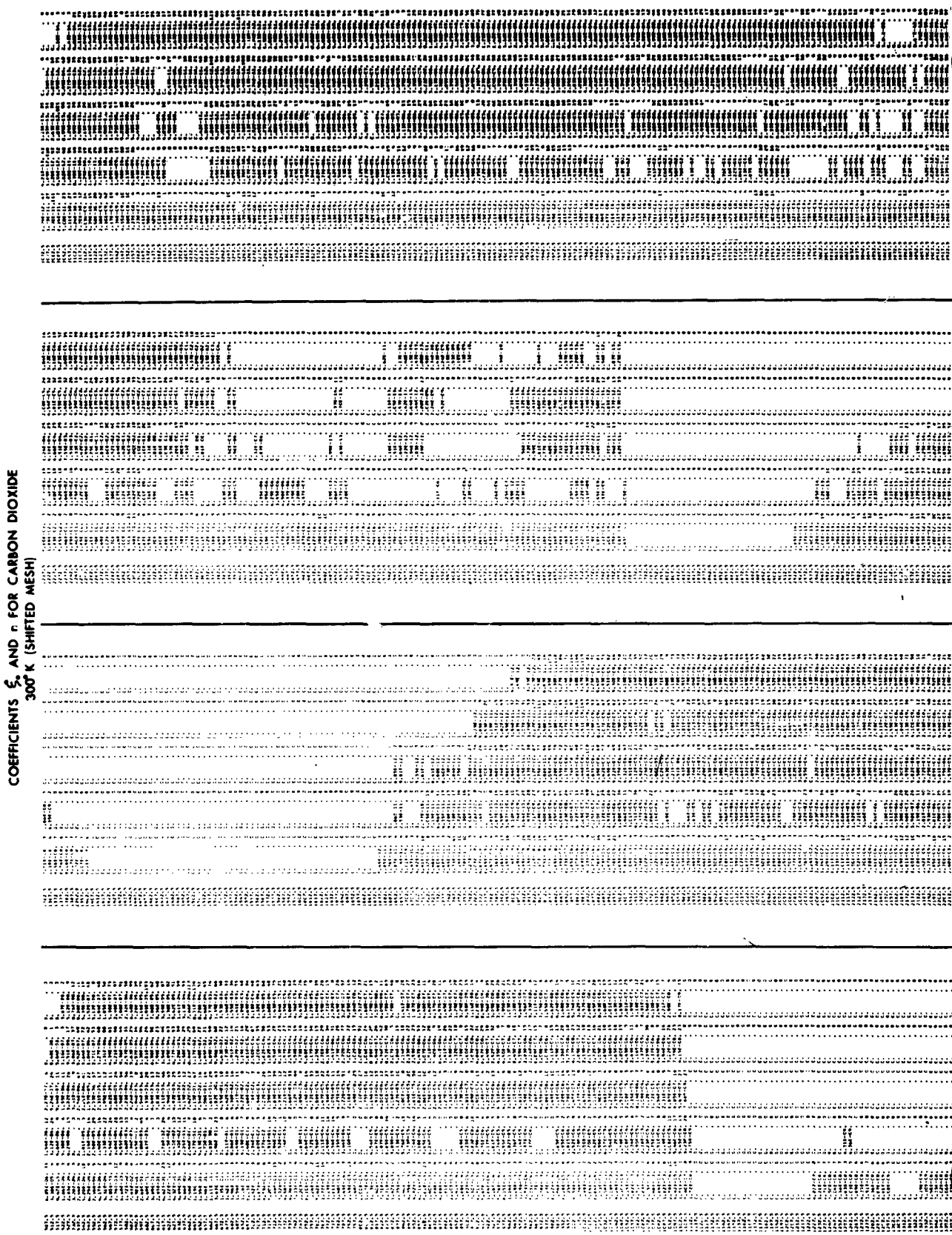


COEFFICIENTS ξ, AND n FOR CARBON DIOXIDE
300° K (UNSHIFTED MESH)

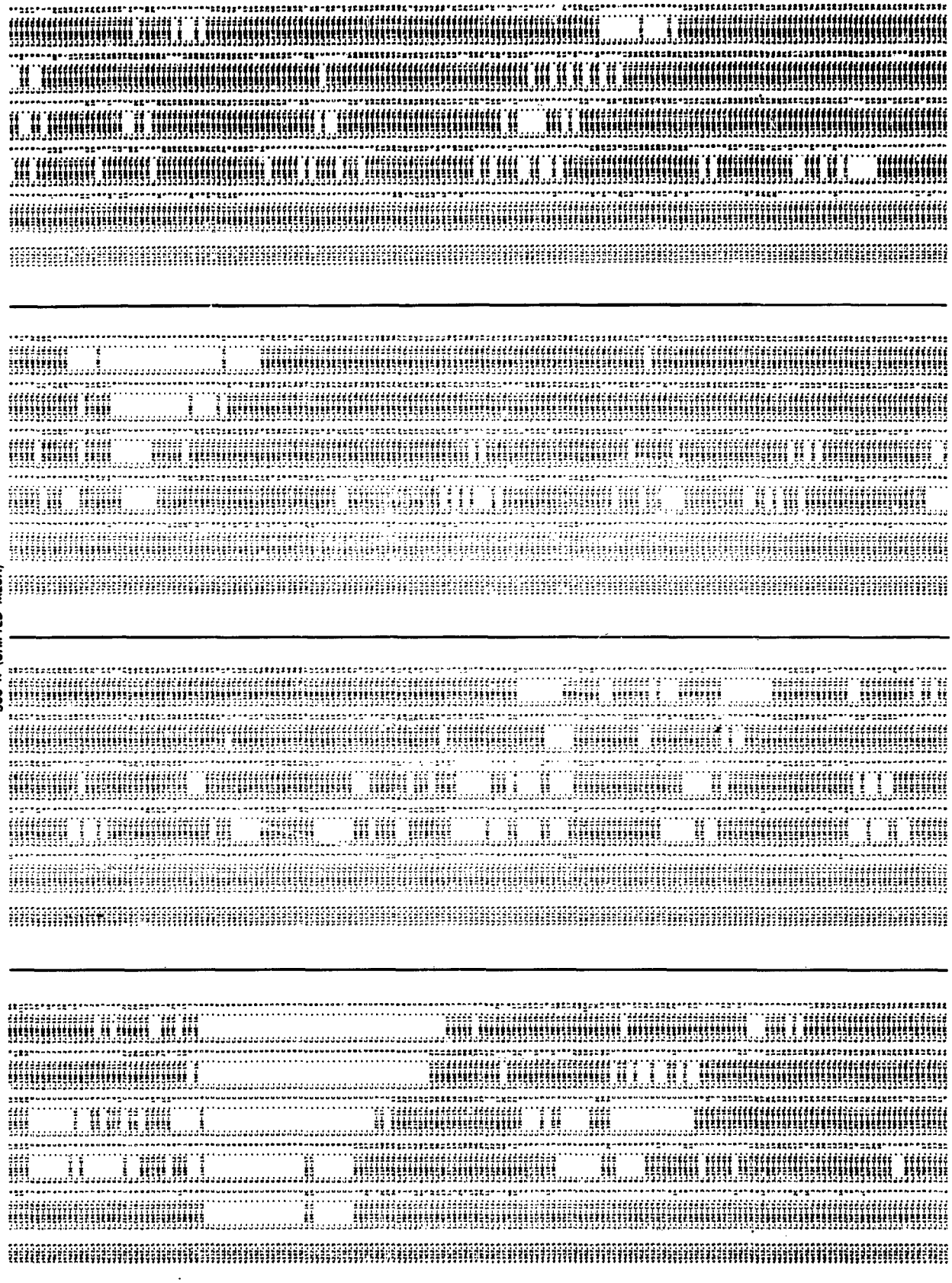


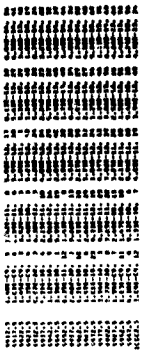
COEFFICIENTS b_i AND n FOR CARBON DIOXIDE
300°K (UNSHIFTED MESH)

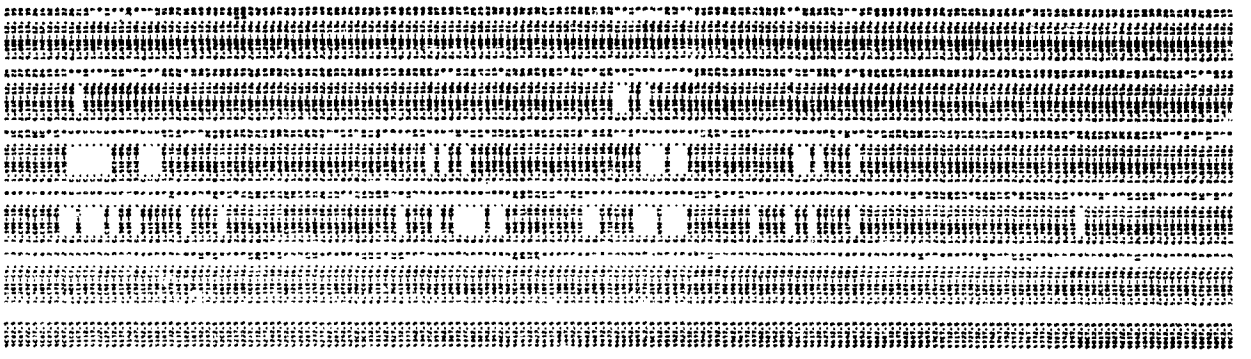
COEFFICIENTS ξ, AND n FOR CARBON DIOXIDE
300° K (UNSHIFTED MESH)


COEFFICIENTS ξ, AND n FOR CARBON DIOXIDE
300° K (SHIFTED MESH)

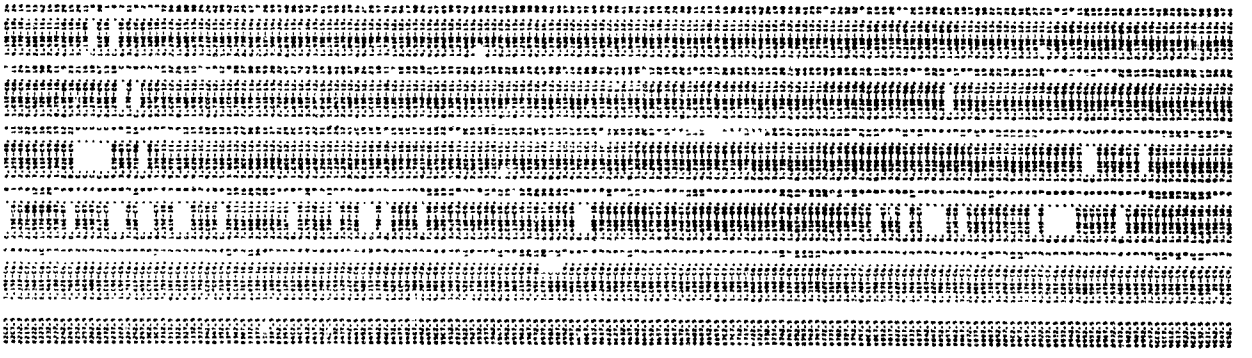
COEFFICIENTS ζ, AND n FOR CARBON DIOXIDE
300° K (SHIFTED MESH)

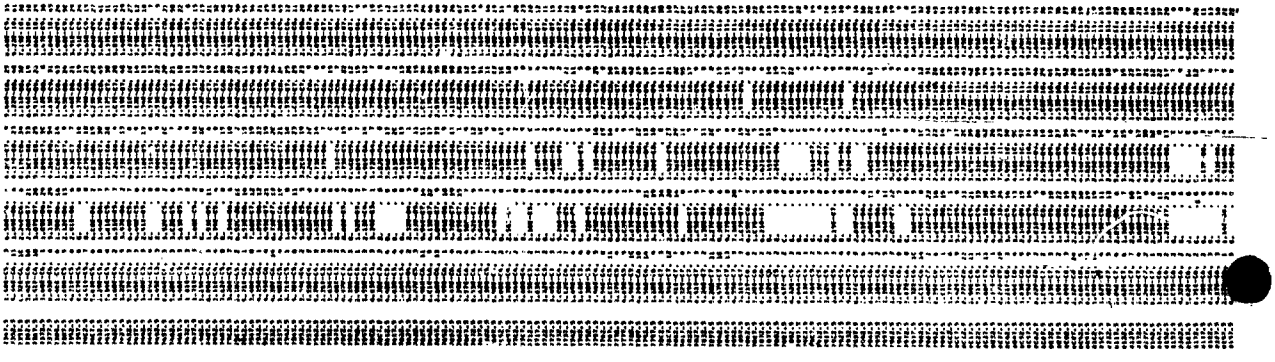


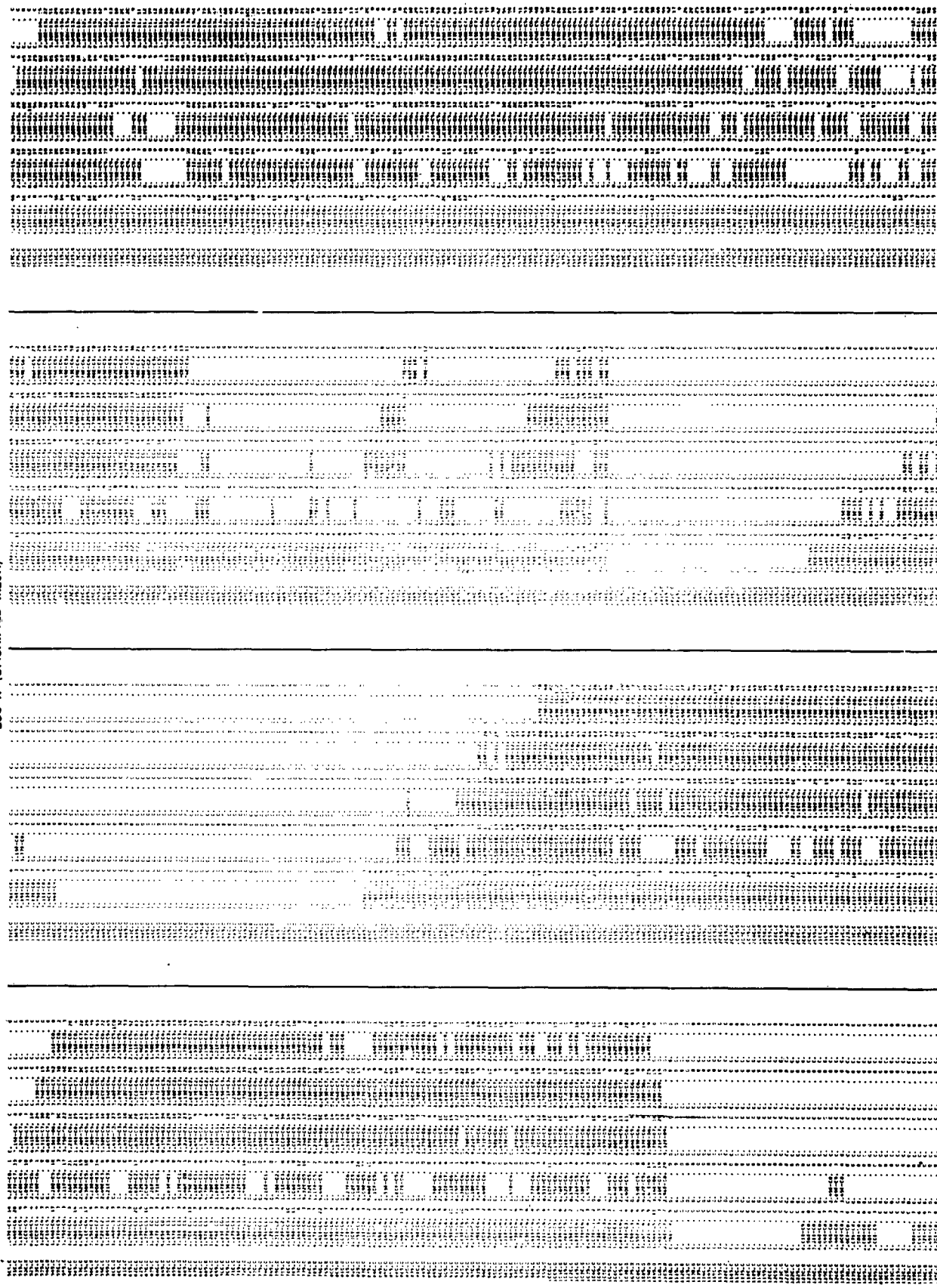




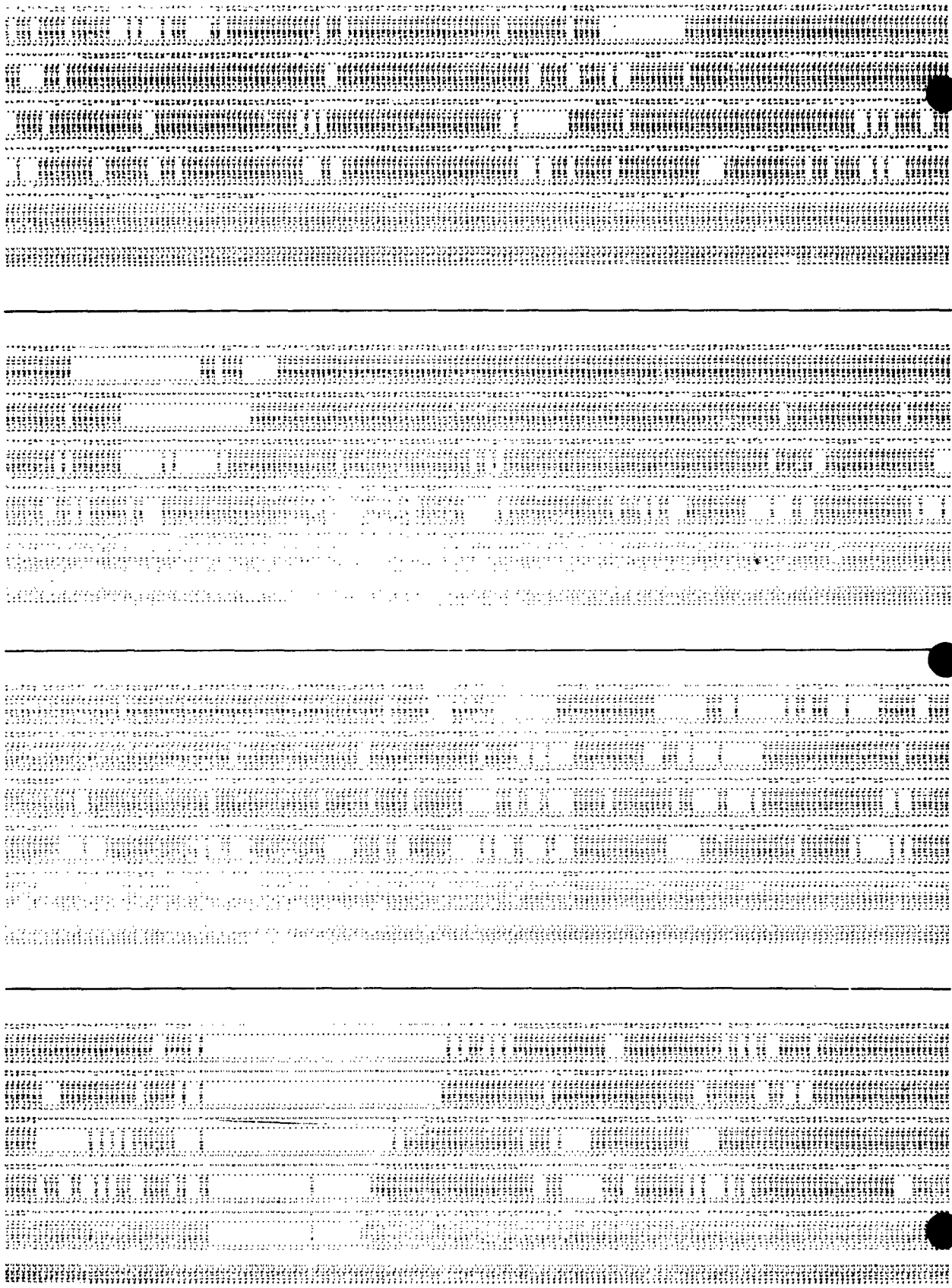
COEFFICIENTS ξ, AND n FOR CARBON DIOXIDE
300° K (SHIFTED MESH)





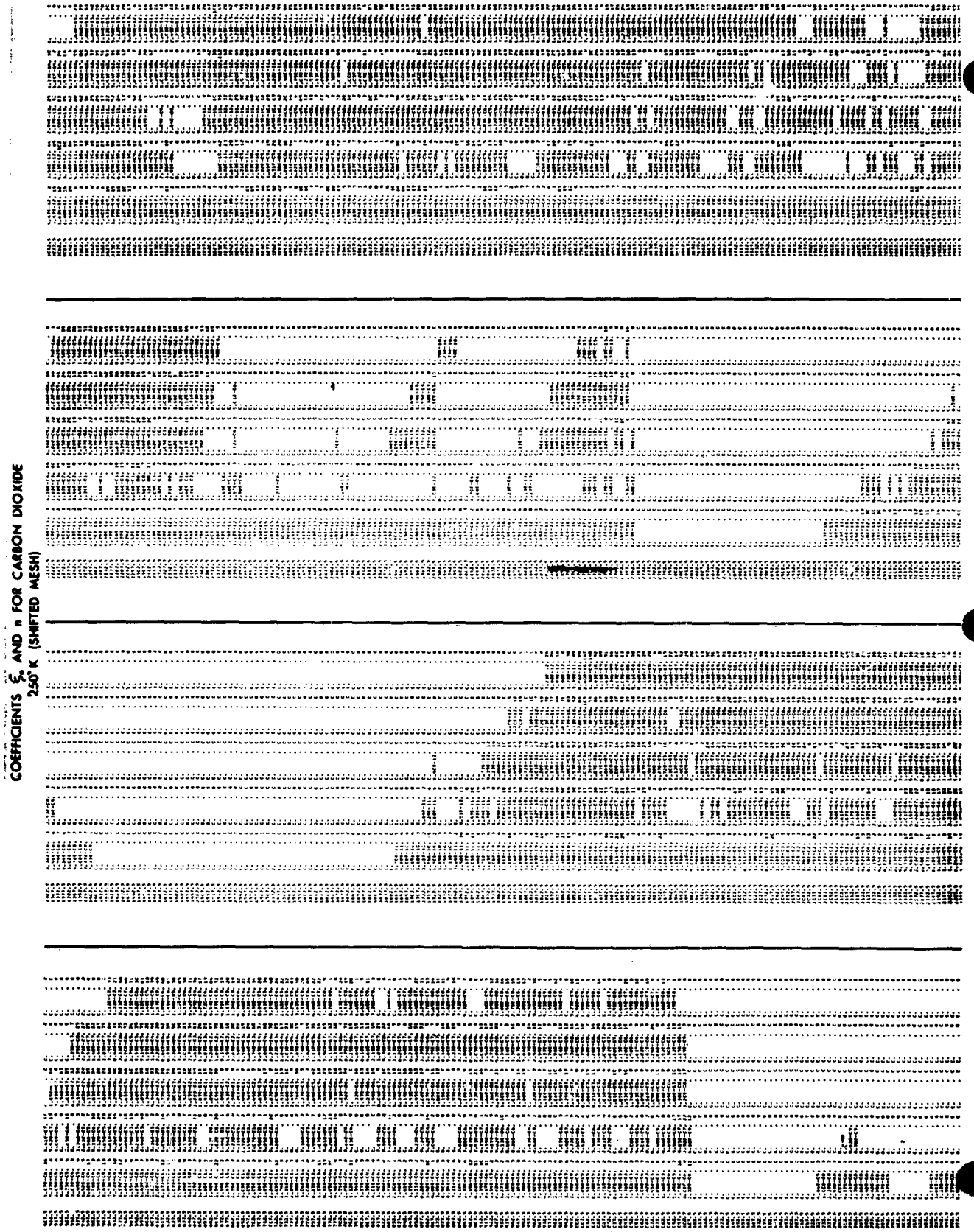


COEFFICIENTS ϵ_n AND γ_n FOR CARBON DIOXIDE
250° K (UNSHIFTED MESH)

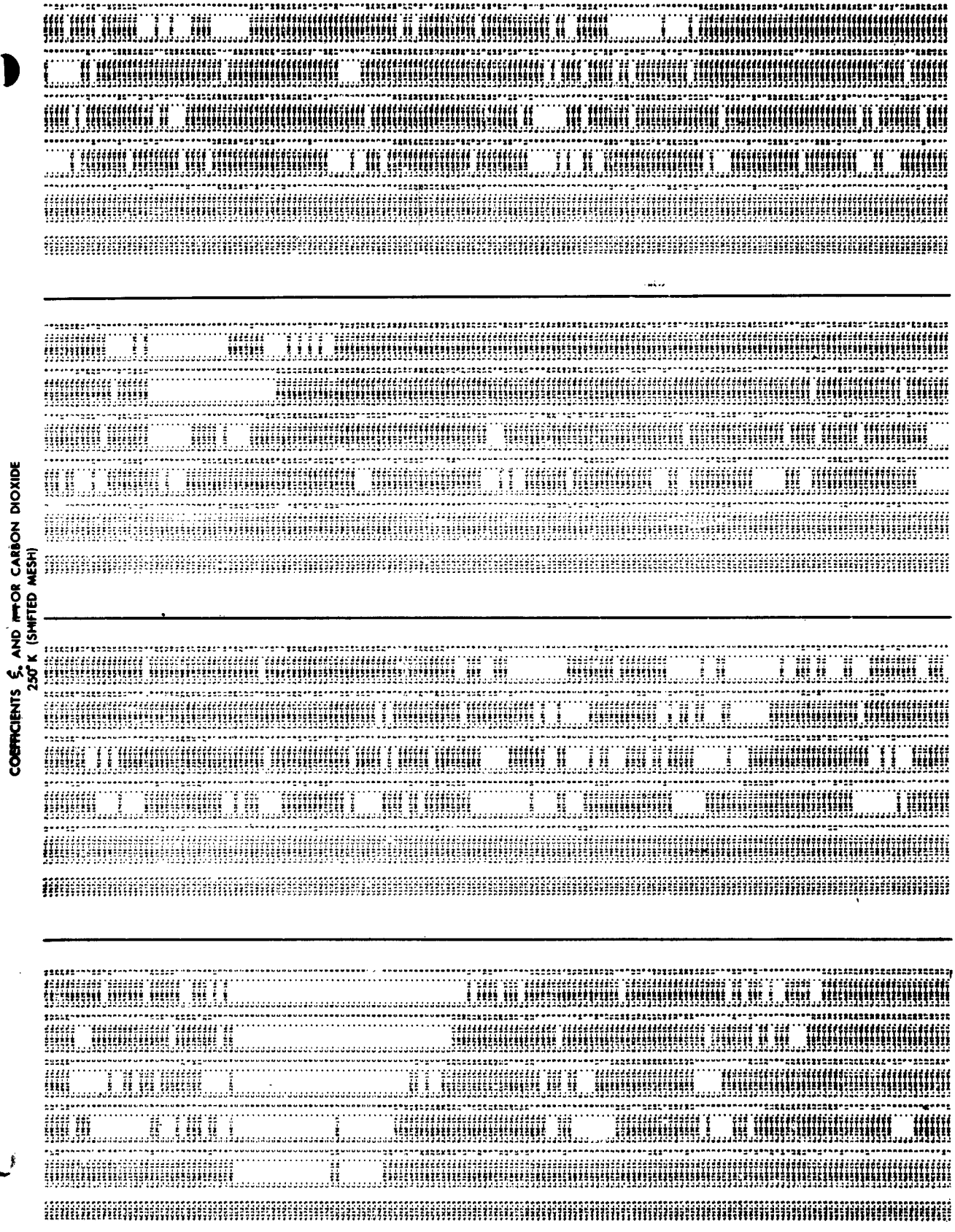


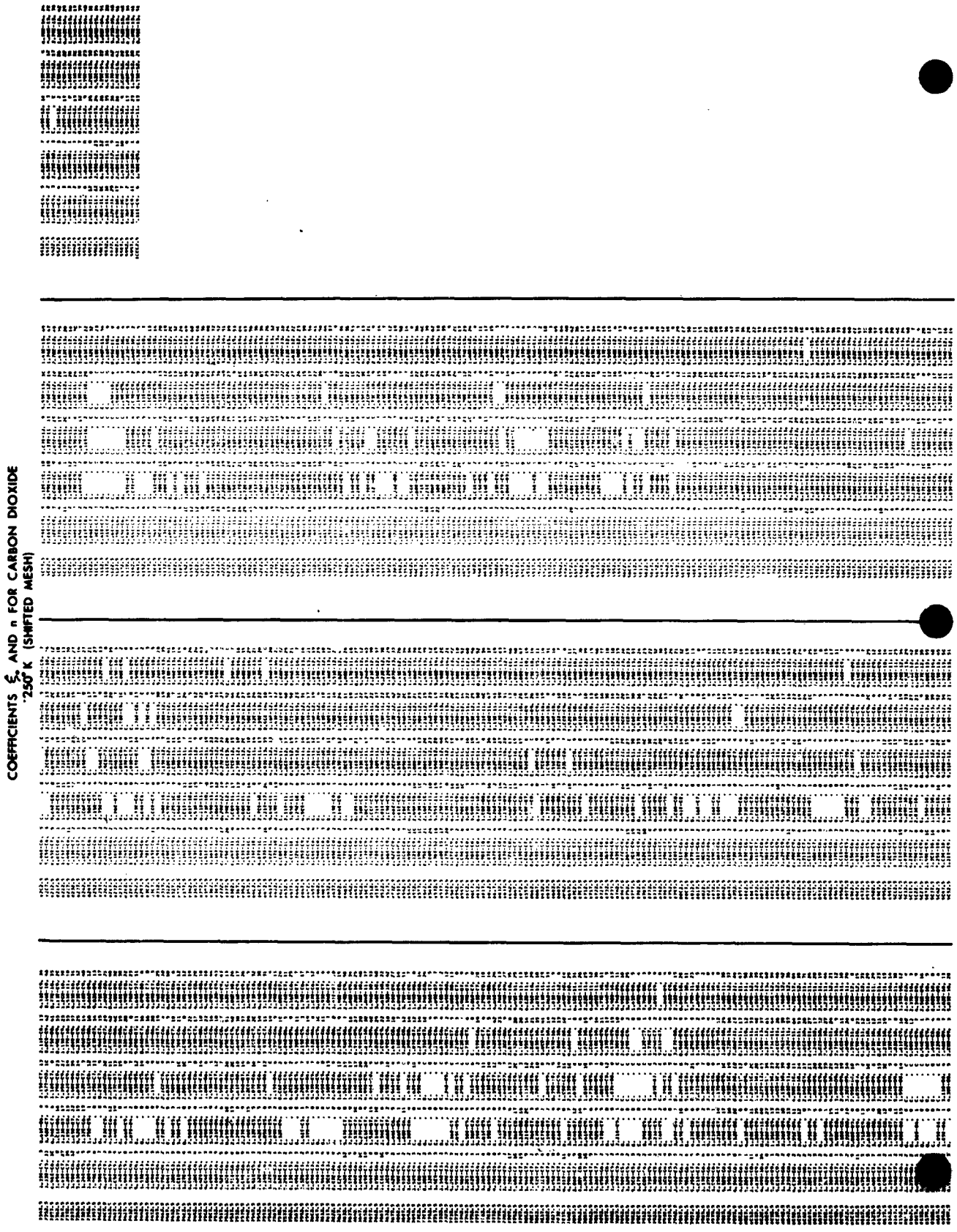
COEFFICIENTS ξ_o AND n FOR CARBON DIOXIDE
250°K (UNSHIFTED MESH)

COEFFICIENTS ξ_n AND $\bar{\nu}_n$ FOR CARBON DIOXIDE
250° K (UNSHIFTED MESH)

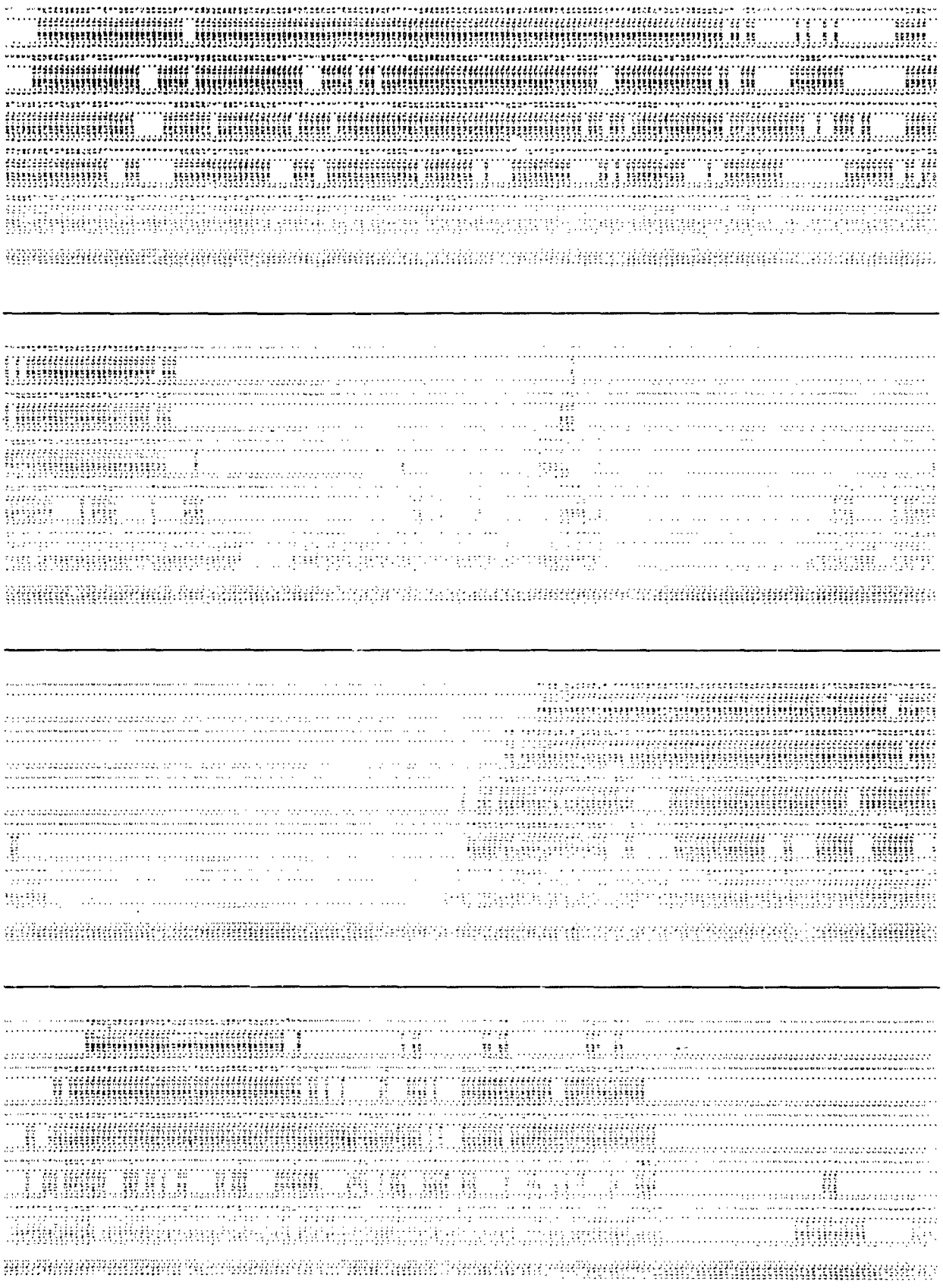


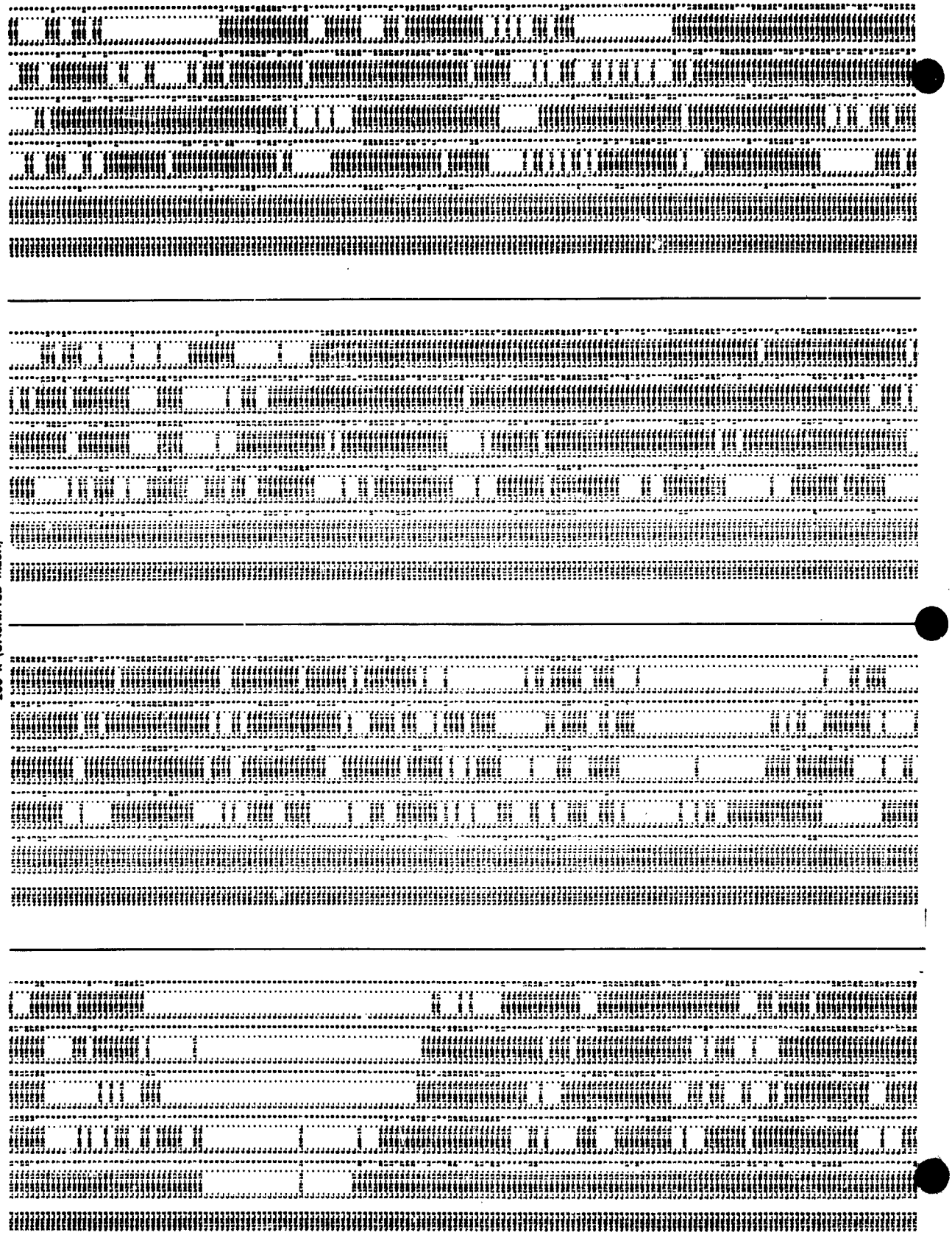
COEFFICIENTS ξ, AND n FOR CARBON DIOXIDE
250° K (SHIFTED MESH)


COEFFICIENTS ξ_i AND m_i FOR CARBON DIOXIDE
250° K (SHIFTED MESH)


COEFFICIENTS ξ, AND n FOR CARBON DIOXIDE
250° K (SHIFTED MESH)

COEFFICIENTS ζ, AND n FOR CARBON DIOXIDE
200°K (UNSHIFTED MESH)





COEFFICIENTS ζ, AND n FOR CARBON DIOXIDE
200° K (UNSHIFTED MESH)

COEFFICIENTS ξ, AND n FOR CARBON DIOXIDE
200°K (UNSHIFTED MESH)

COEFFICIENTS ξ, AND n FOR CARBON DIOXIDE
200°K (SHIFTED MESH)

COEFFICIENTS ξ, AND n FOR CARBON DIOXIDE
200° K (SHIFTED MESH)

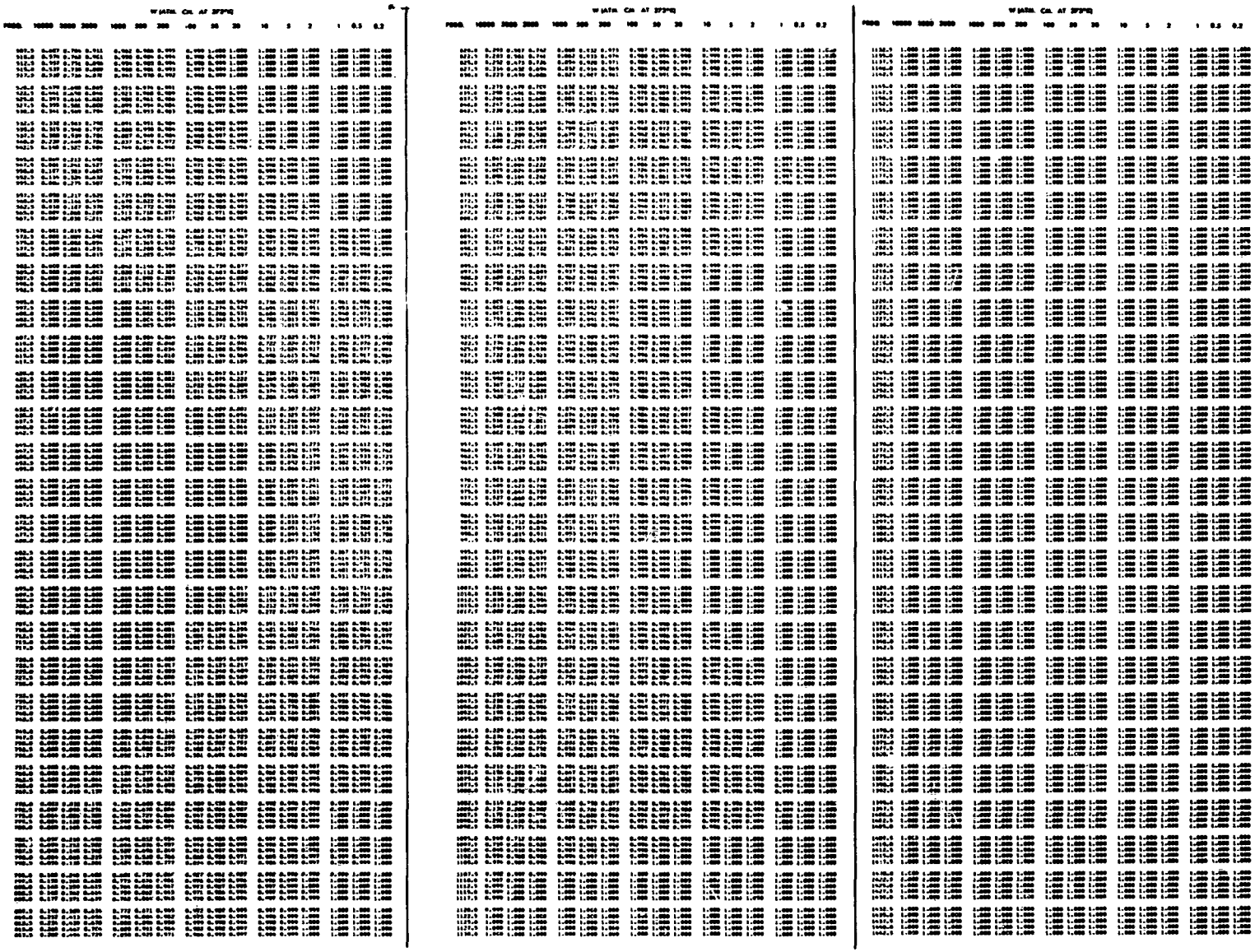
COEFFICIENTS ξ, AND n FOR CARBON DIOXIDE
200° K (SHIFTED MESH)

APPENDIX C

CARBON DIOXIDE TRANSMISSIONS BASED ON THE BENEDICT LINE SHAPE

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 300°K

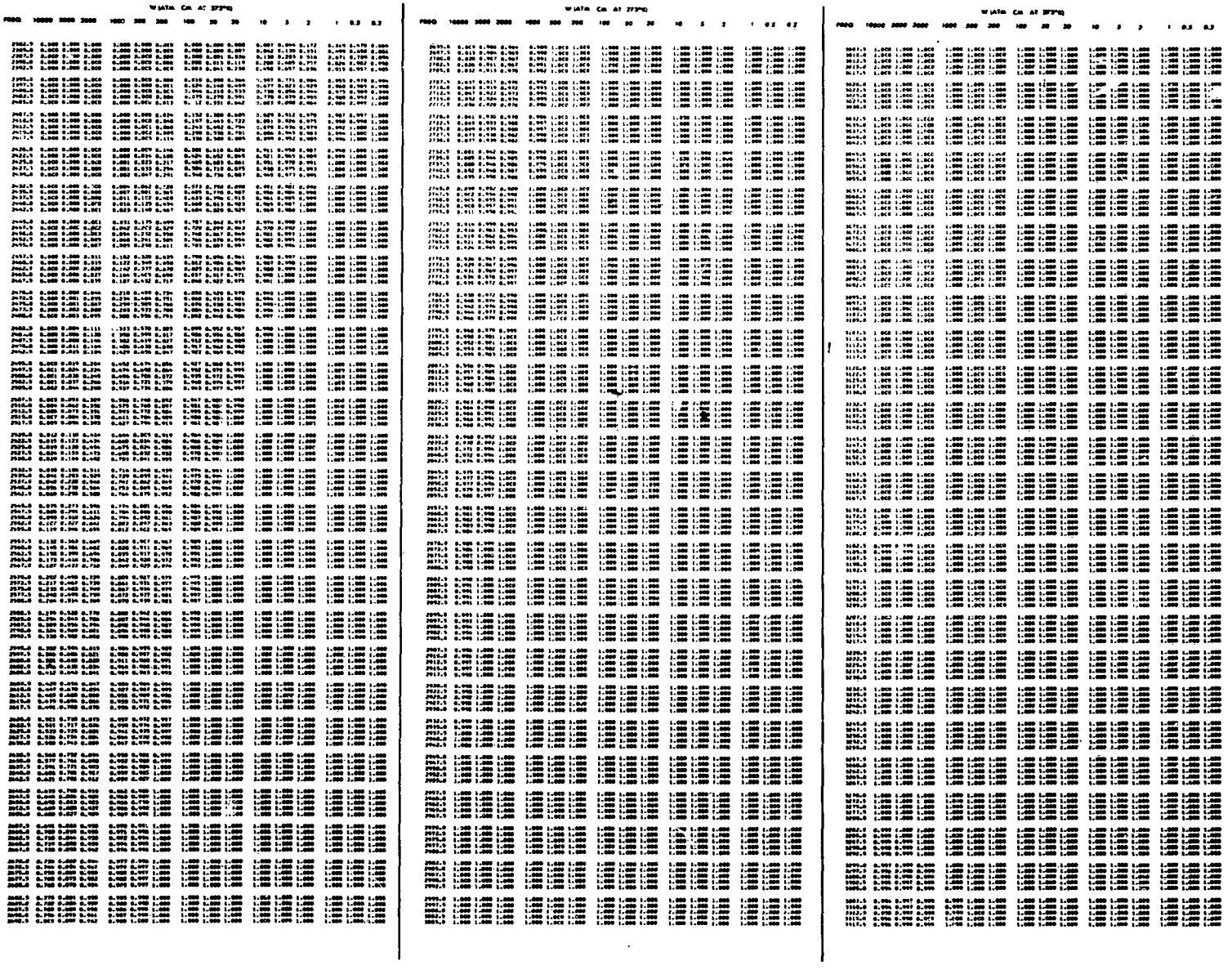


CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 300°K

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 300°K

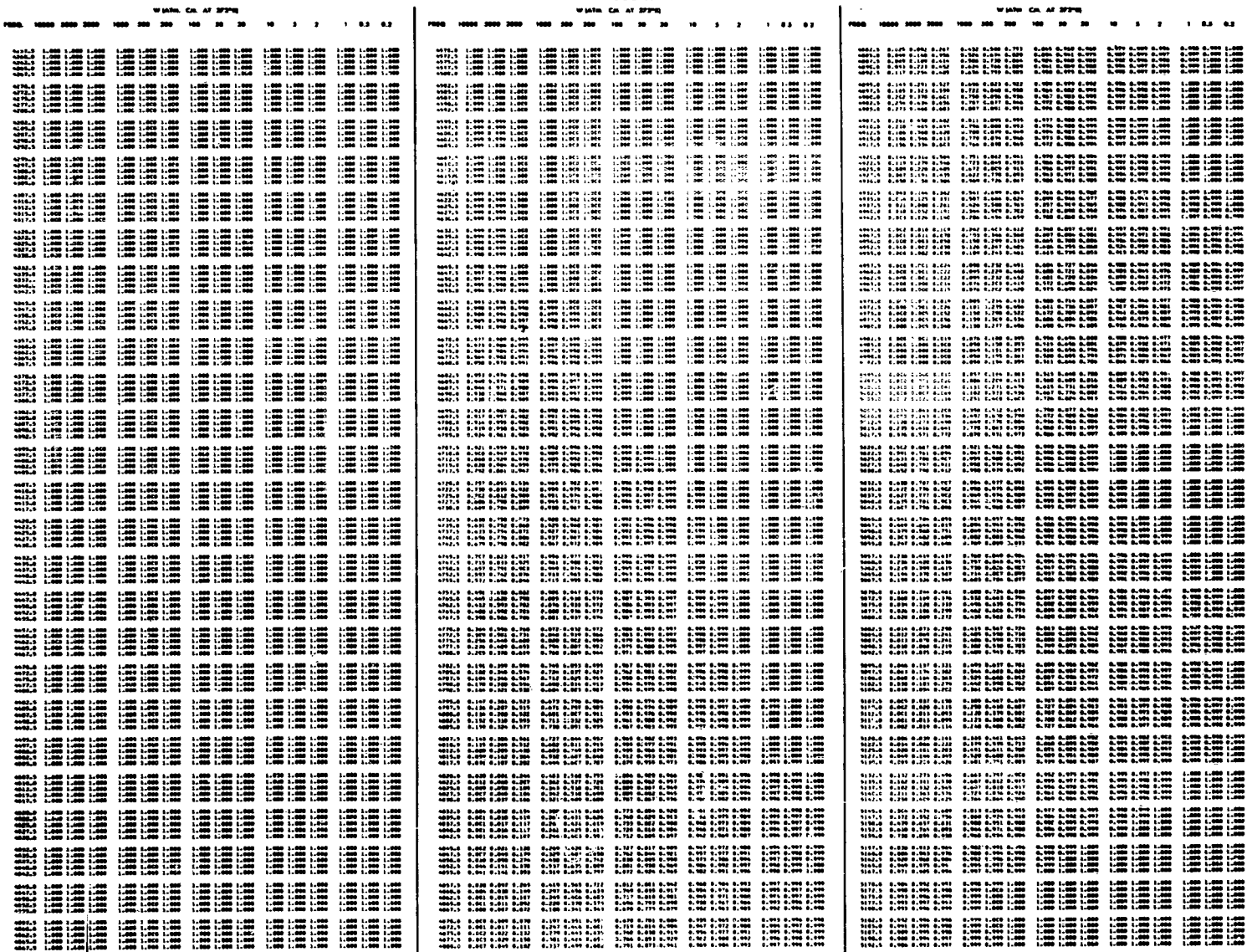


CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 300°K

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

$\bar{T}$ = 300°K

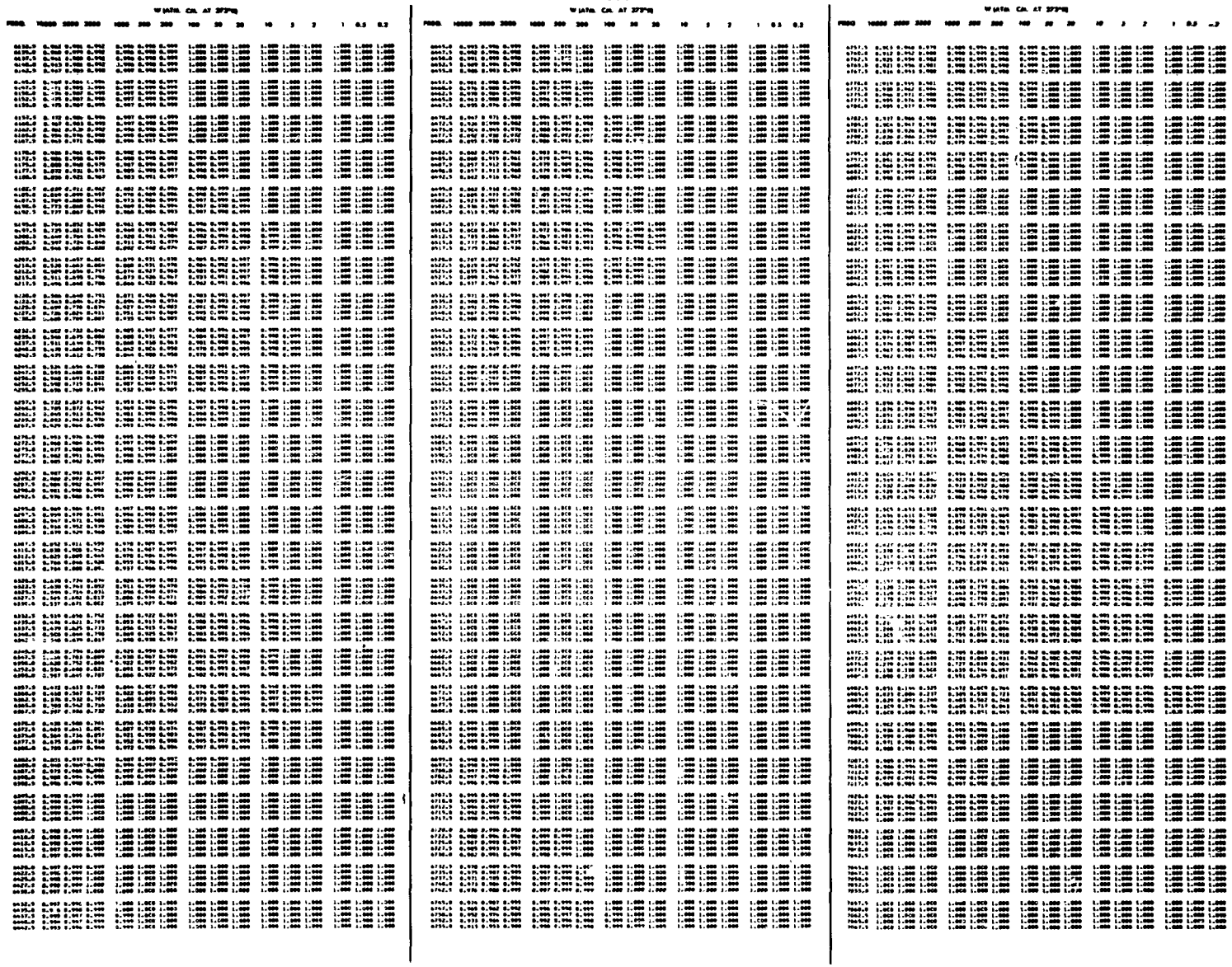


CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 300°K

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 300°K

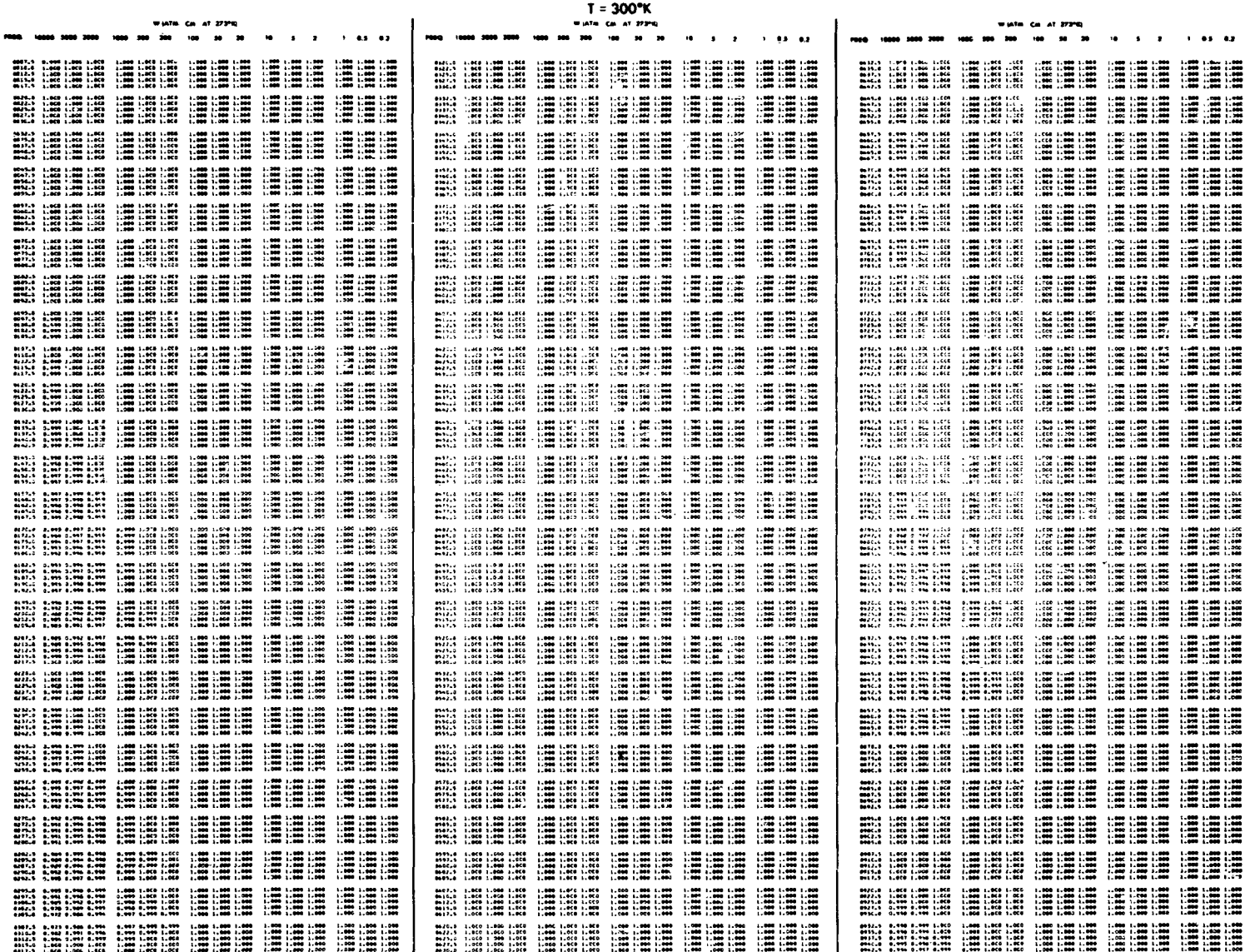


CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 300°K

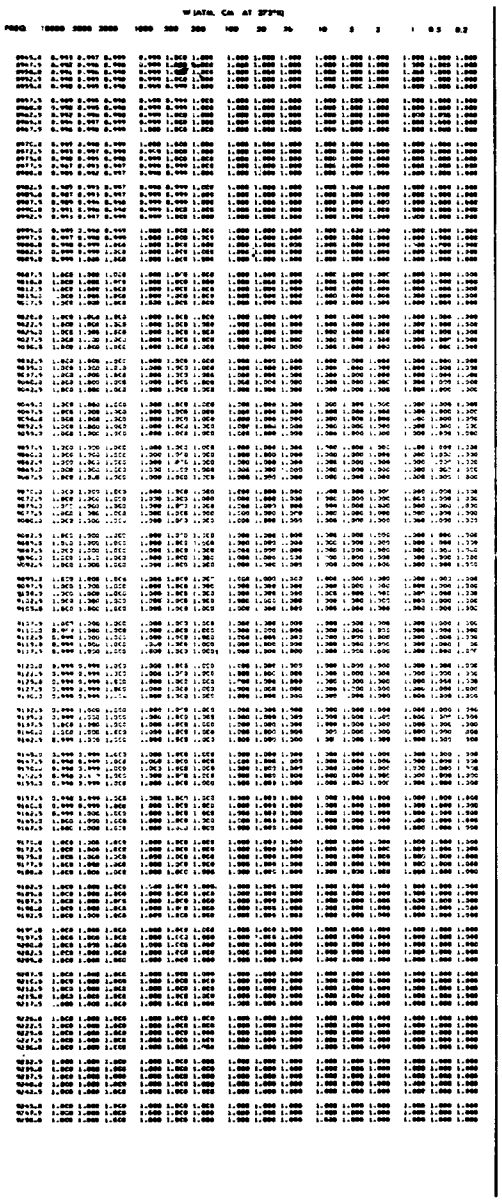
CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

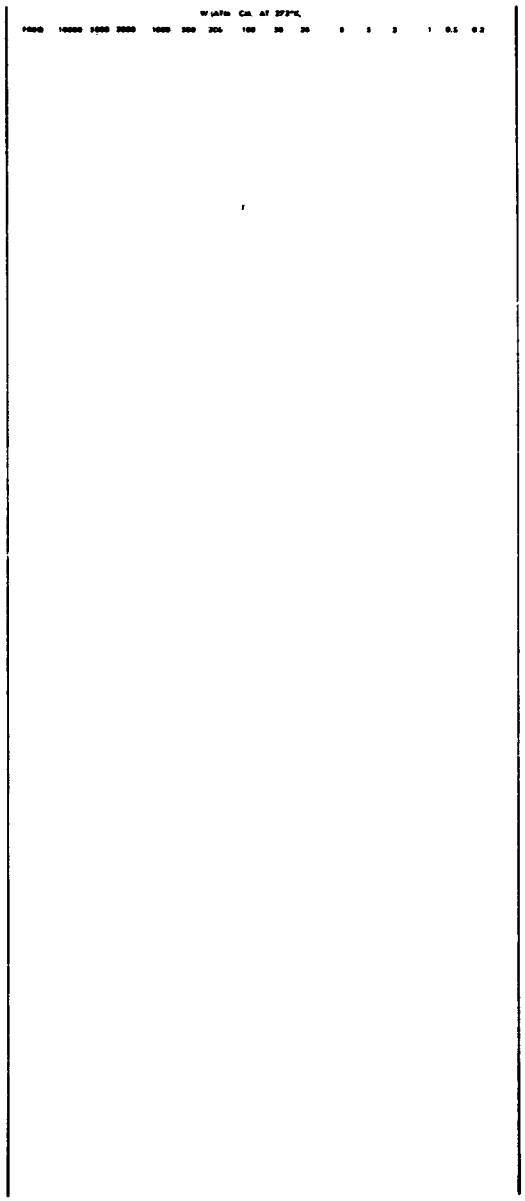
T = 300°K

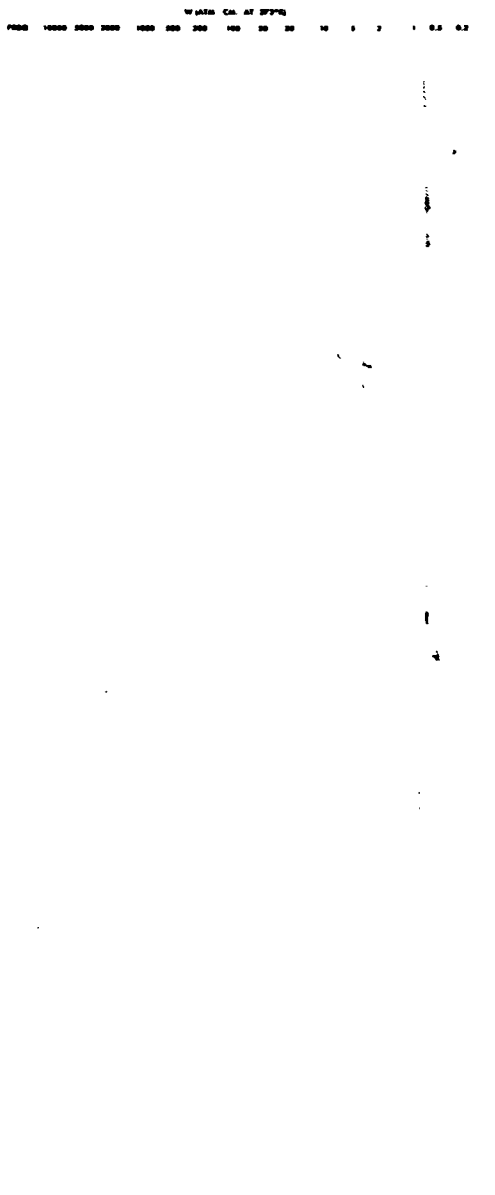


CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 300°K

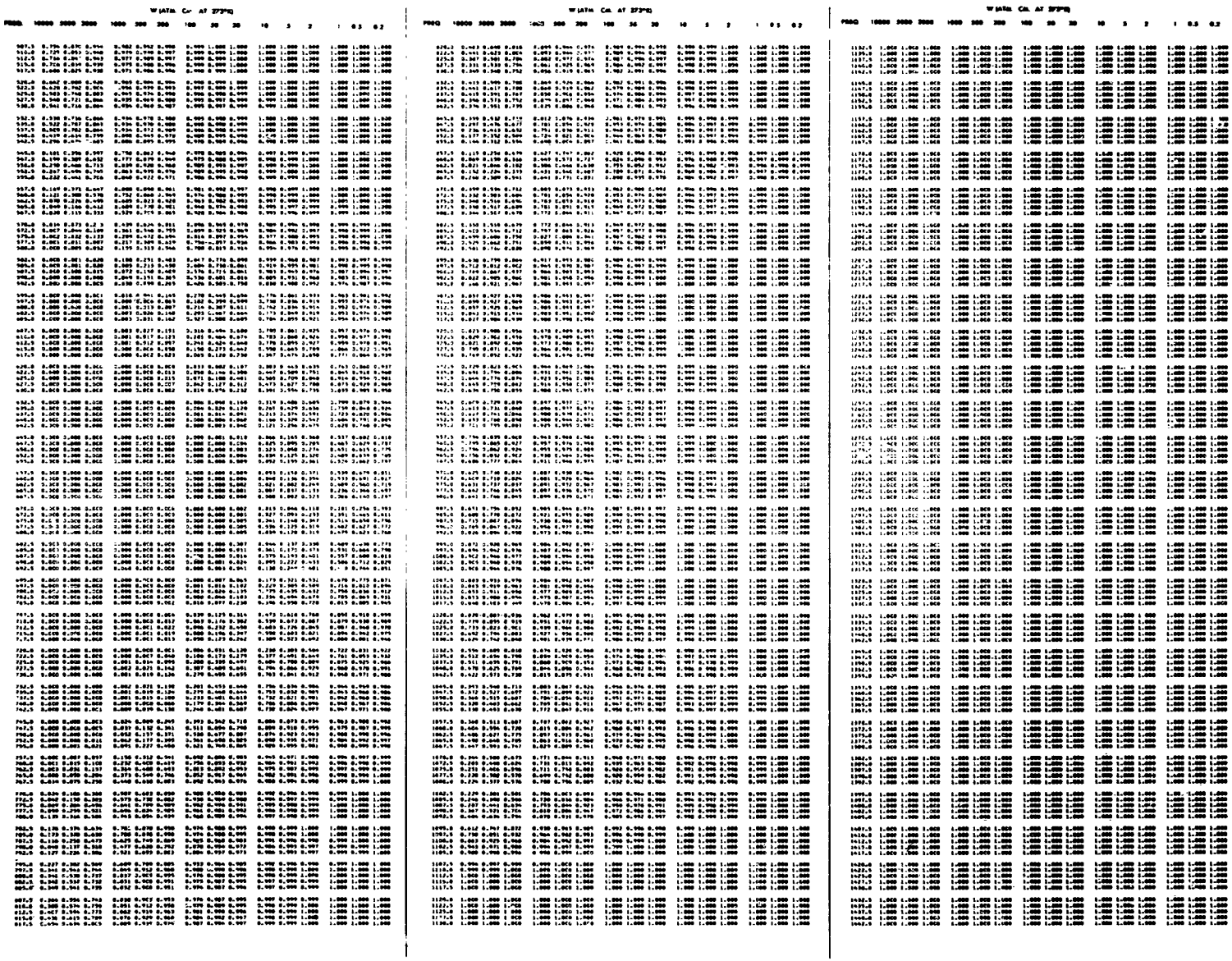






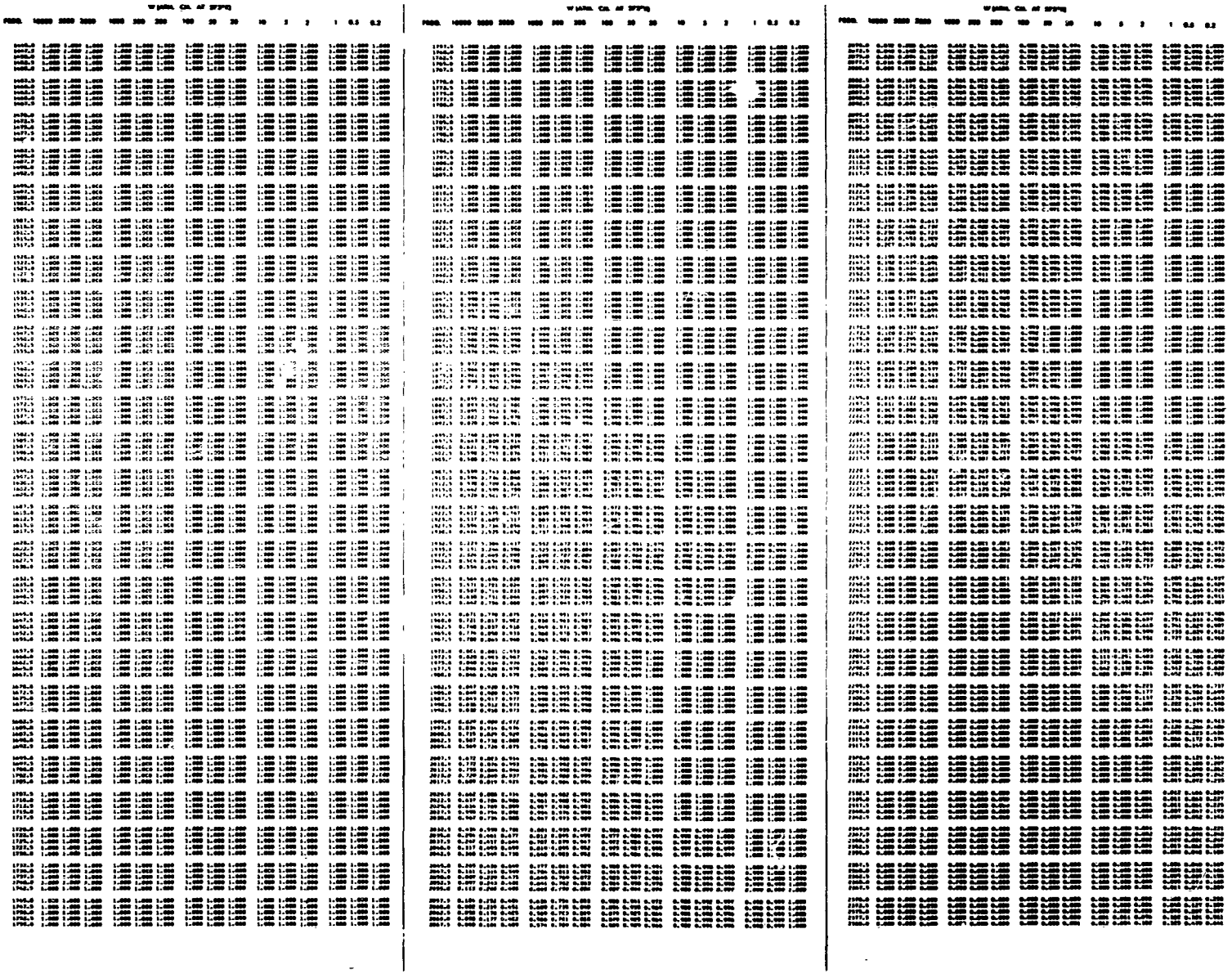
CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T = 300°K



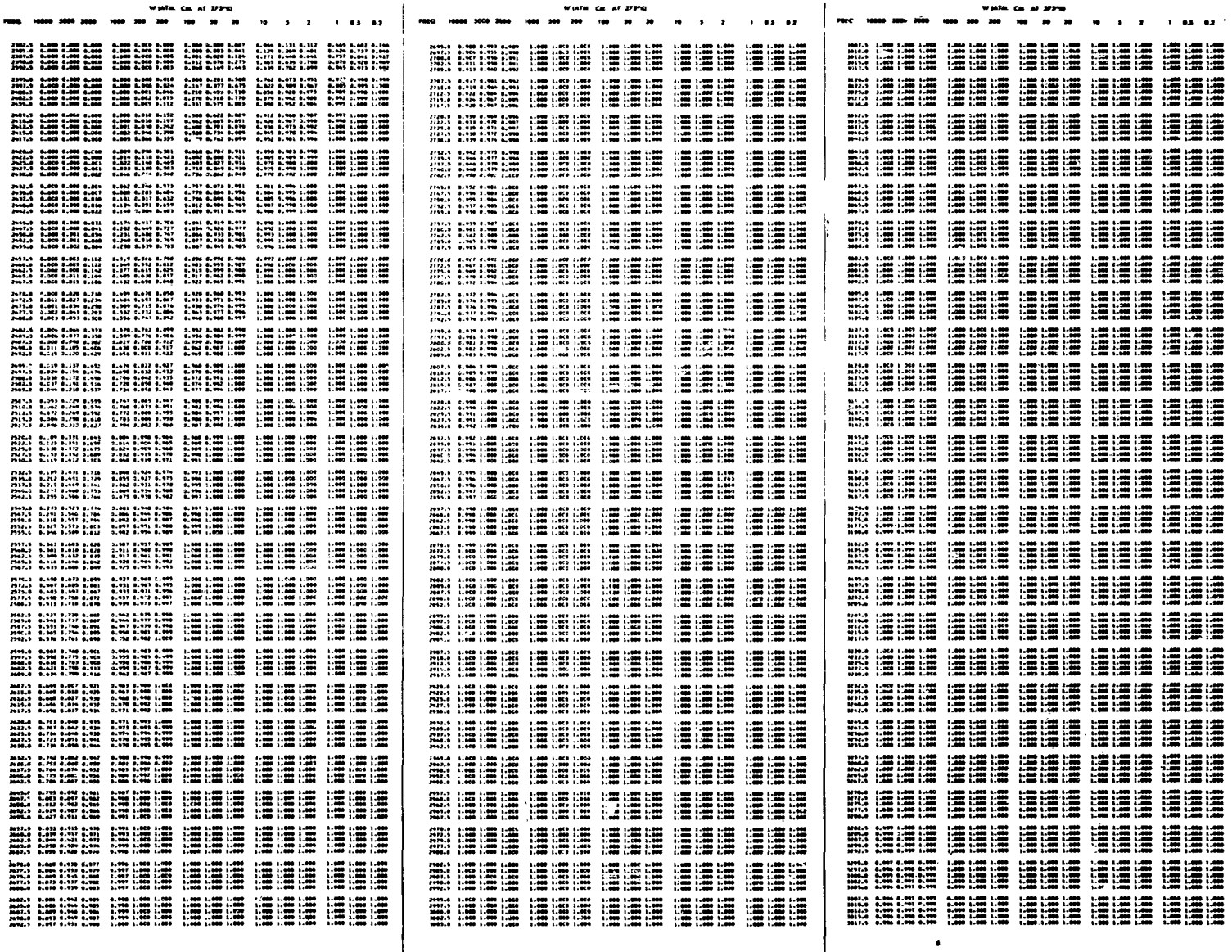
CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T = 300°K



CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T = 300°K

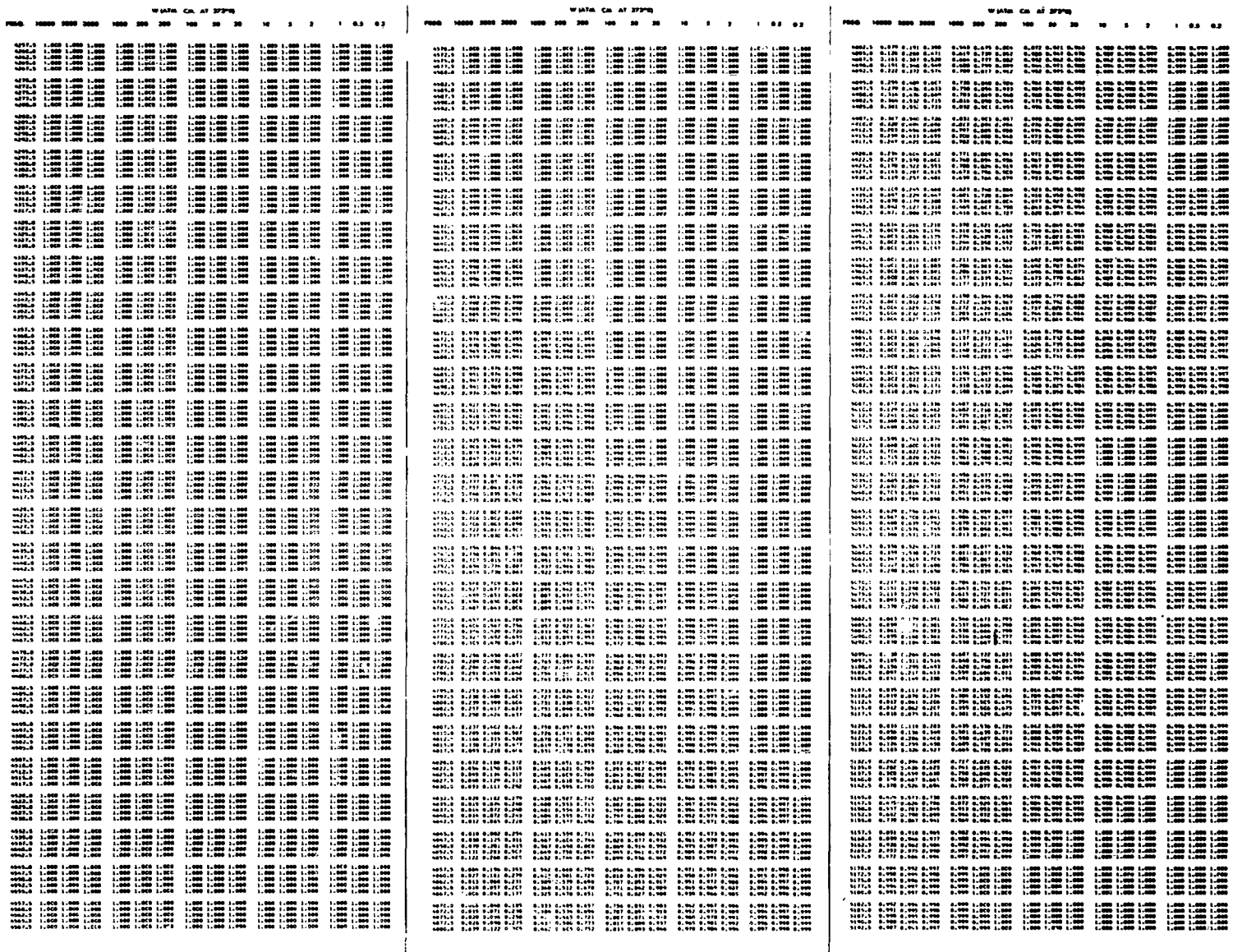


CARBON DIOXIDE AT 0.30 ATMOSPHERE PRESSURE

T = 300°K

CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T = 300°K

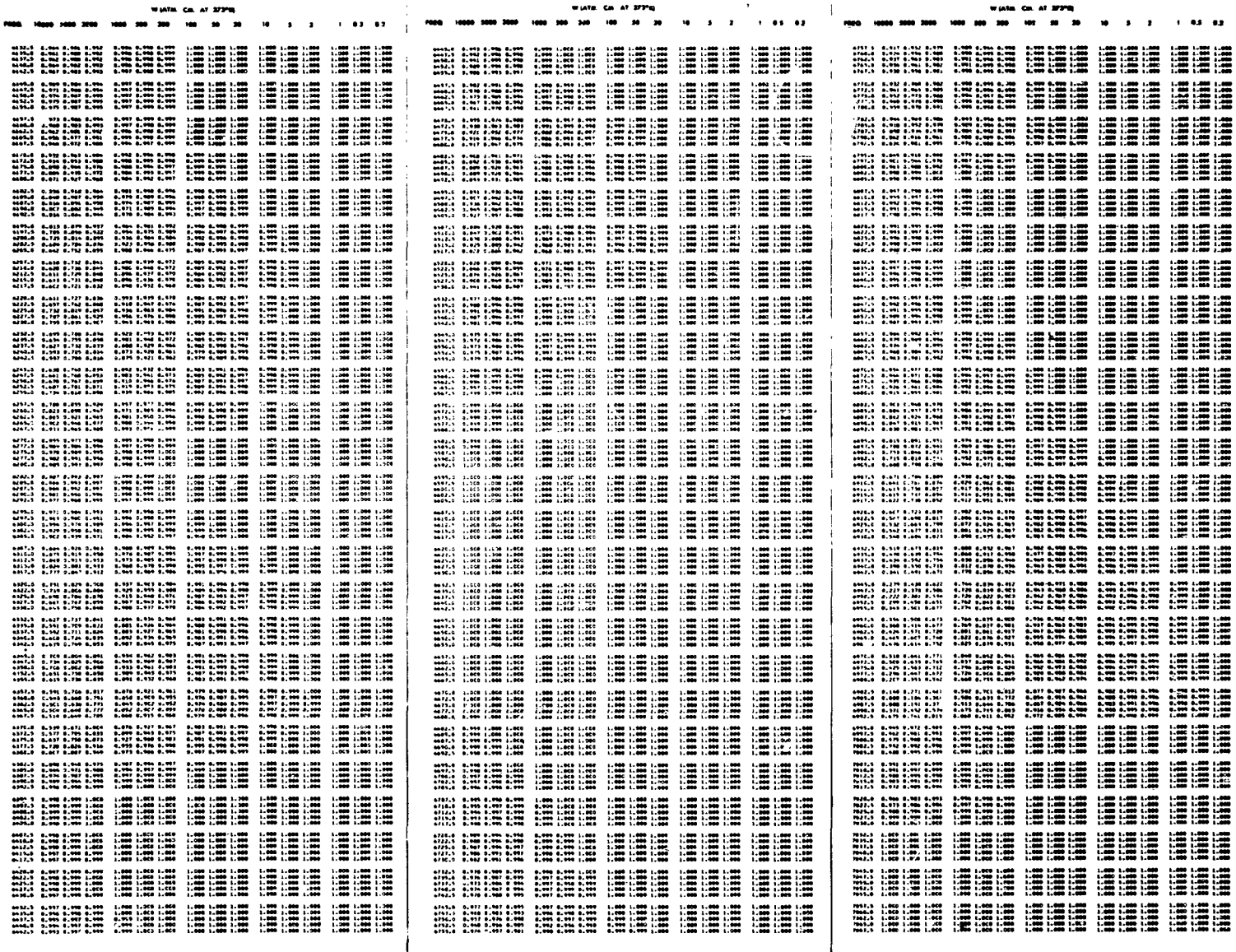


CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T = 300°K

CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T = 300°K

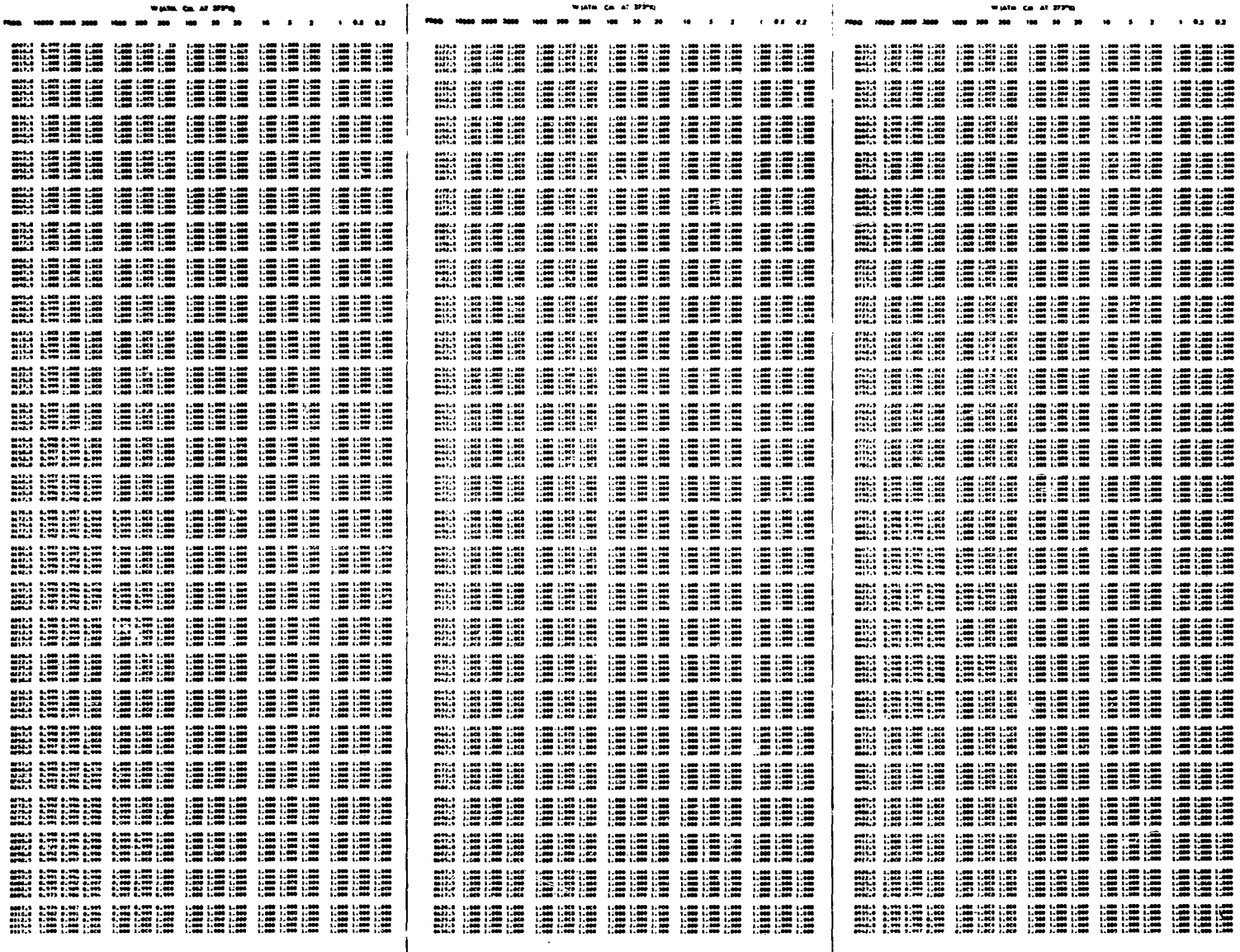


CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T = 300°K

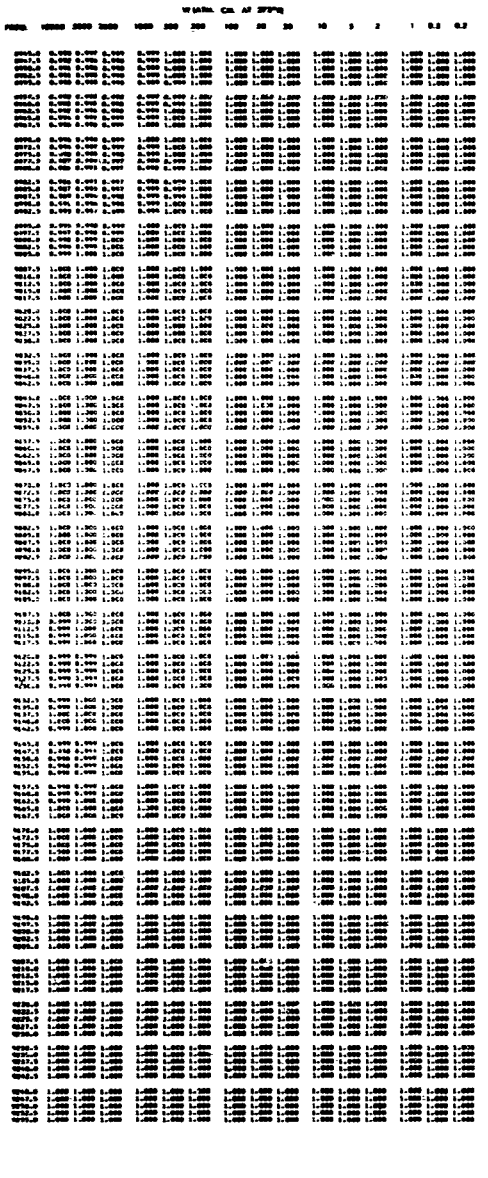
CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

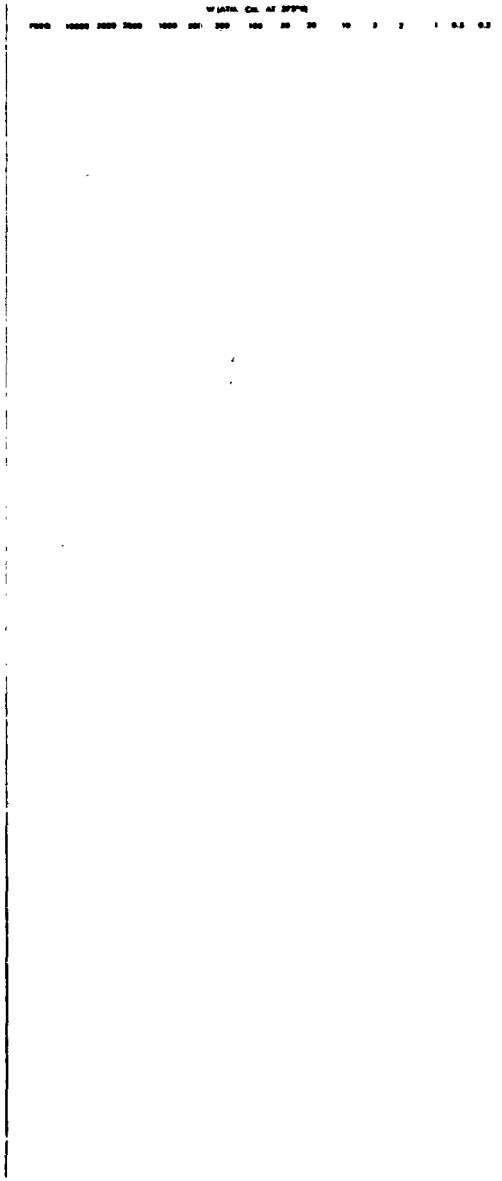
T = 300°K

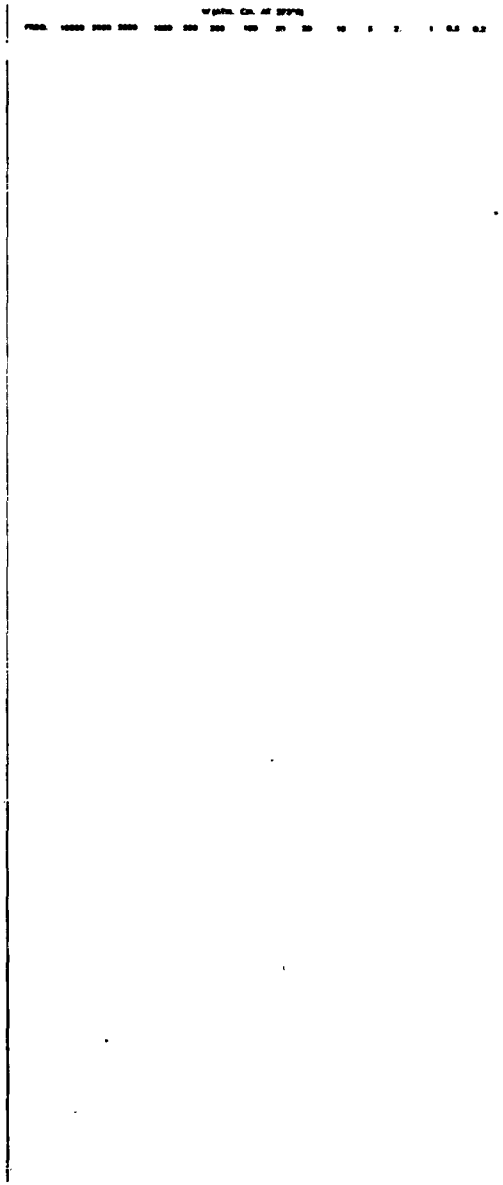


CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T = 300°K

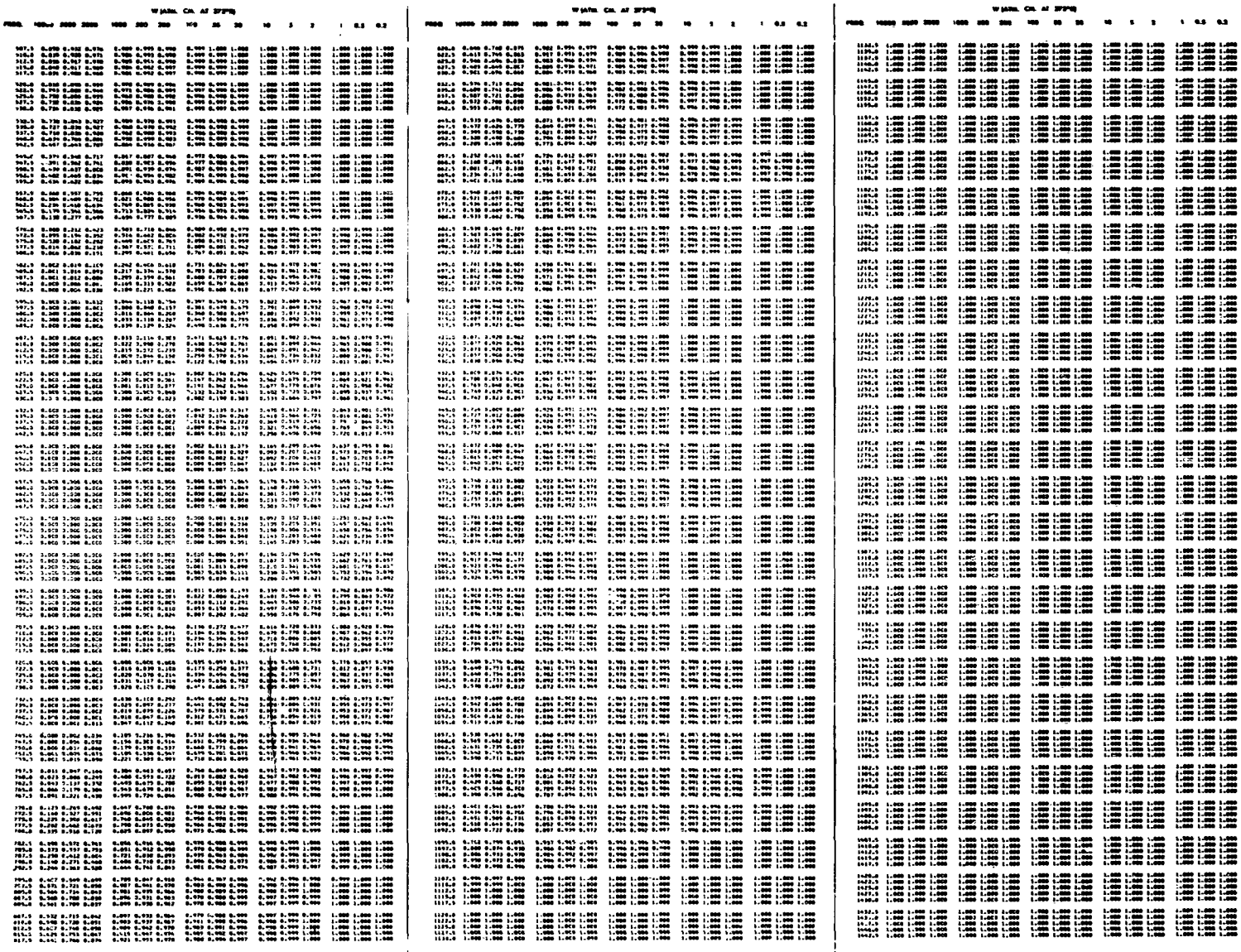






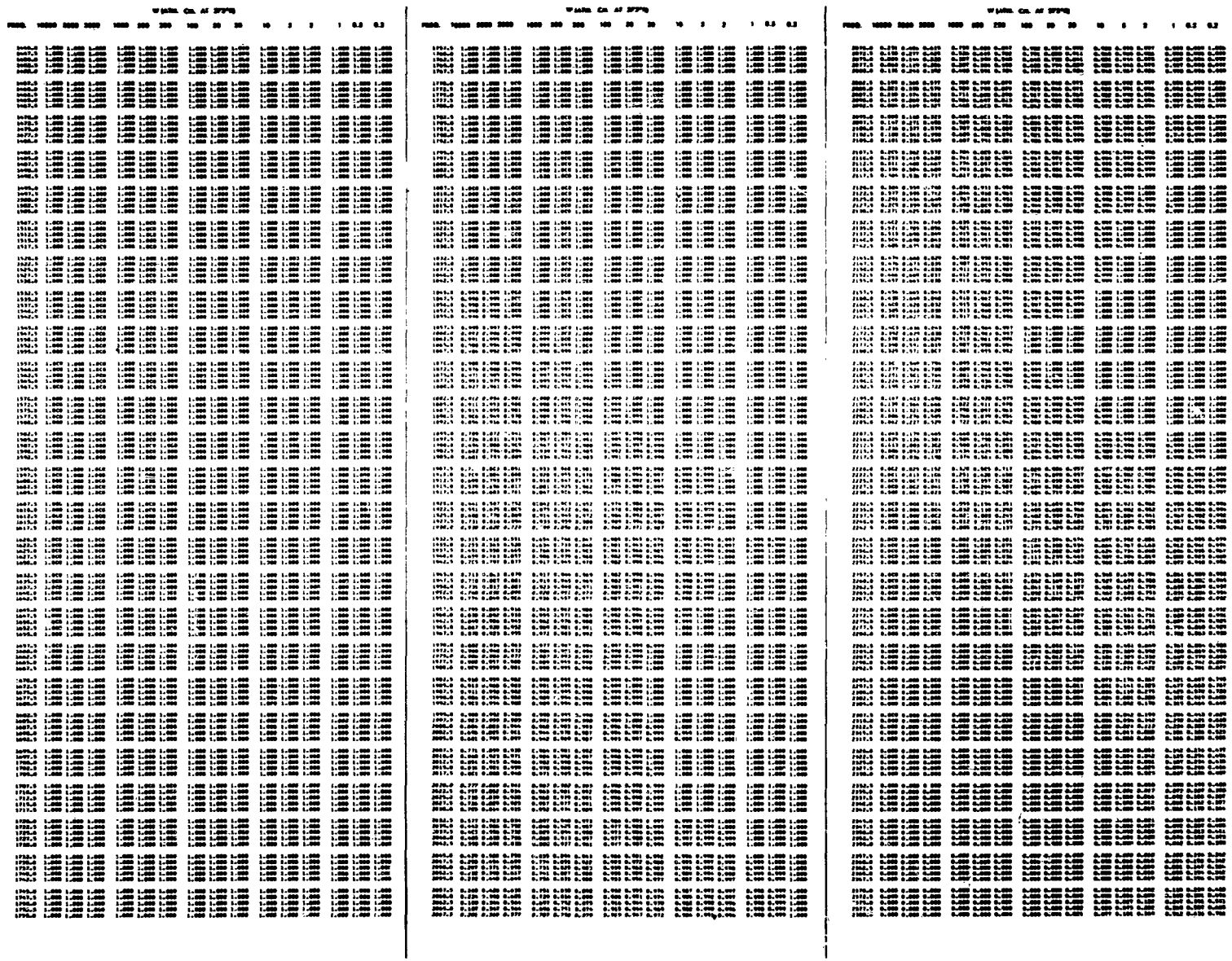
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T = 300°K



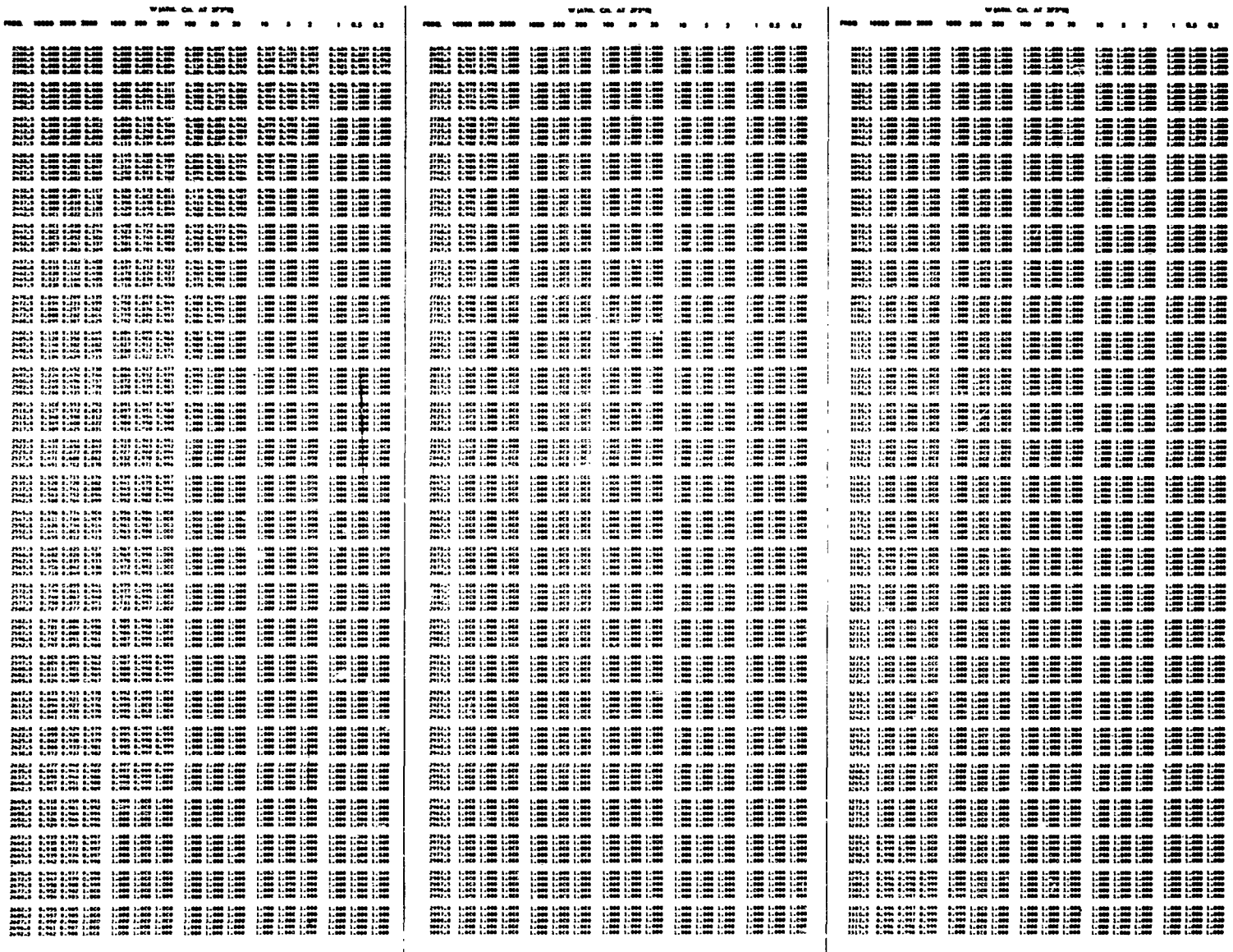
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T = 300°K



CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T = 300°K

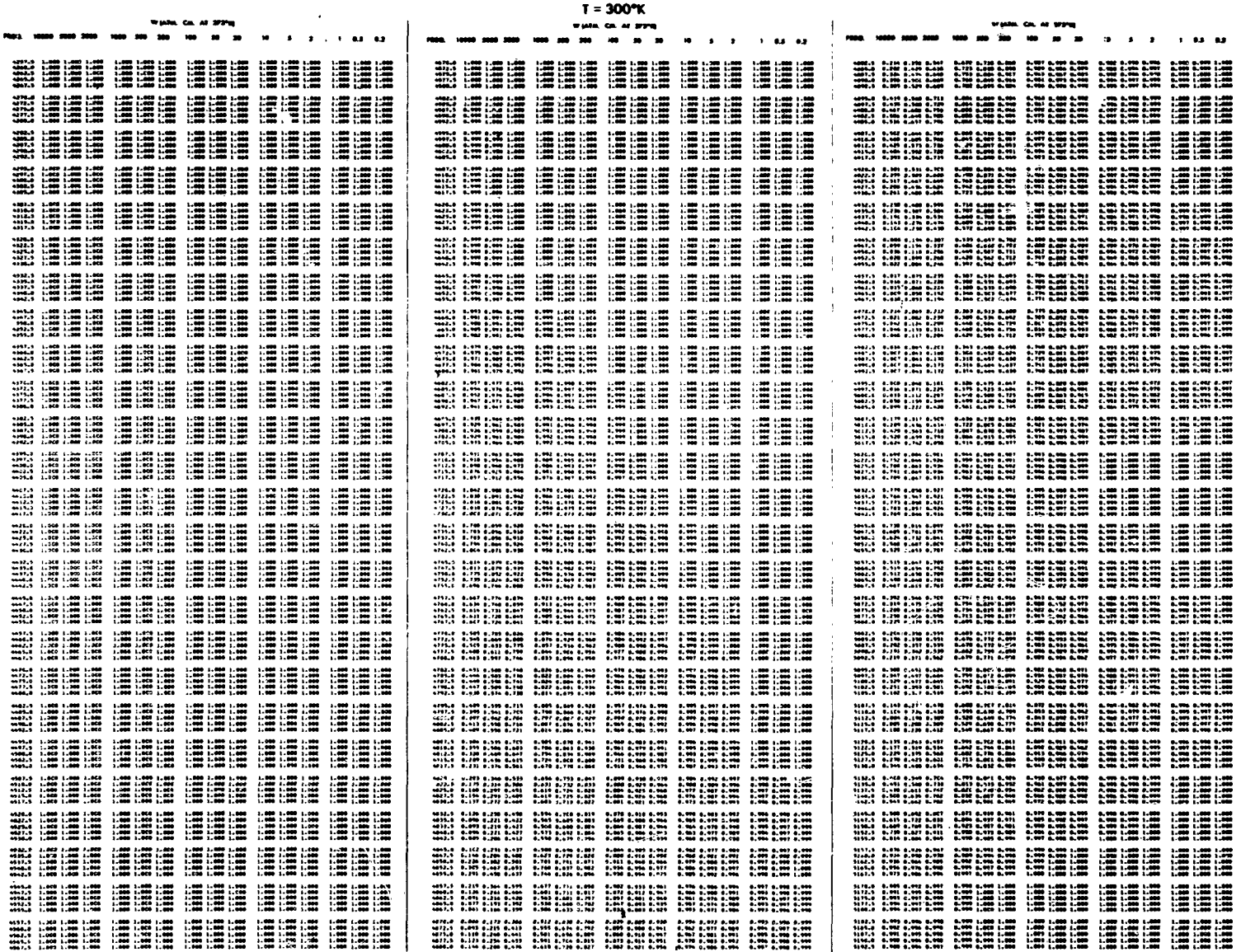


CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T = 300°K

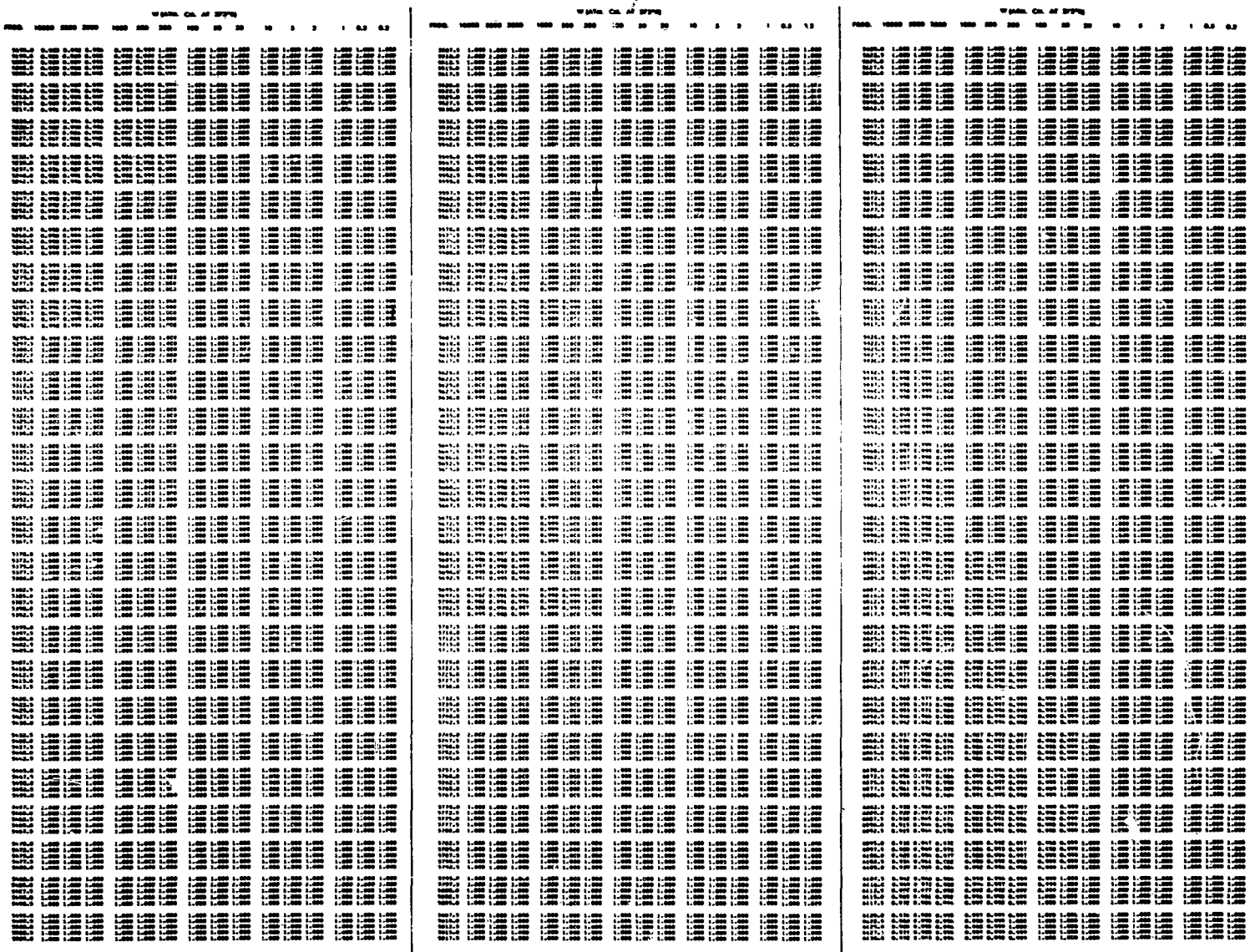
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T = 300°K



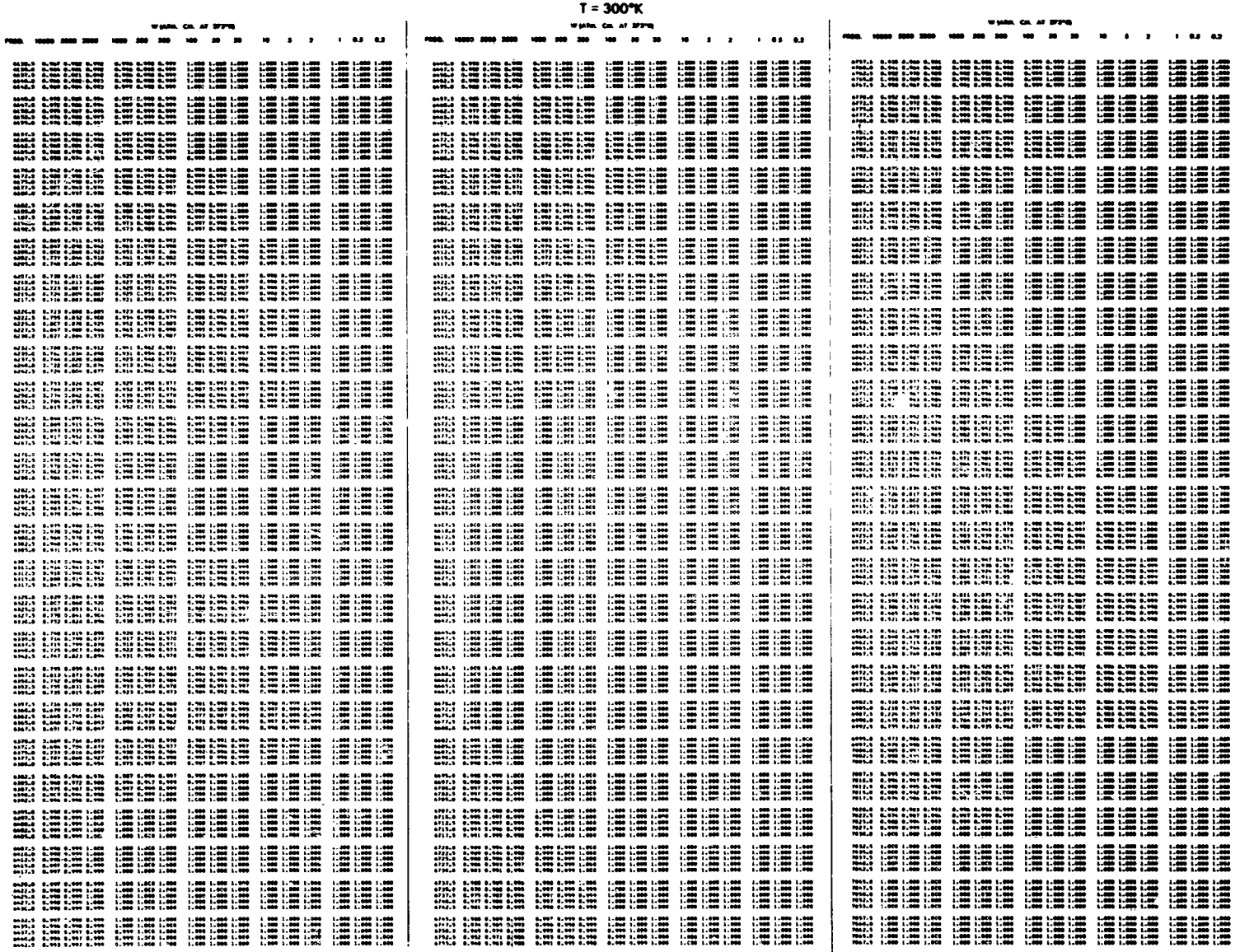
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T = 300°K



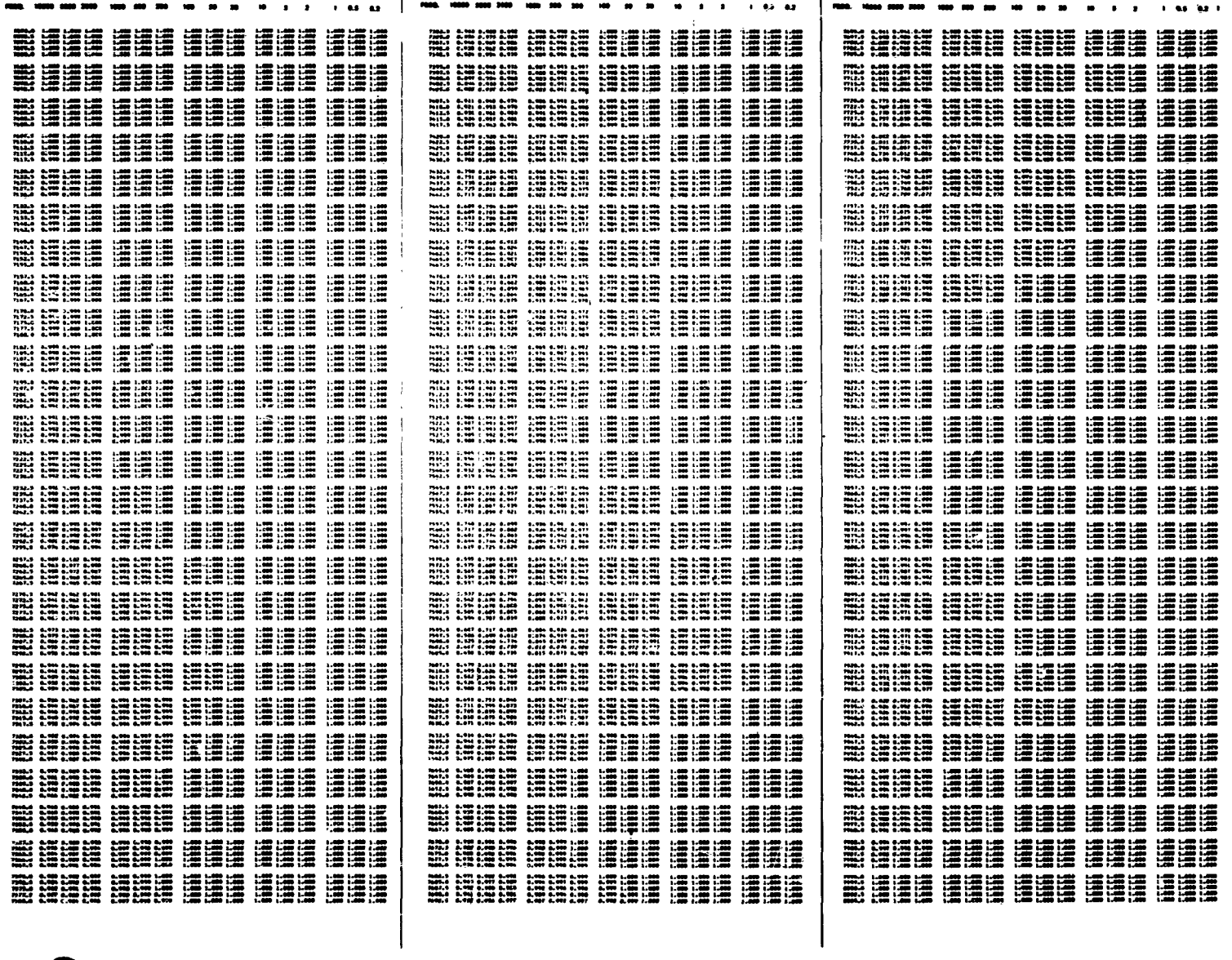
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T = 300°K



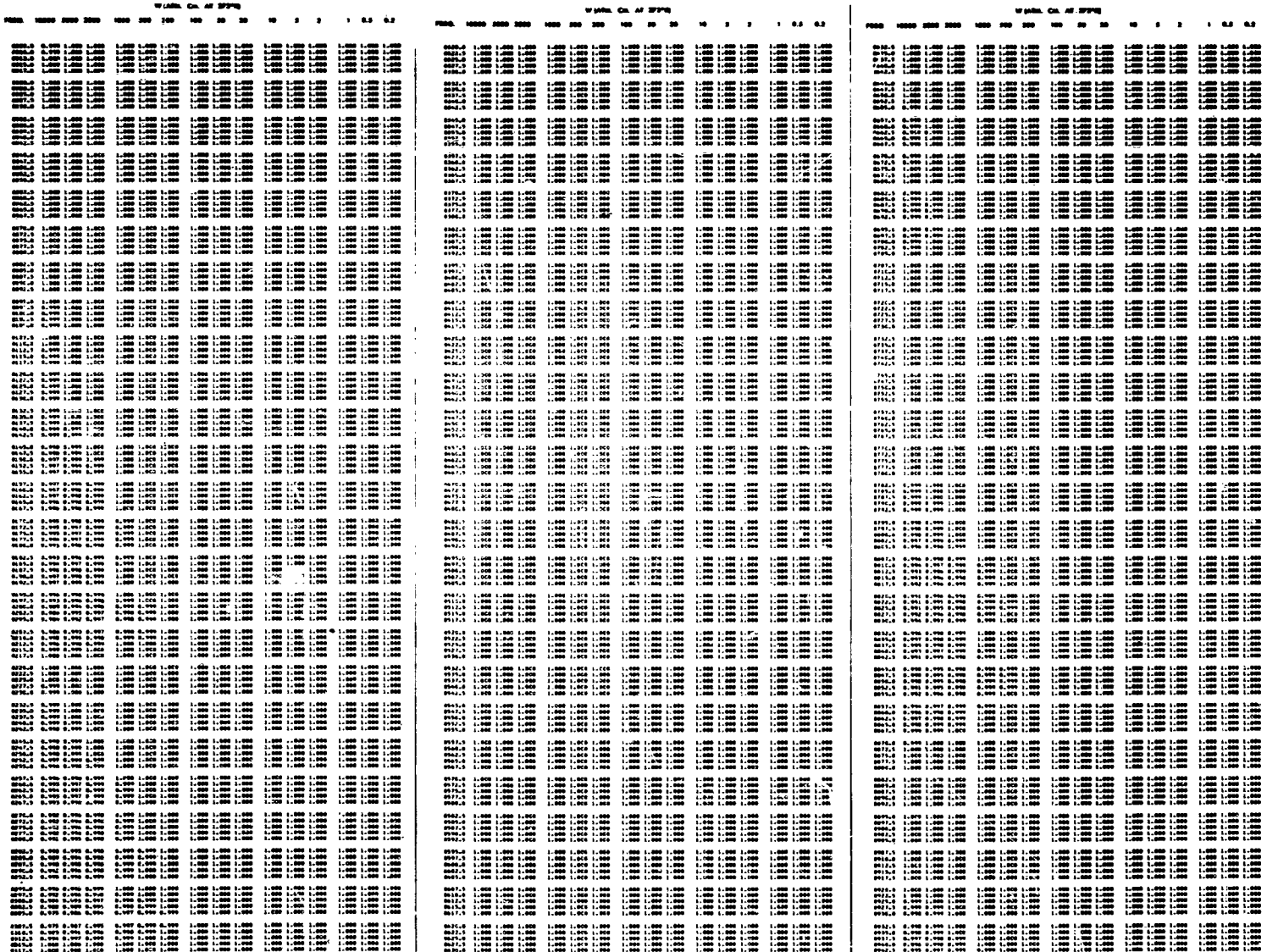
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T = 300°K



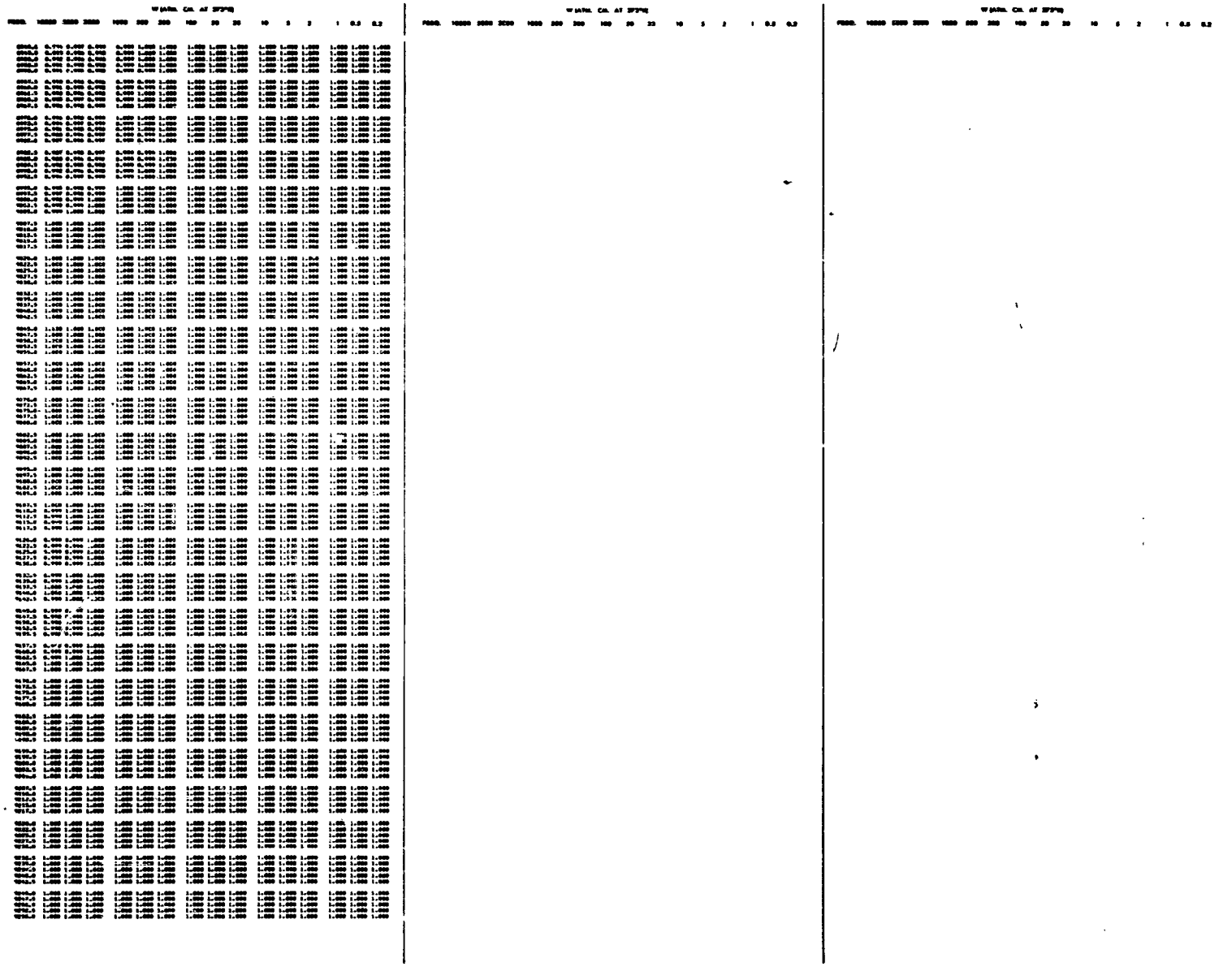
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T = 300°K



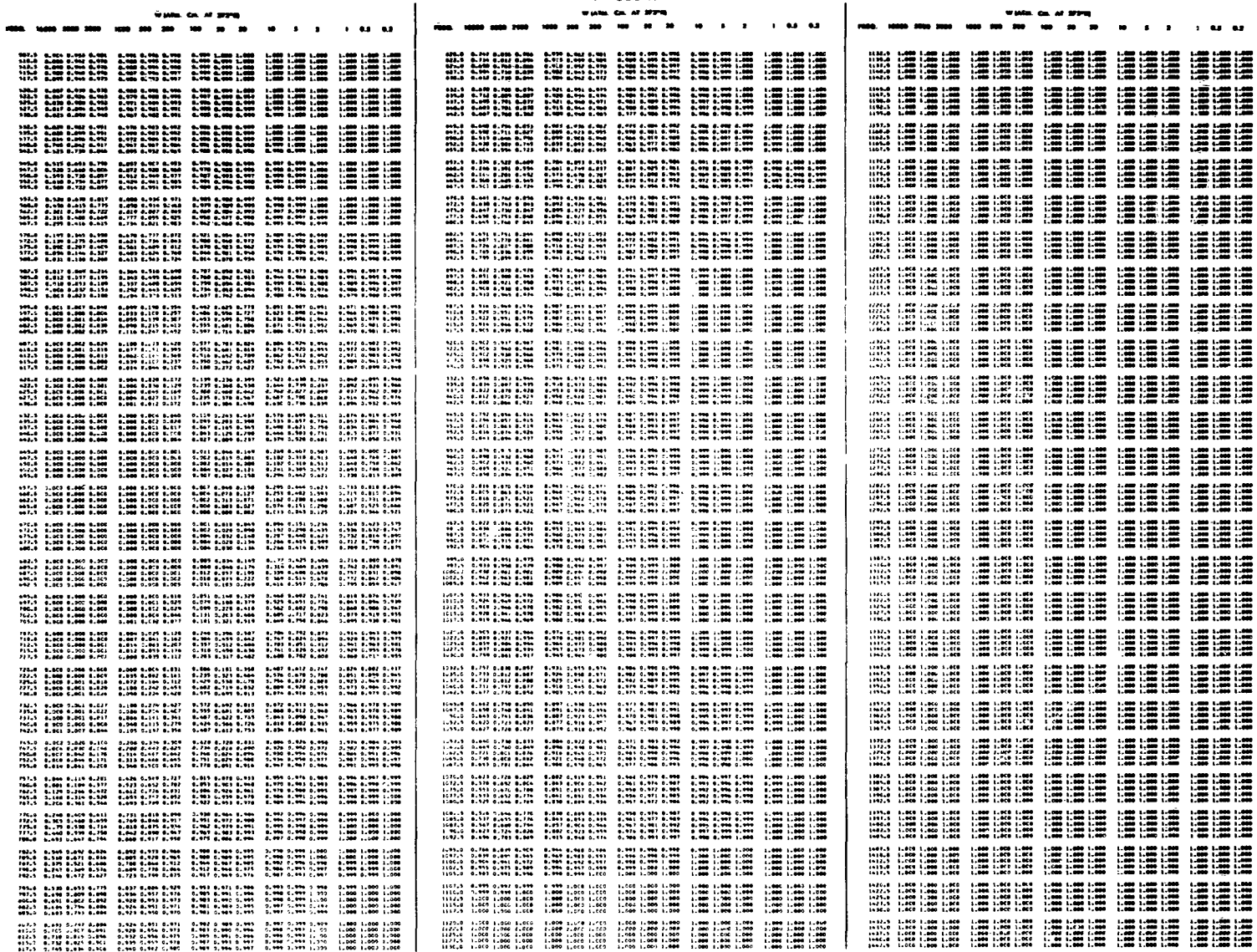
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T = 300°K



CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T = 300°K

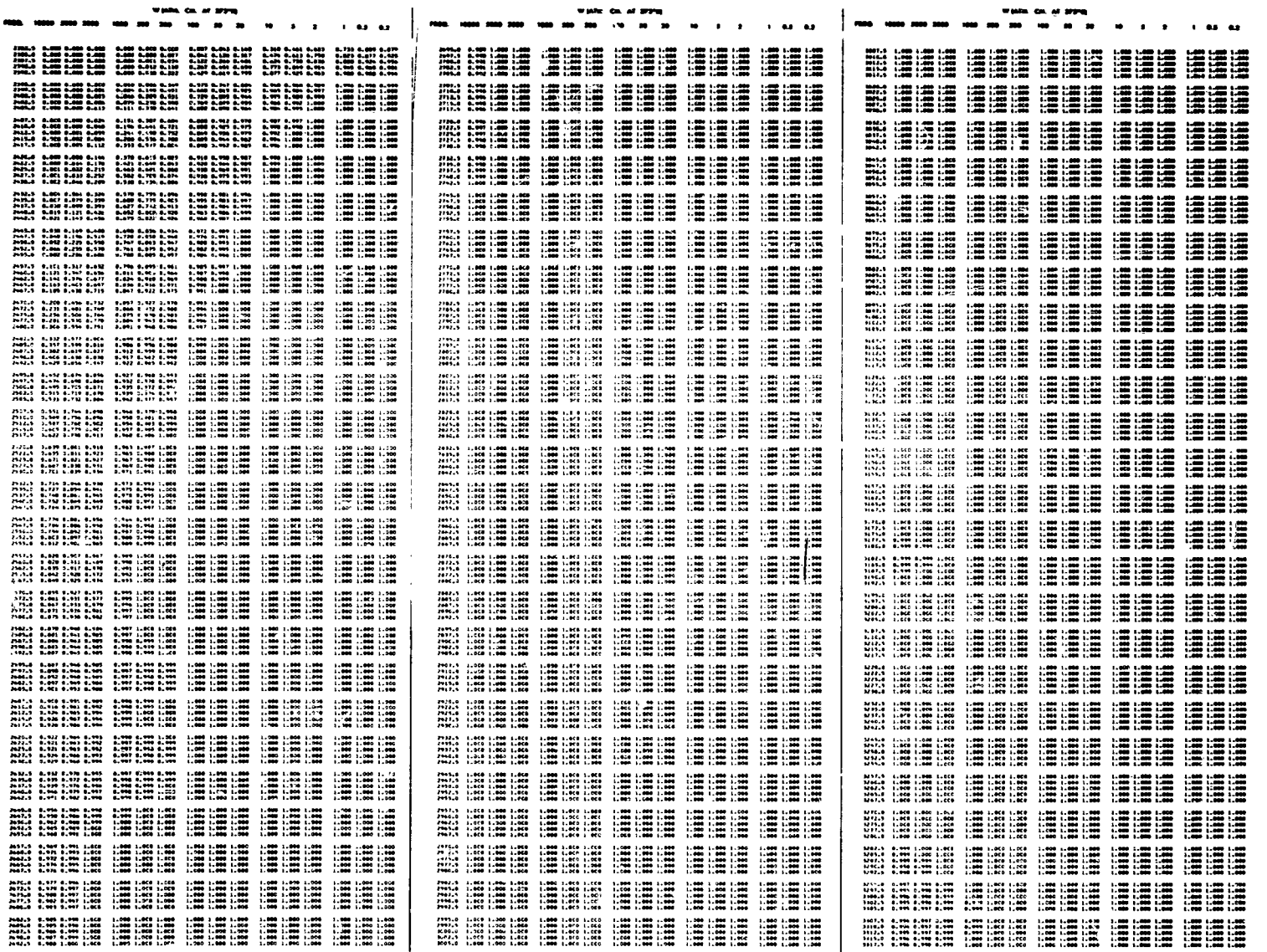


CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T = 300°K

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T = 300°K

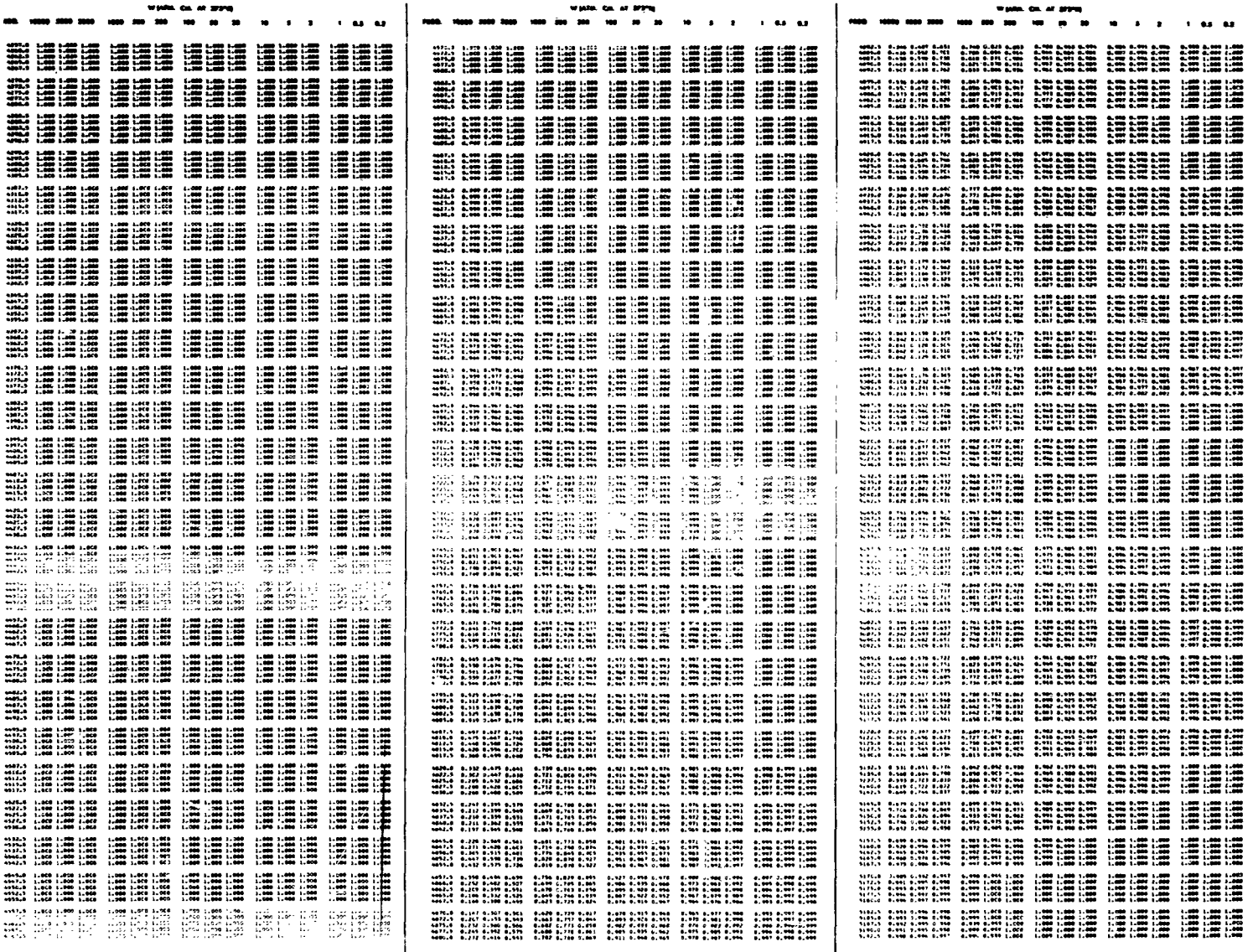


CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T = 300°K

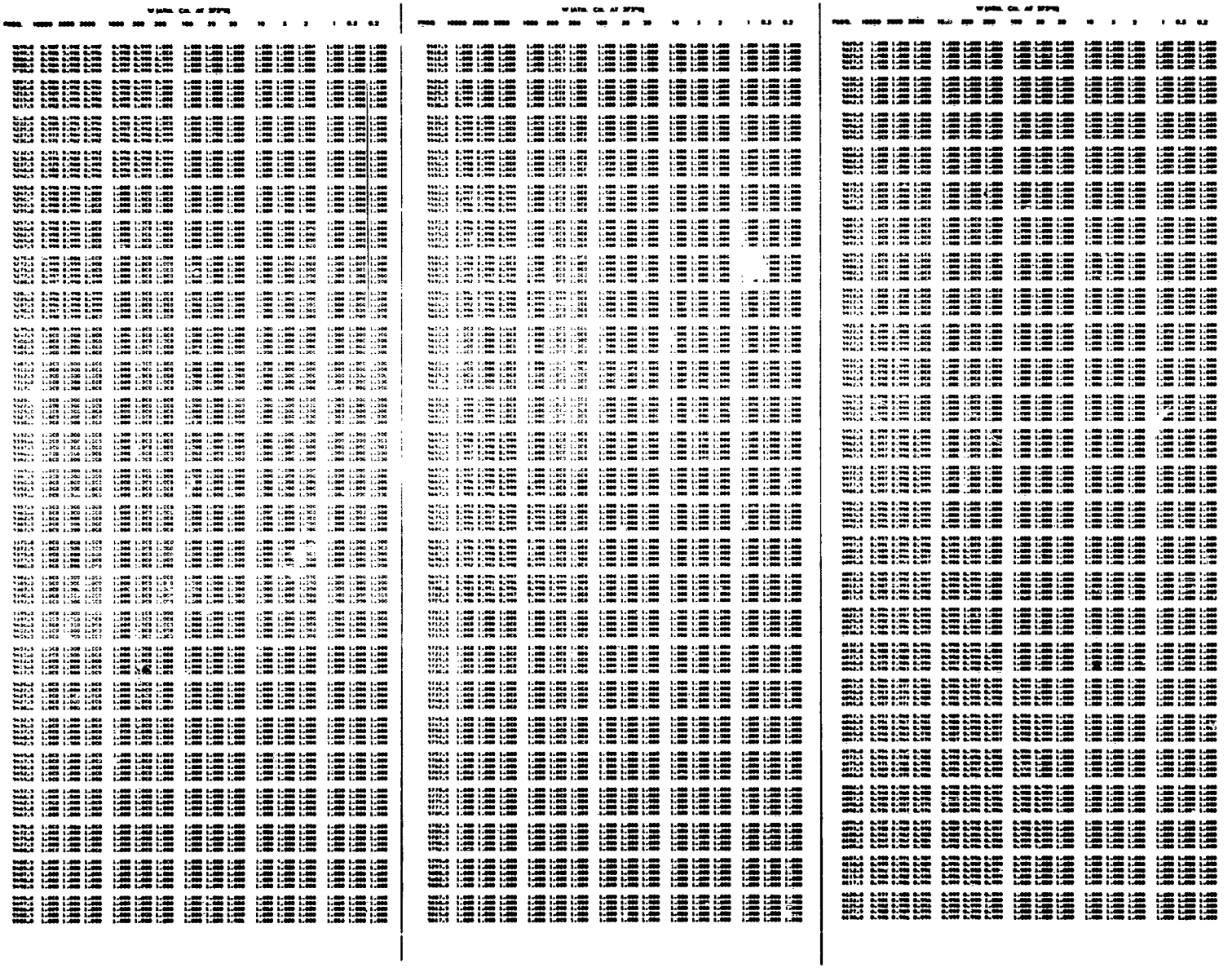
CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T = 300°K



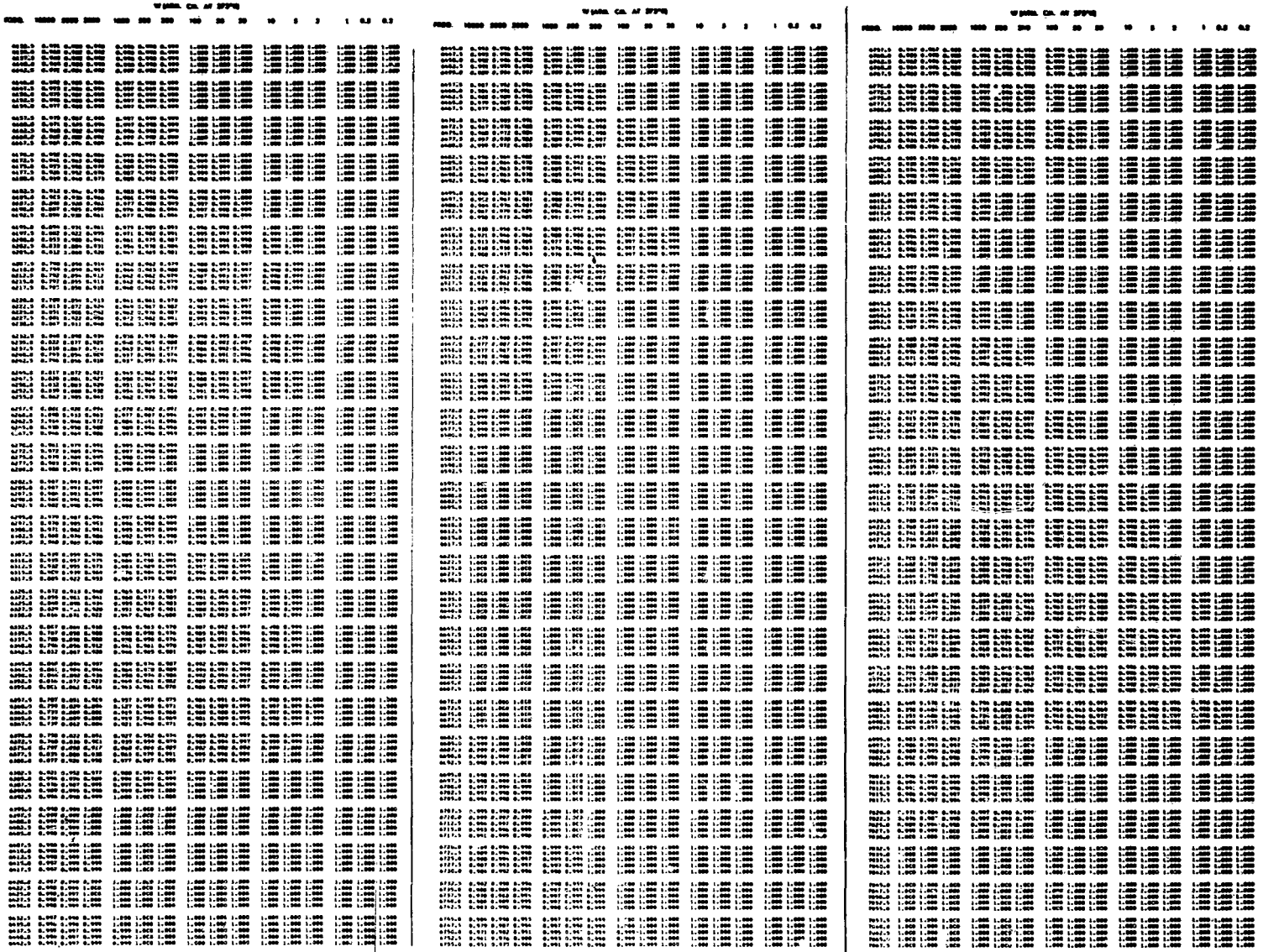
CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T = 300°K



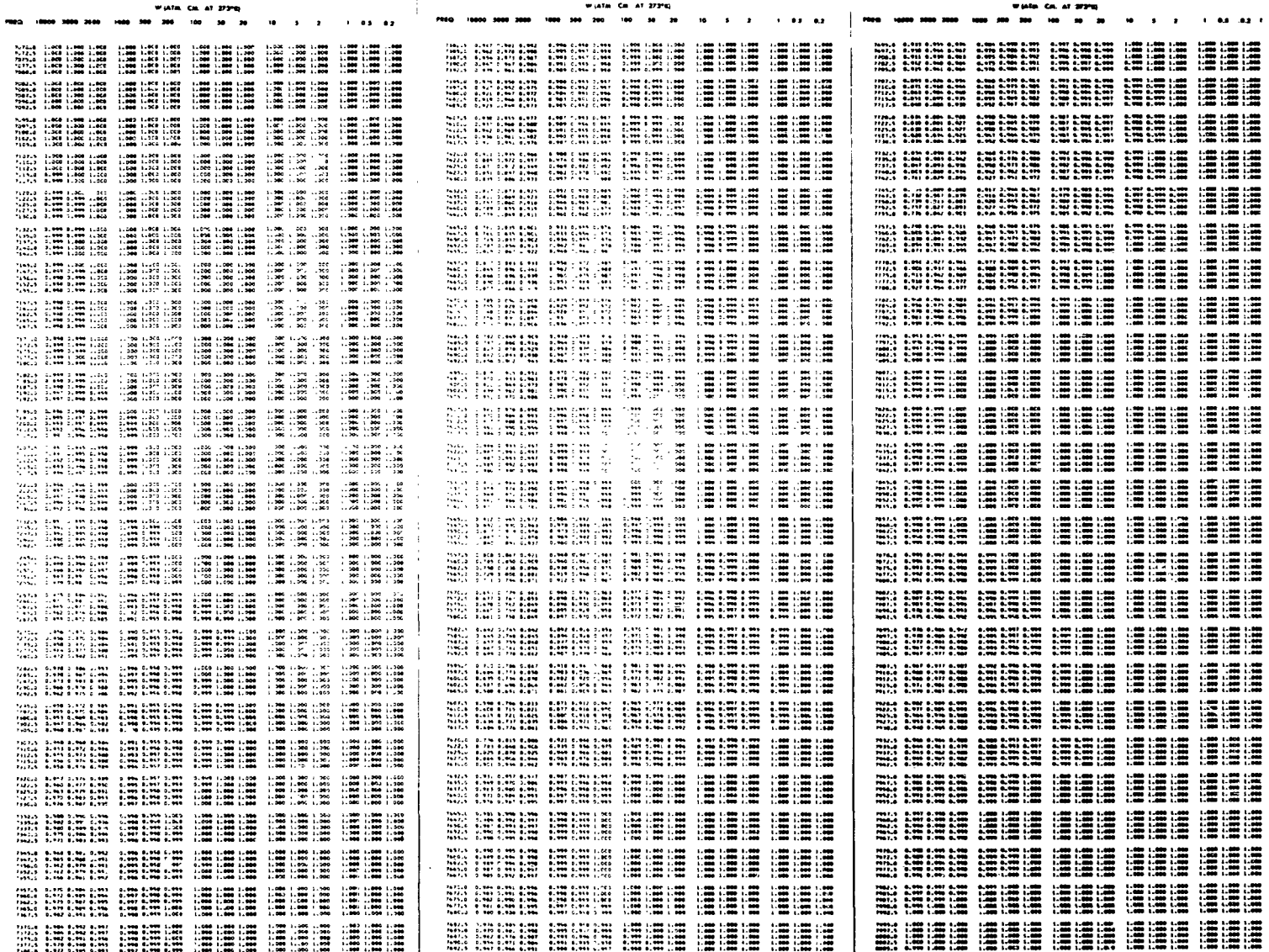
CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T = 300°K



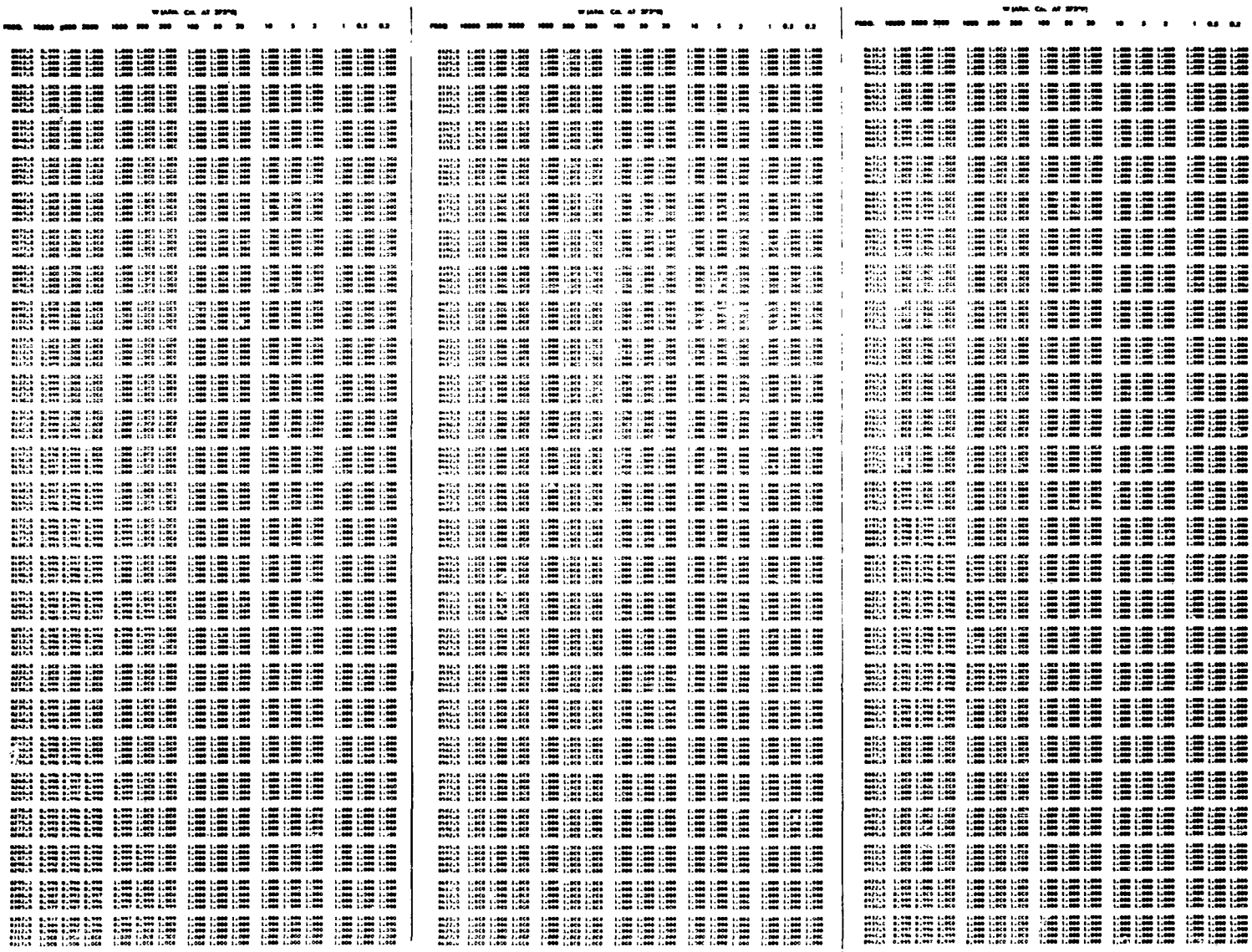
CARBON DIOXIDE AT 010 ATMOSPHERE PRESSURE

T = 300°K



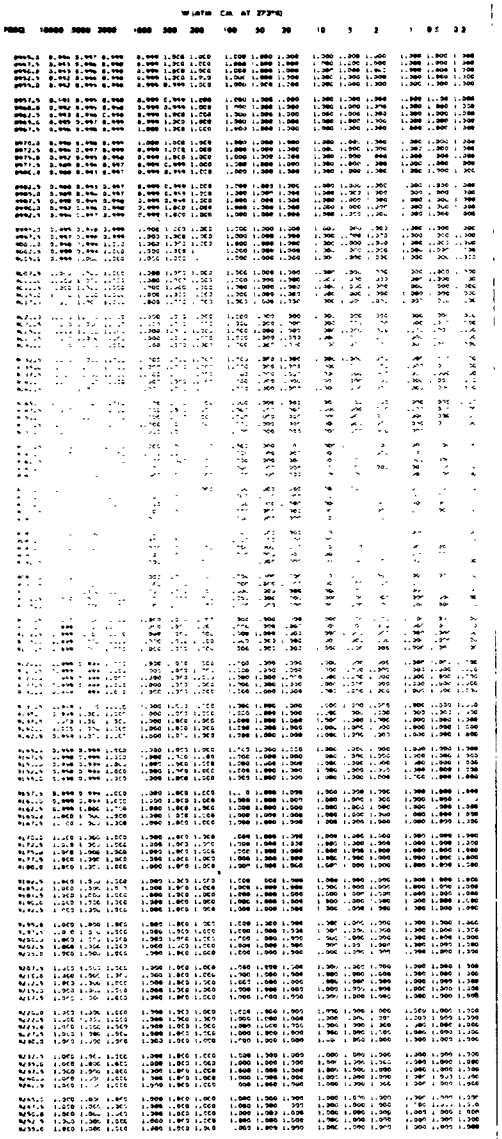
CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

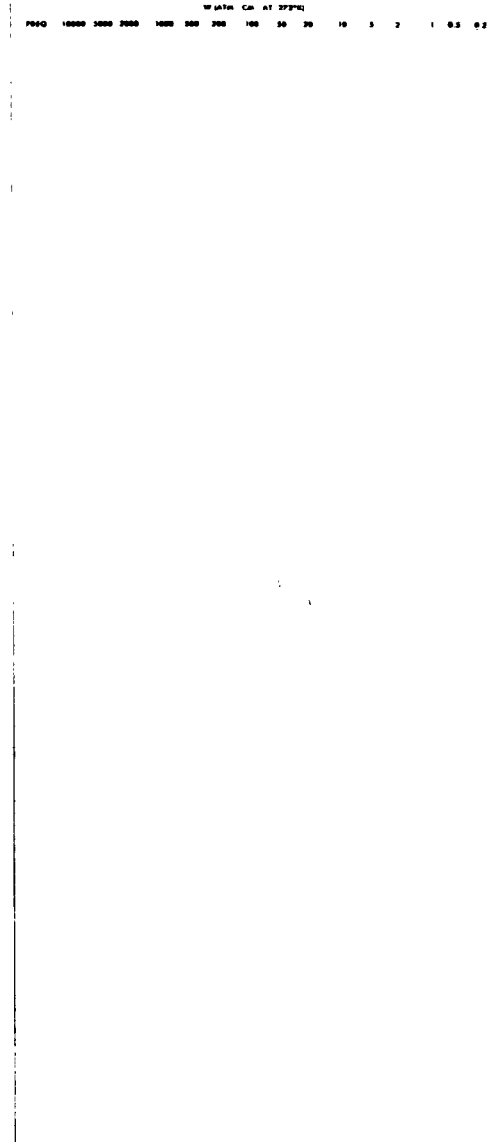
T = 300°K



CARBON DIOXIDE AT 010 ATMOSPHERE PRESSURE

T = 300°K





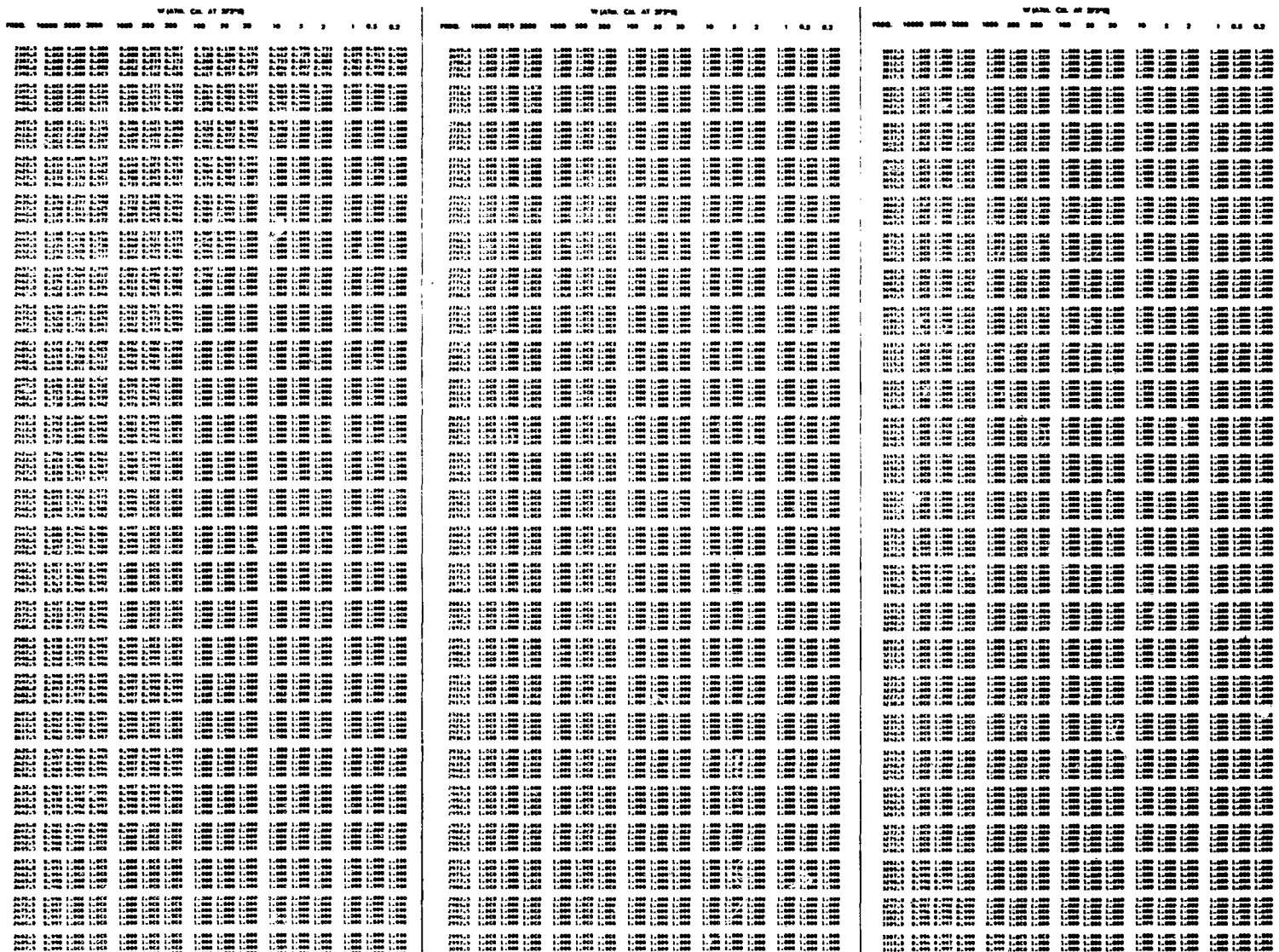
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T = 300°K

CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T = 300°K

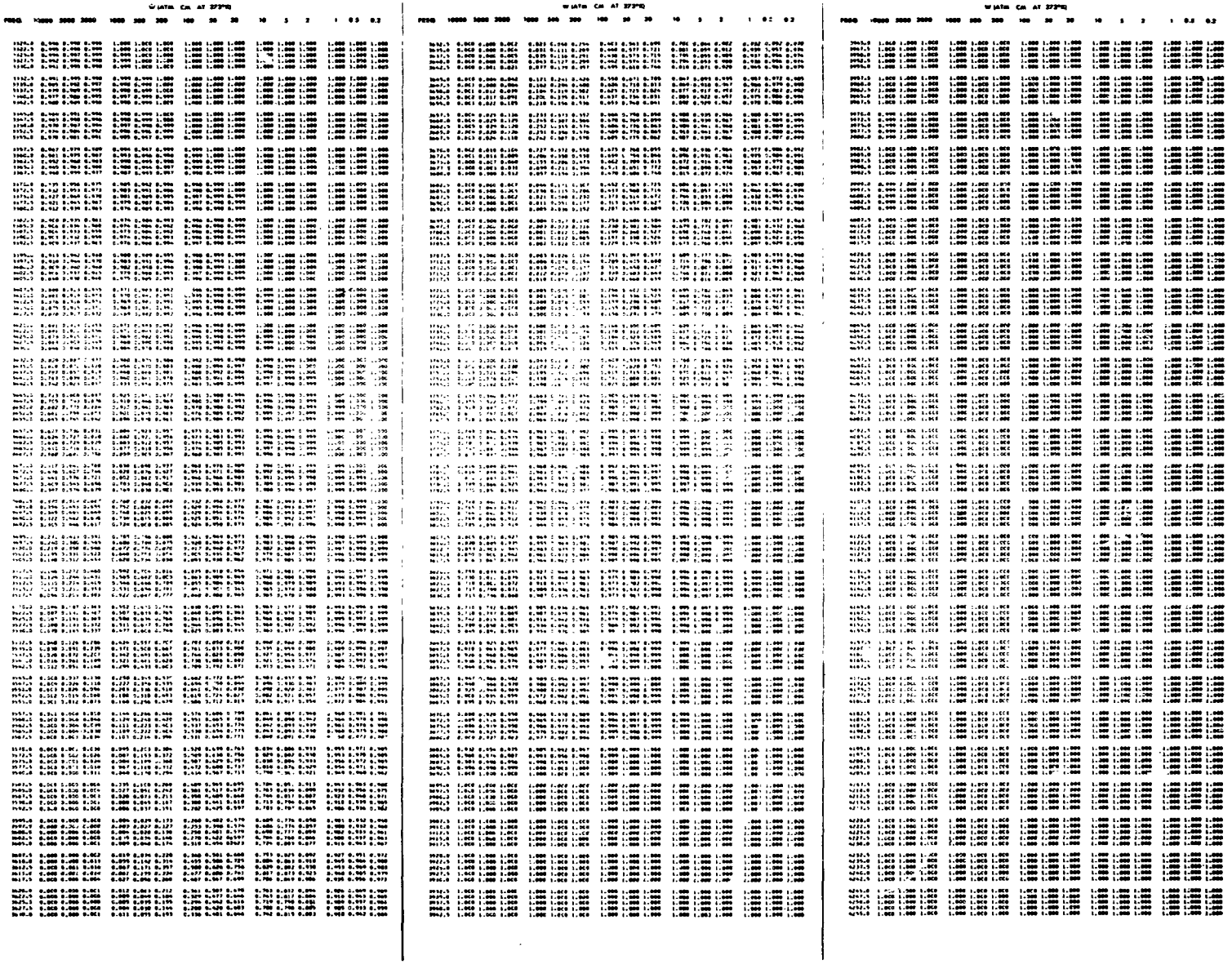
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T = 300°K



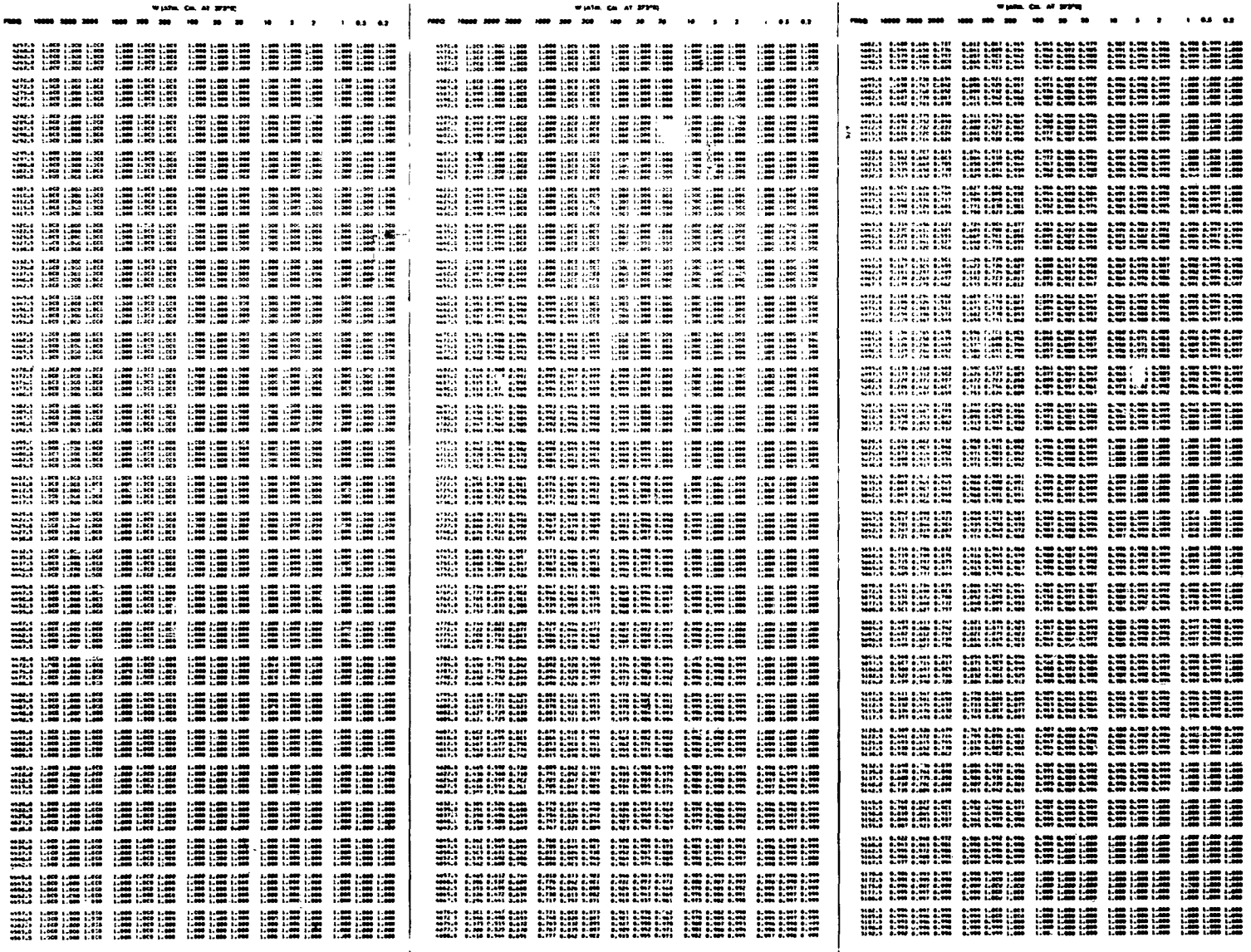
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T = 300°K



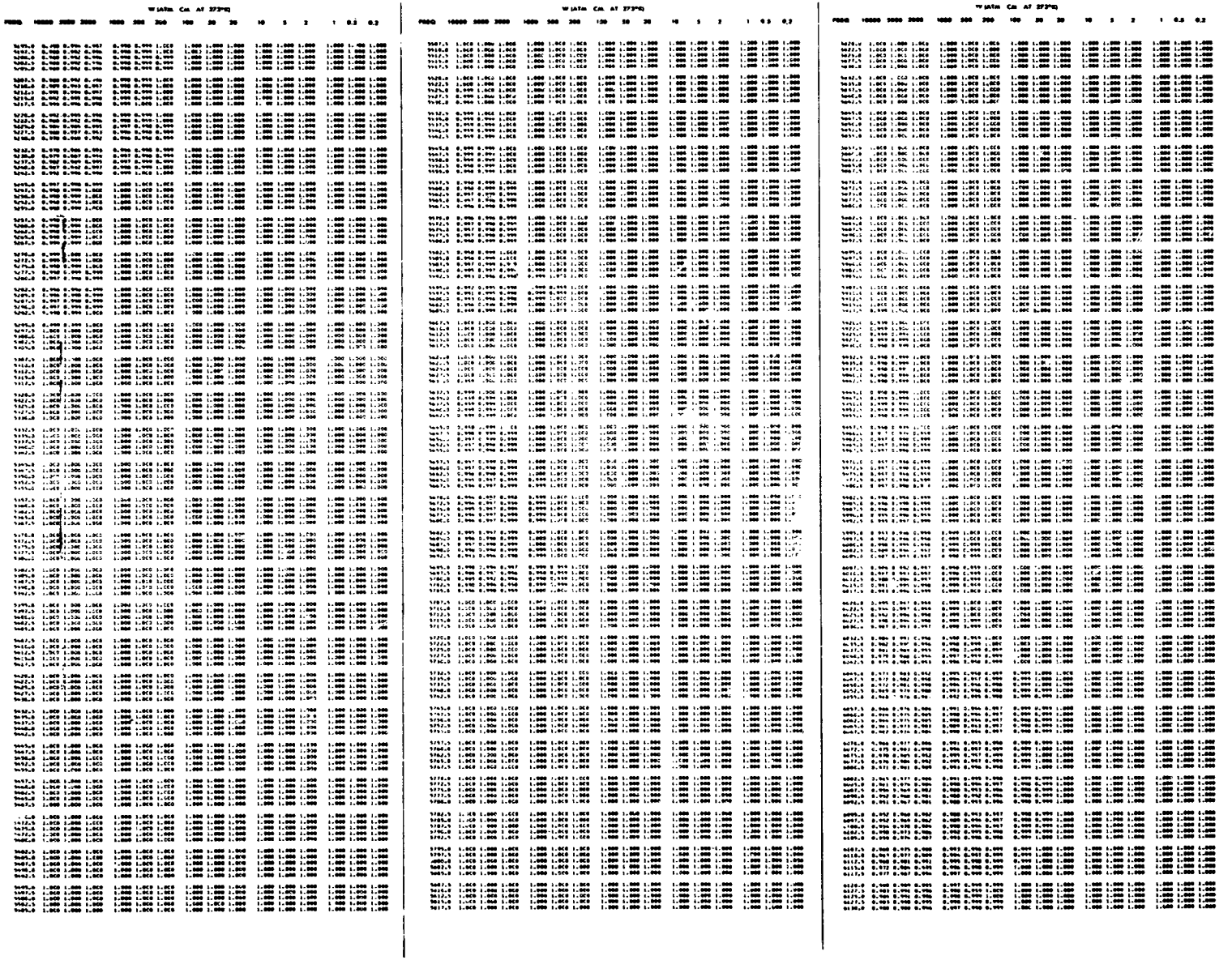
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T = 300°K



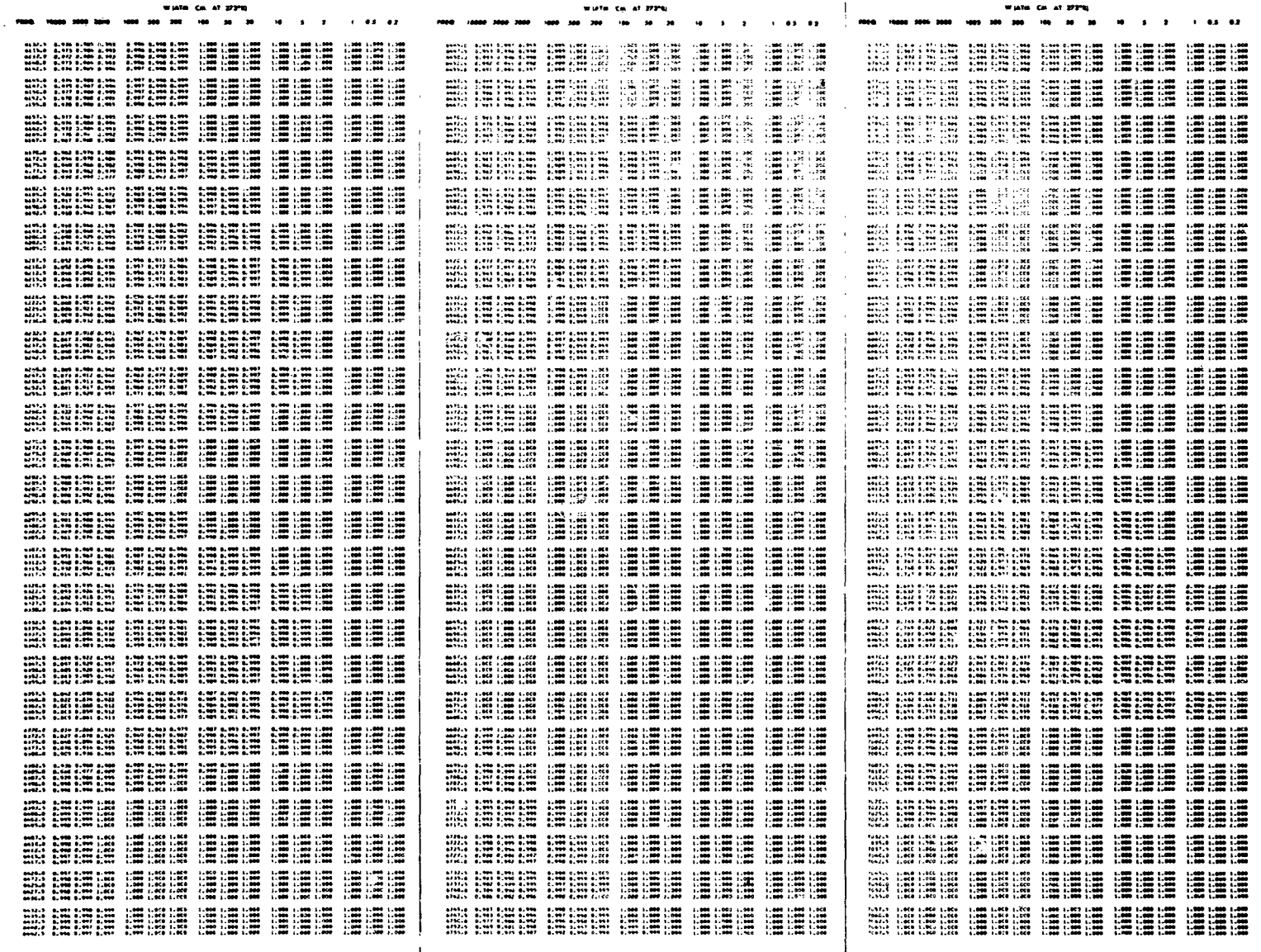
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T = 300°K



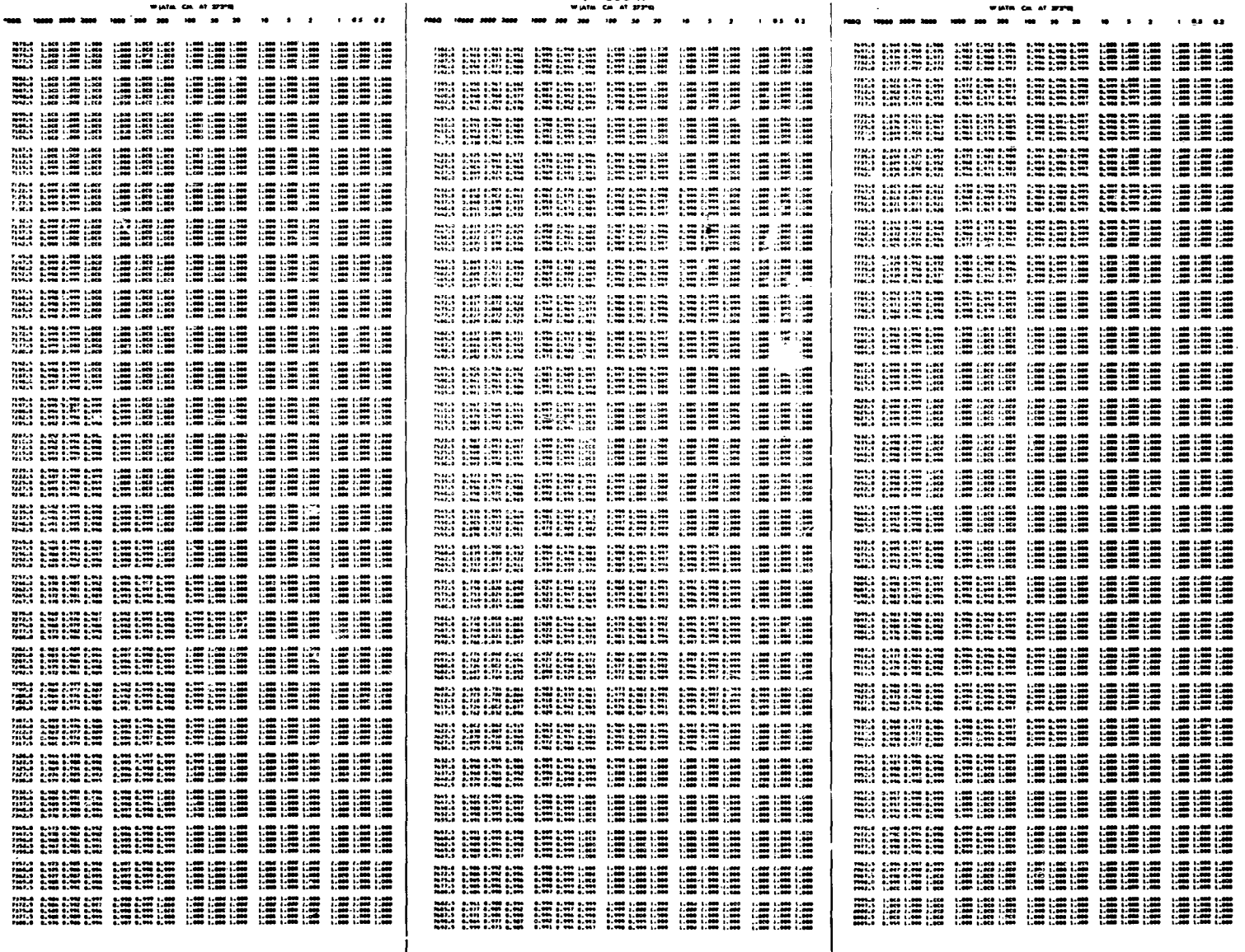
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T = 300°K



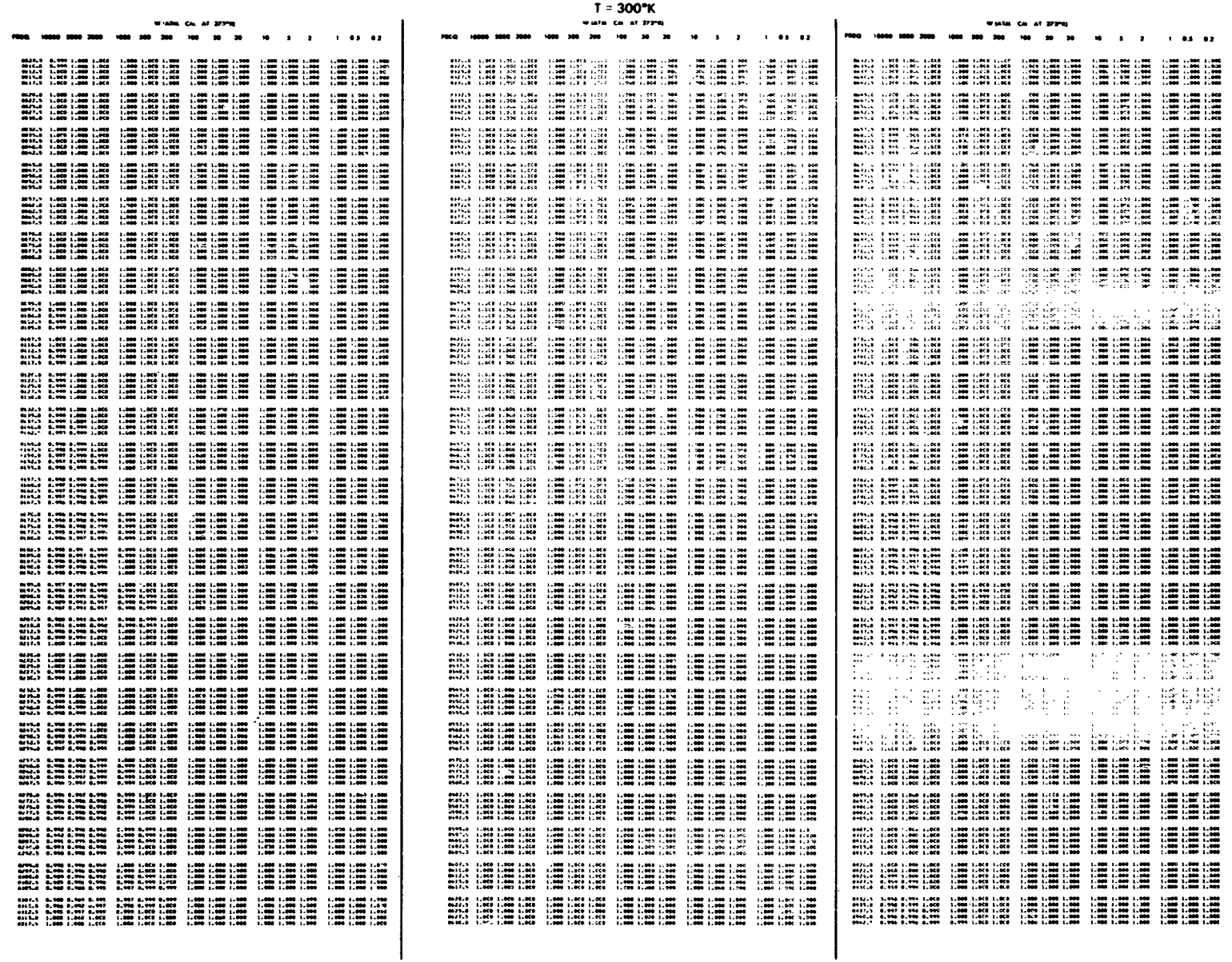
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T = 300°K



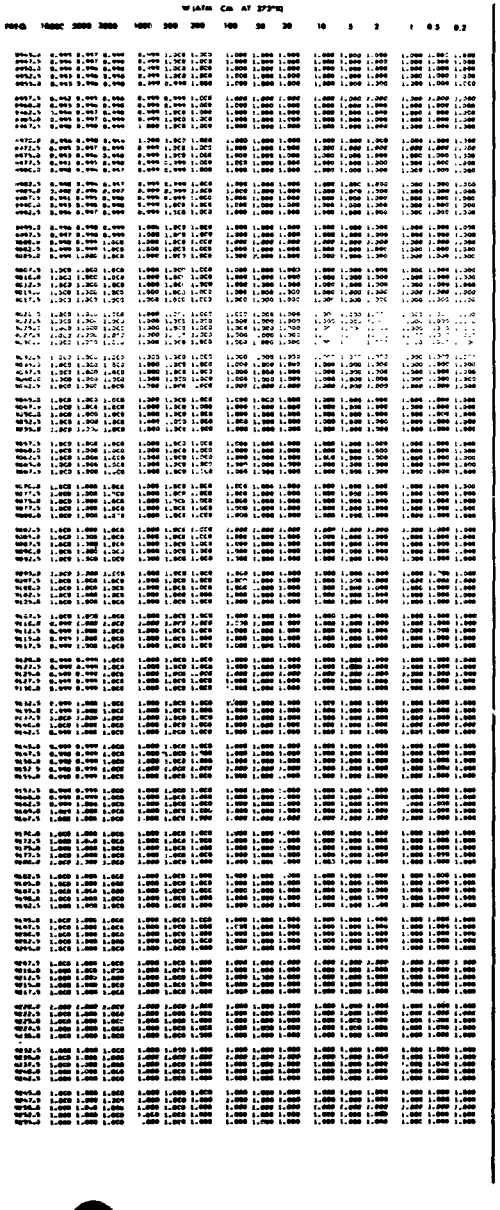
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

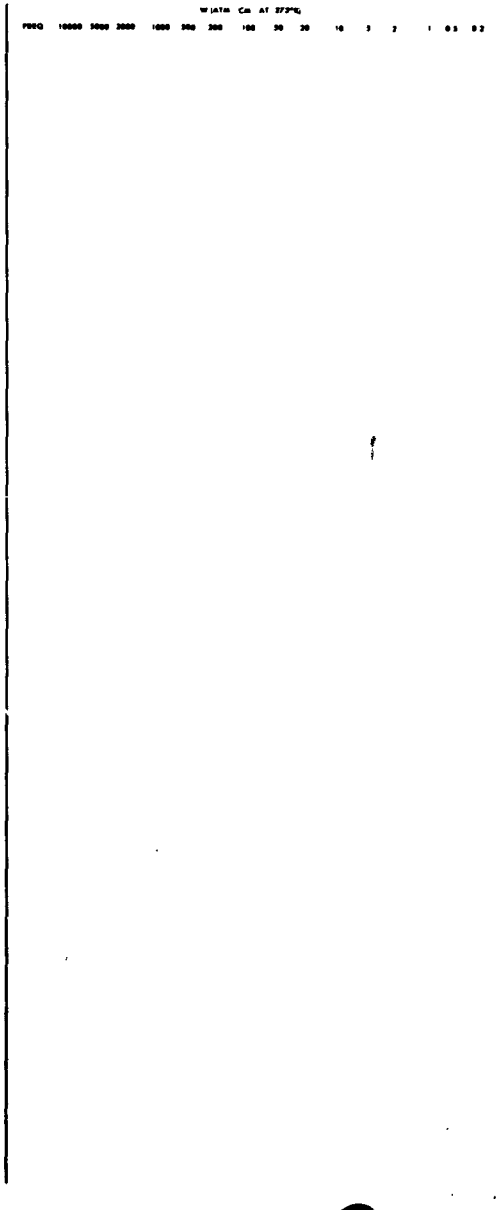
T = 300°K



CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T = 300°K



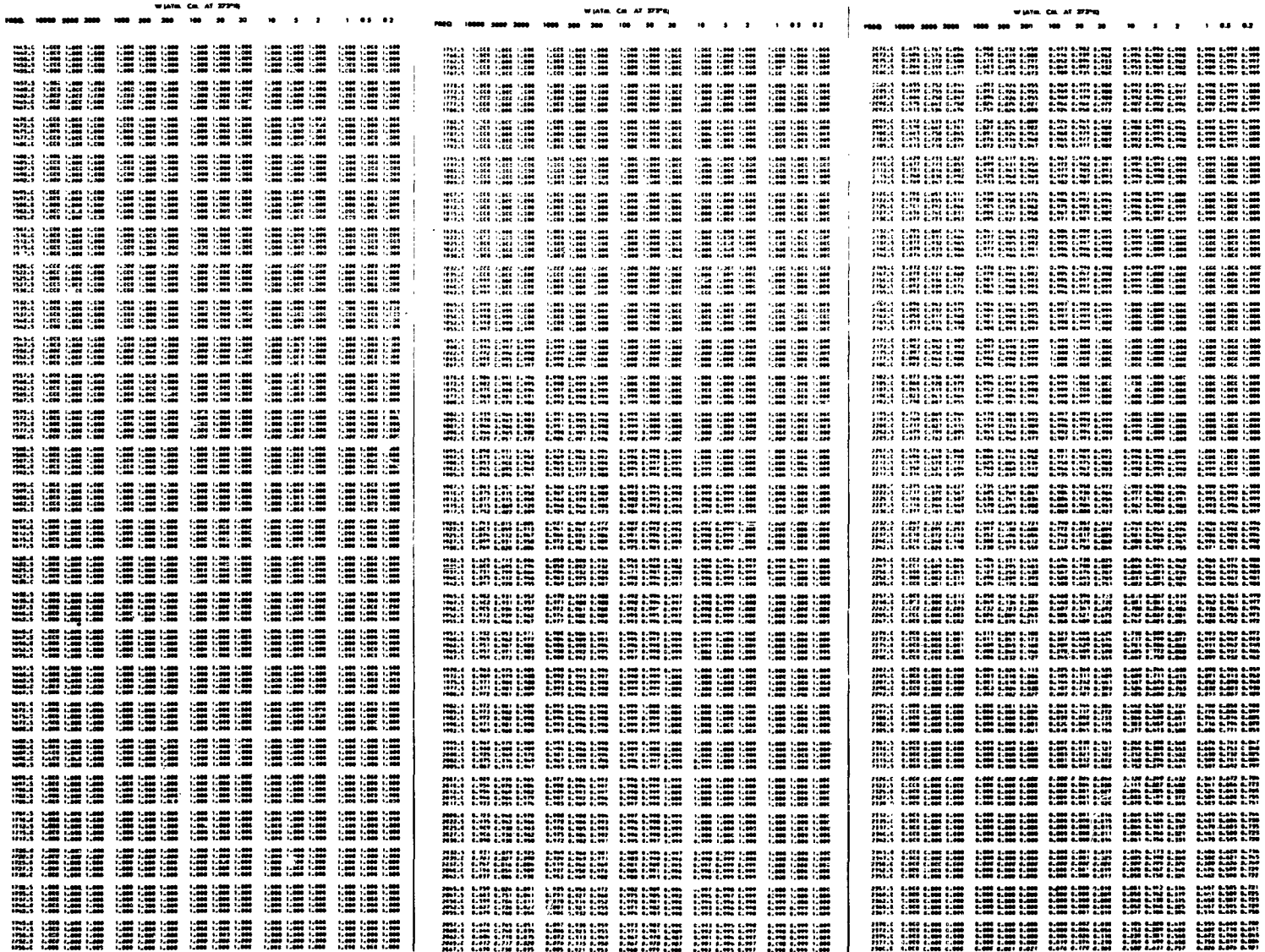


CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T = 300°K

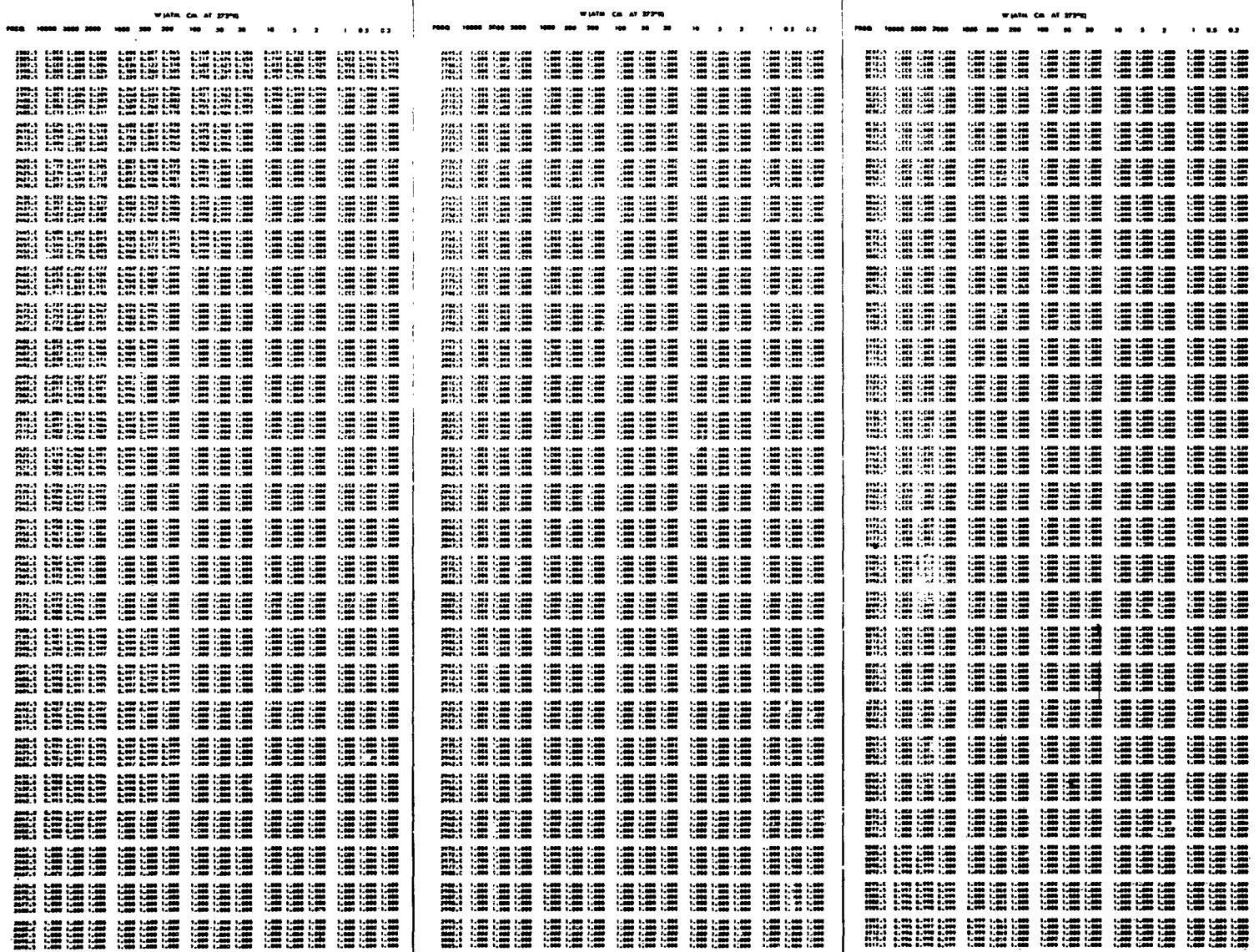
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T = 300°K



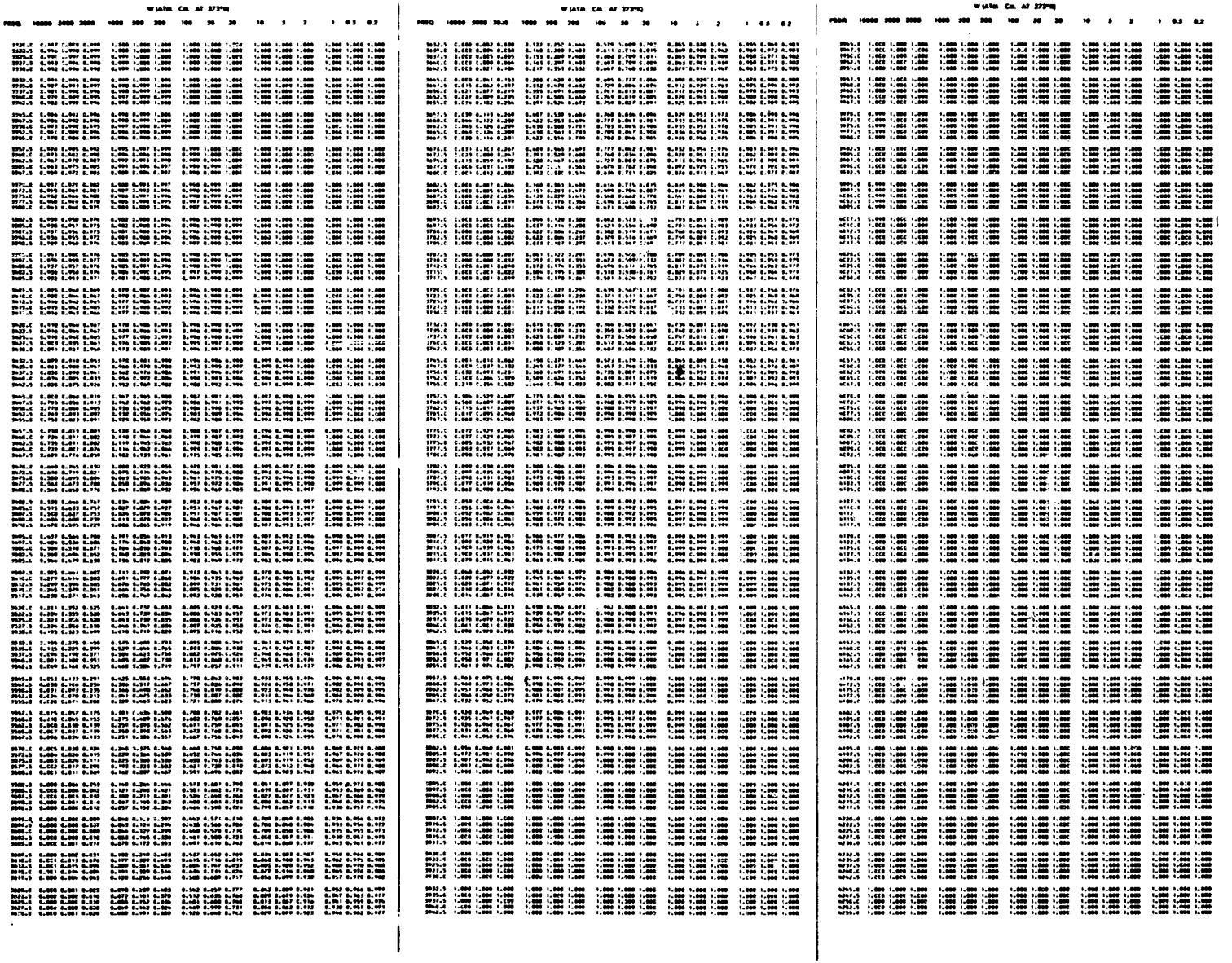
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T = 300°K



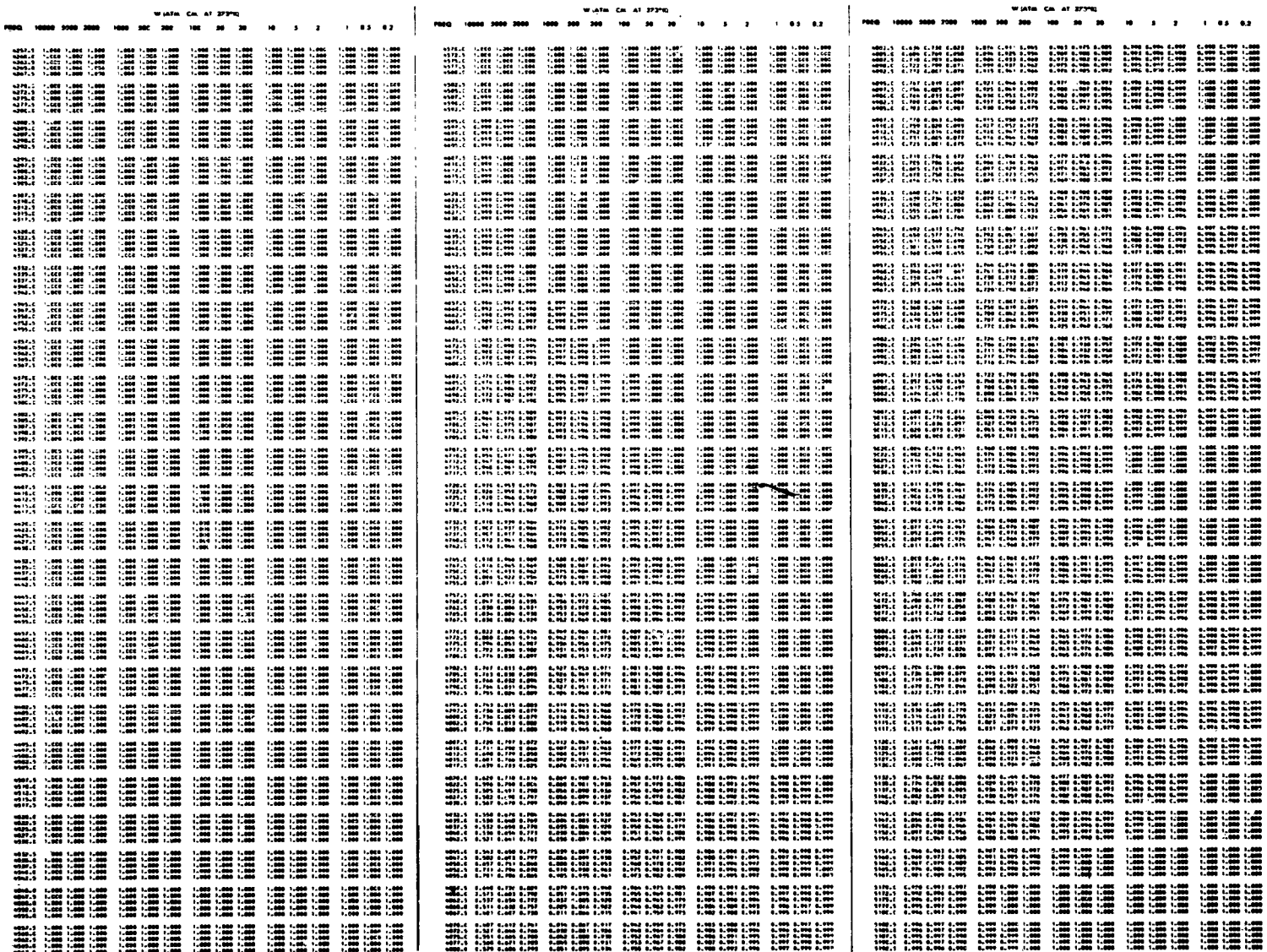
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T = 300°K



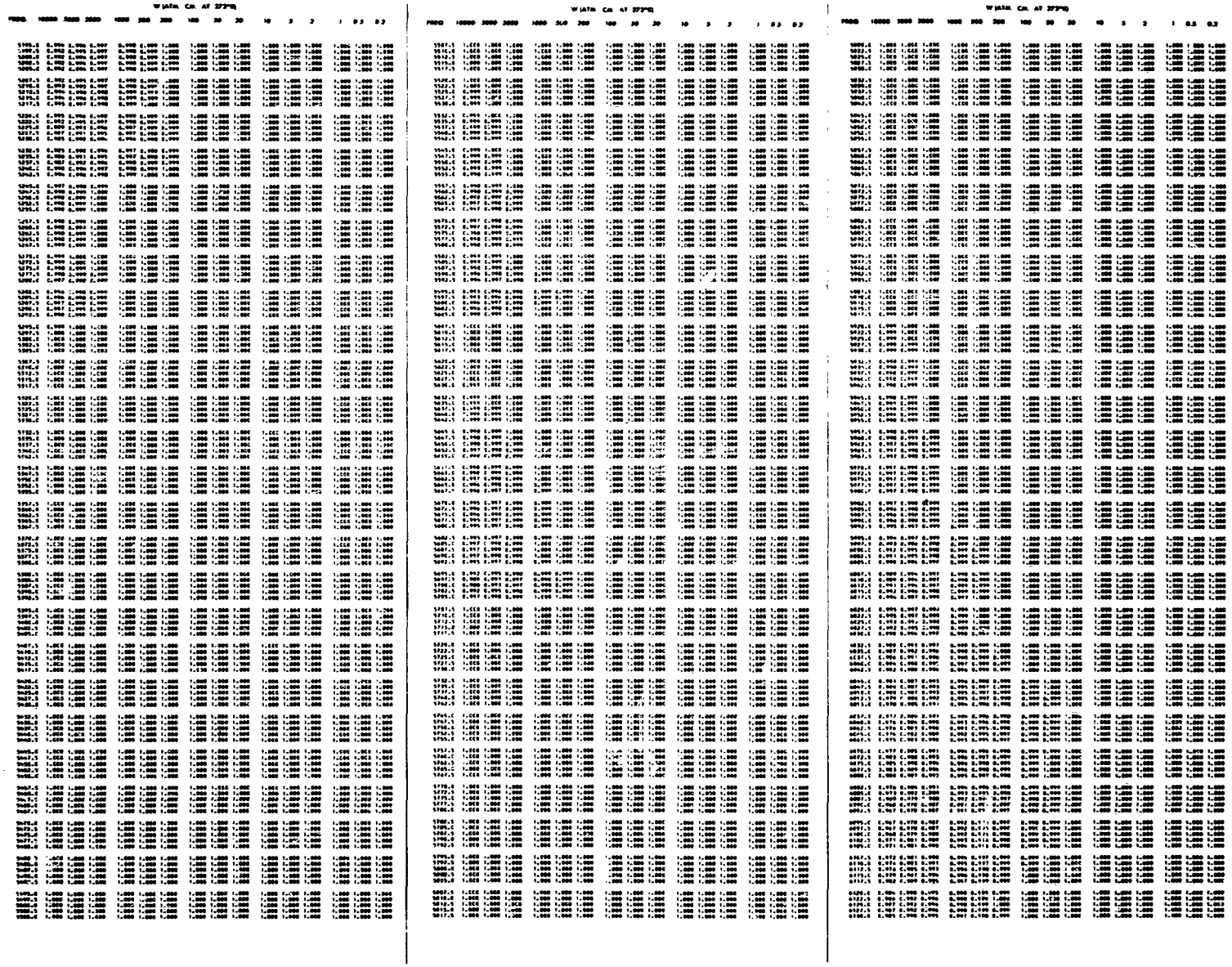
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T = 300°K



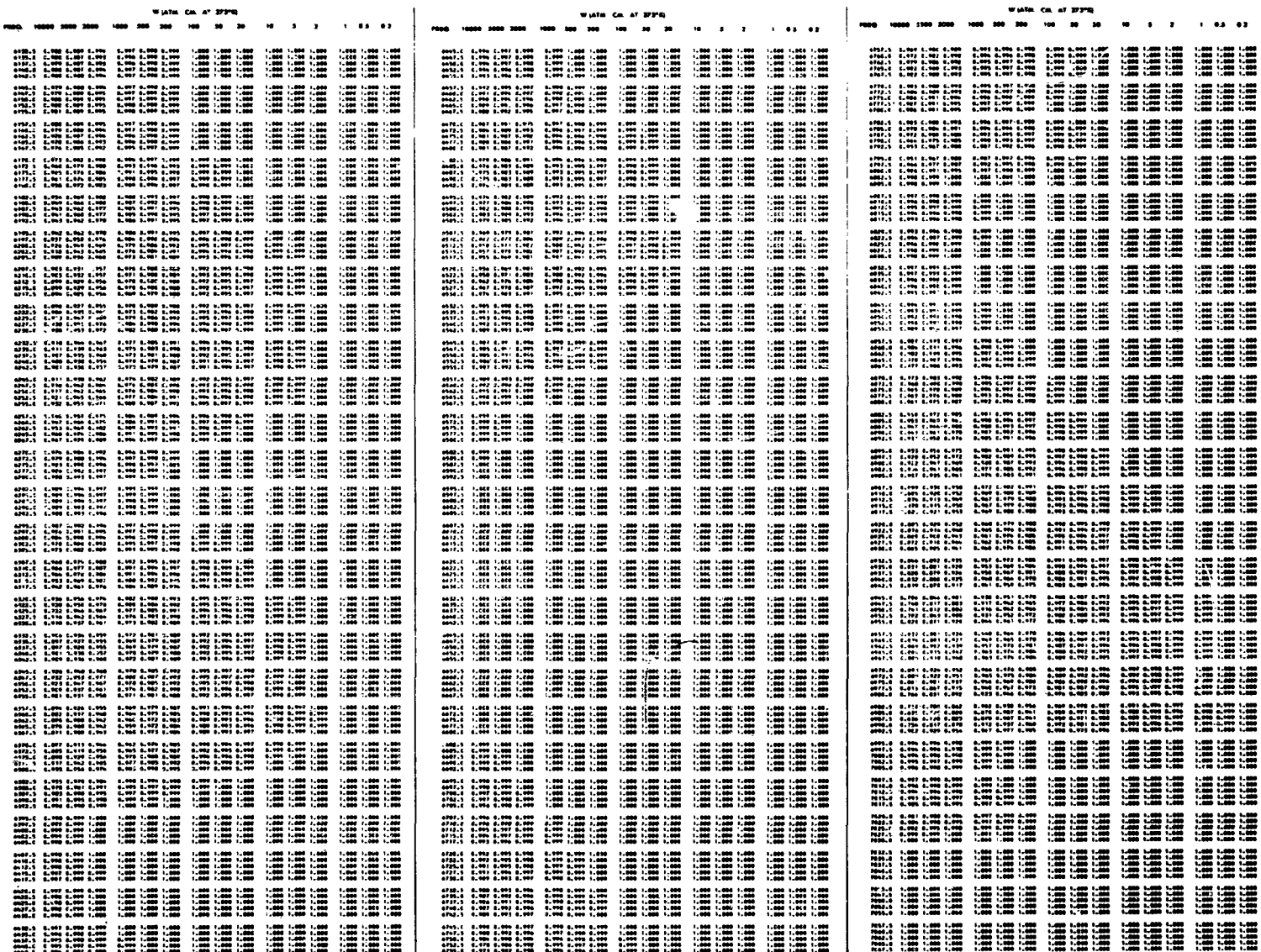
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T = 300°K



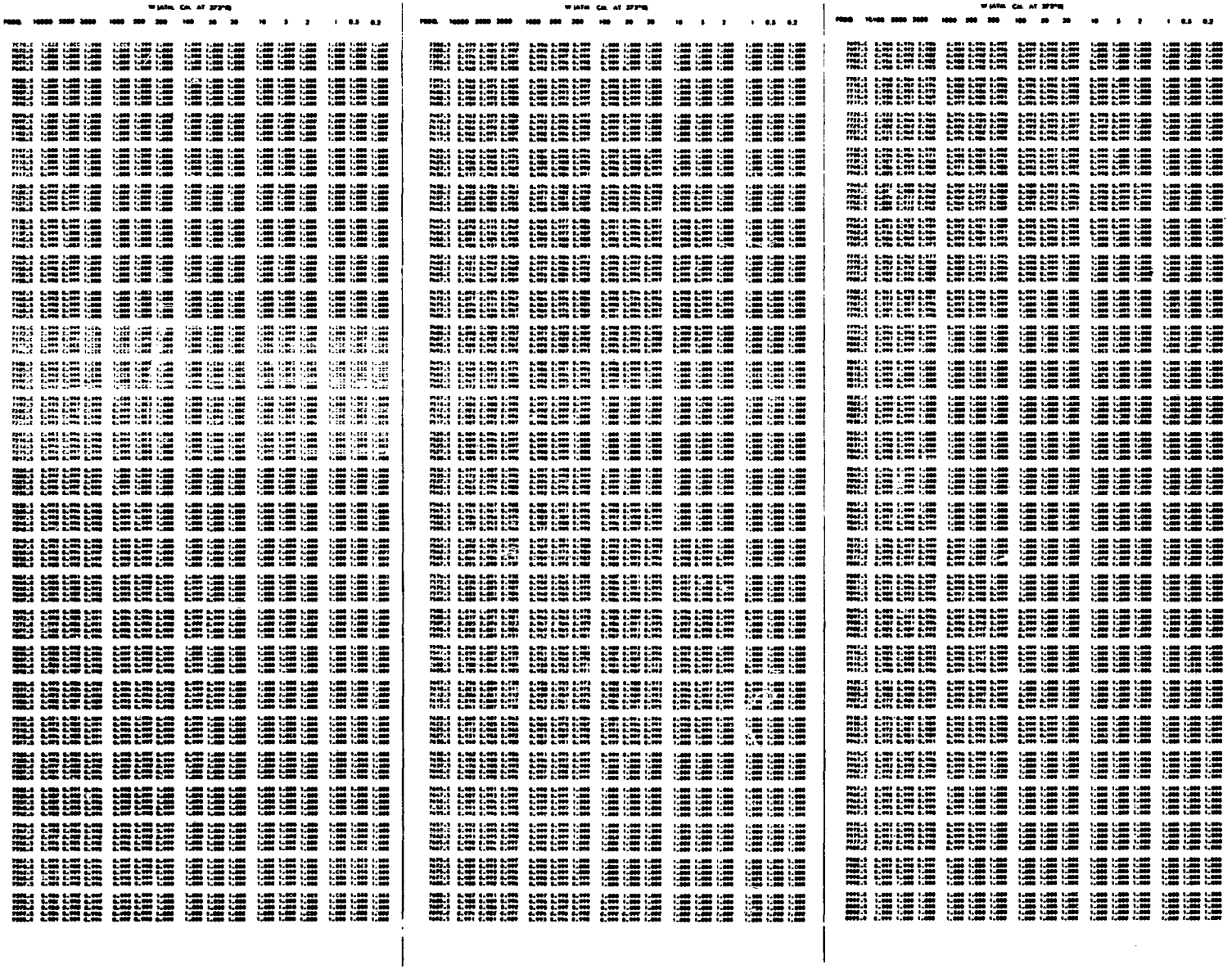
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T = 300°K



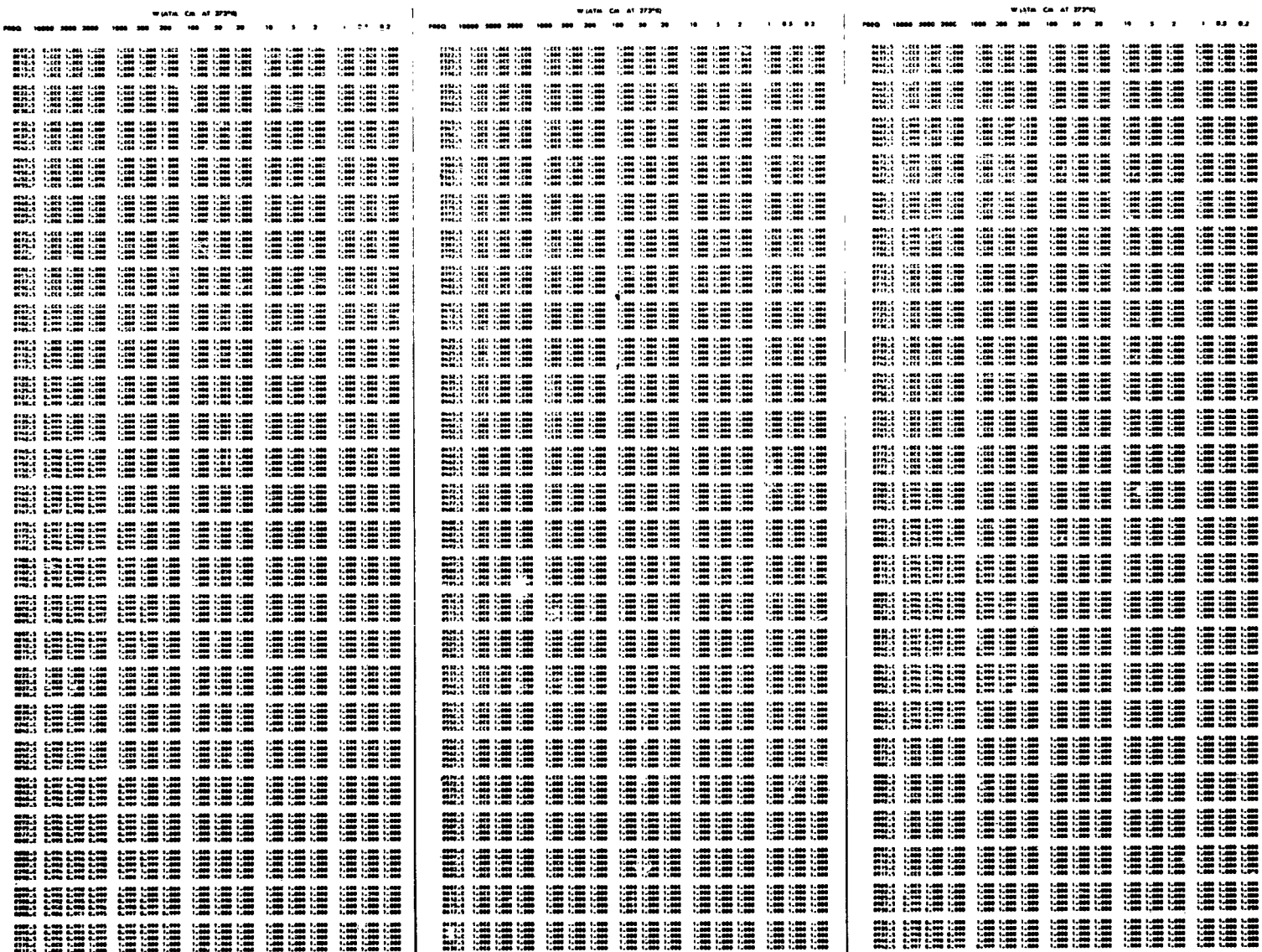
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T = 300°K



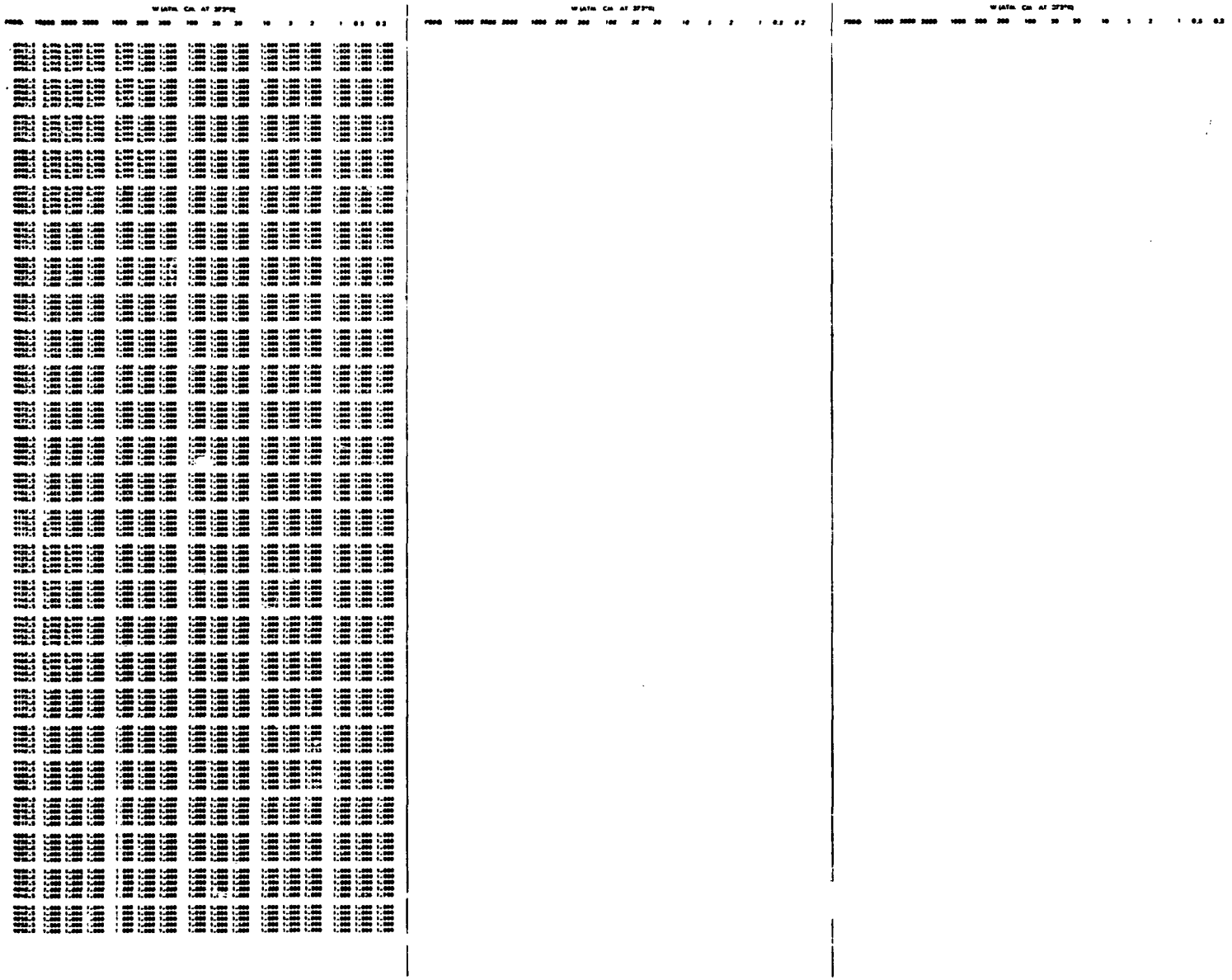
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T = 300°K



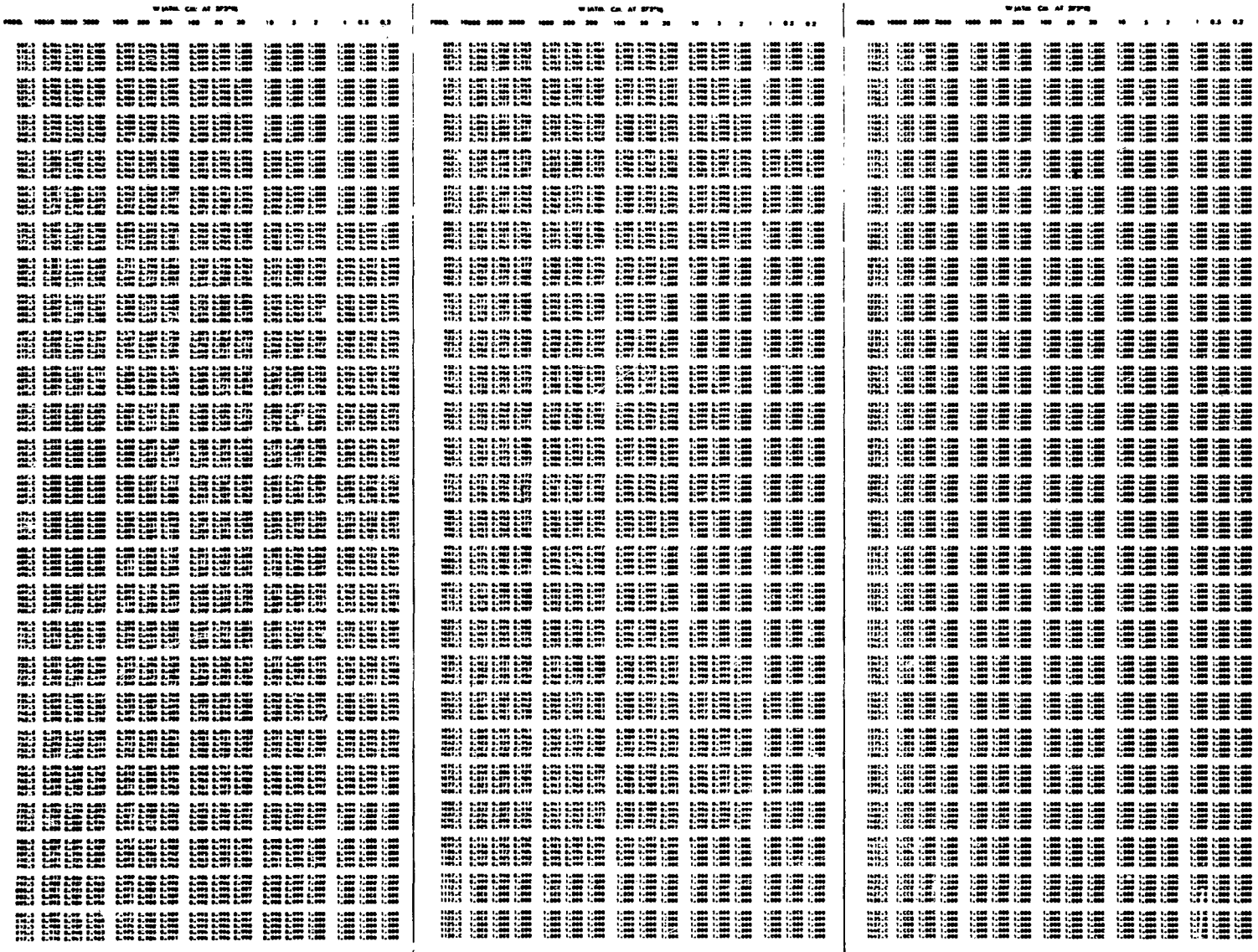
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T = 300°K



CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T = 300°K

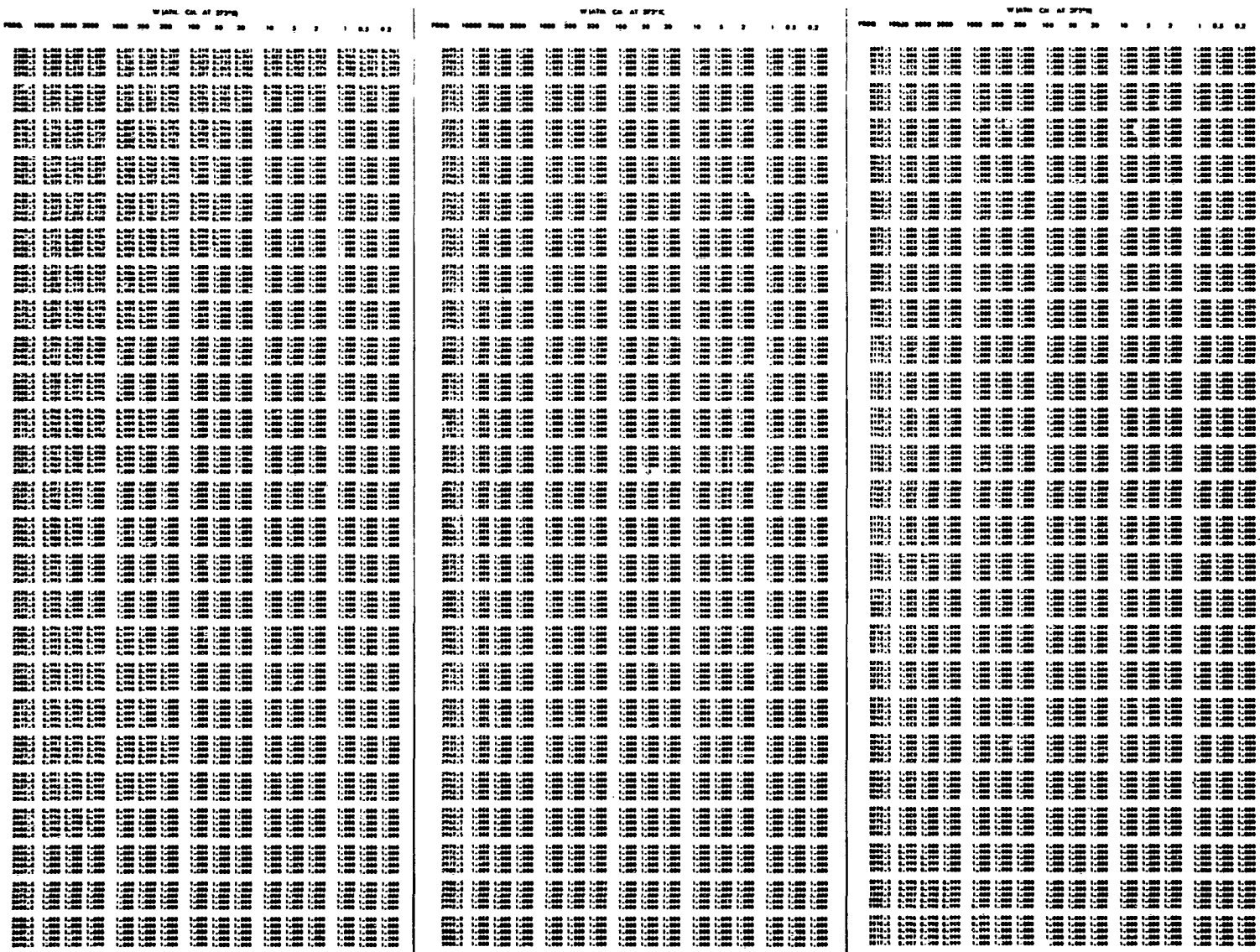


CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T = 300°K

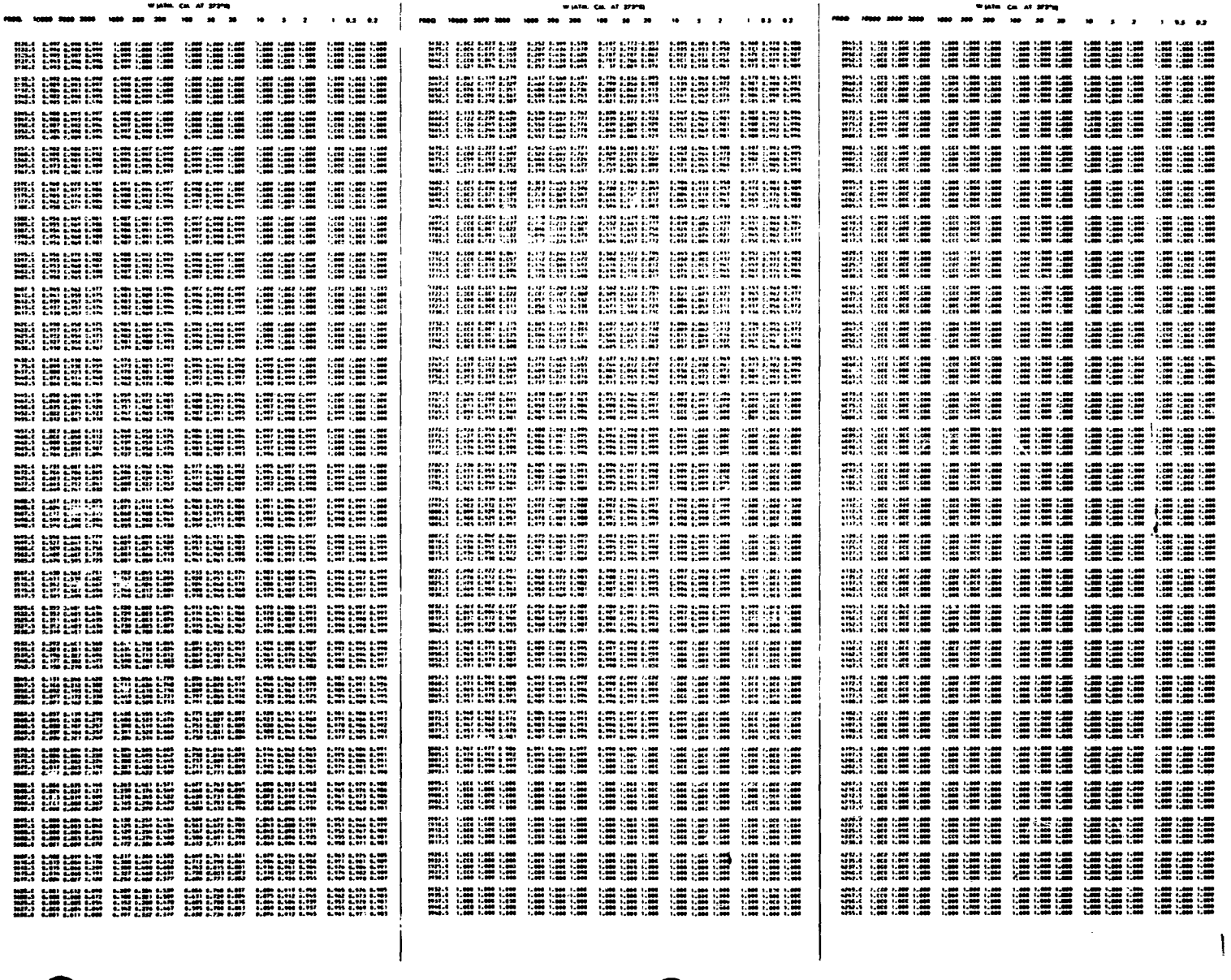
CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T = 300°K



CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T = 300°K

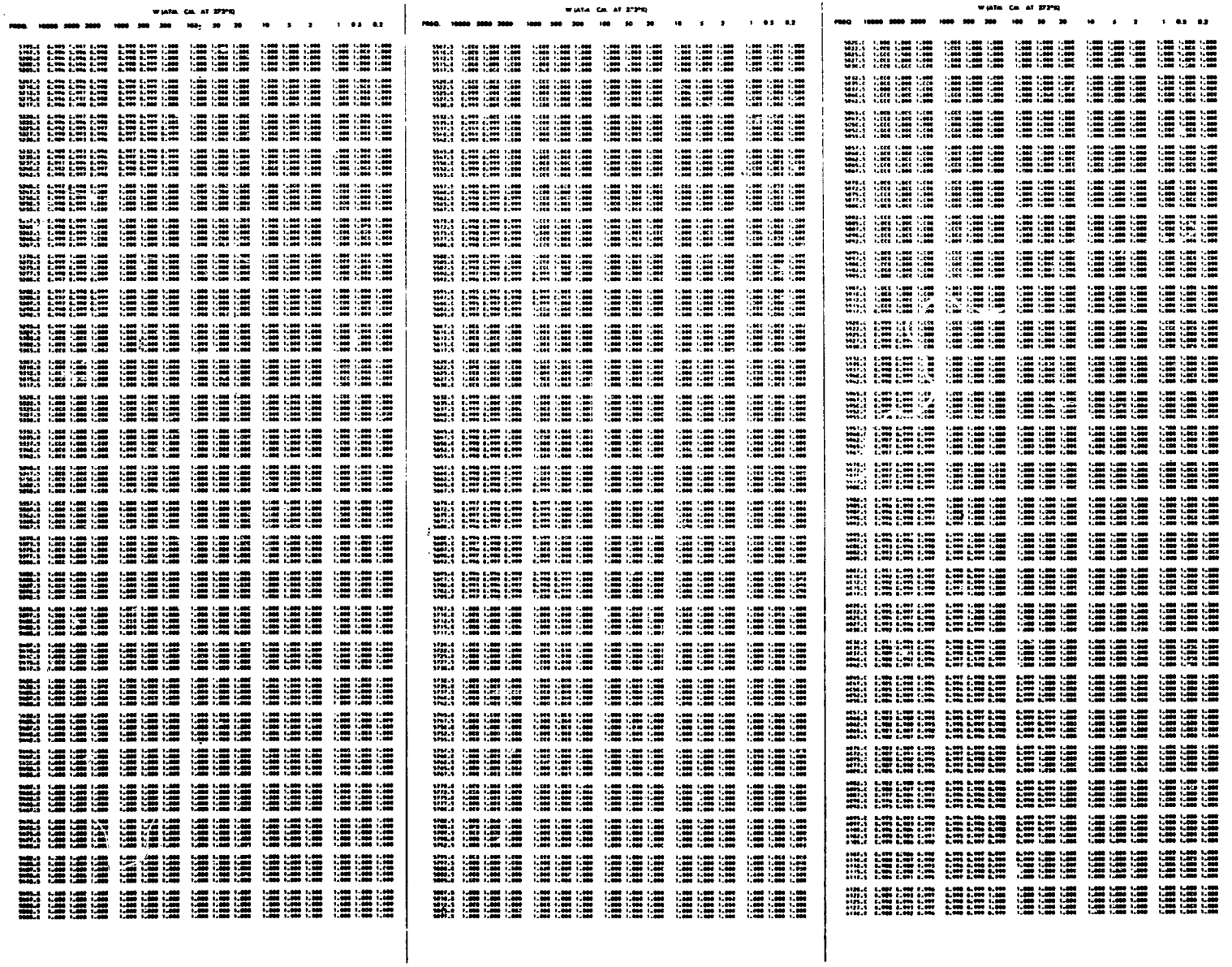


CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T = 300°K

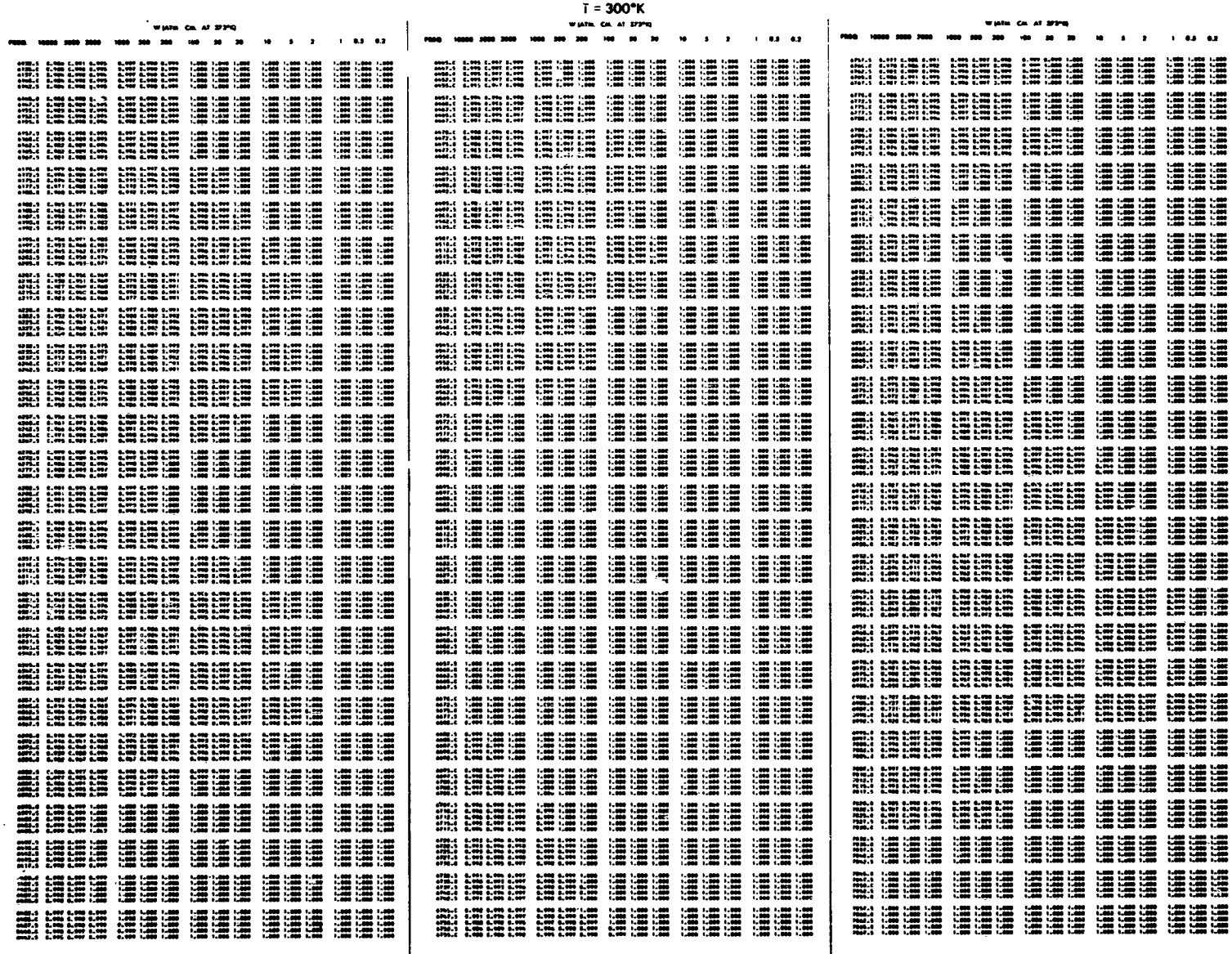
CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T = 300°K



CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

$\bar{T}$ = 300°K

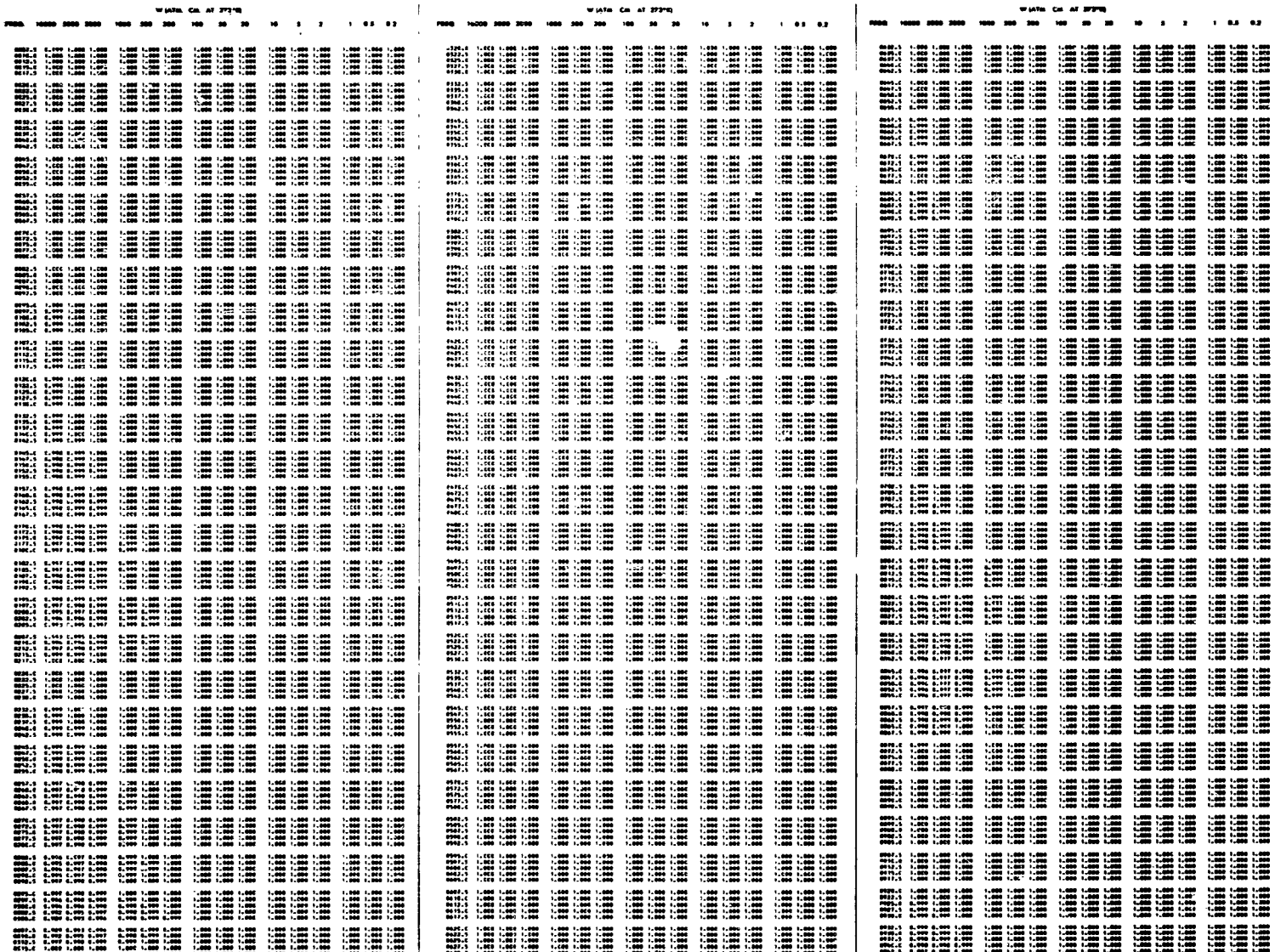


CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T = 300°K

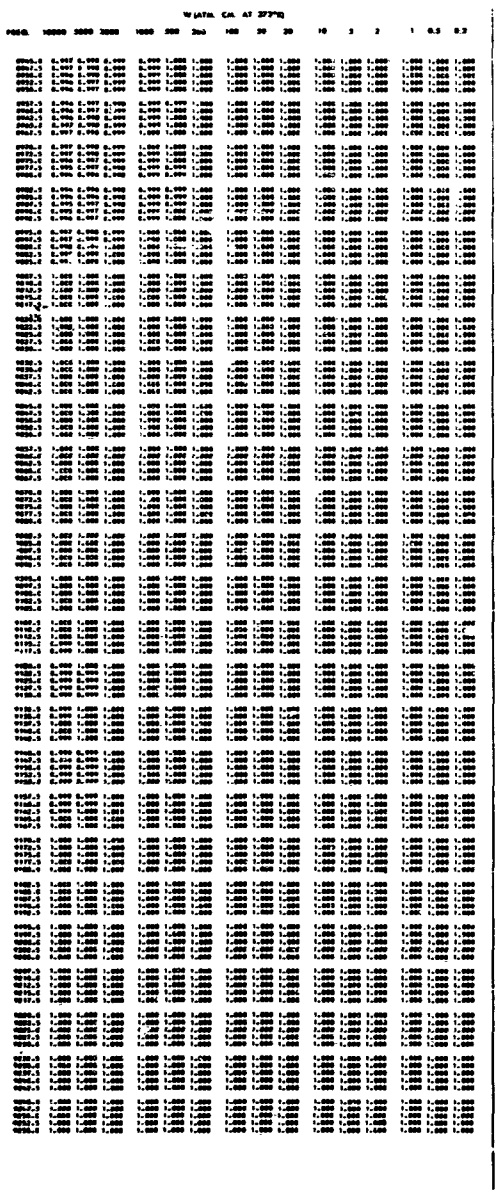
CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

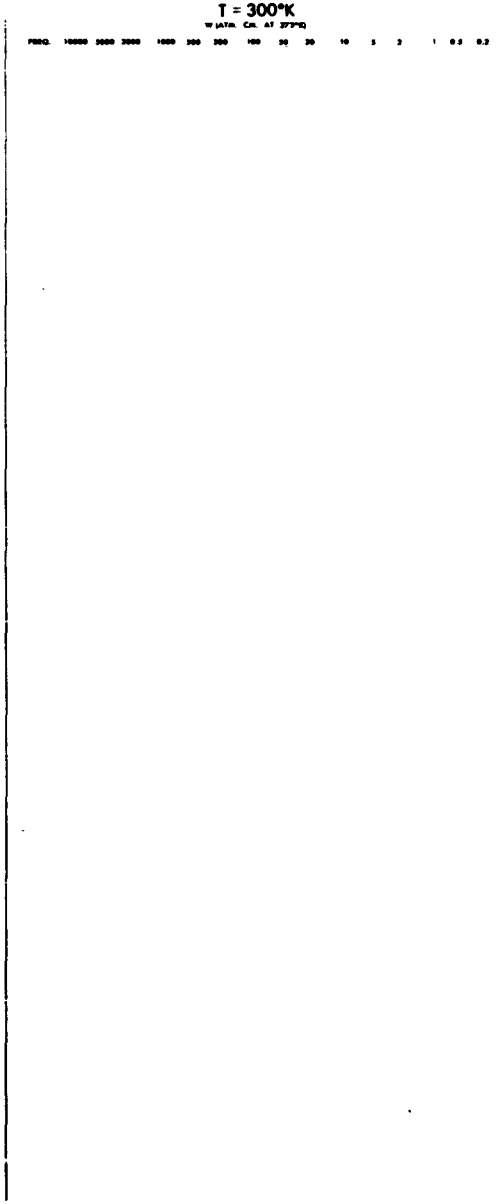
T = 300°K

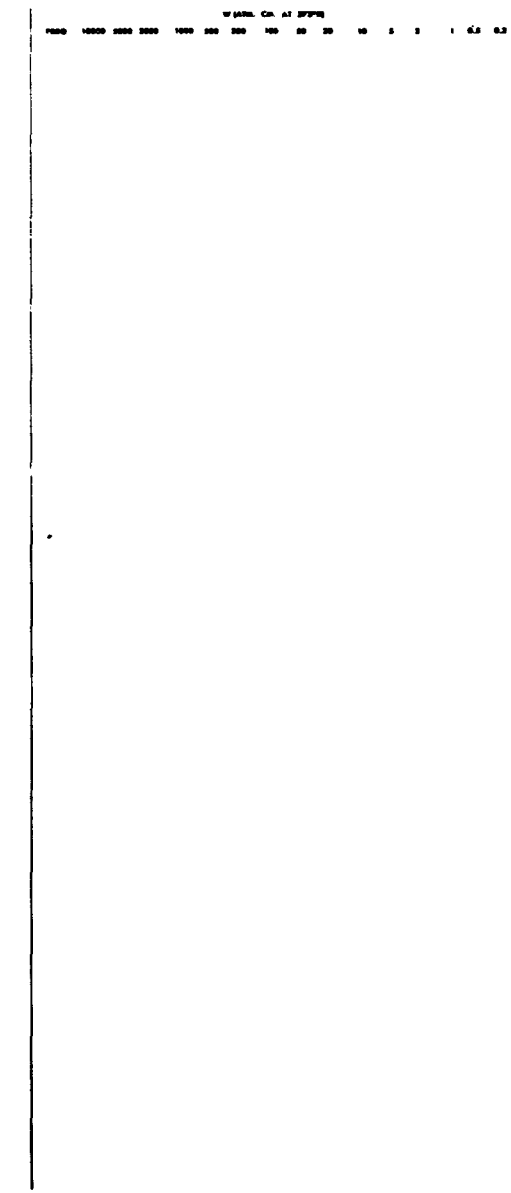


CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T = 300°K





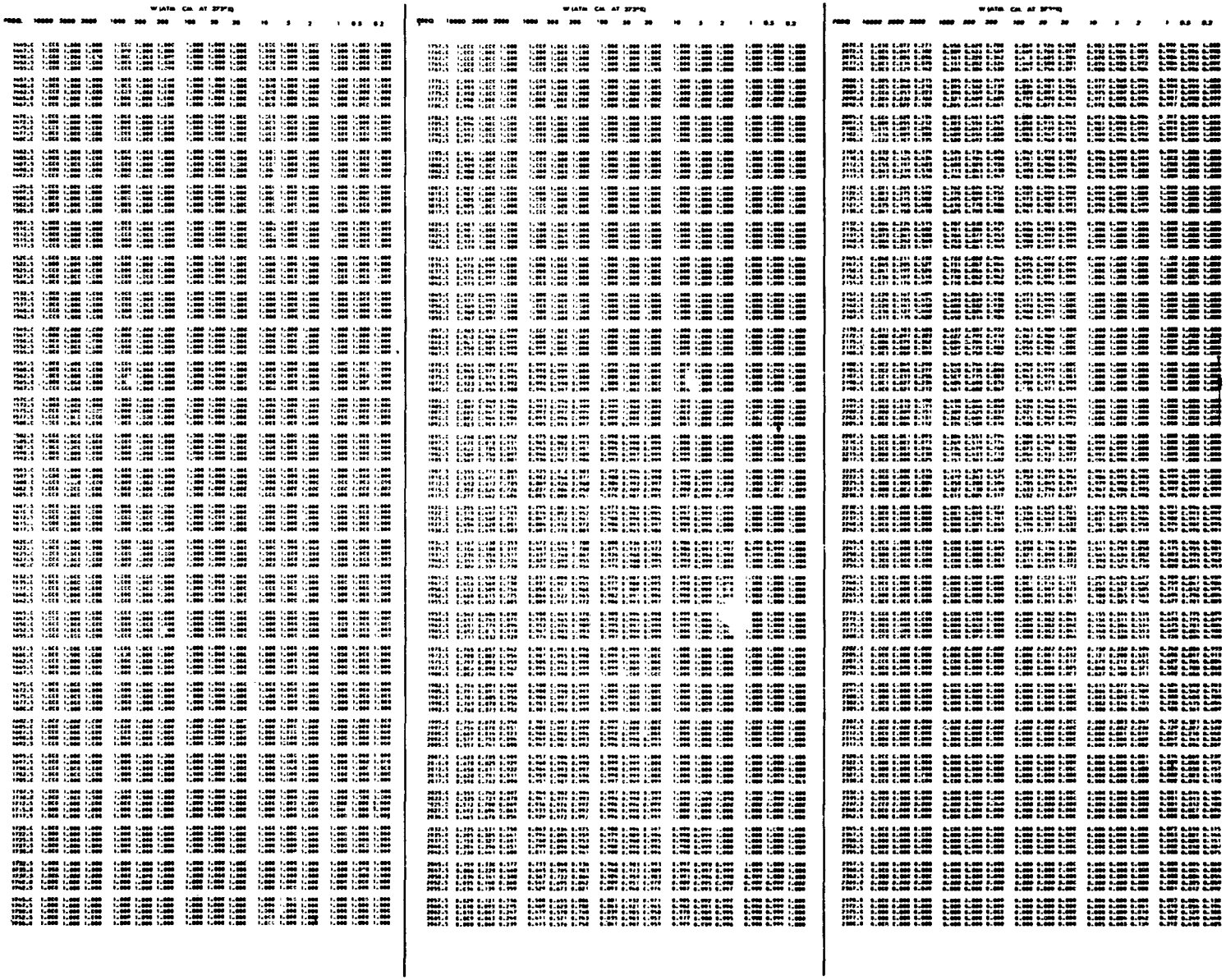


CARBON DIOXIDE AT 100 ATMOSPHERE PRESSURE

T=250° K

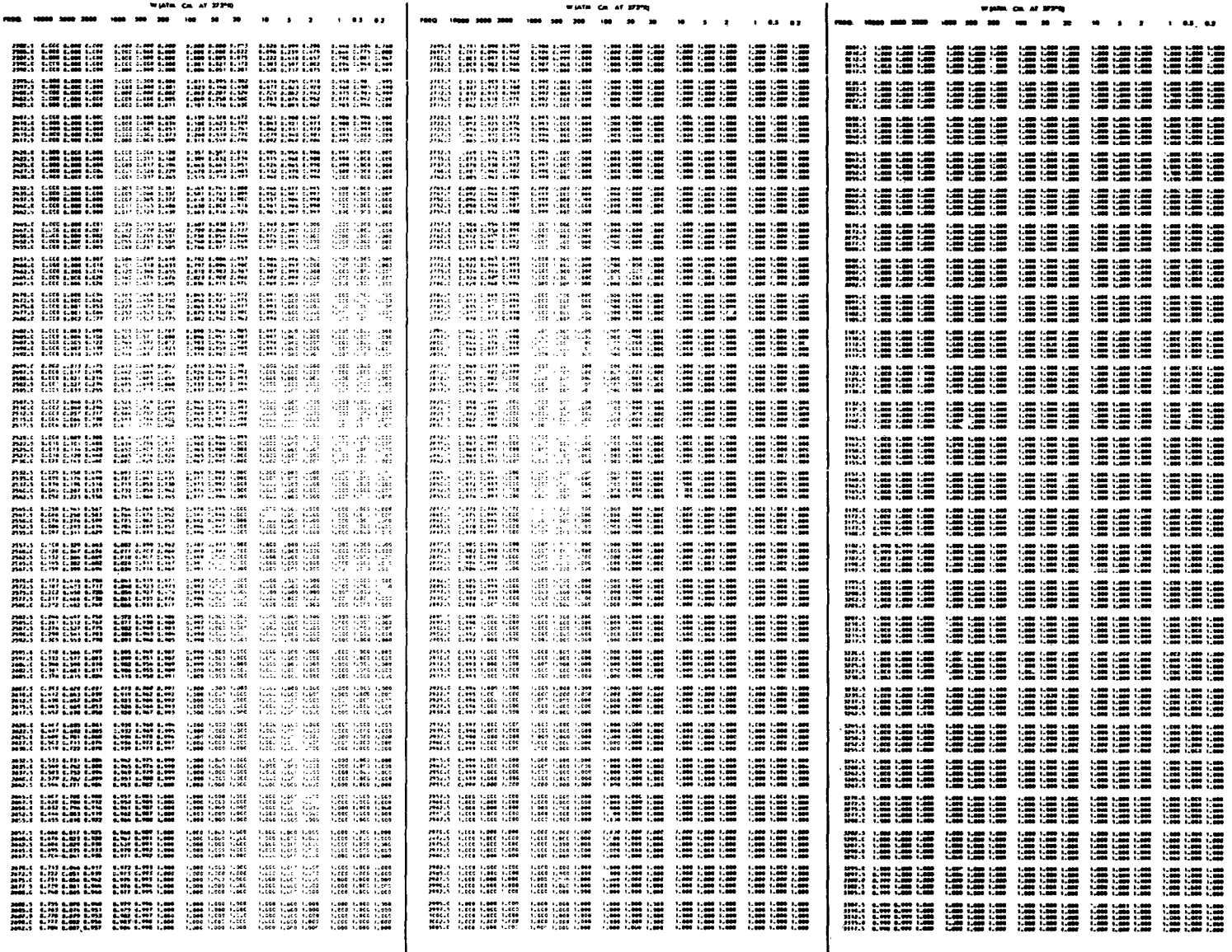
CARBON DIOXIDE AT 100 ATMOSPHERE PRESSURE

T=250° K



CARBON DIOXIDE AT 100 ATMOSPHERE PRESSURE

T=250° K

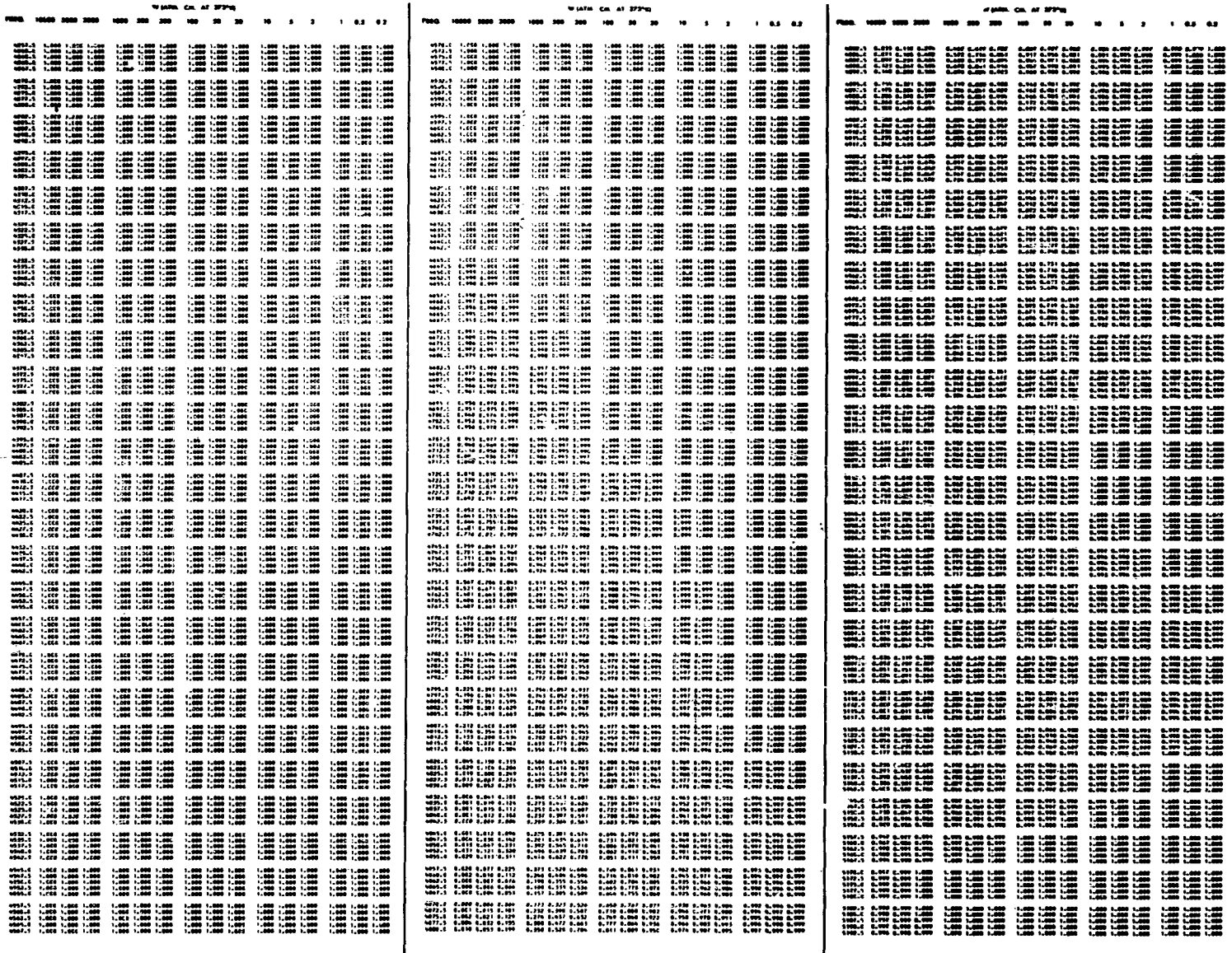


CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

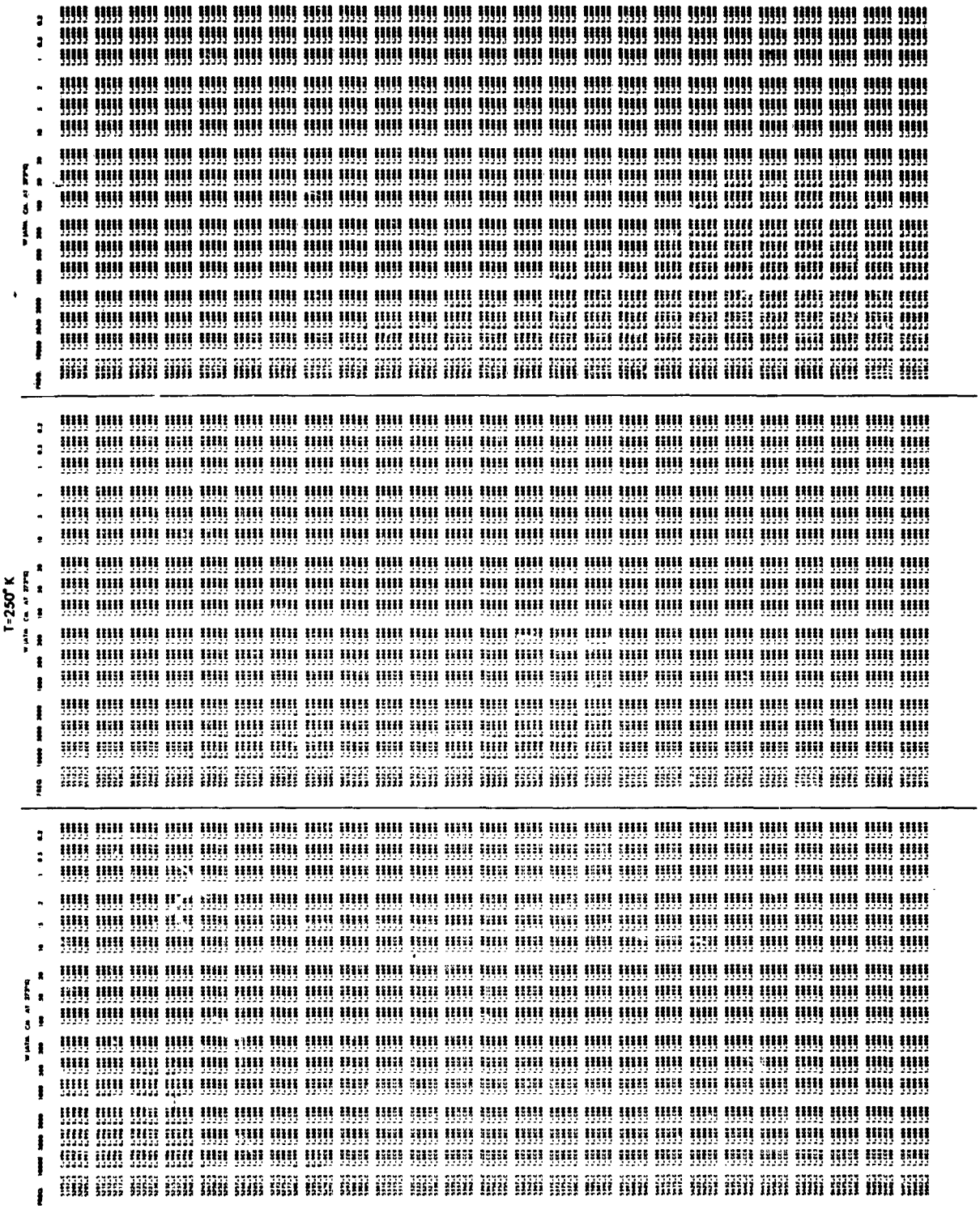
T=250° K

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=250° K

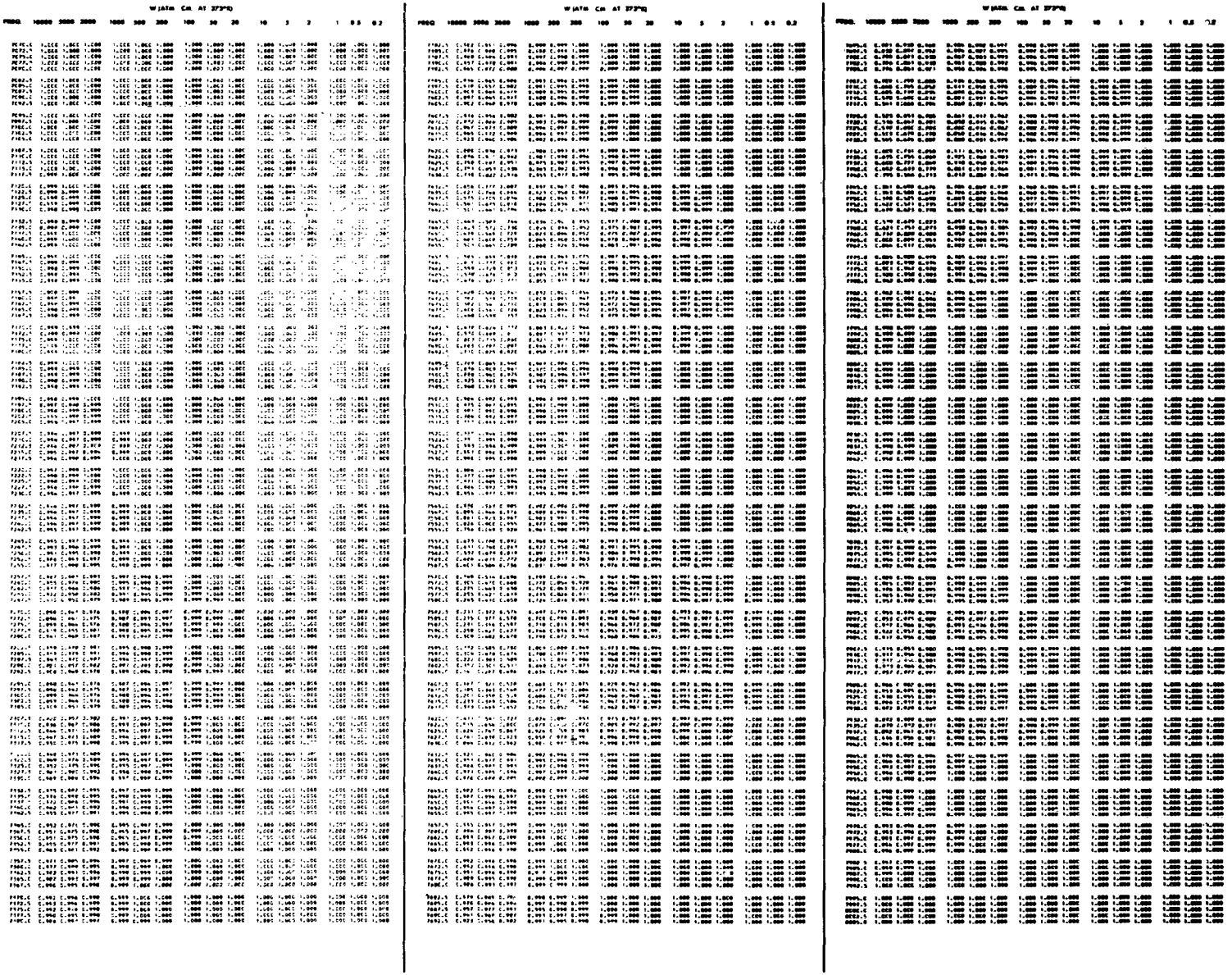


CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE
T=250° K



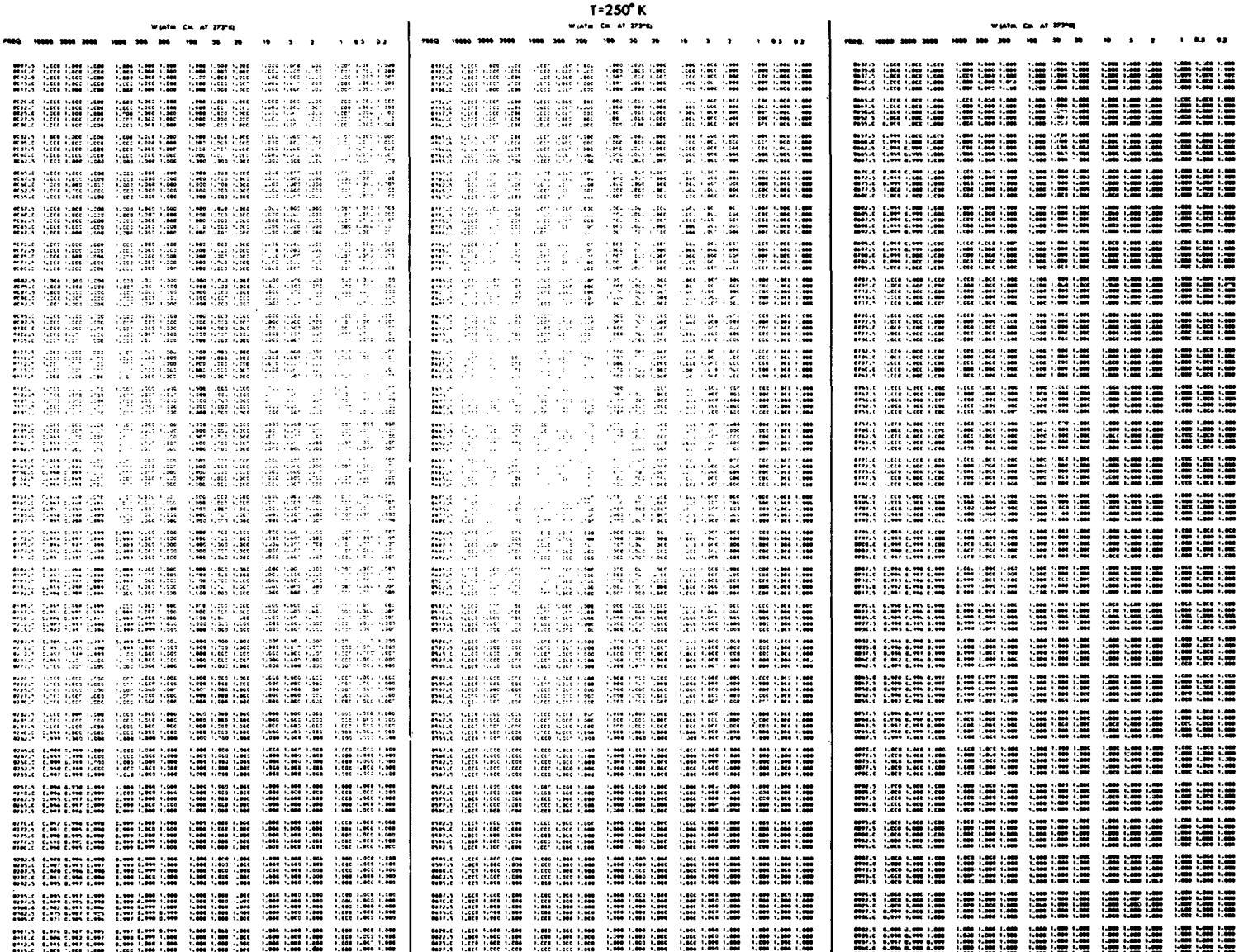
CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE
T=250°K

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE
T=250° K



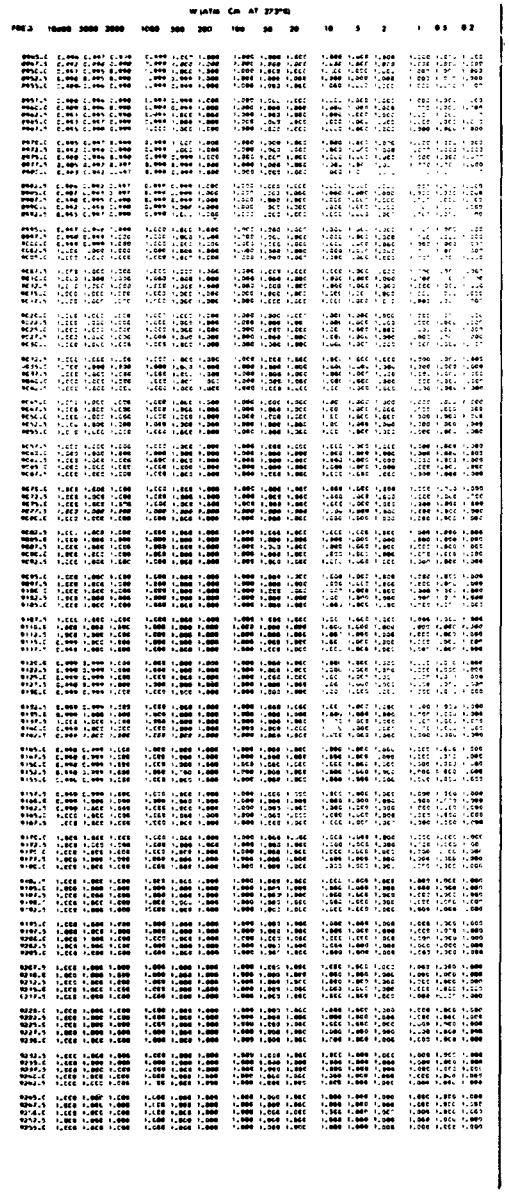
CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

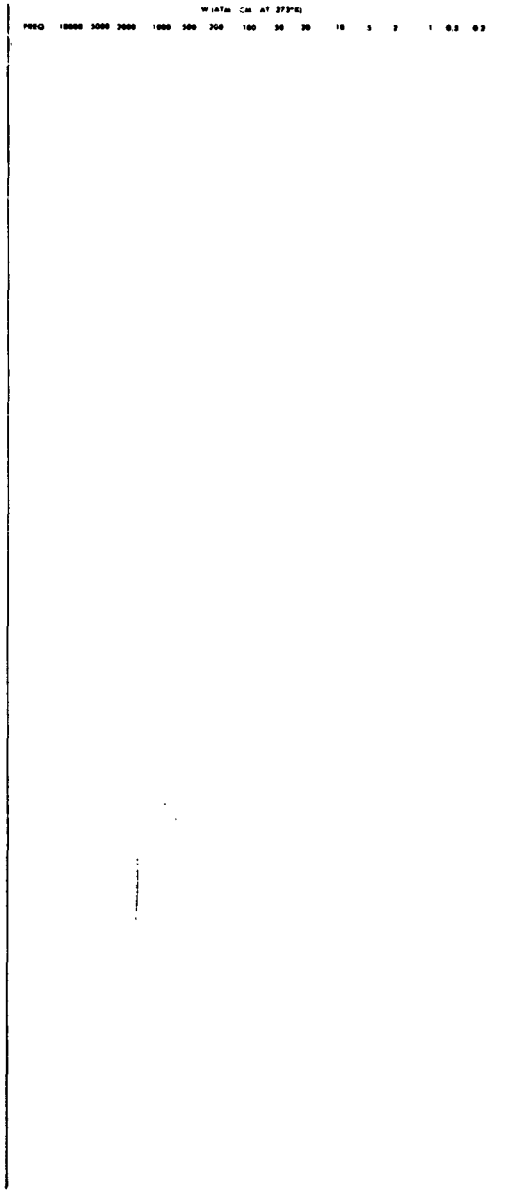
T=250° K

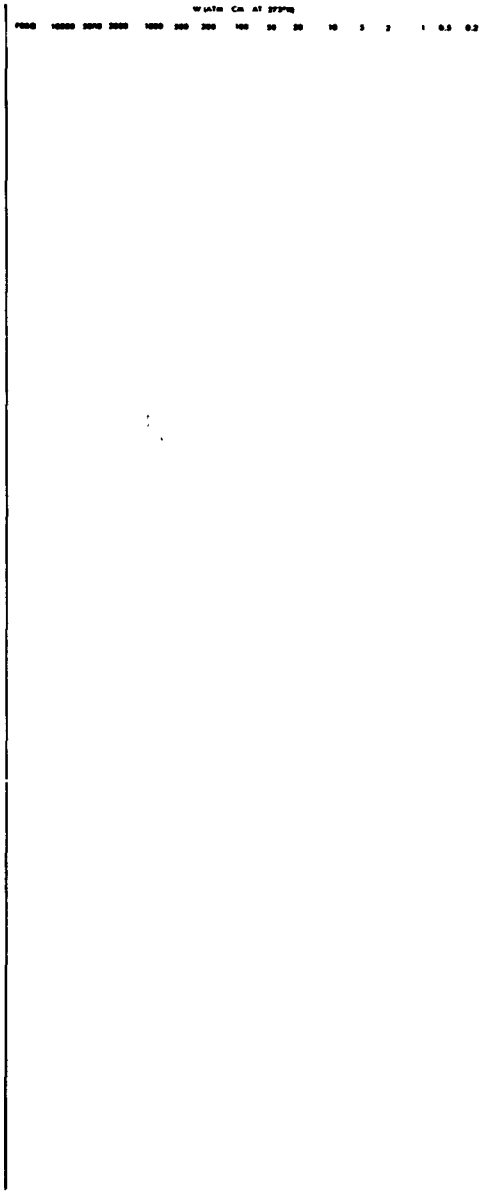


CARBON DIOXIDE AT 100 ATMOSPHERE PRESSURE

T=250° K

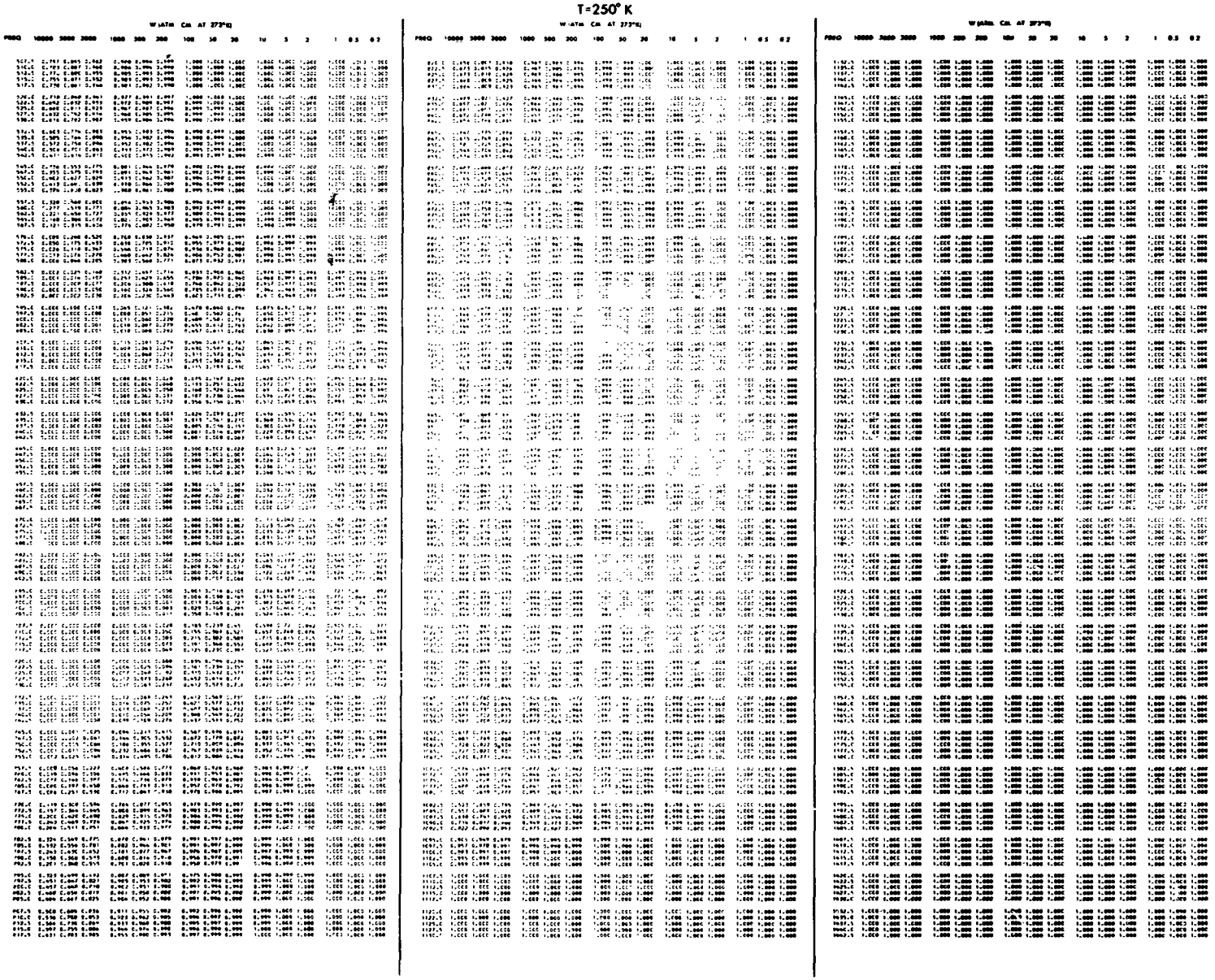






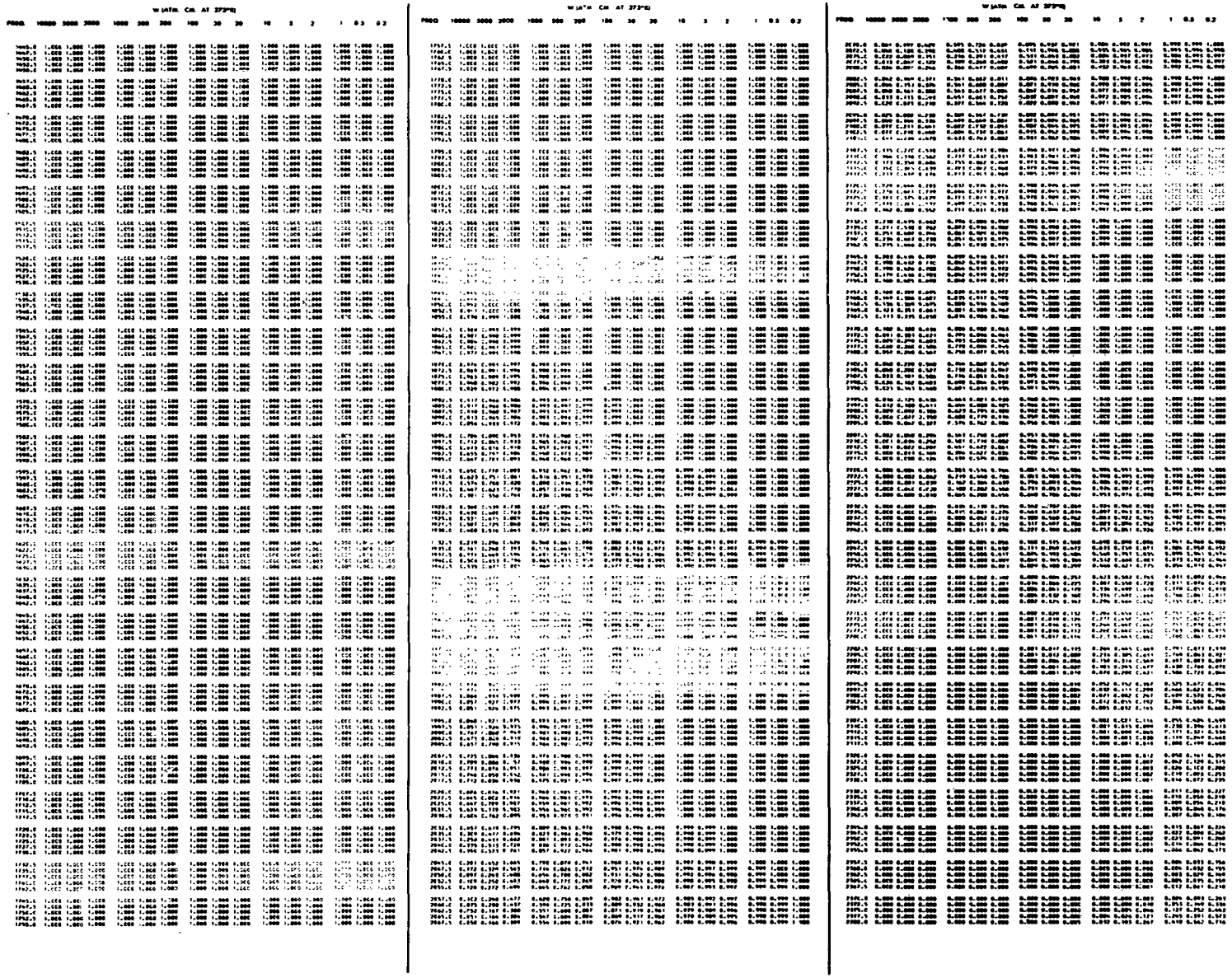
CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=250° K



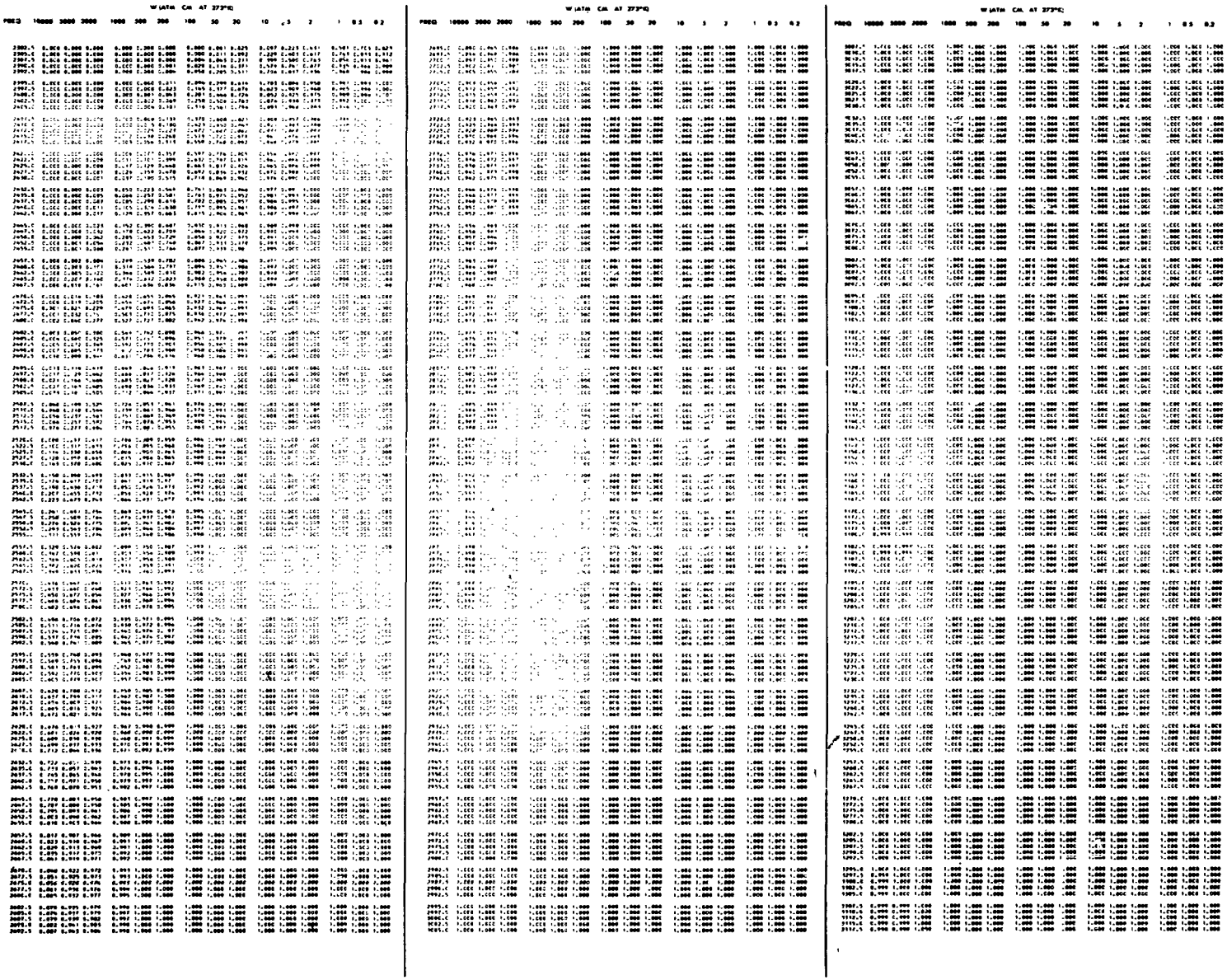
CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=250° K



CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=250° K

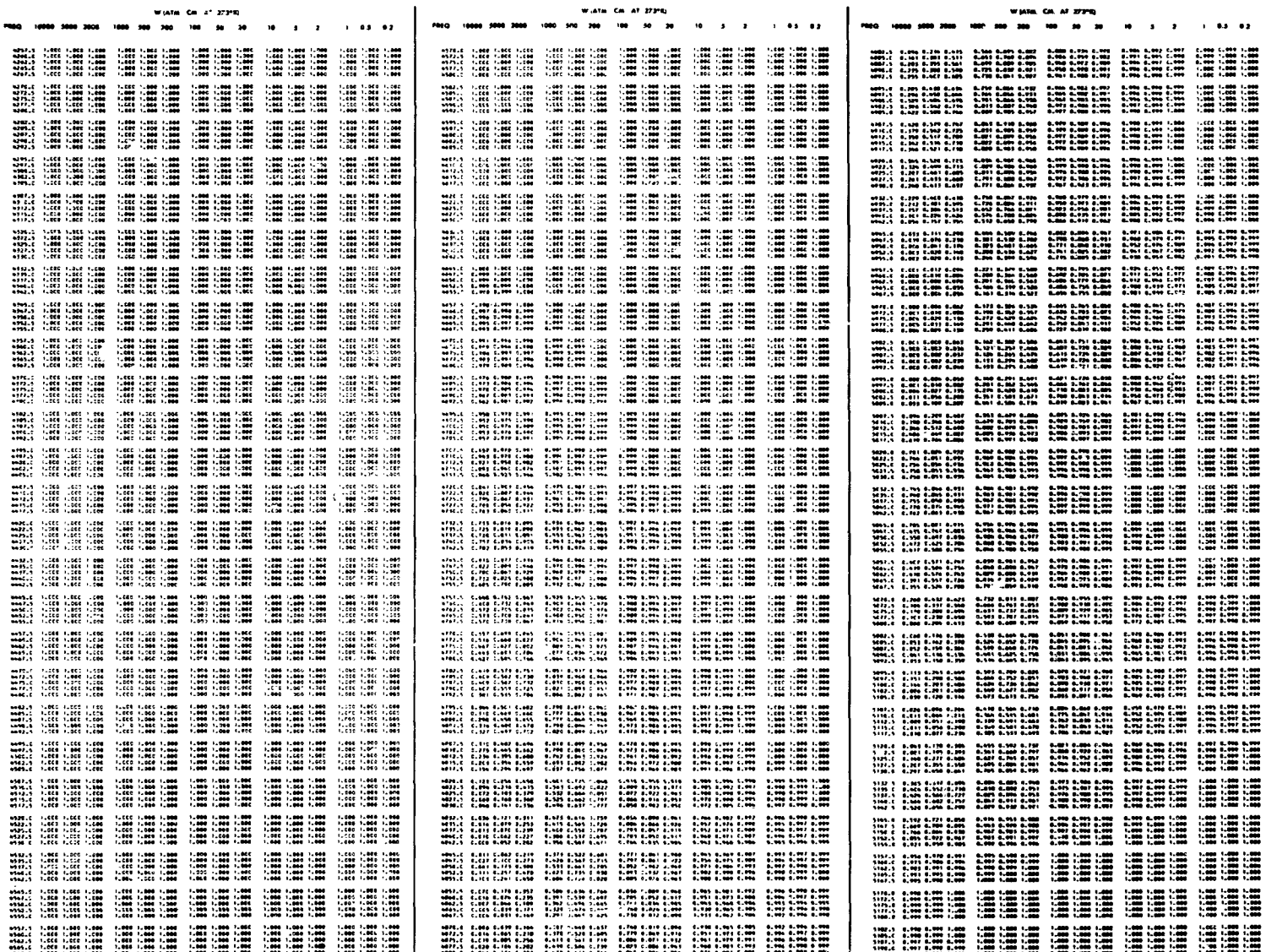


CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=250° K

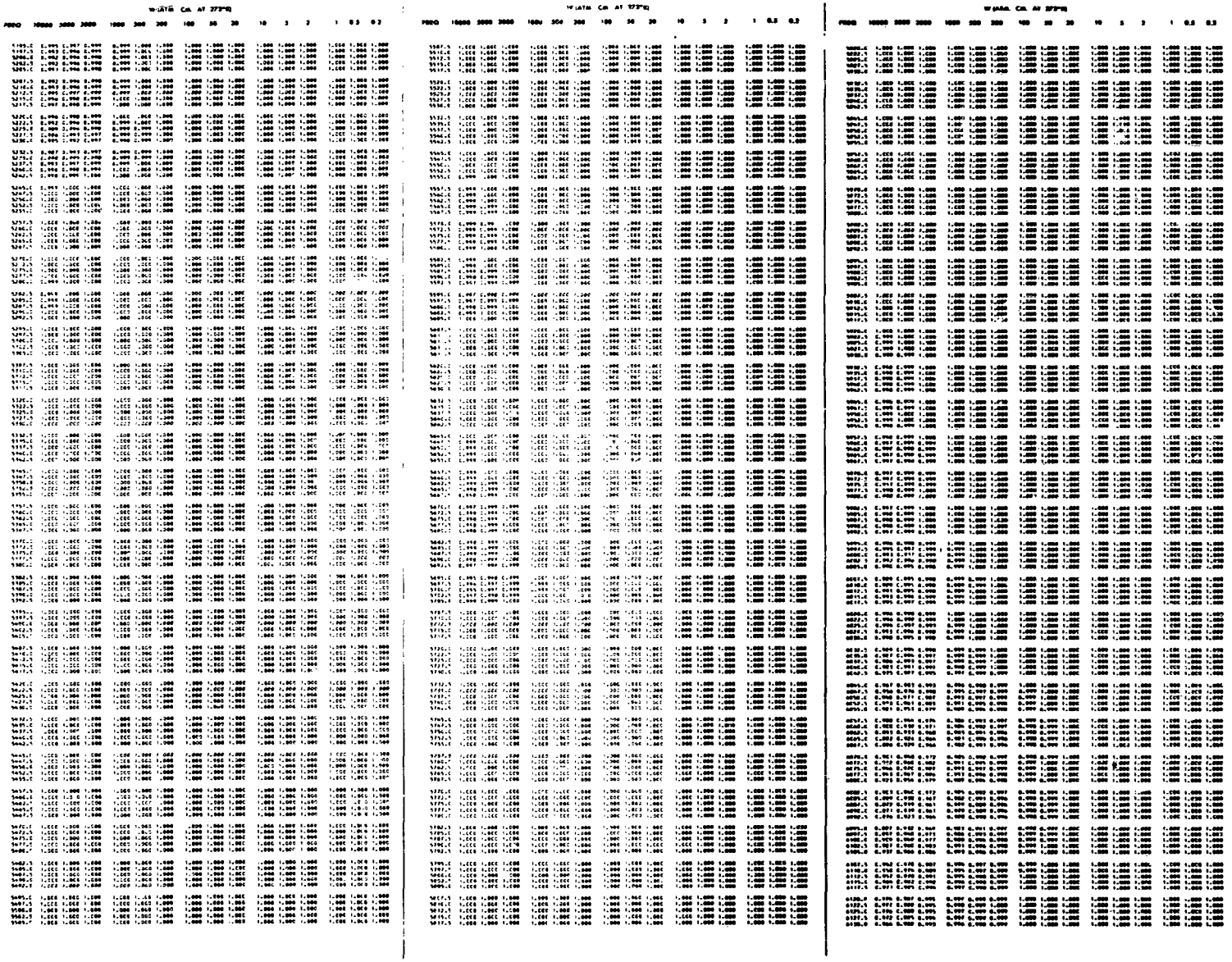
CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=250° K

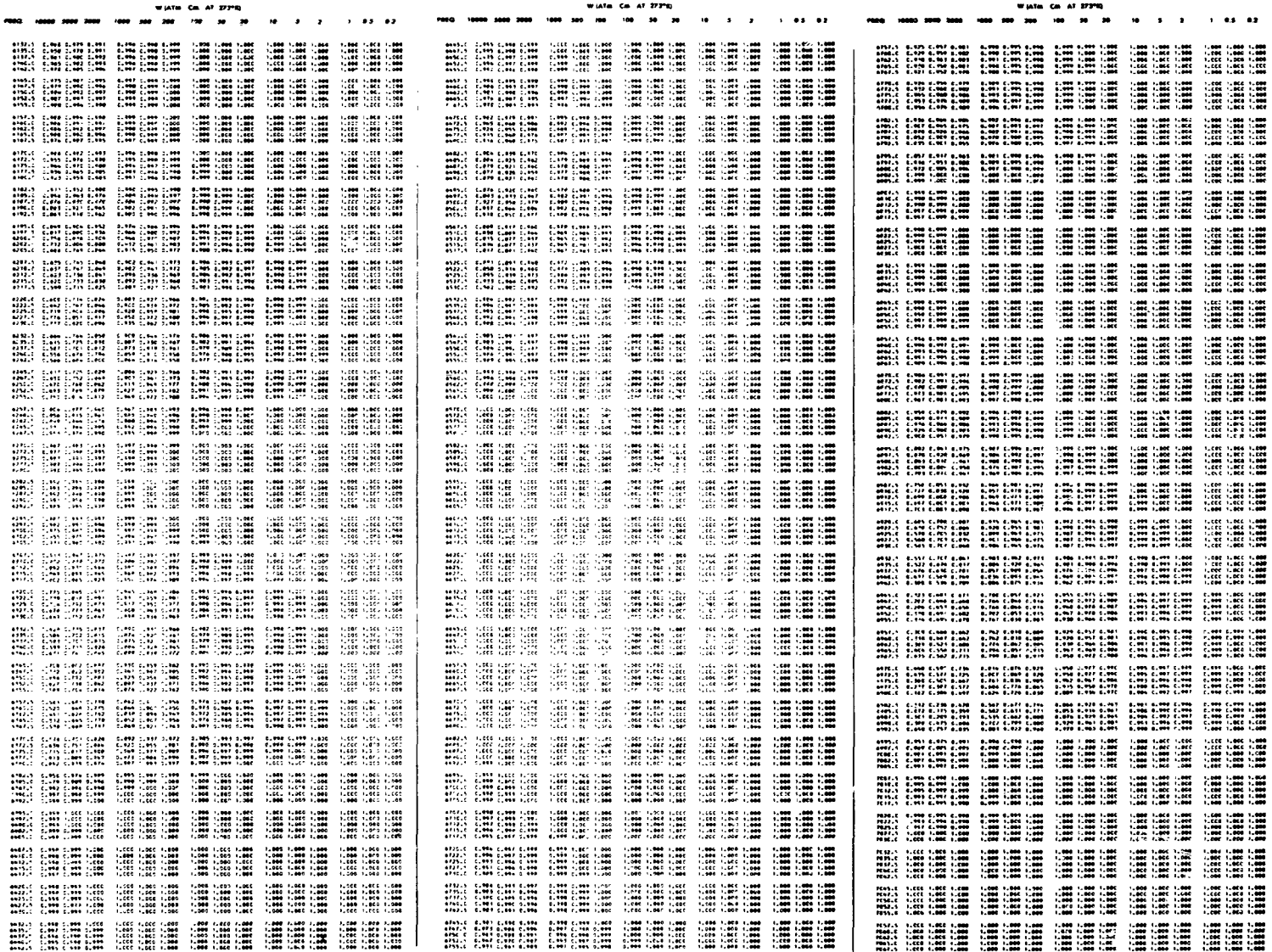


CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

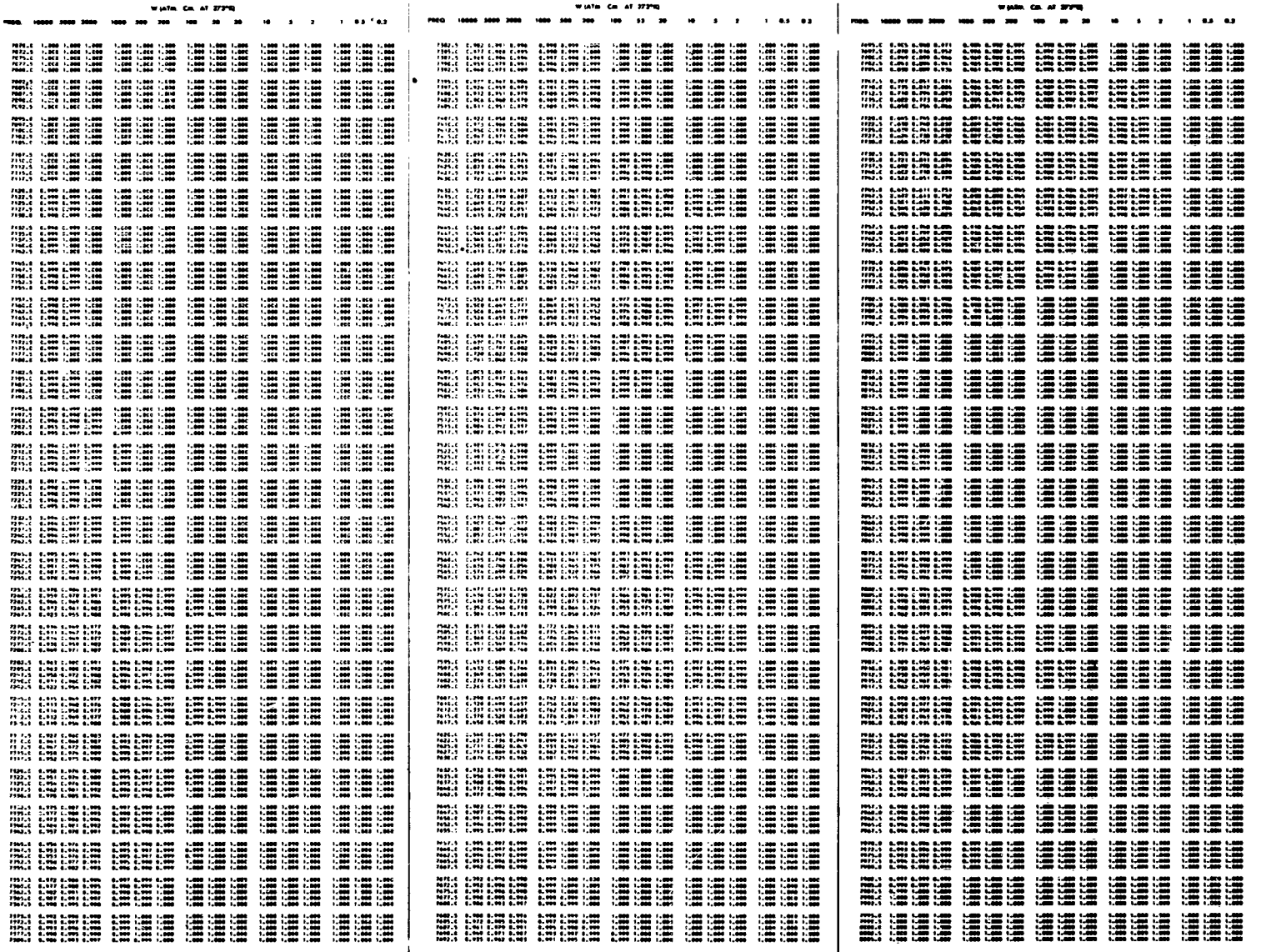
T=250° K



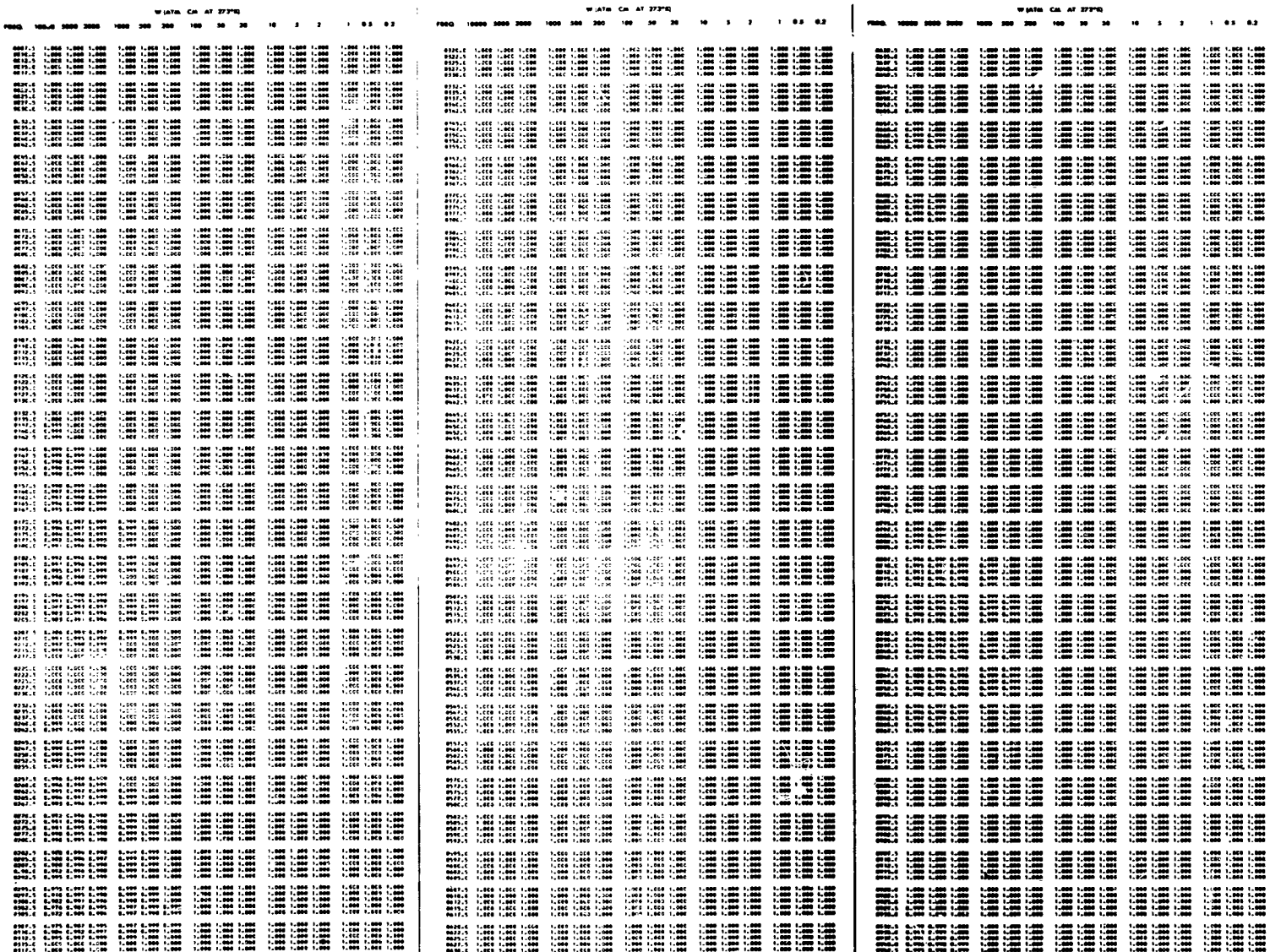
CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE
T=250° K



CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE
T=250° K

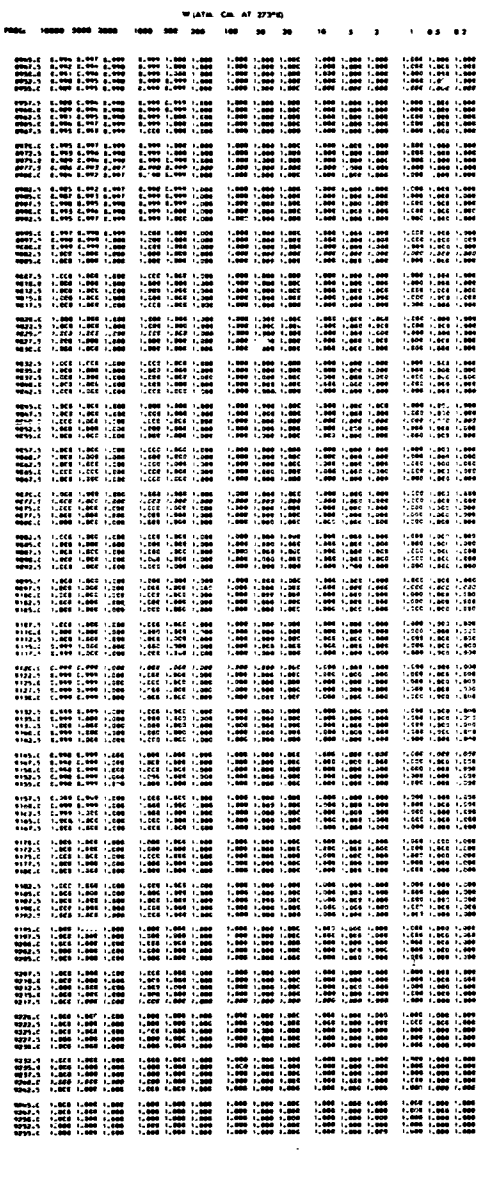


CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE
T=250° K



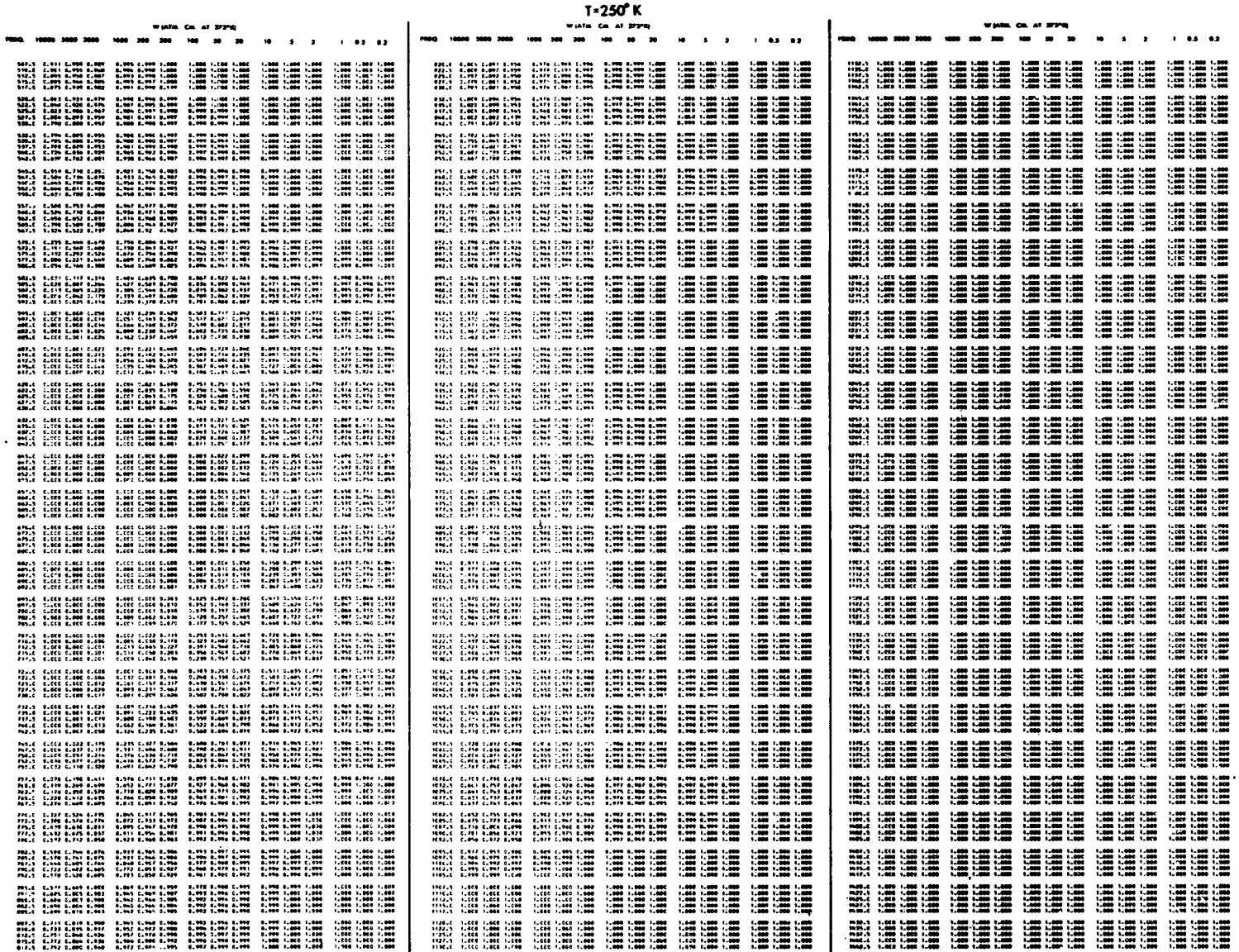
CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=250° K



CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=250° K

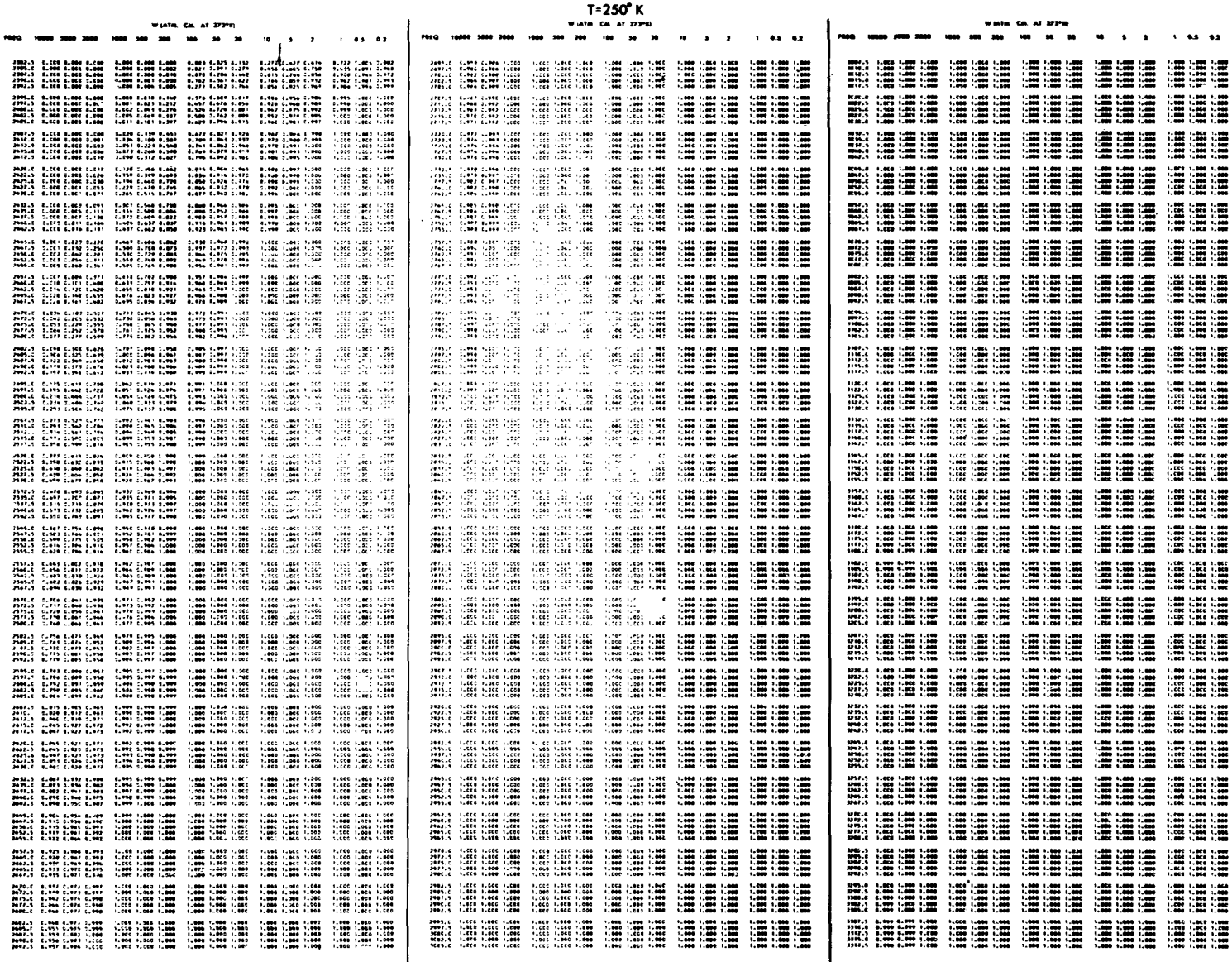


CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=250° K

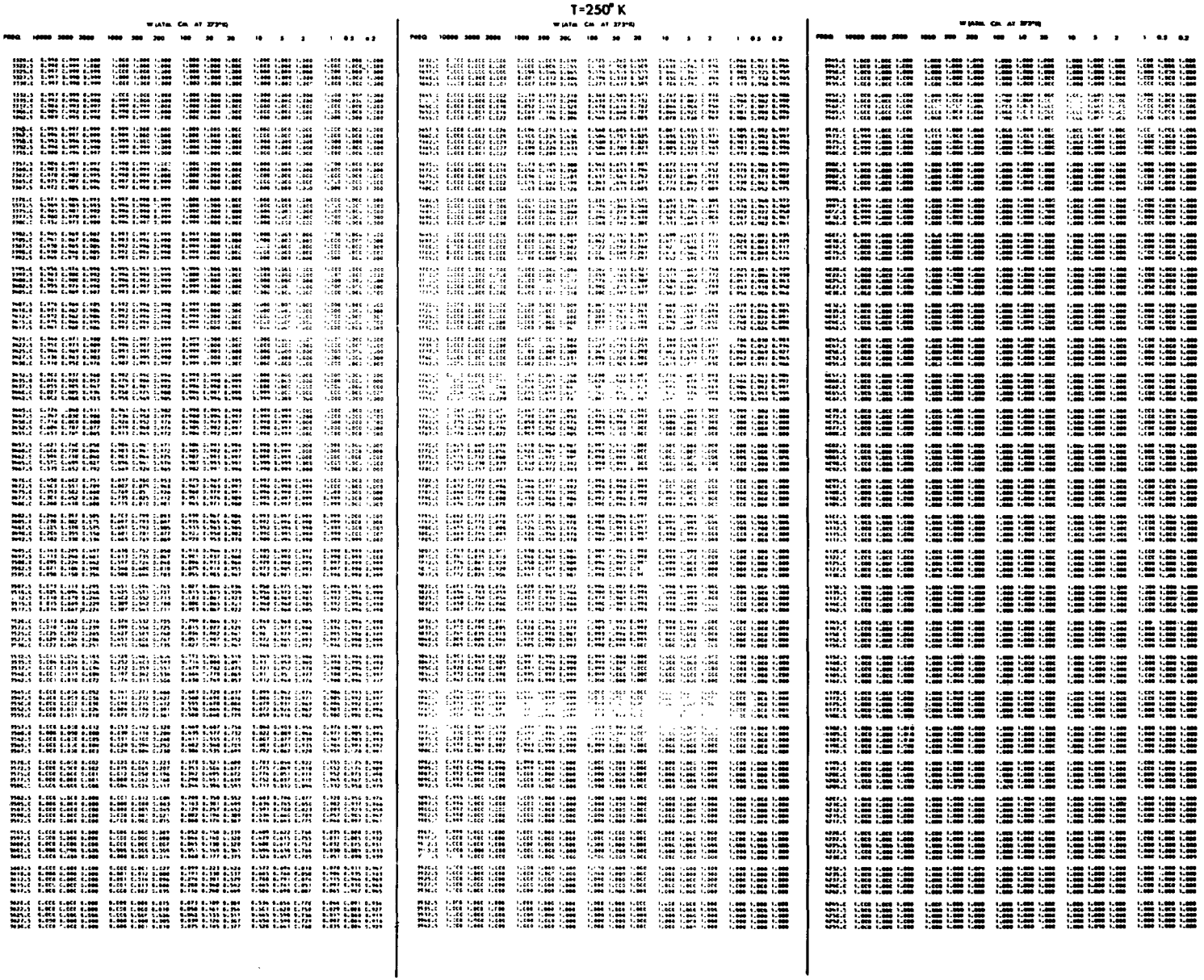
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=250° K



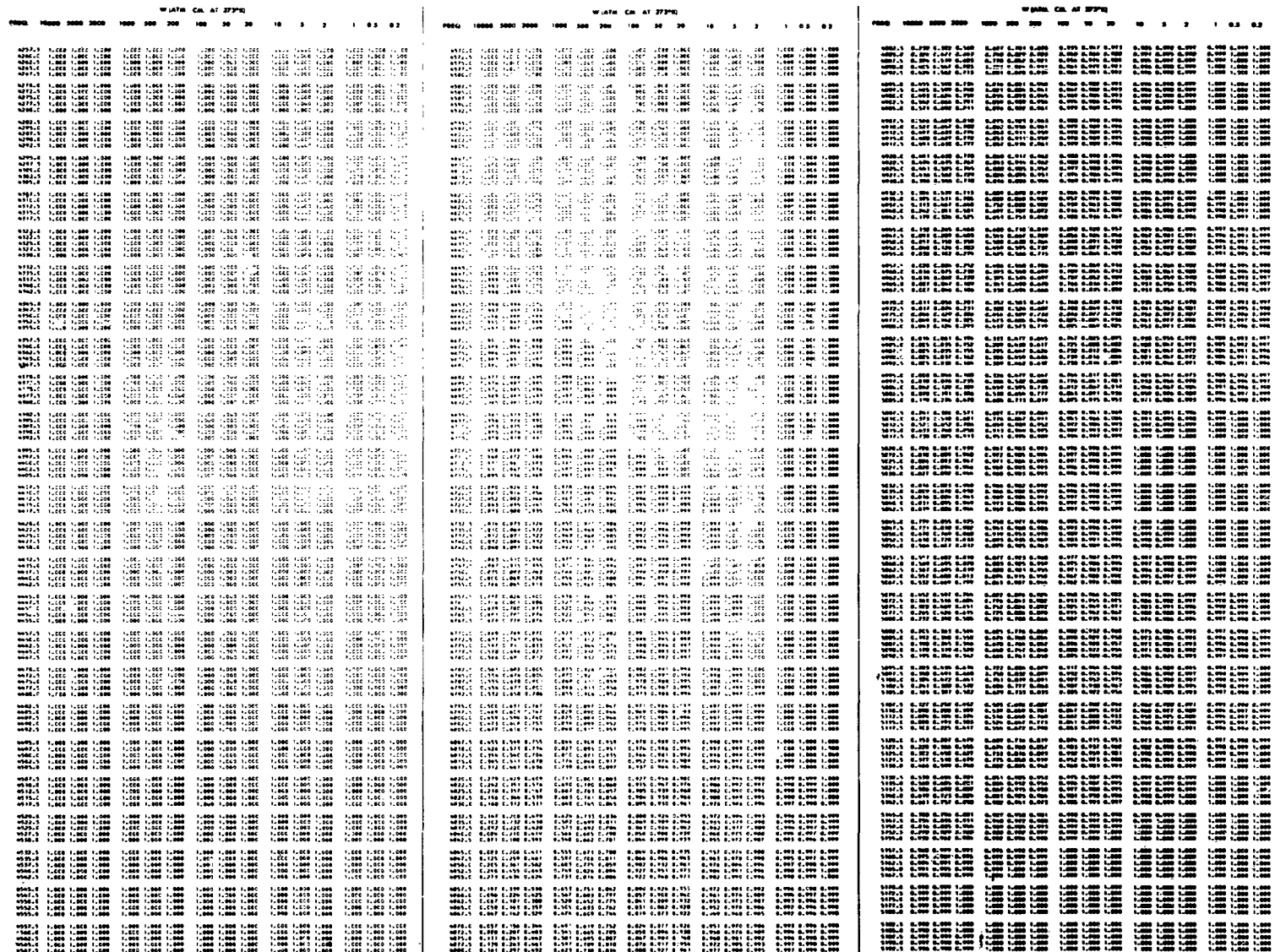
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=250° K



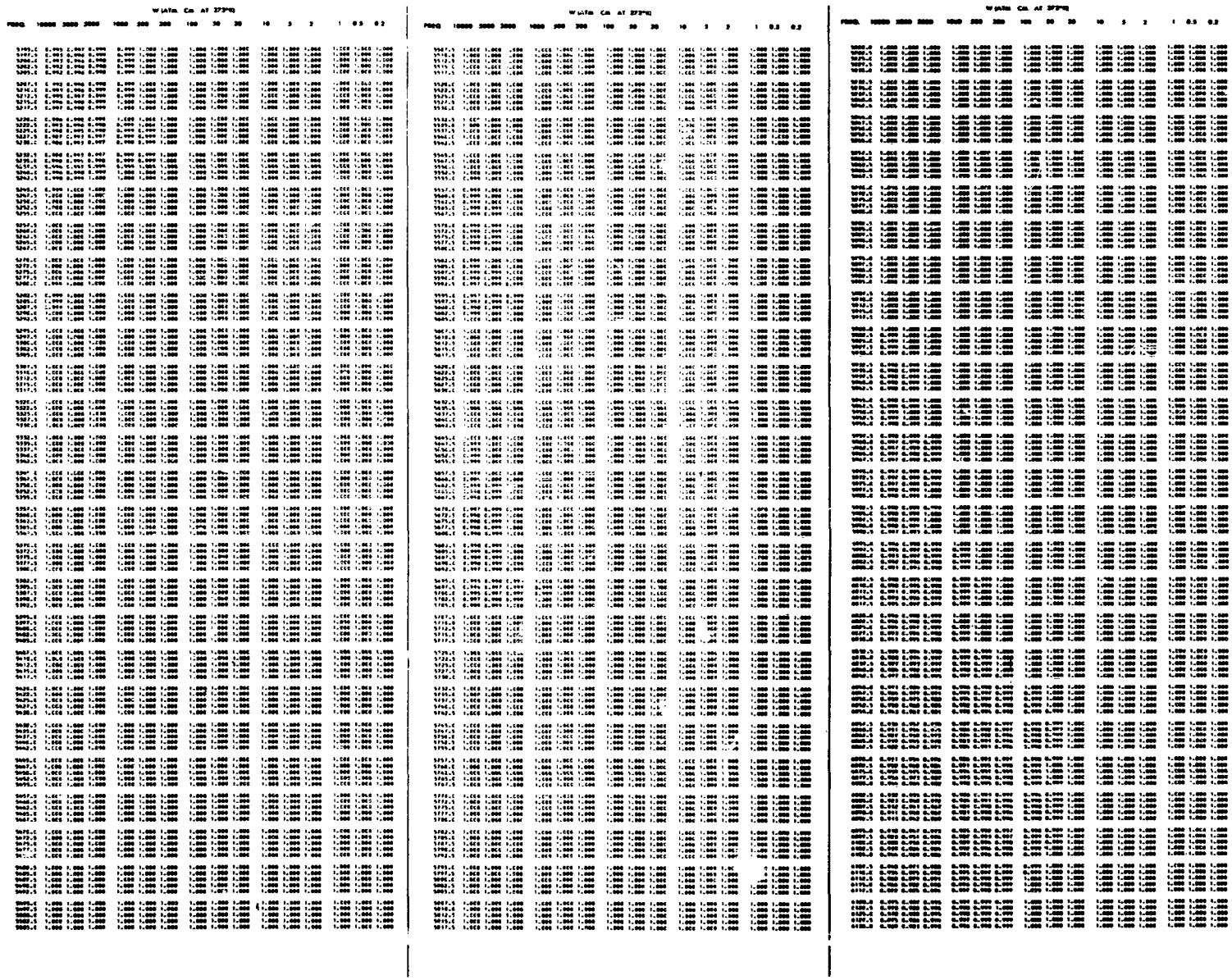
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=250° K

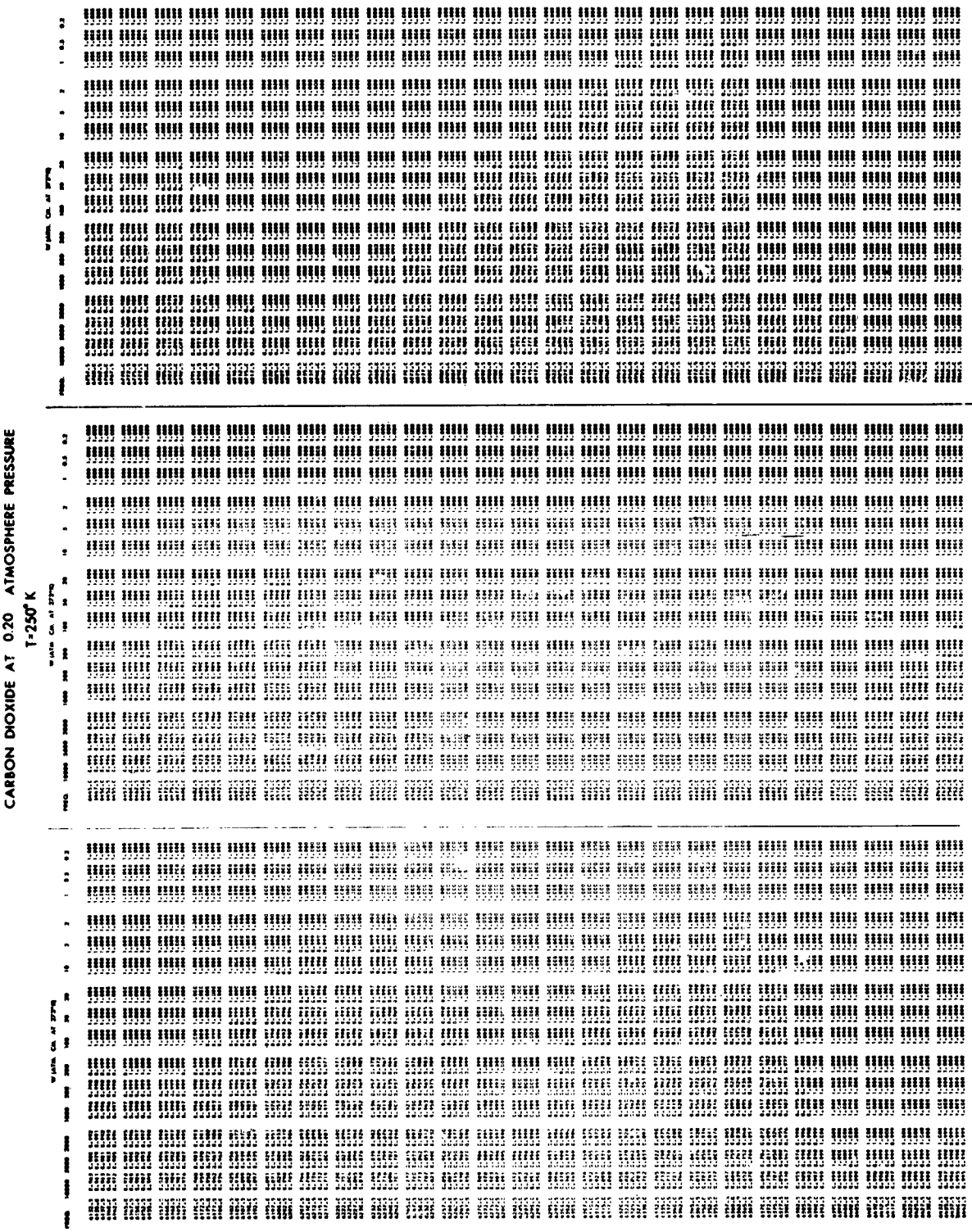


CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=250° K



CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE
T=250° K

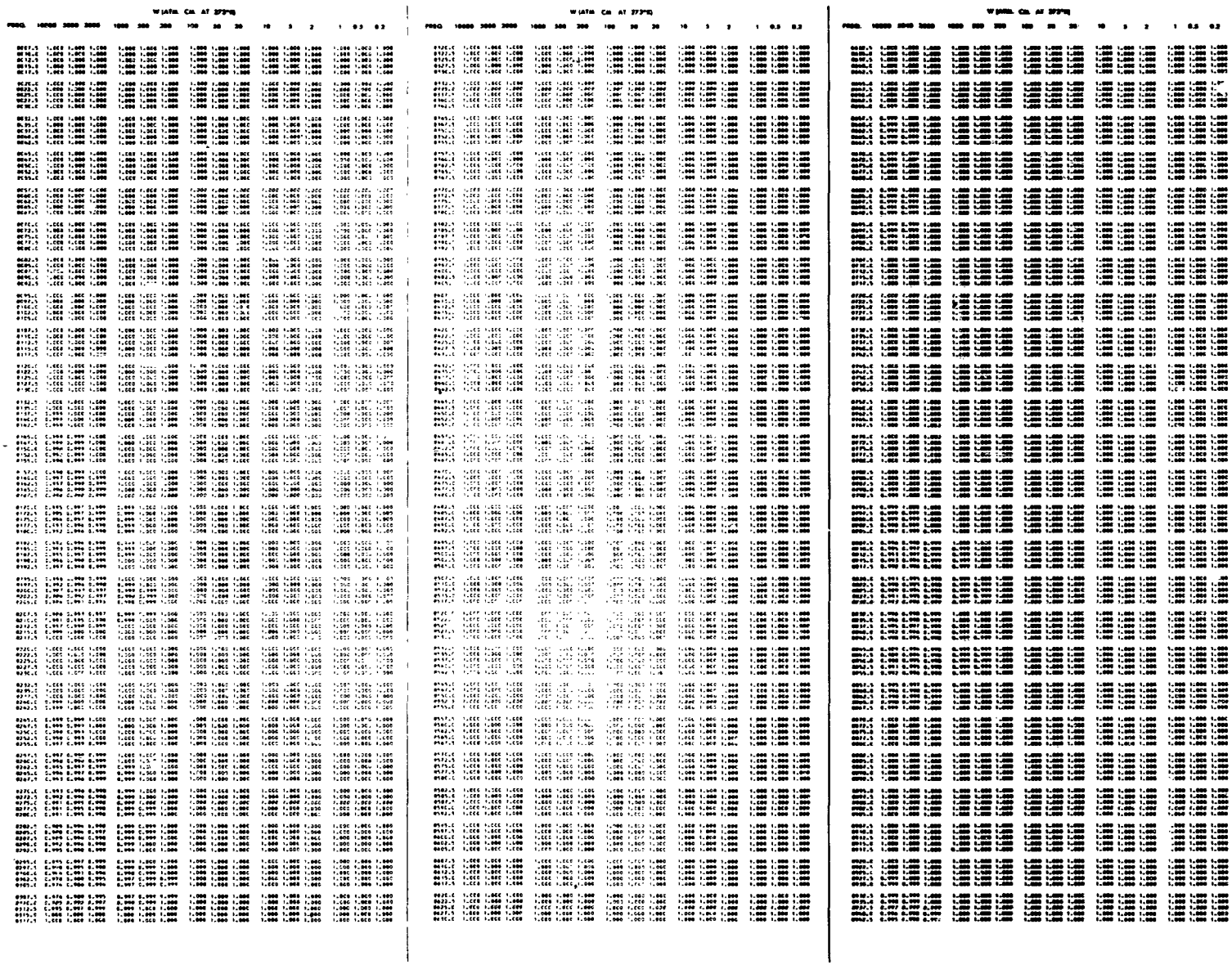


CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=250° K

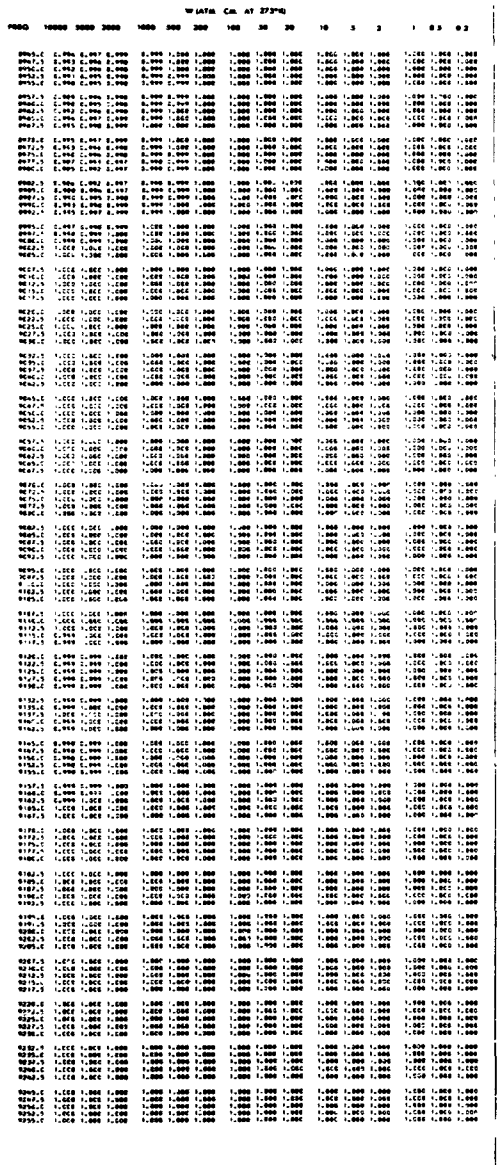
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

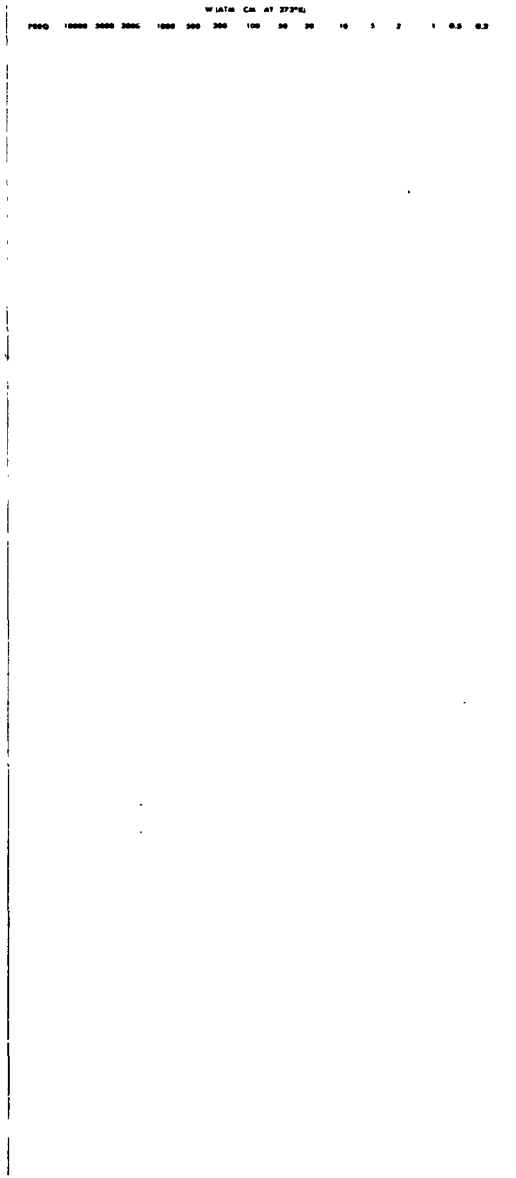
T=250° K

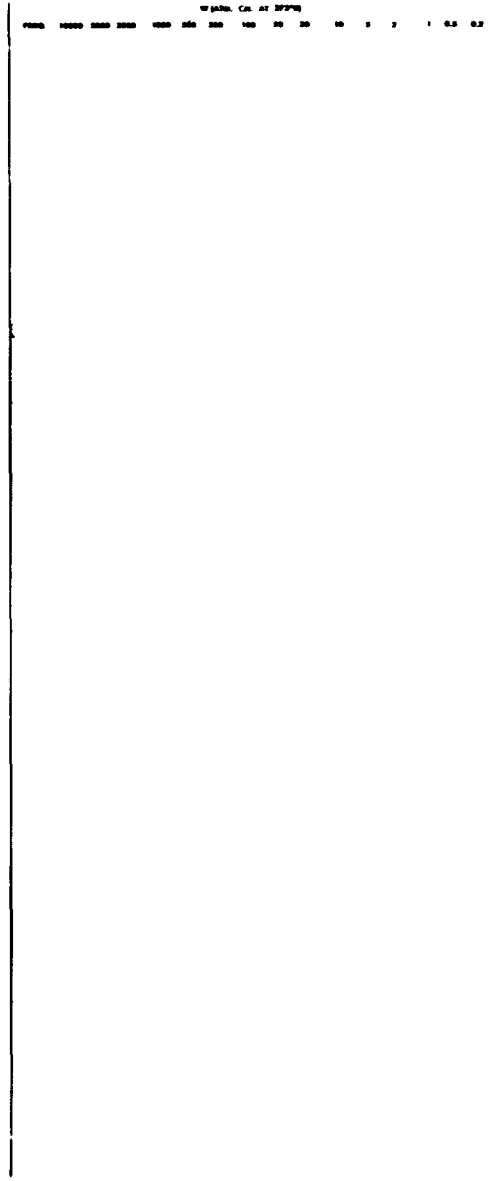


CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=250° K



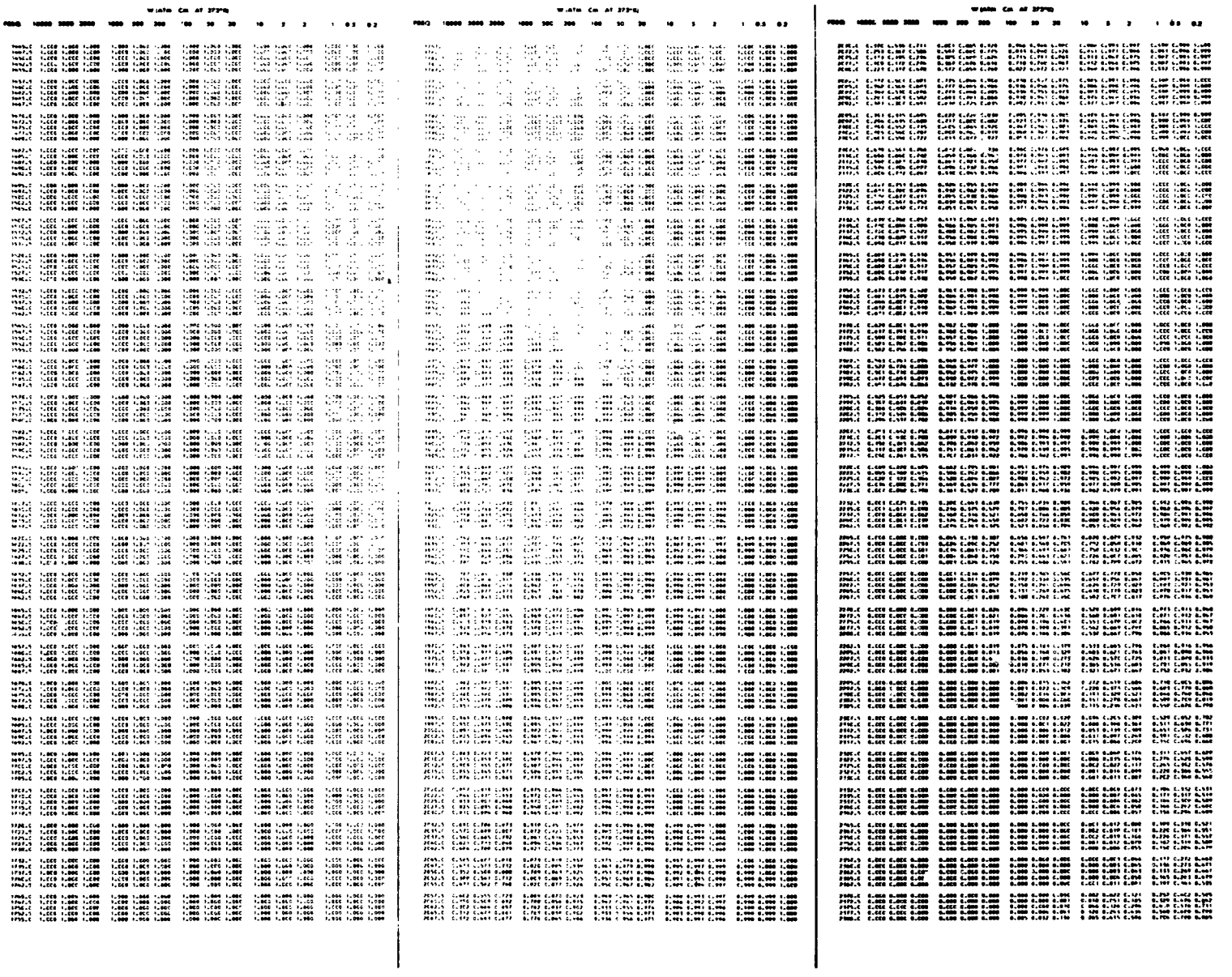




CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE
T=250° K

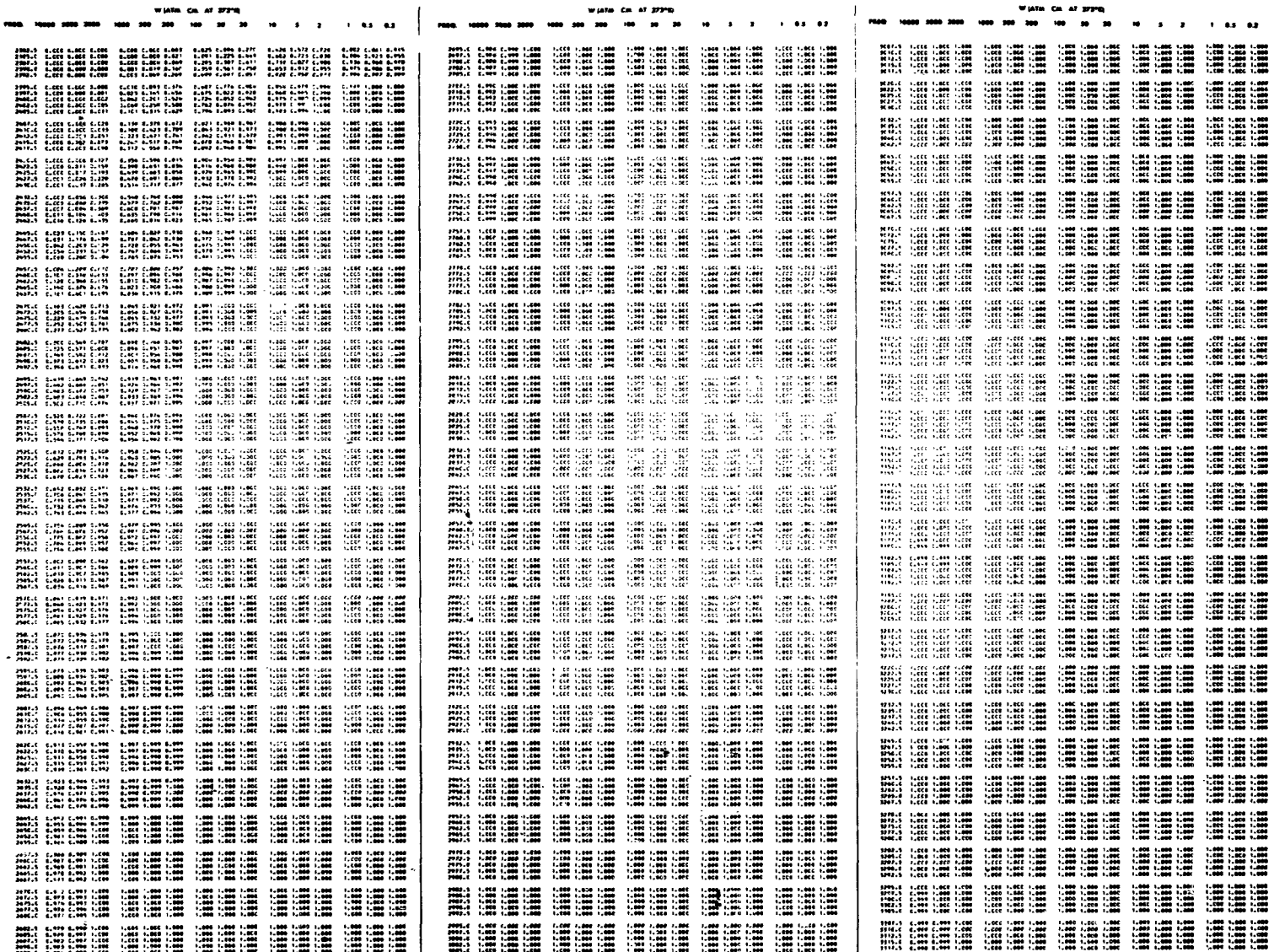
CARBON DIOXIDE AT 010 ATMOSPHERE PRESSURE

T=250° K

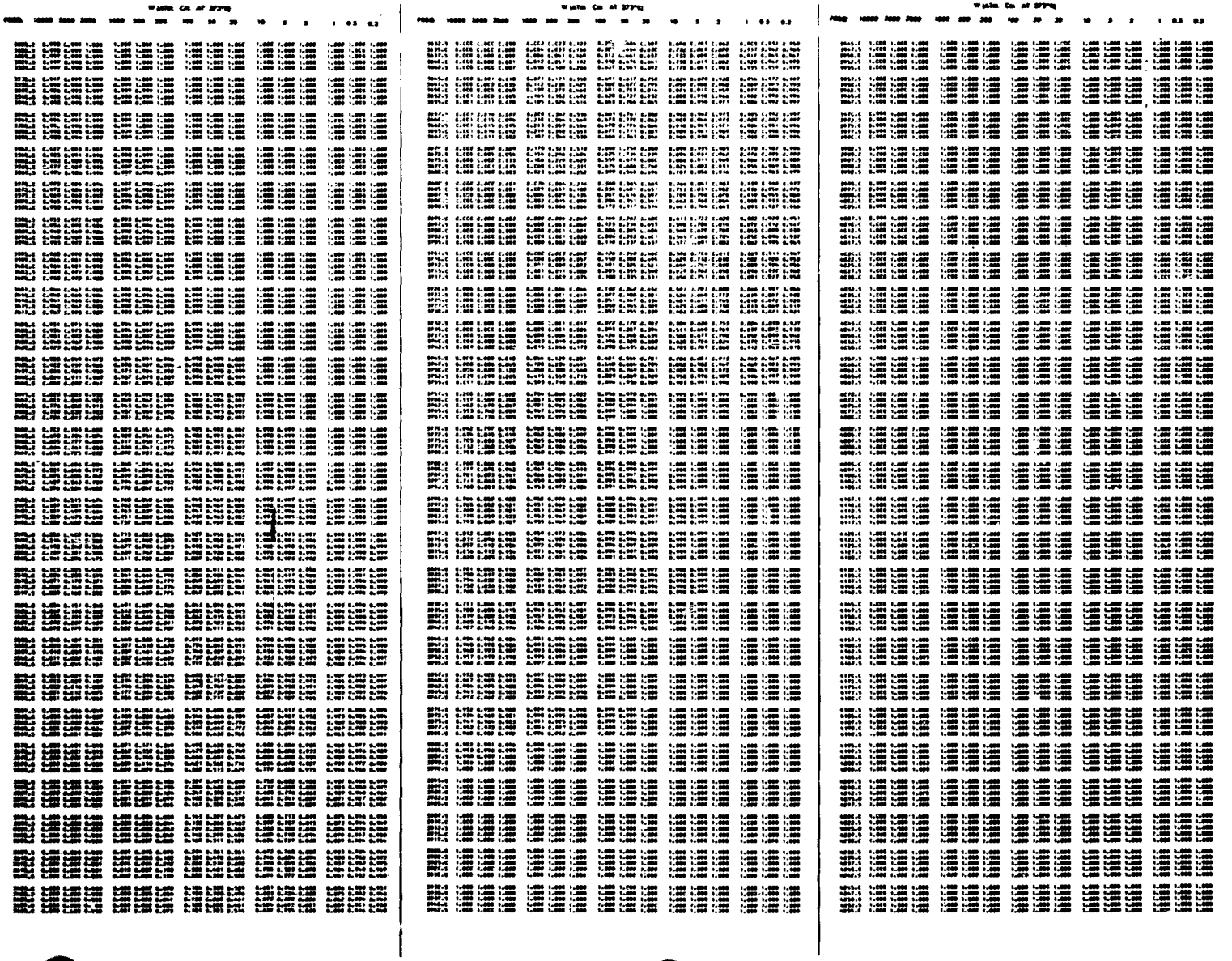


CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T=250° K



CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE
T=250° K



CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE
T-250° K

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

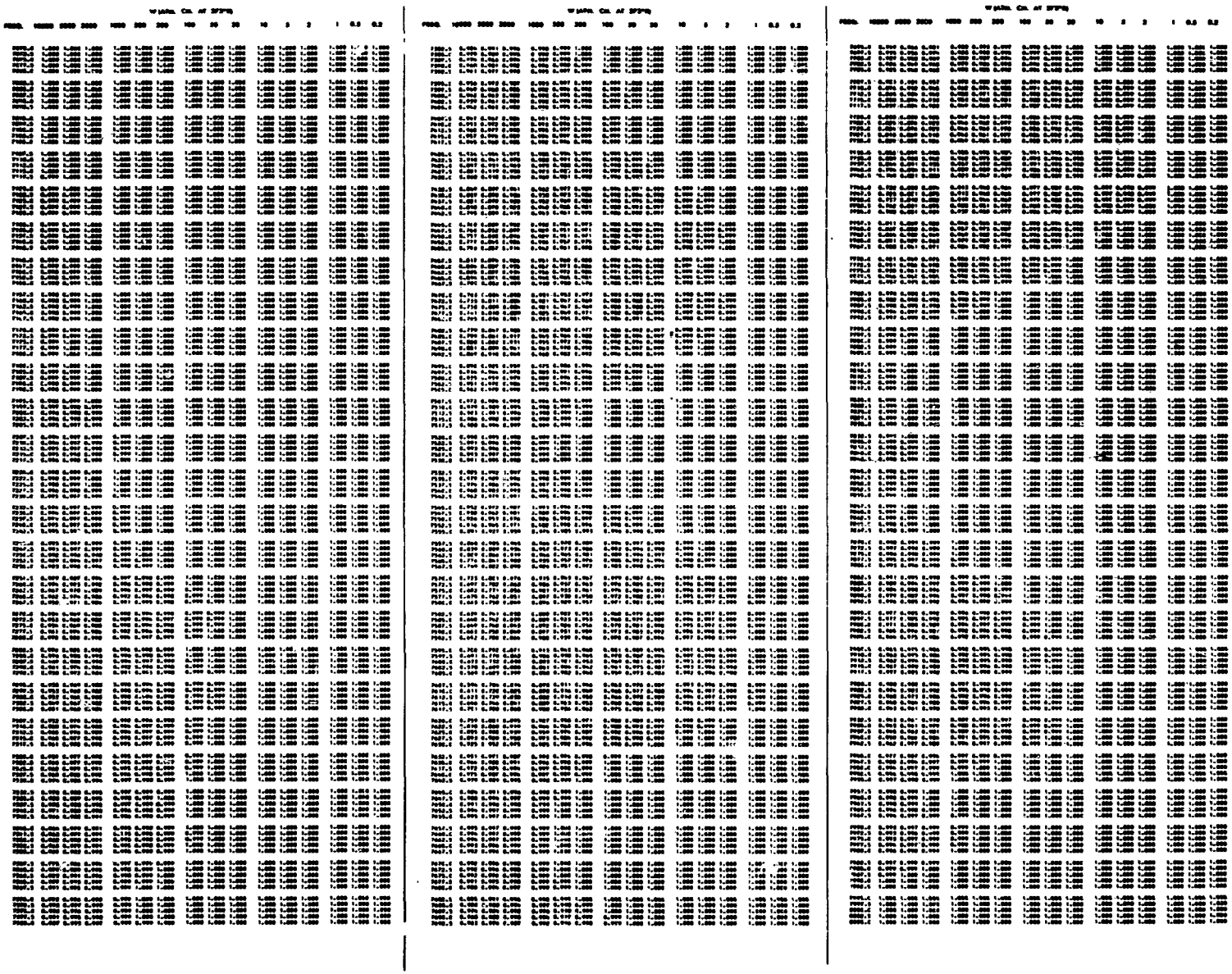
T=250° K

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

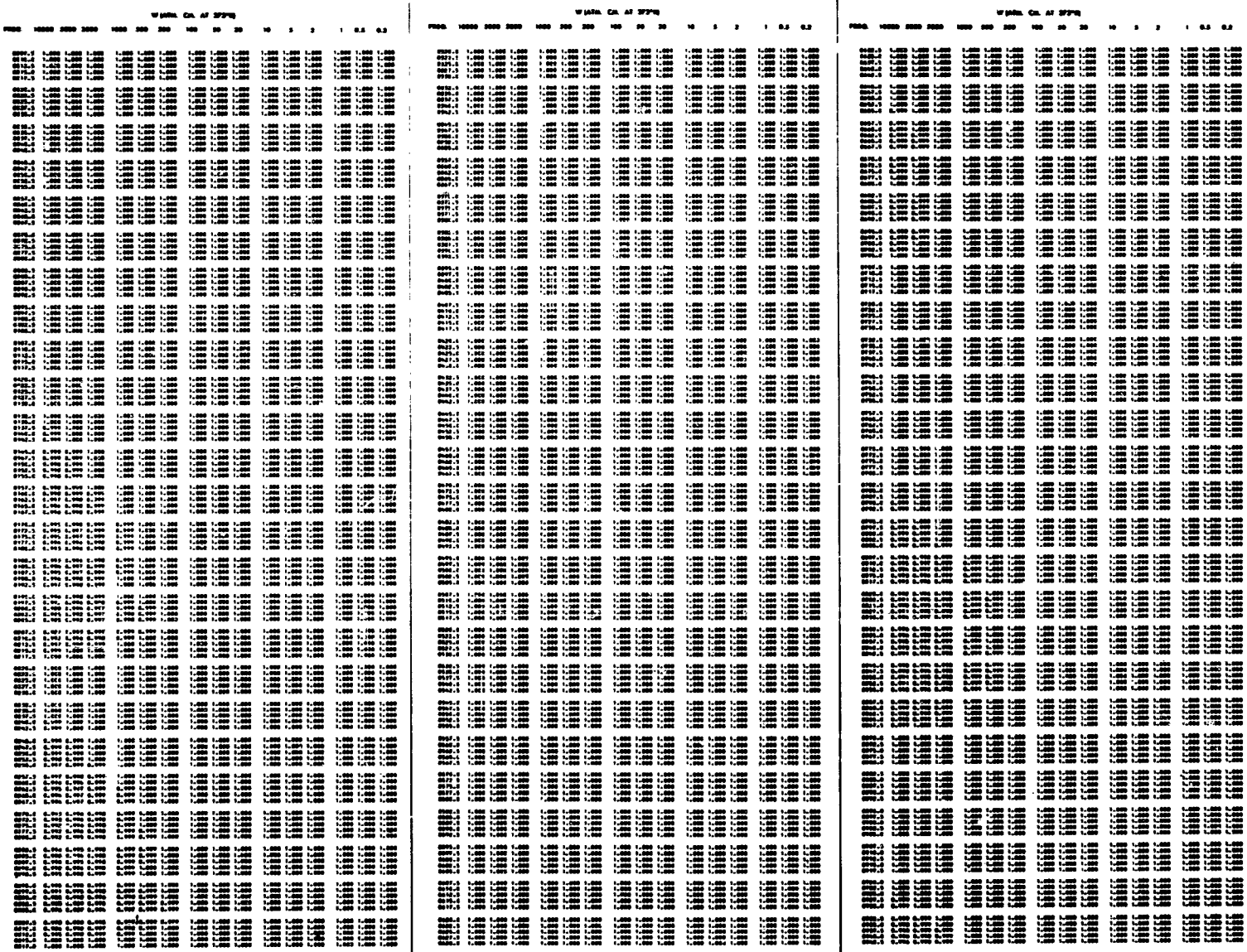
T-250° K

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T=250° K

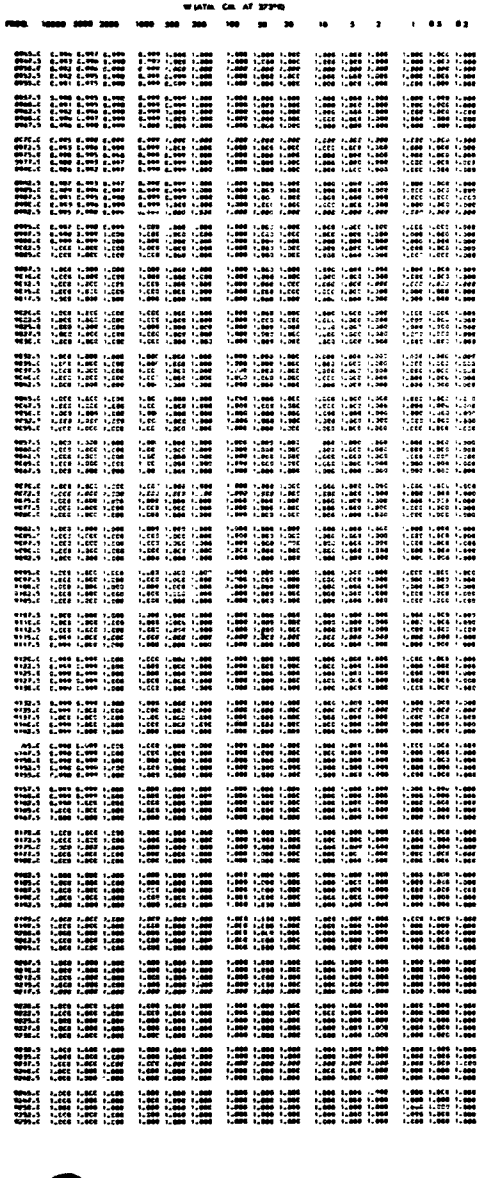


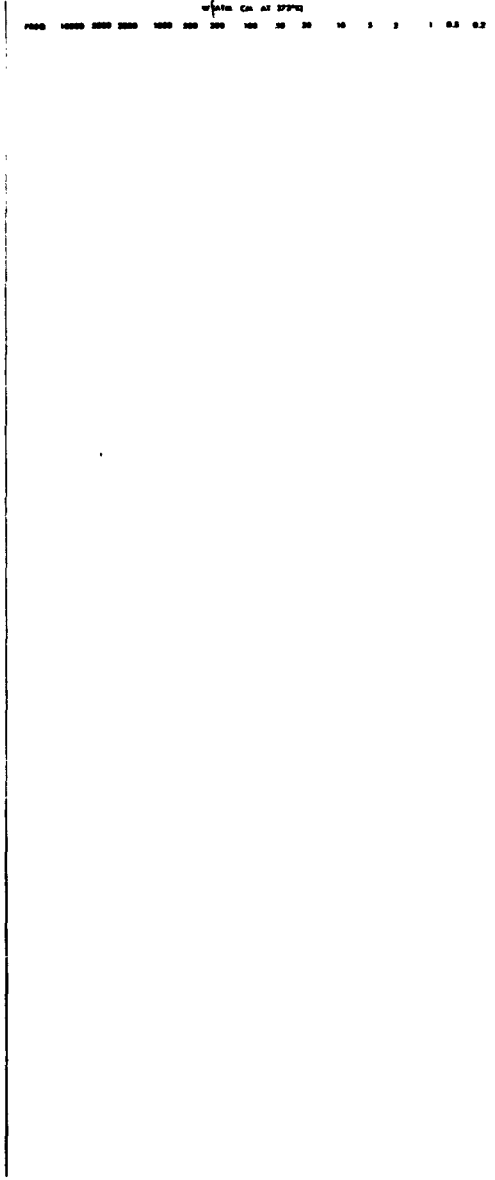
CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE
T=250° K



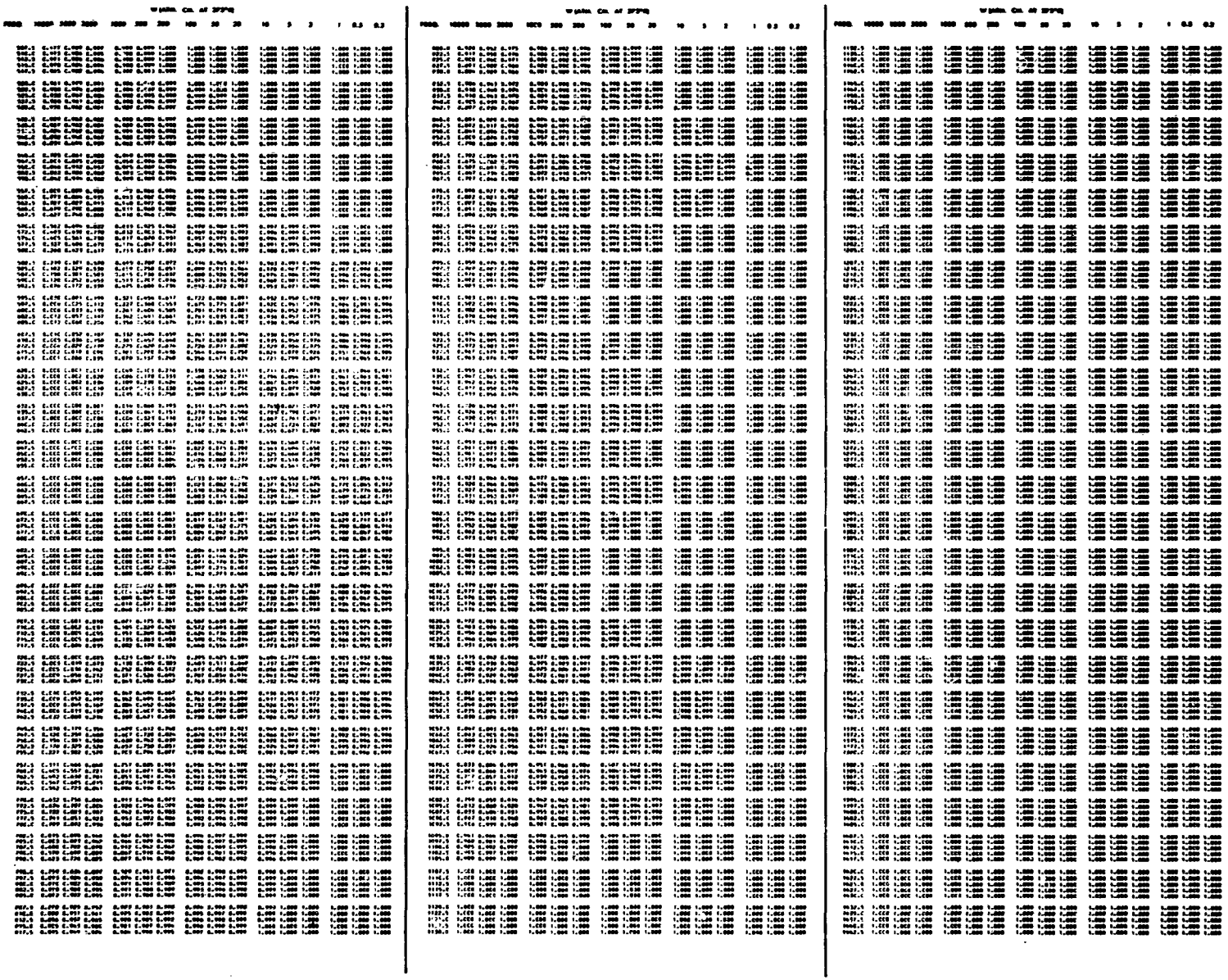
CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T=250° K





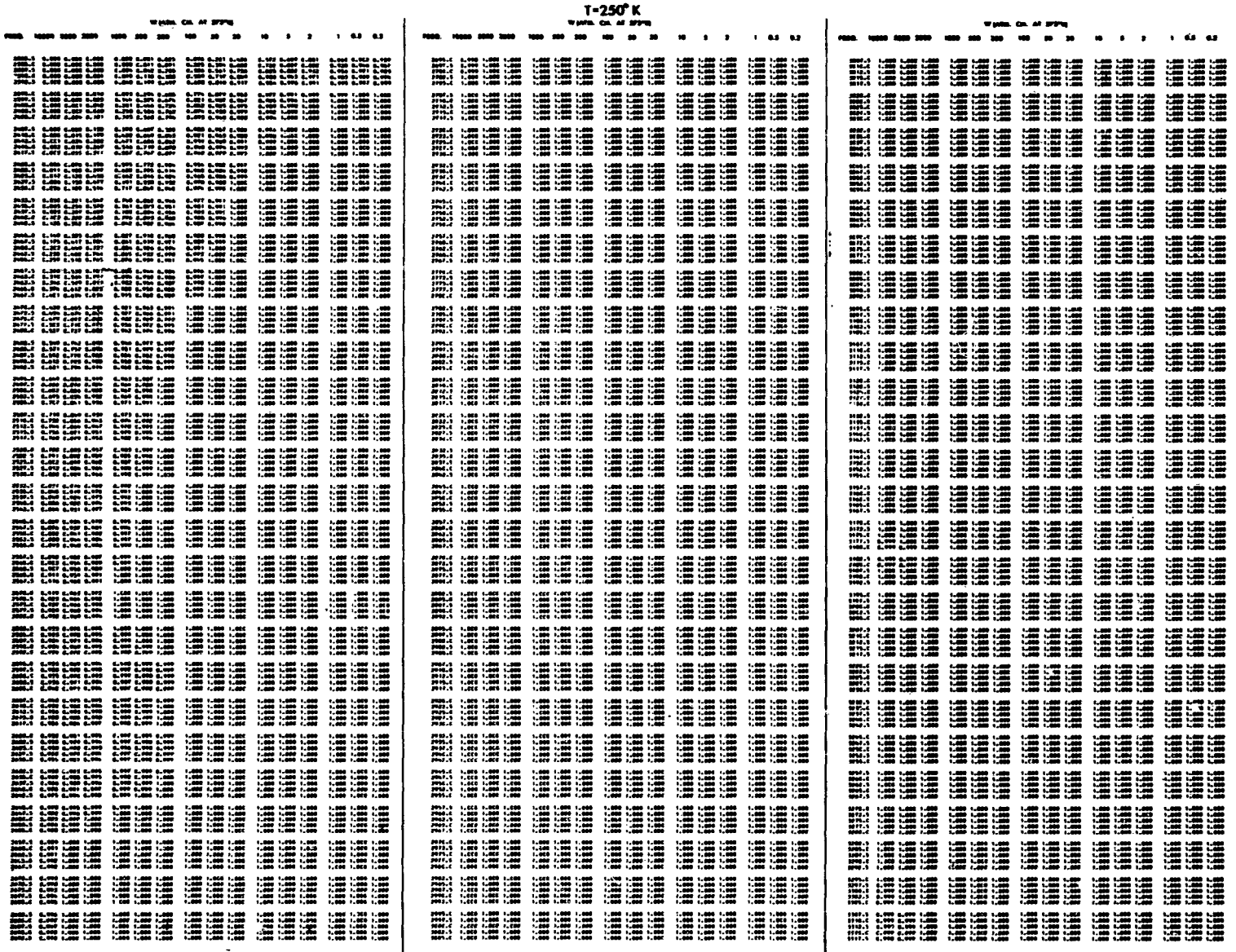
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T=250° K



CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T=250° K

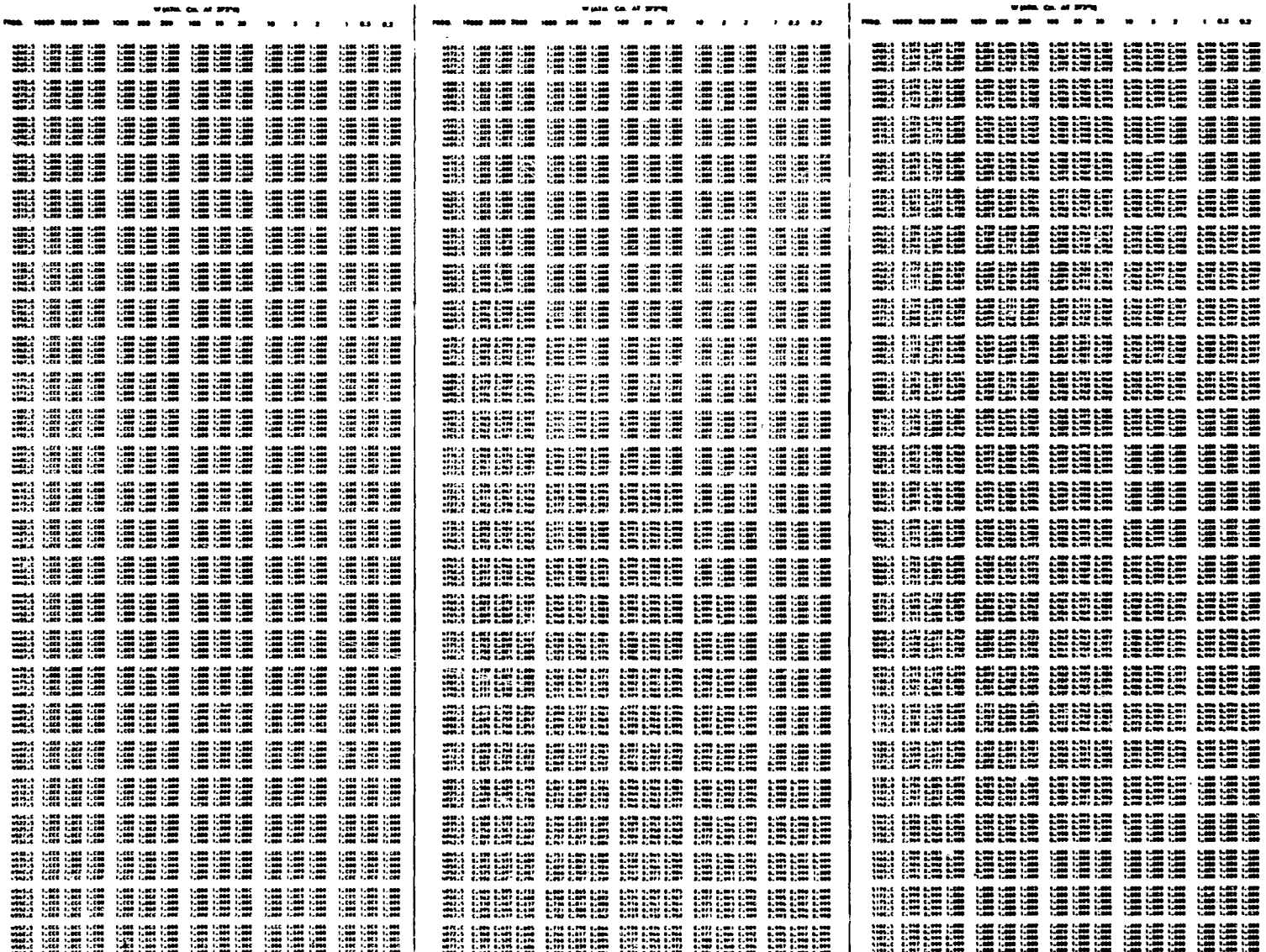
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T=250° K



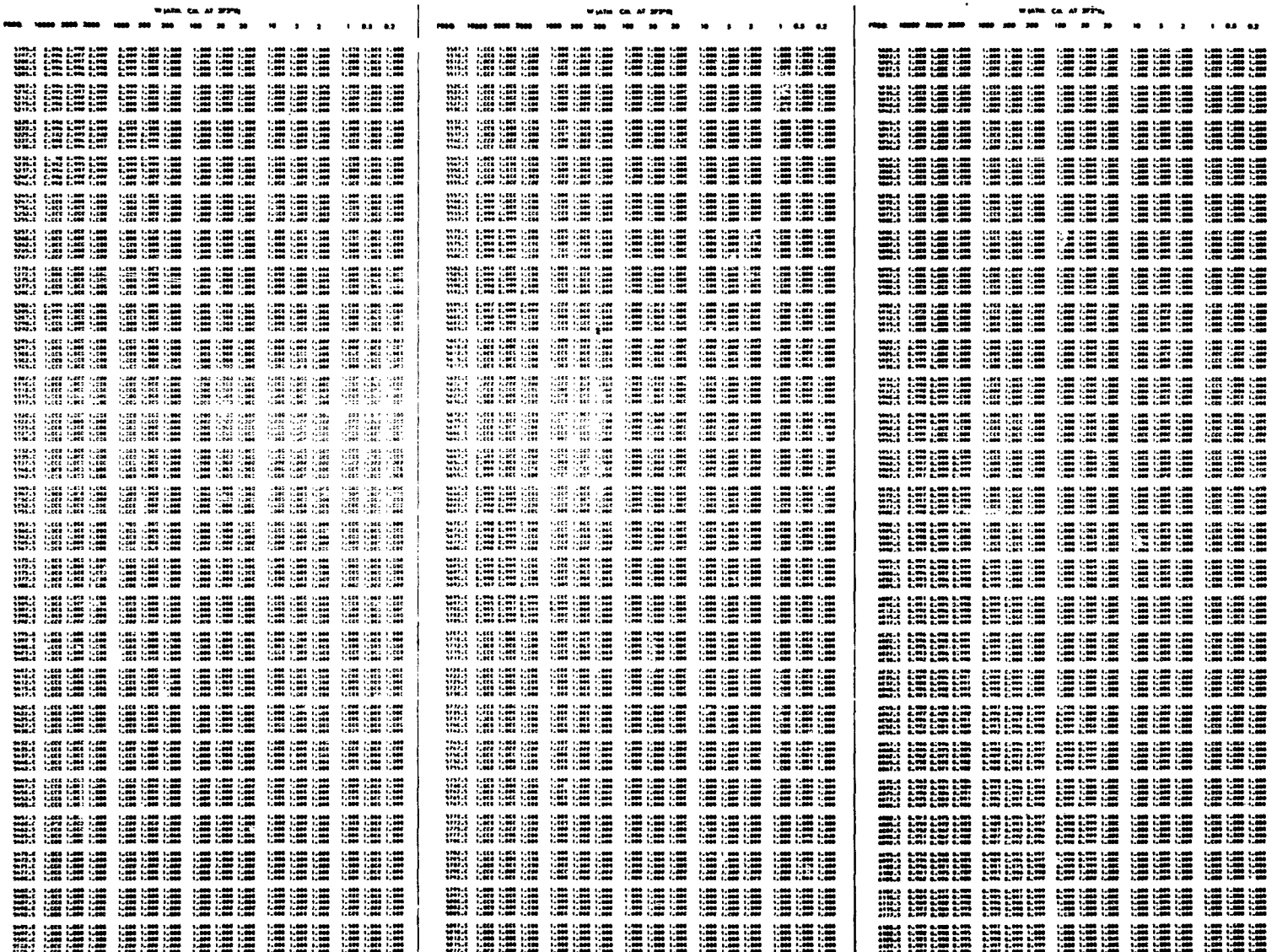
CARBON DIOXIDE AT 005 ATMOSPHERE PRESSURE
T=250° K

CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T=250° K



CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

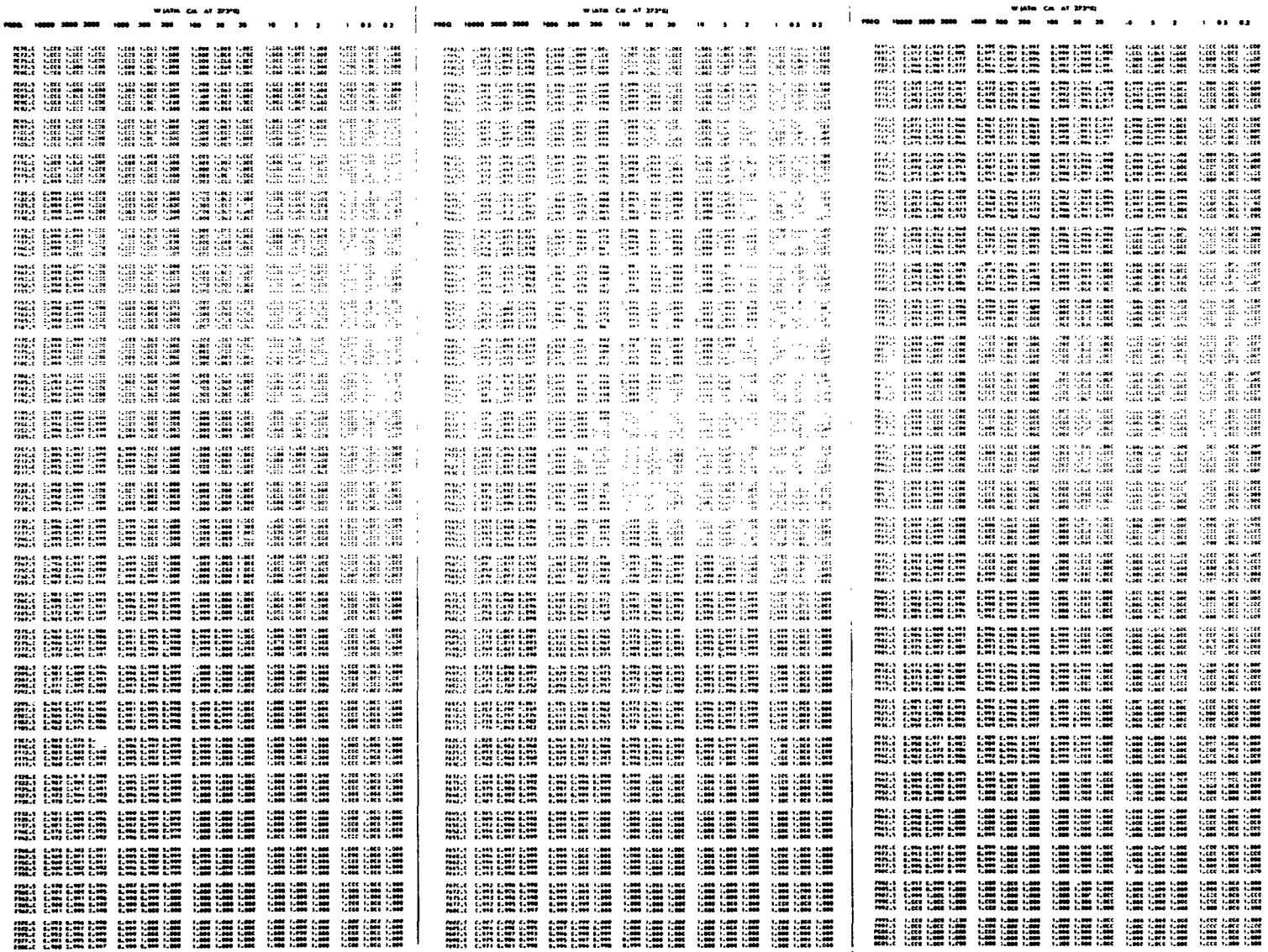
T=250° K



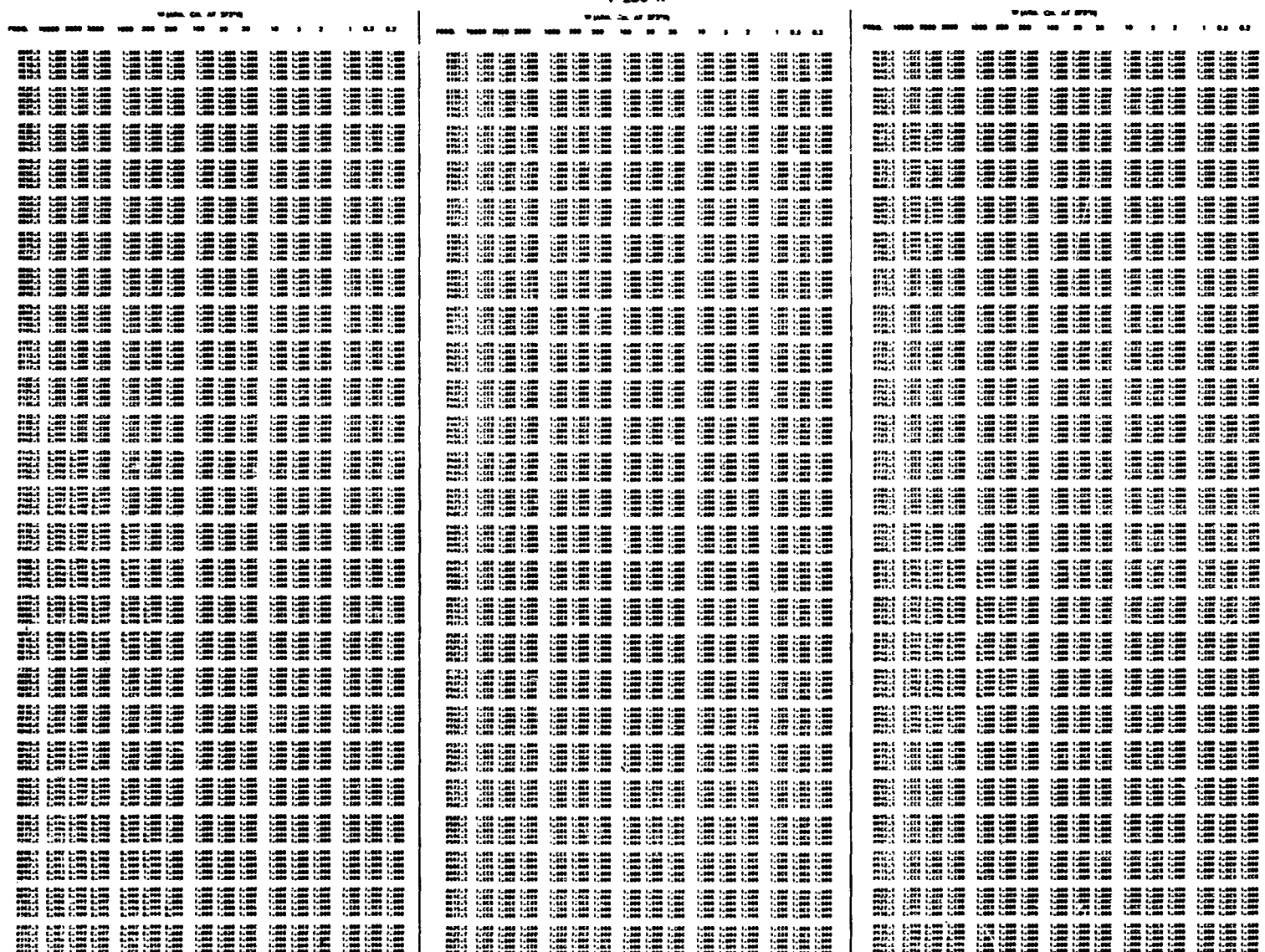
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T=250° K

CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T=250° K

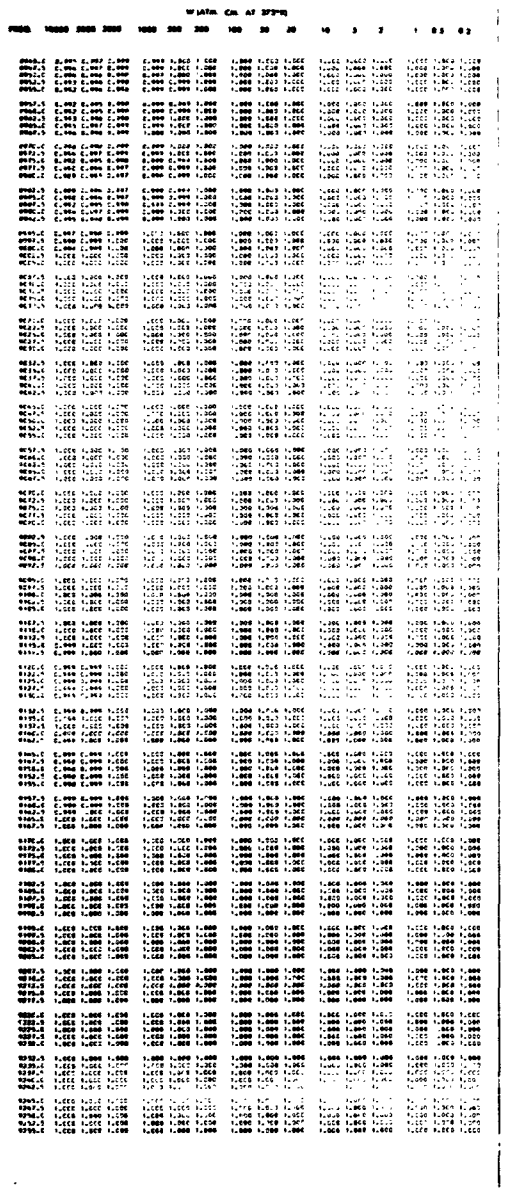


CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T=250° K



CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T=250° K

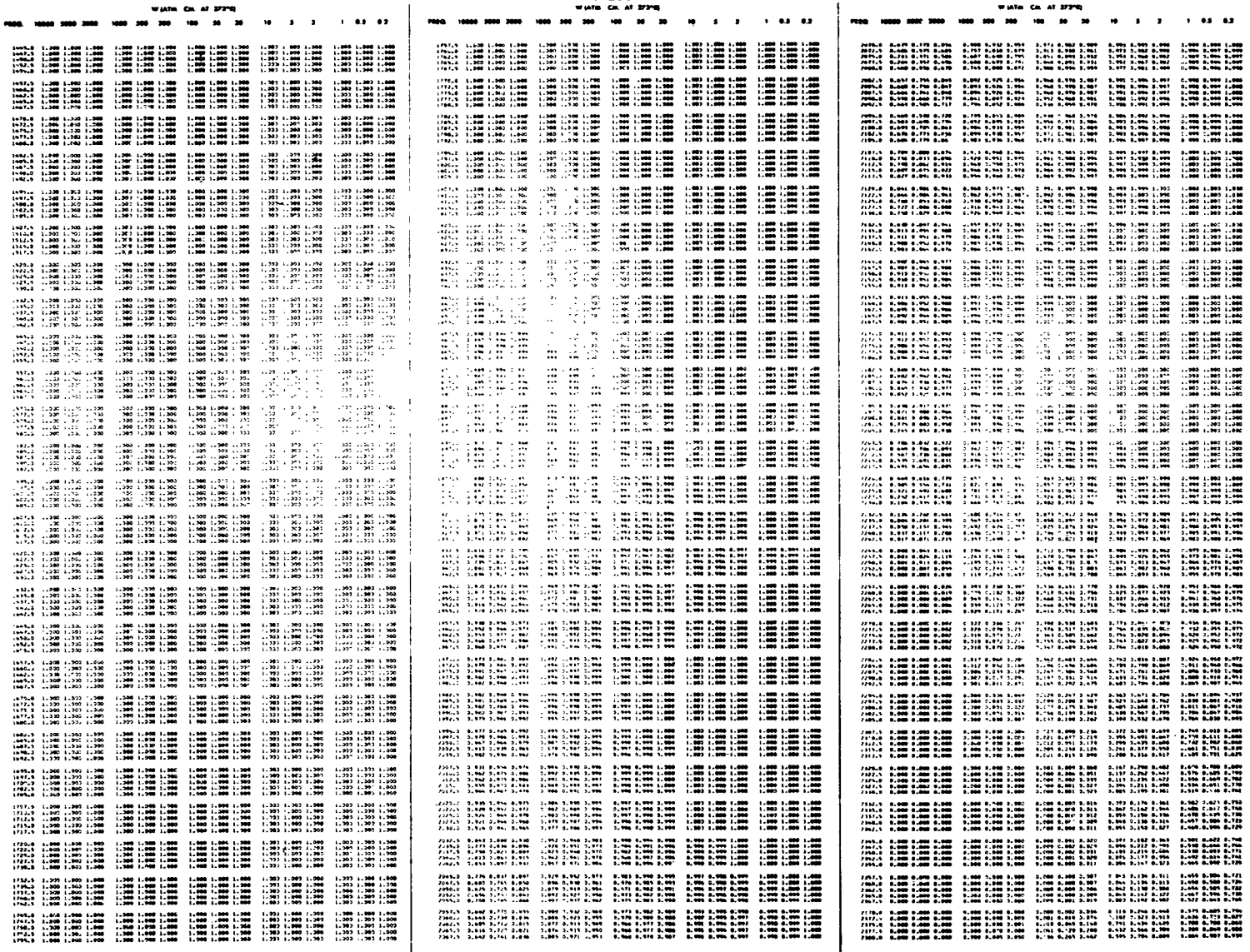


CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

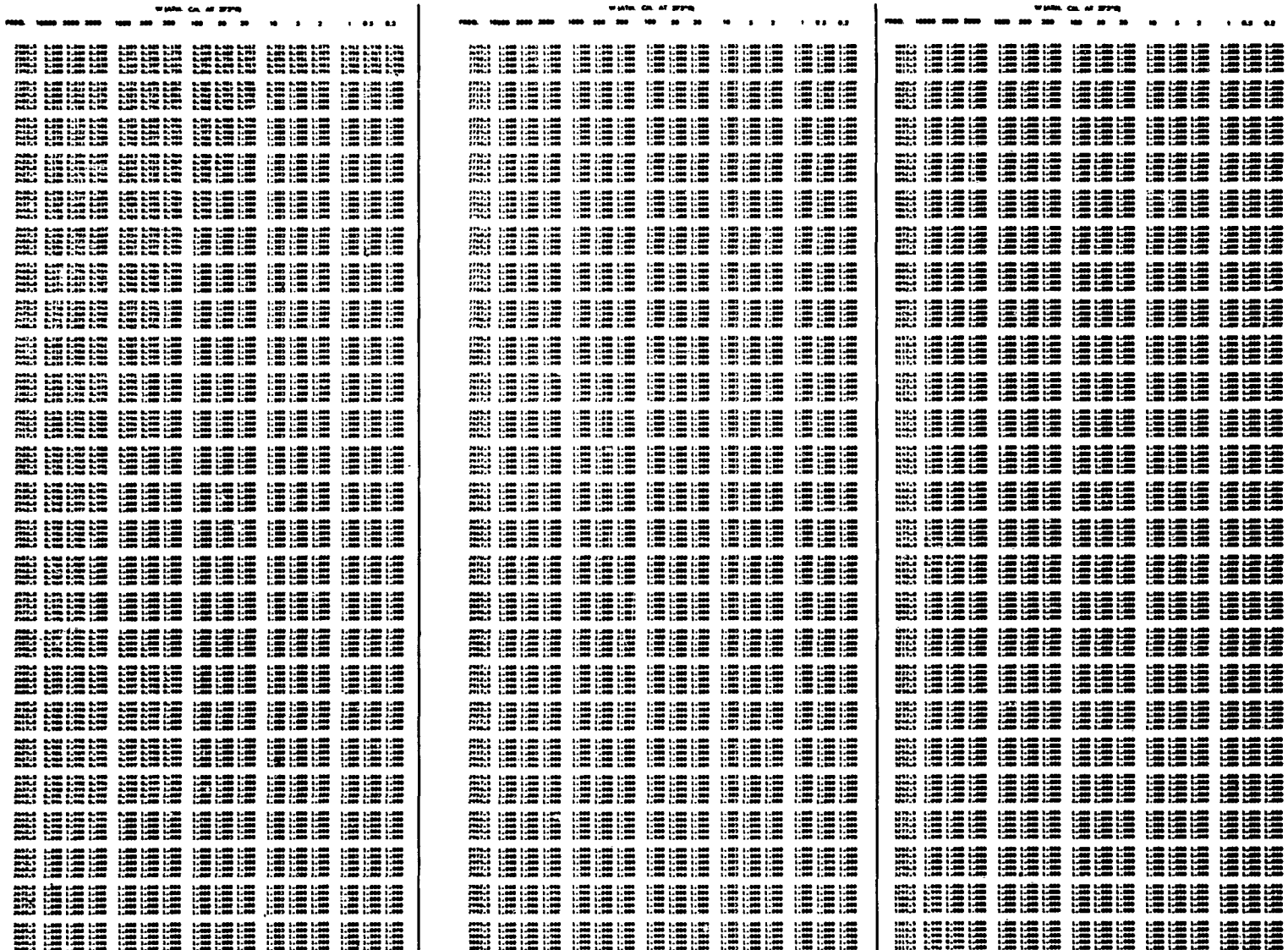
T-250° K

CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

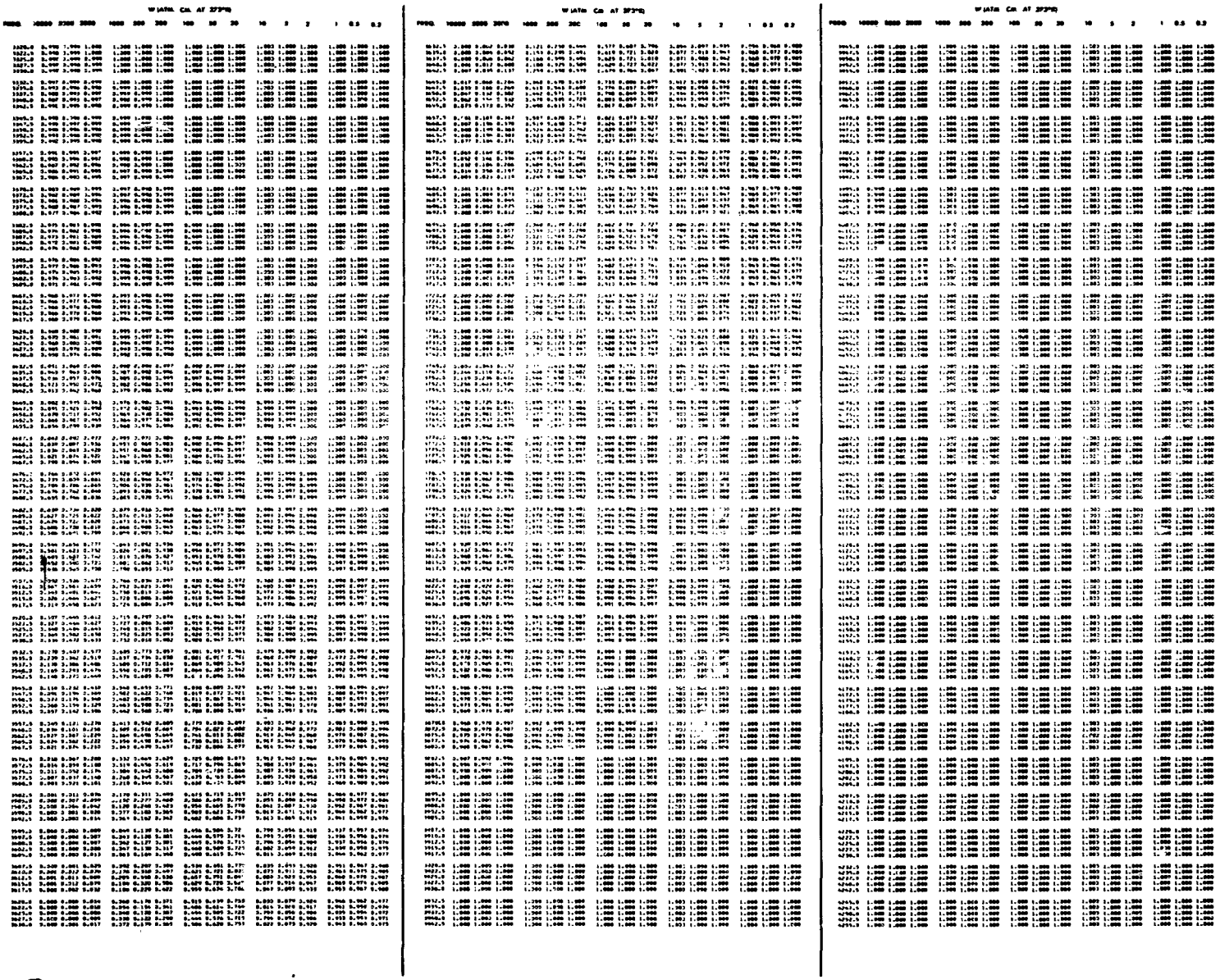
T=250° K



CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE
T=250° K

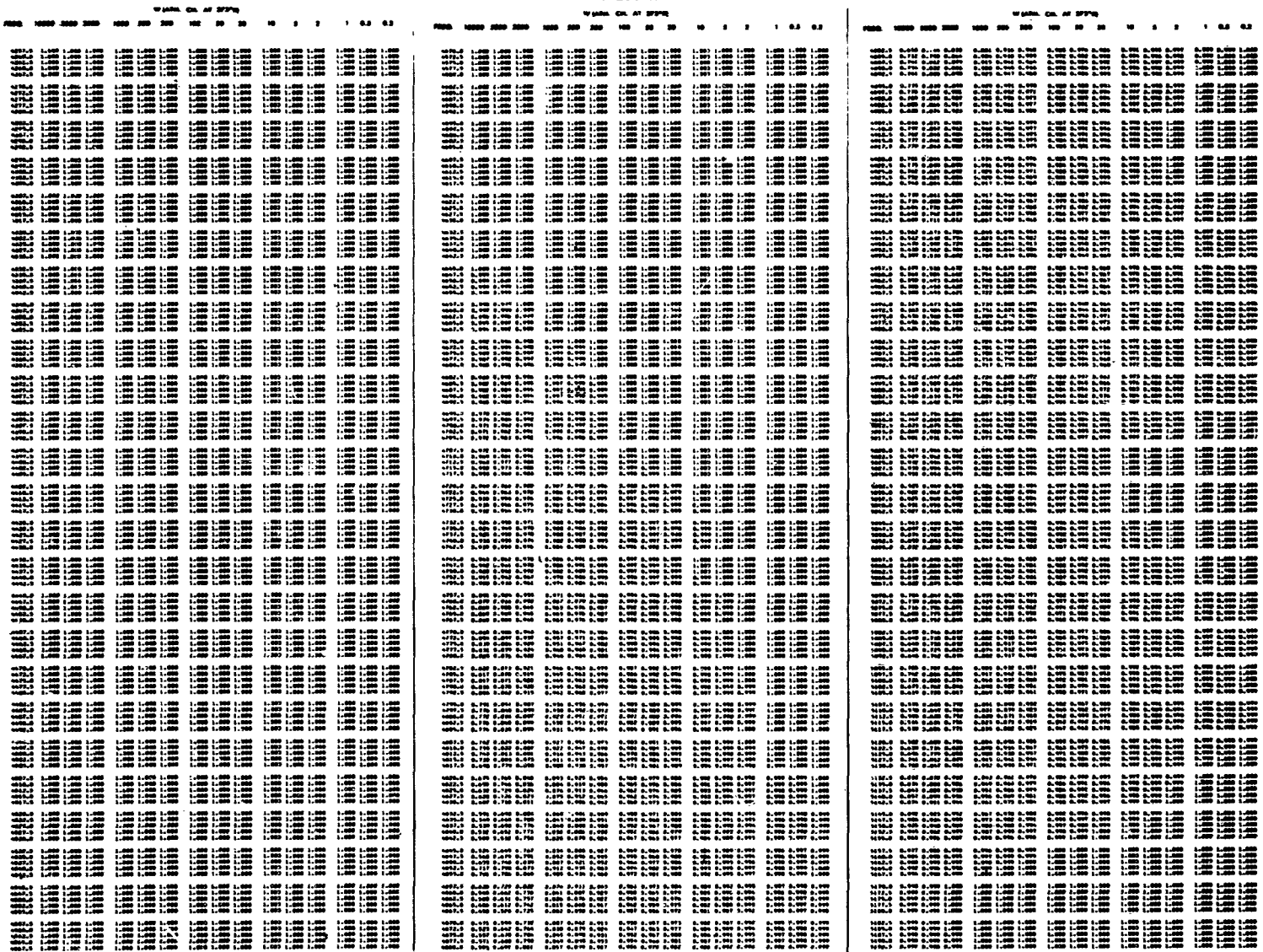


CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE
T=250° K

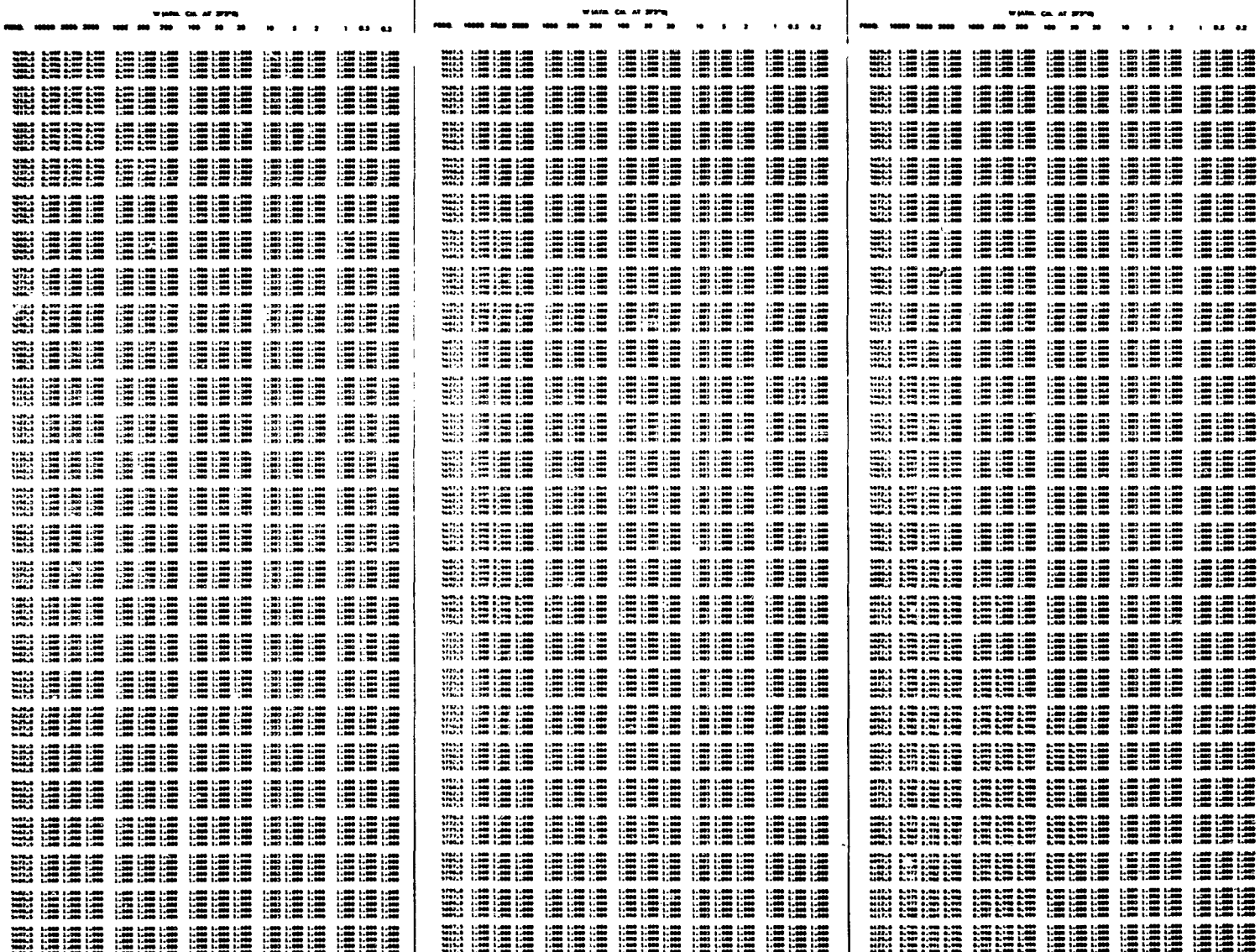


CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T=250° K



CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE
T=250° K



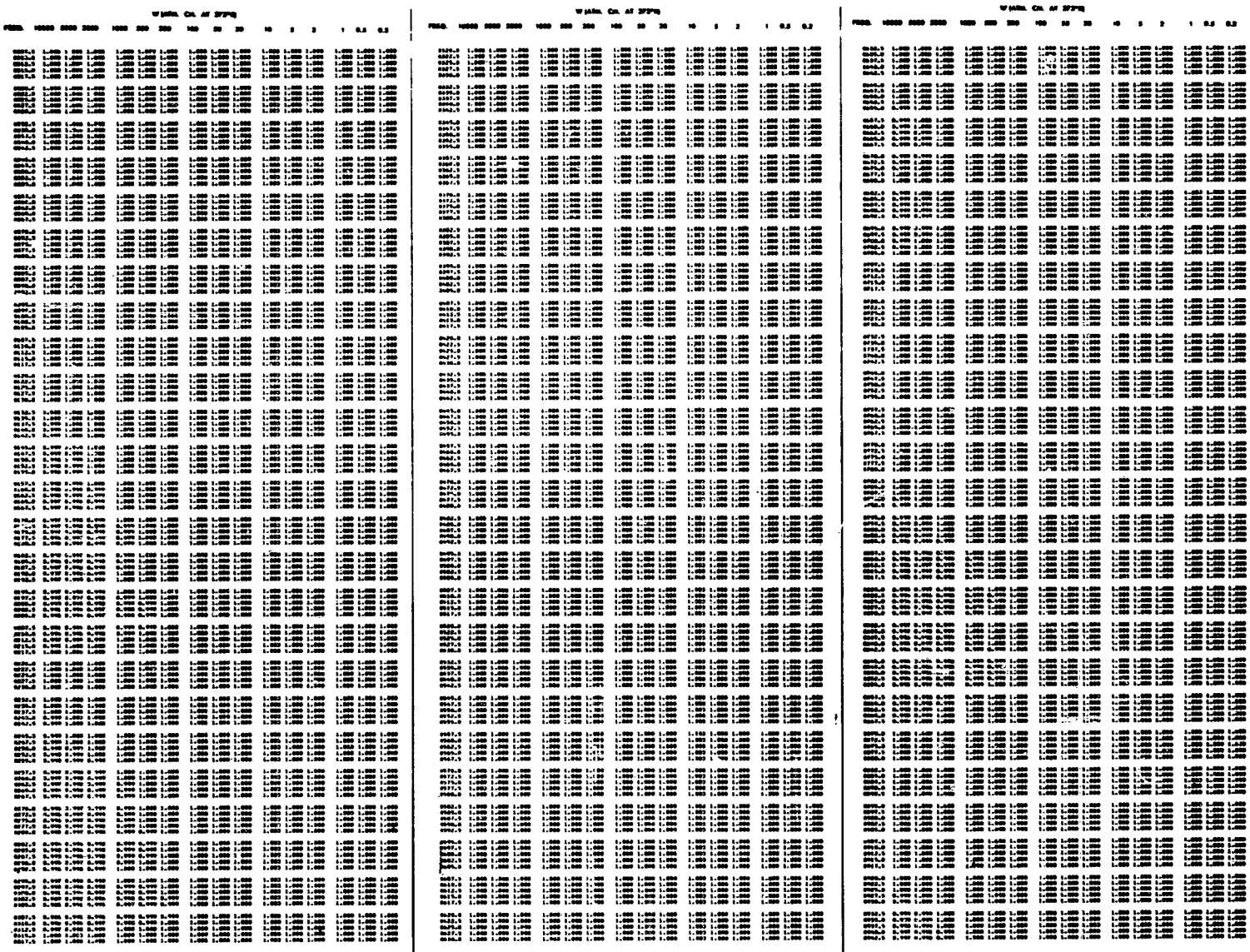
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T-250° K

CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

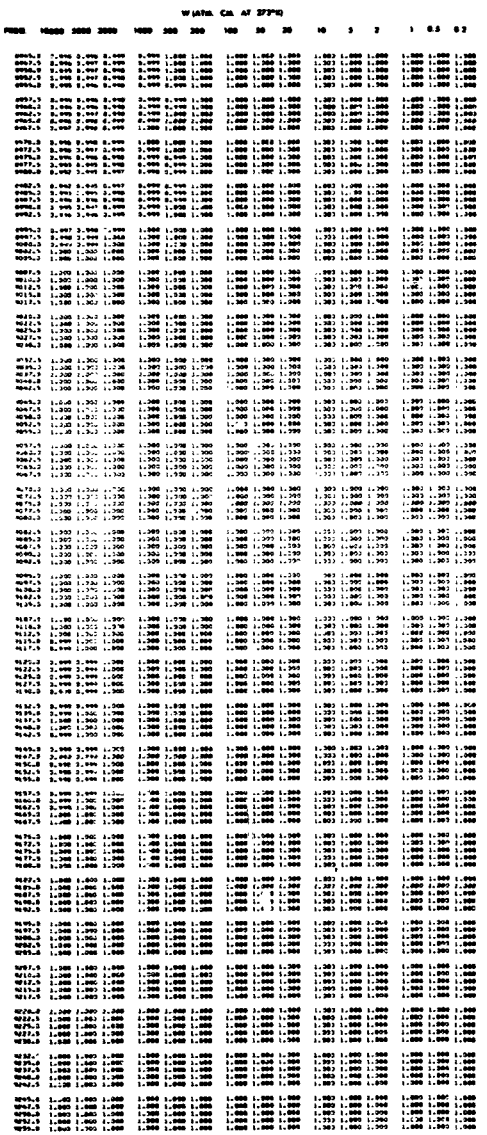
T=250° K

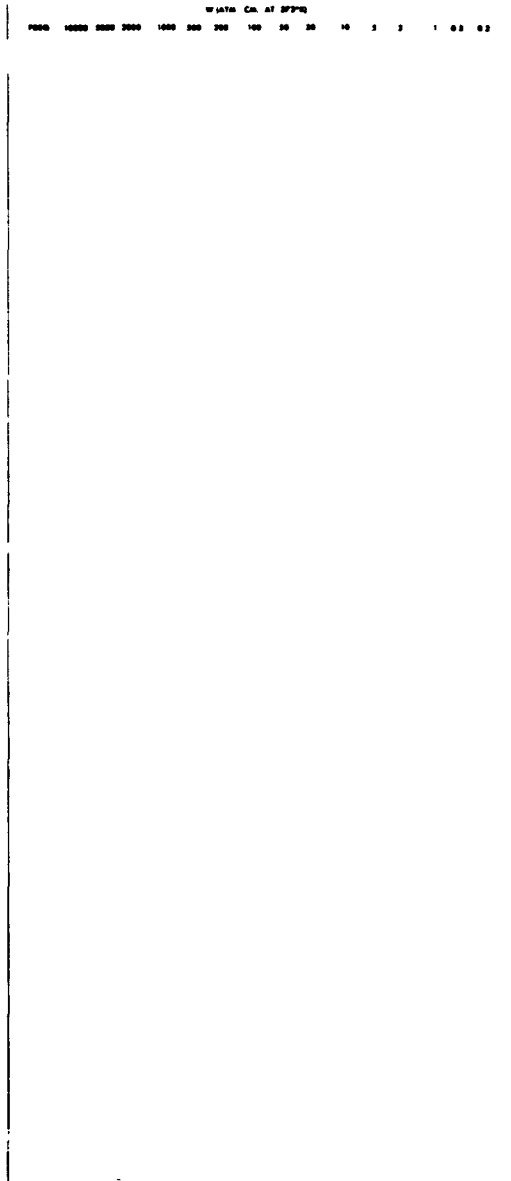
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE
T=250° K

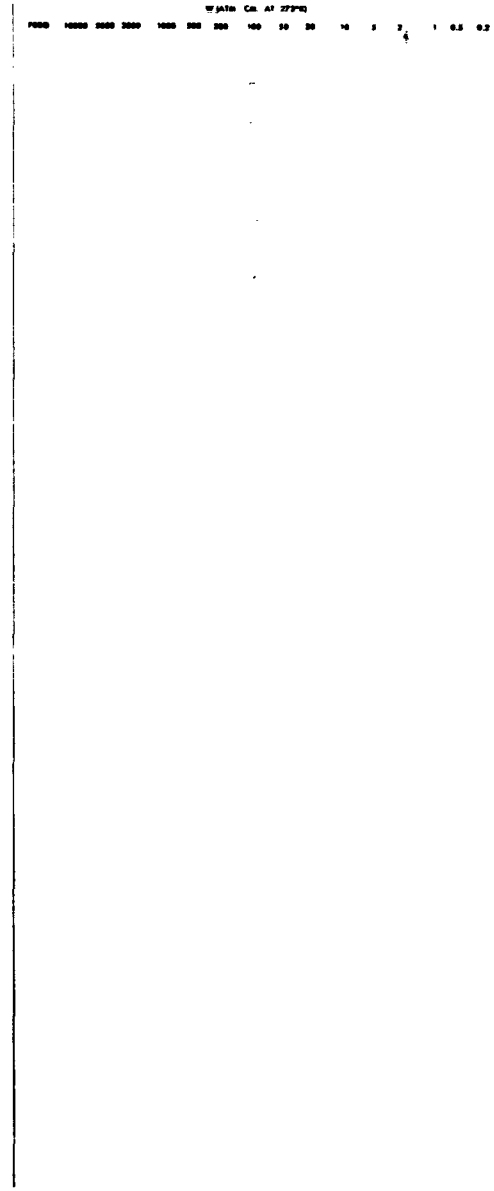


CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T=250° K

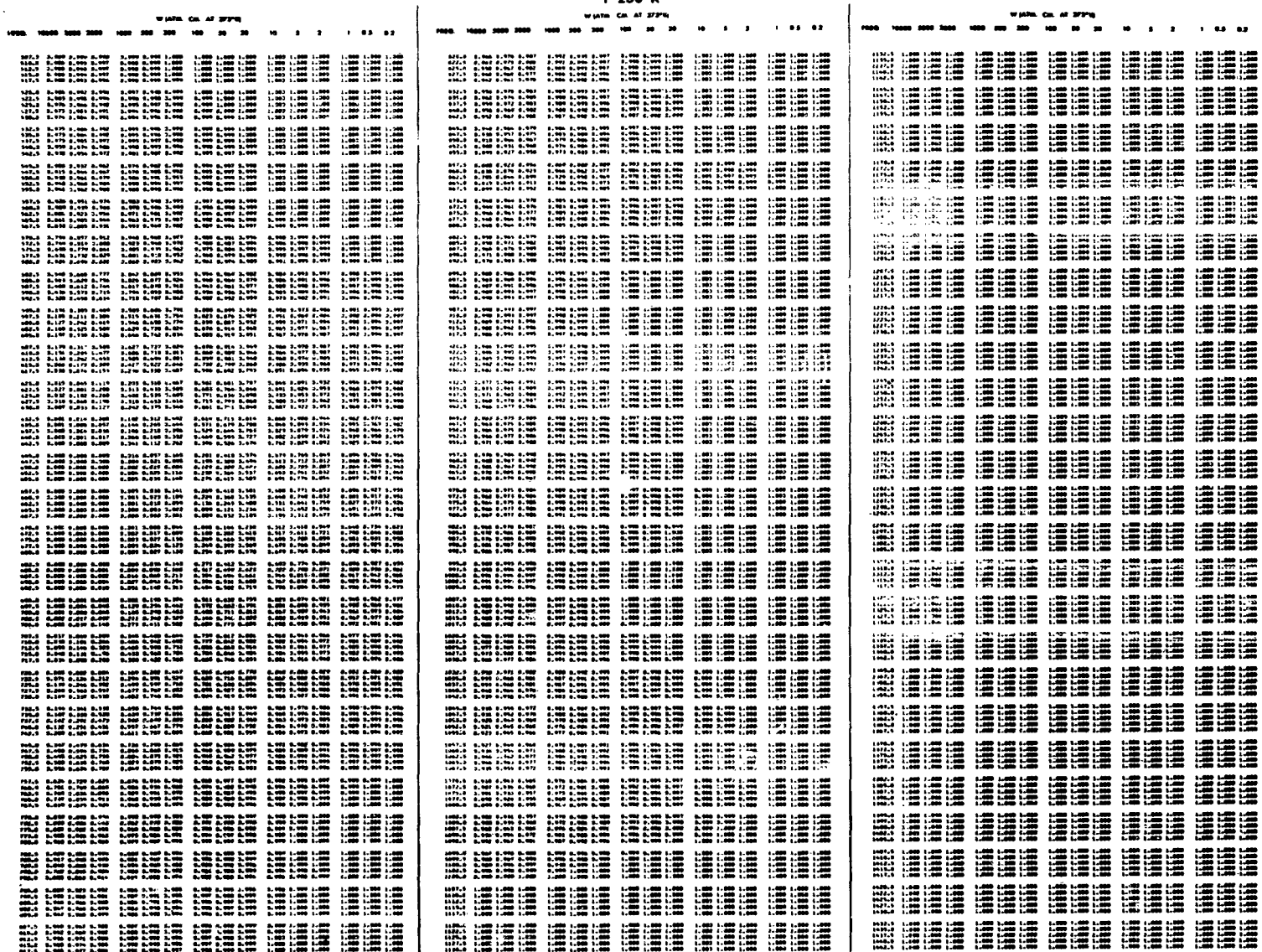






CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T=250° K

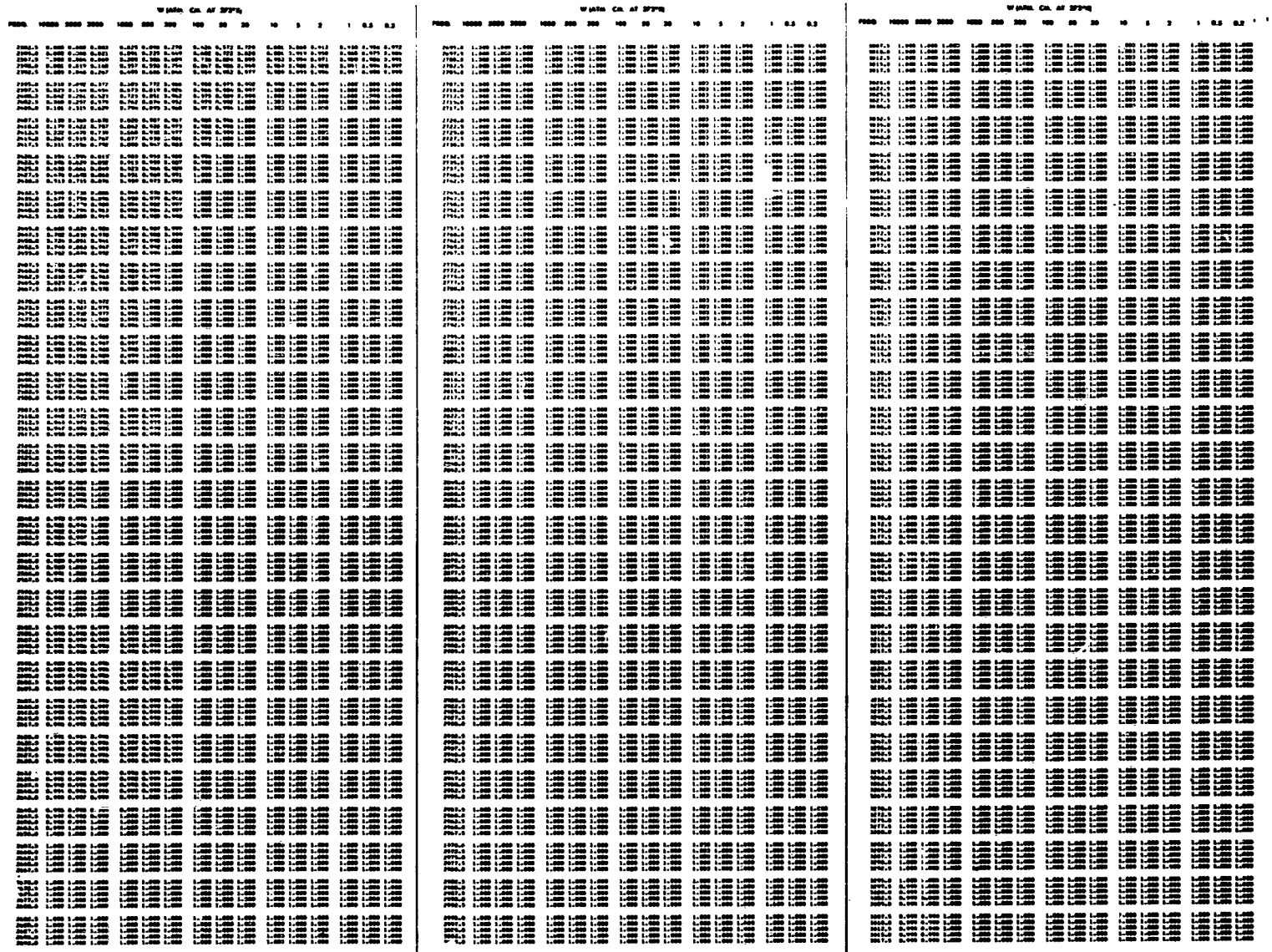


CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T=250° K

CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T=250° K

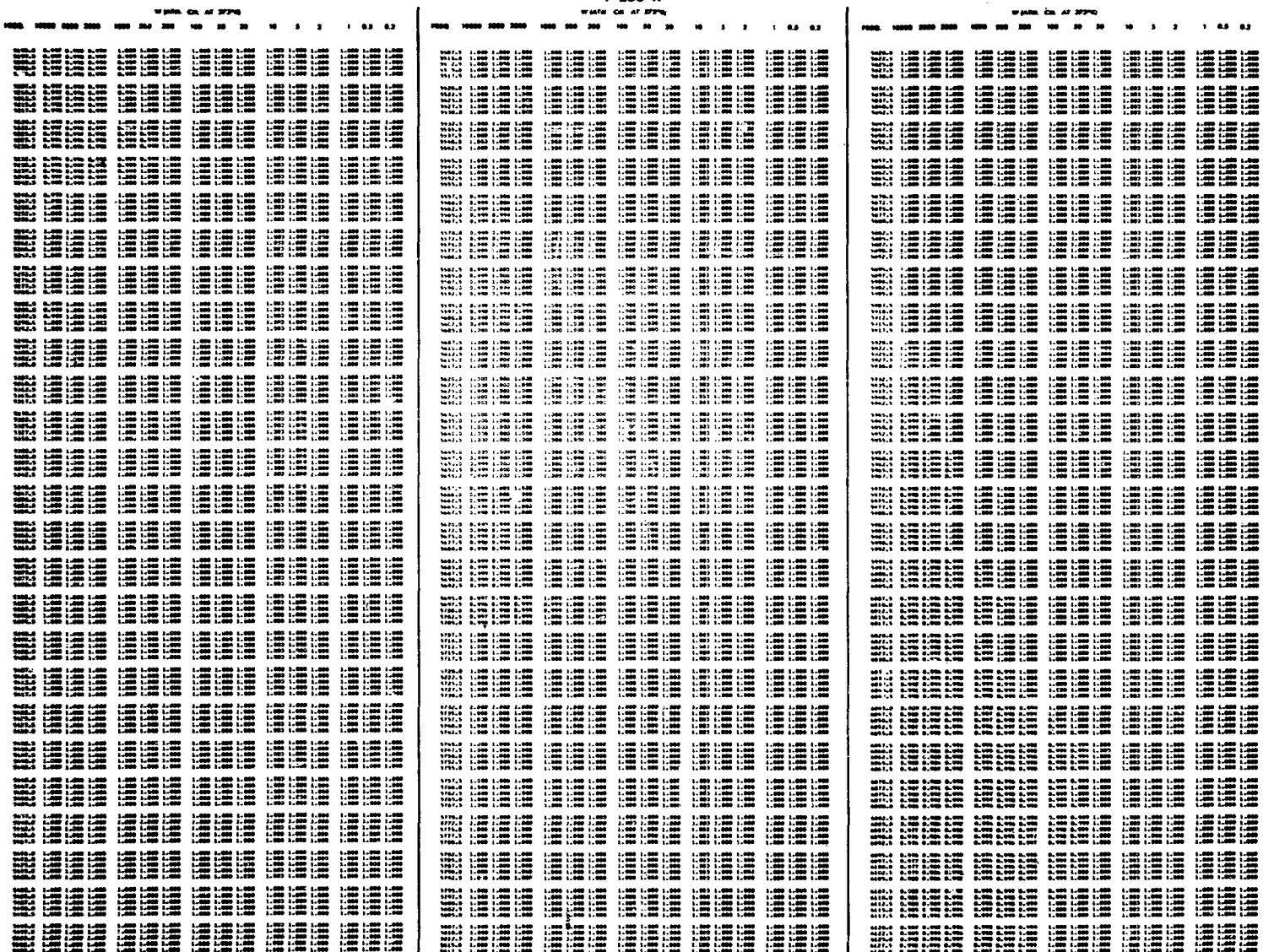


CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T=250° K

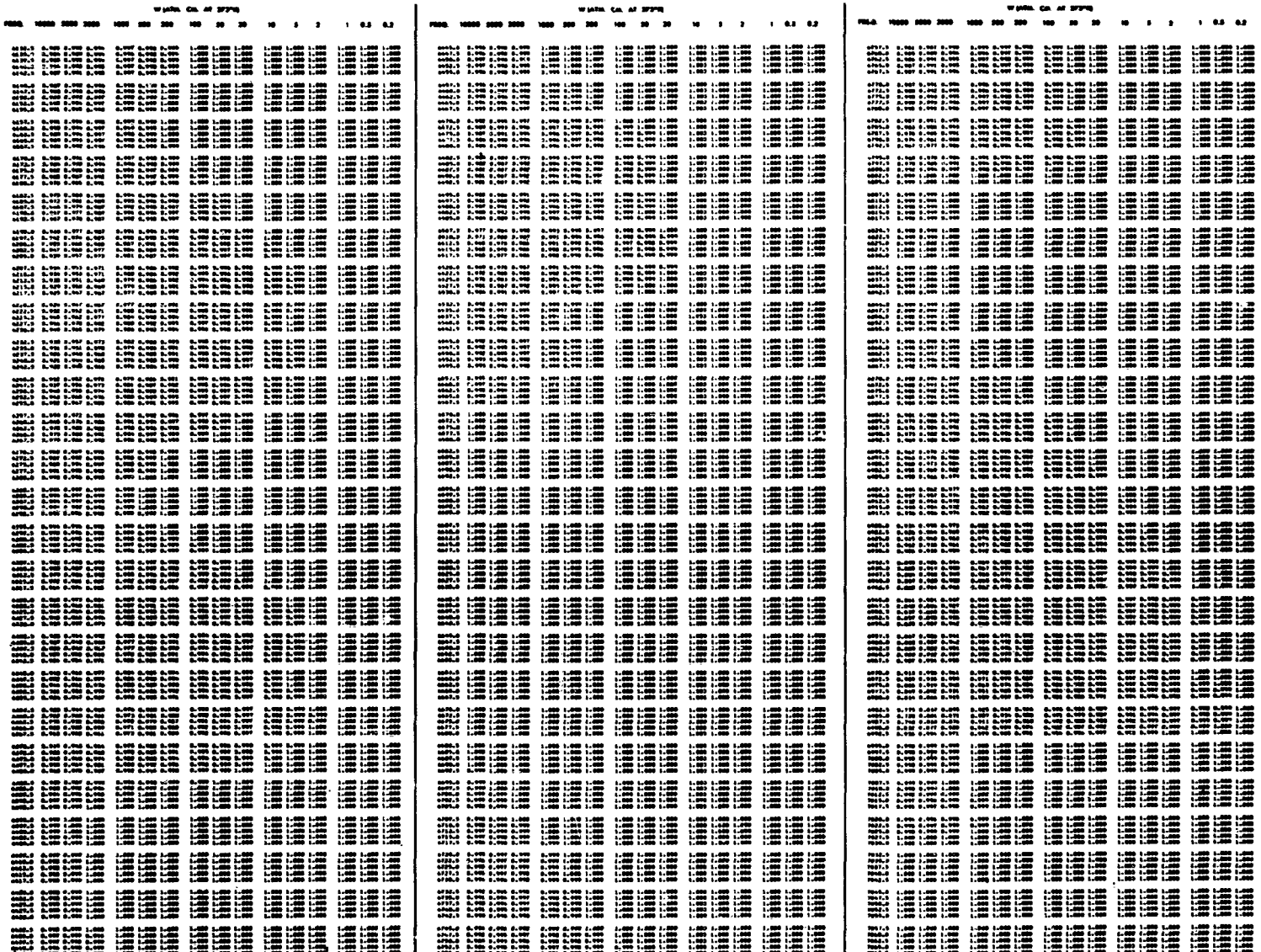
CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T=250° K



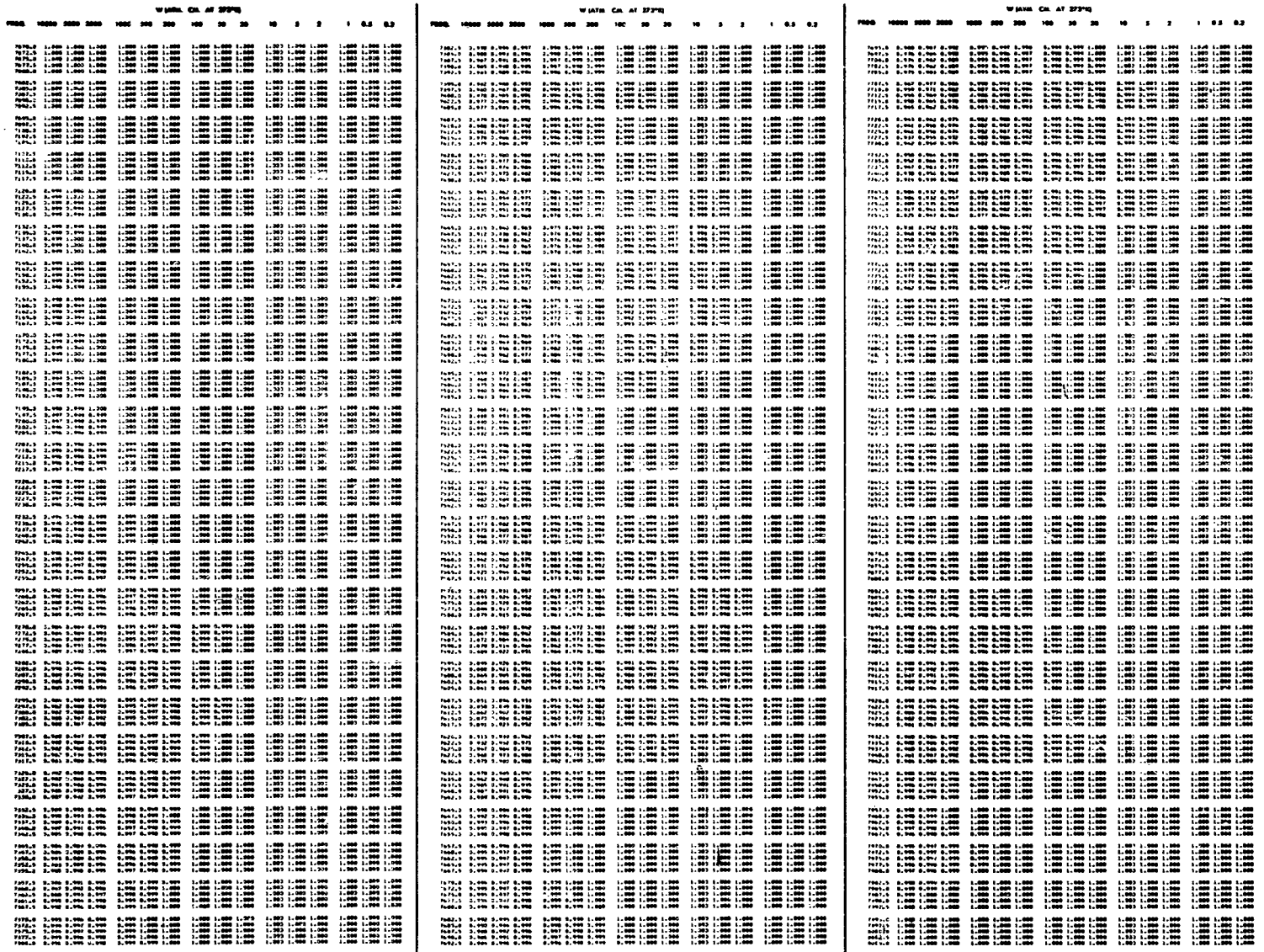
CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T=250° K



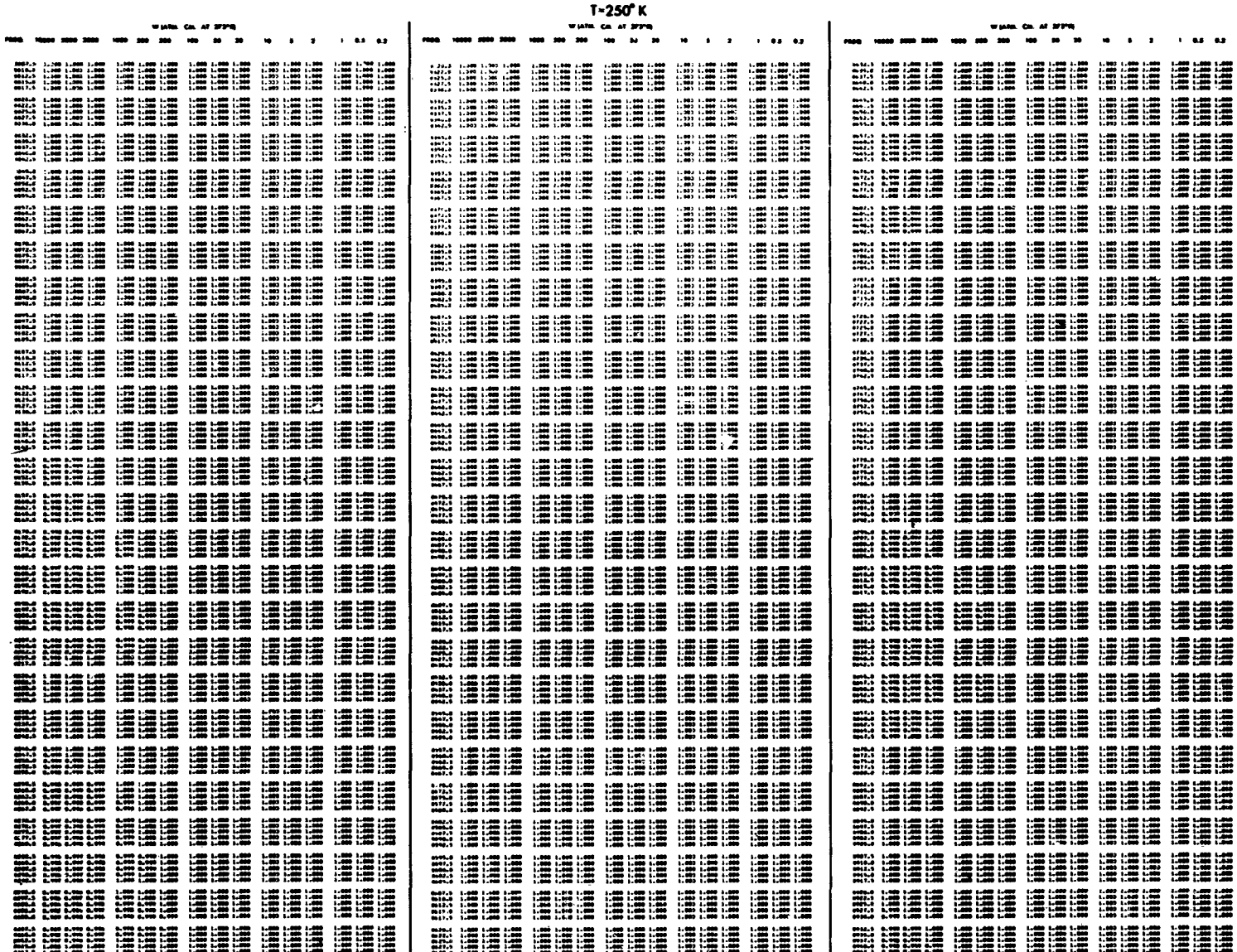
CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T=250° K



CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T=250° K



CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE
T-250°K

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=200° K

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T-200°K

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

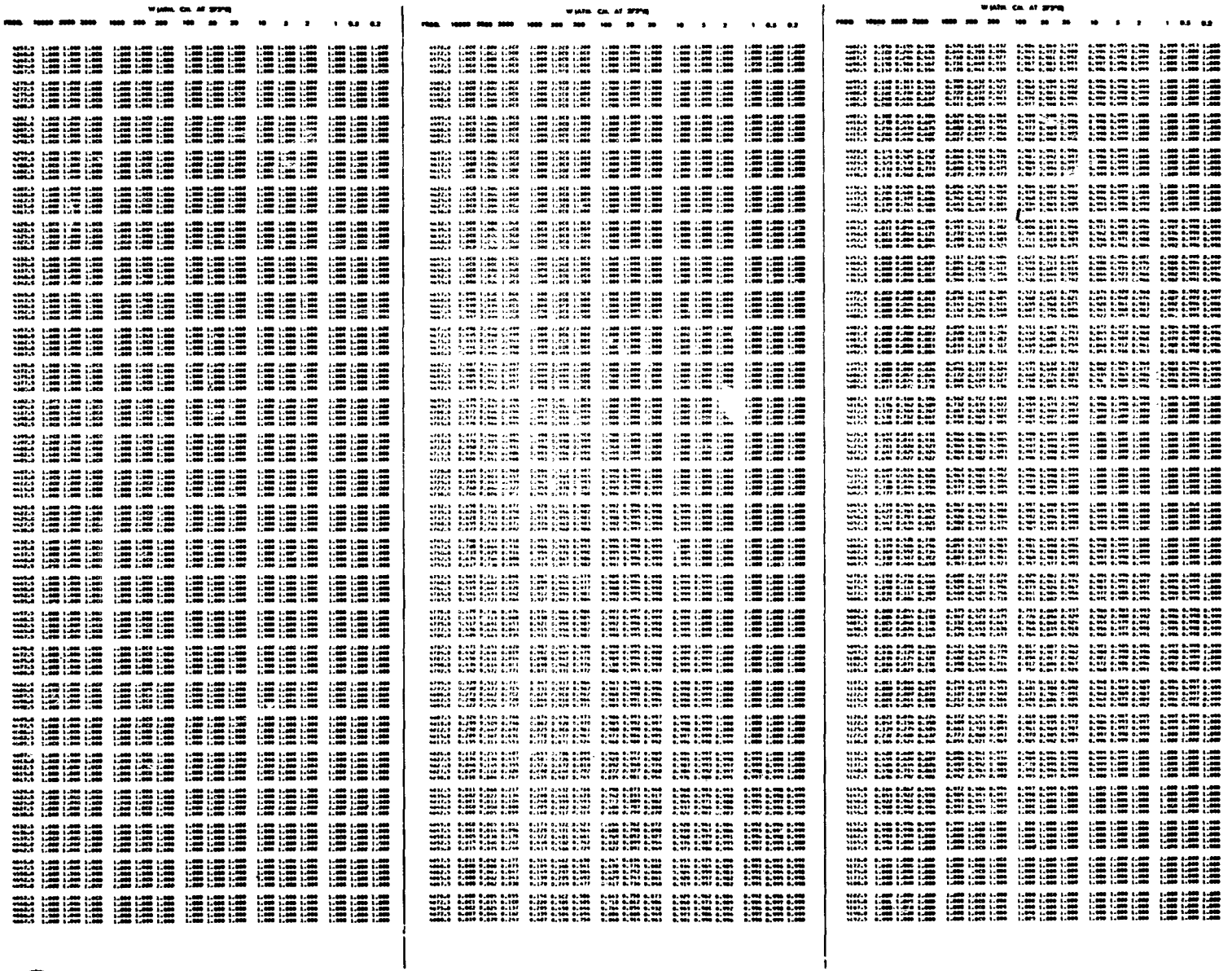
T=200° K

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

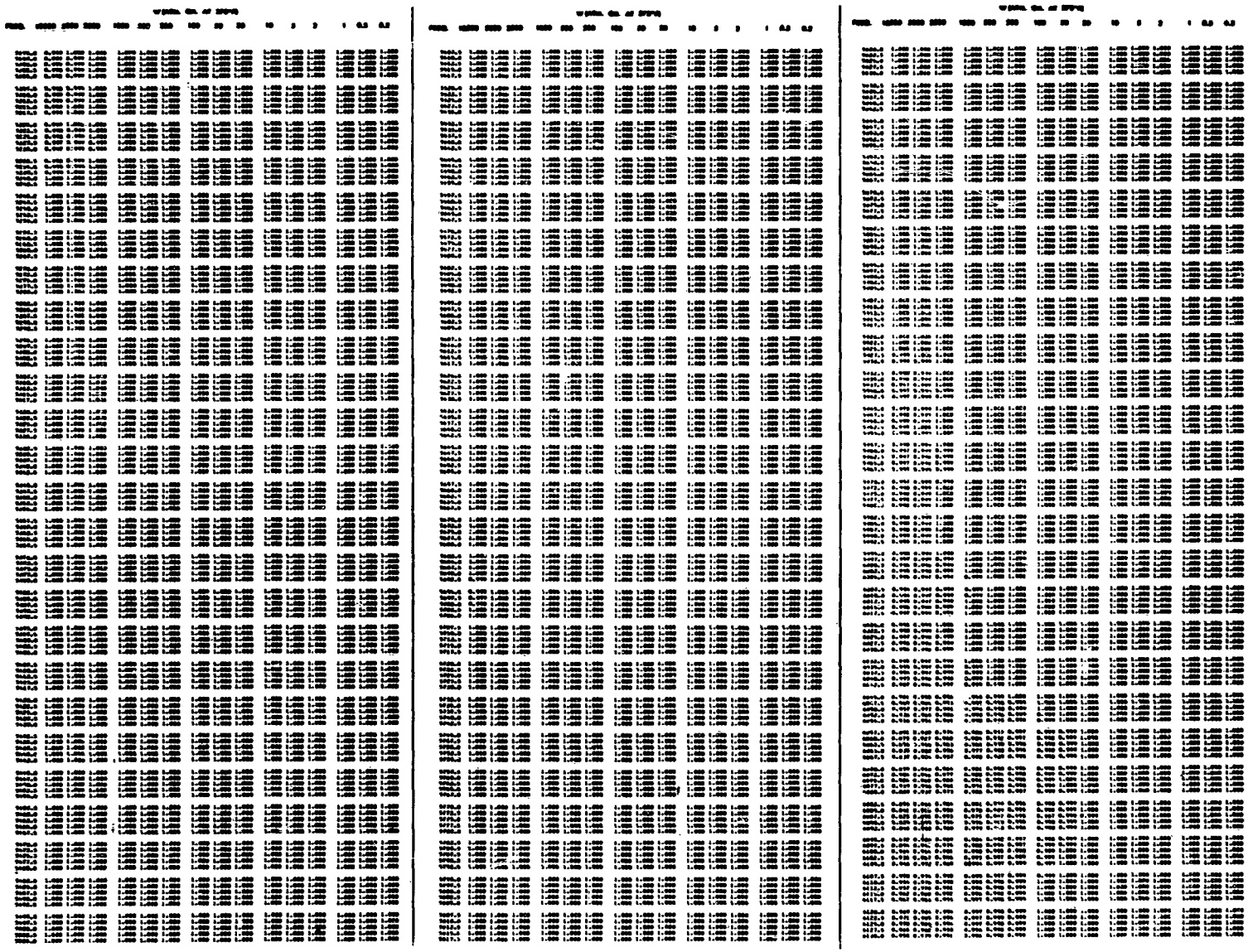
T-200° K

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=200° K



CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE
T=200° K

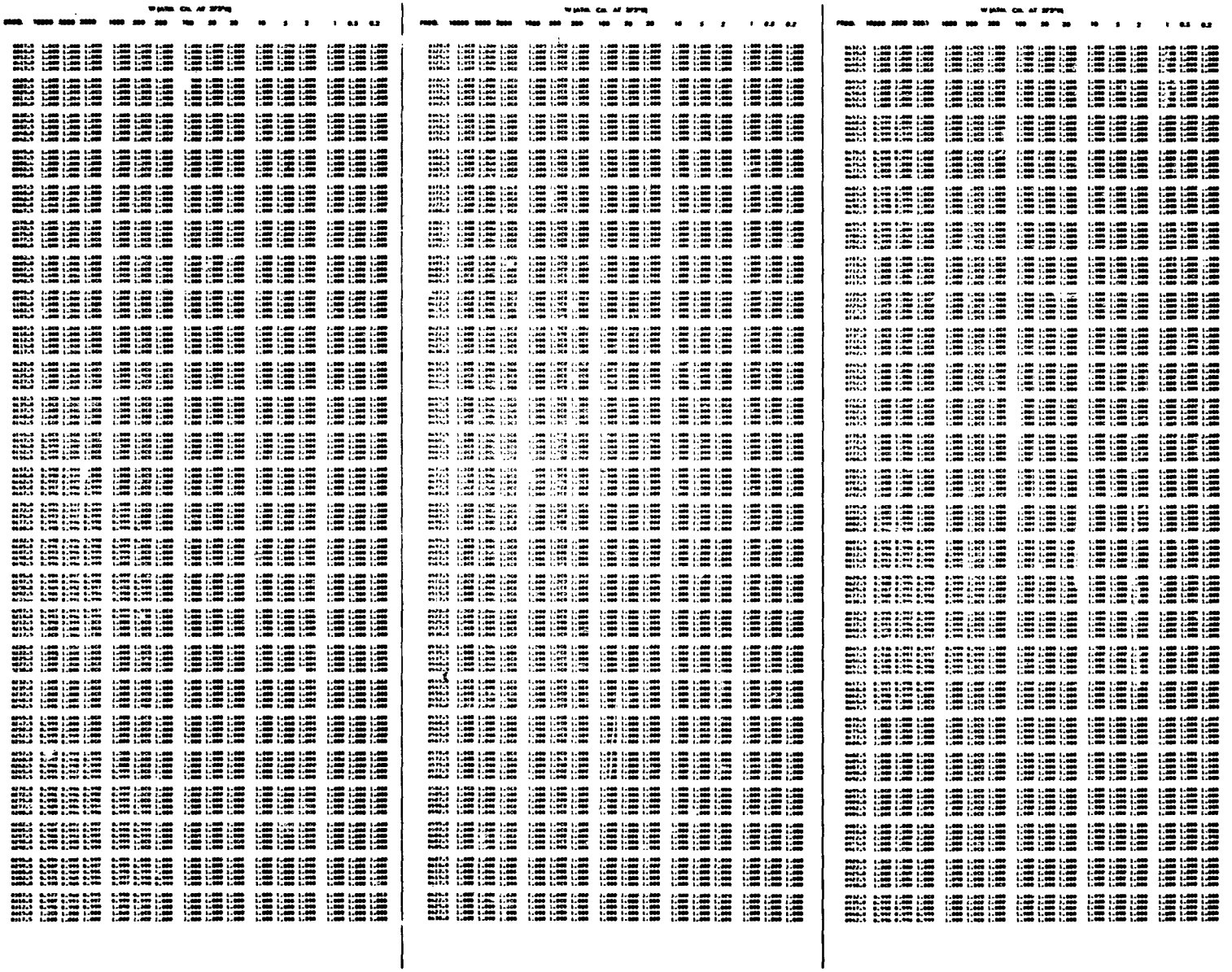


CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE
T-200°K

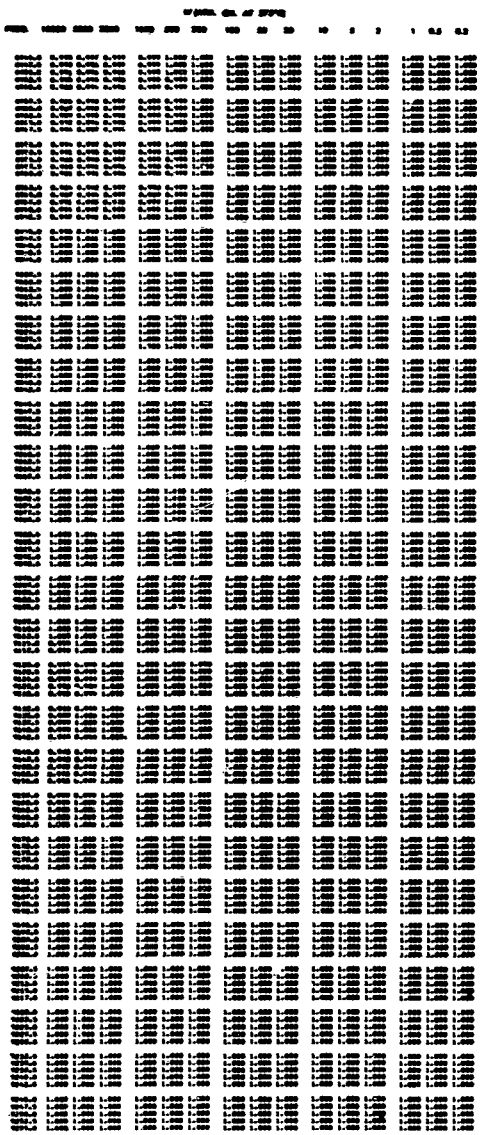
CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE
T-200°K

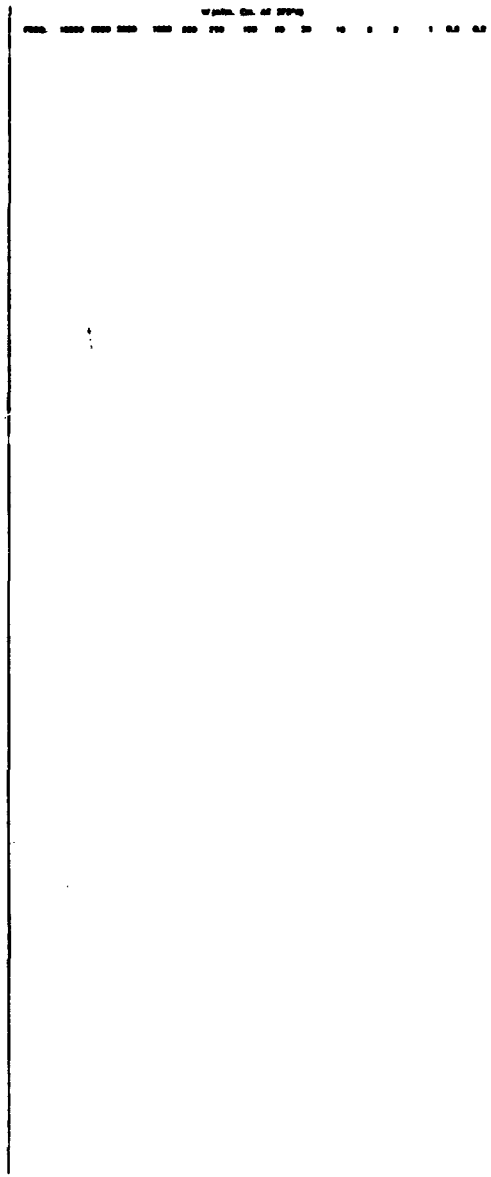
CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=200°K



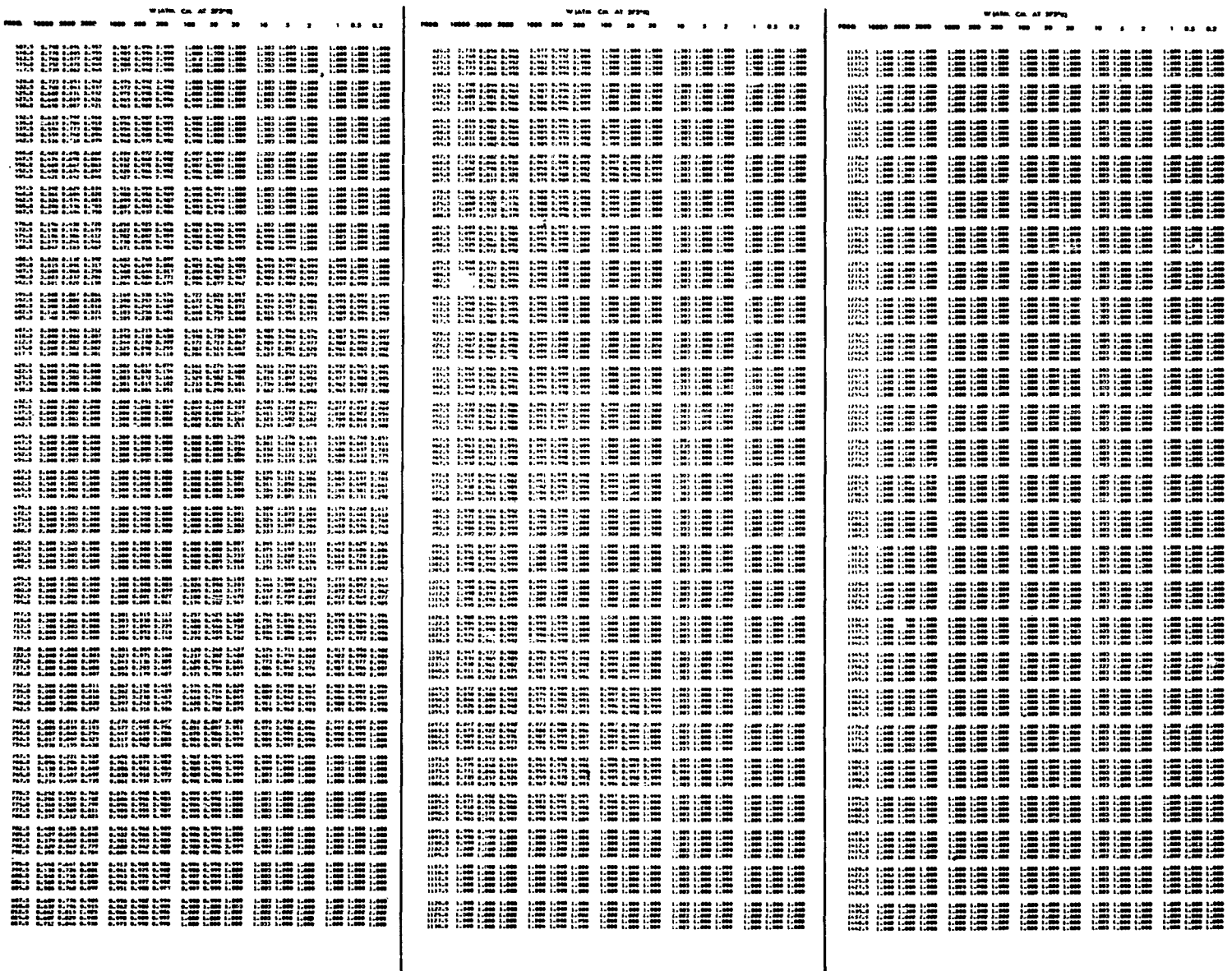
CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE
T=200° K





CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=200° K

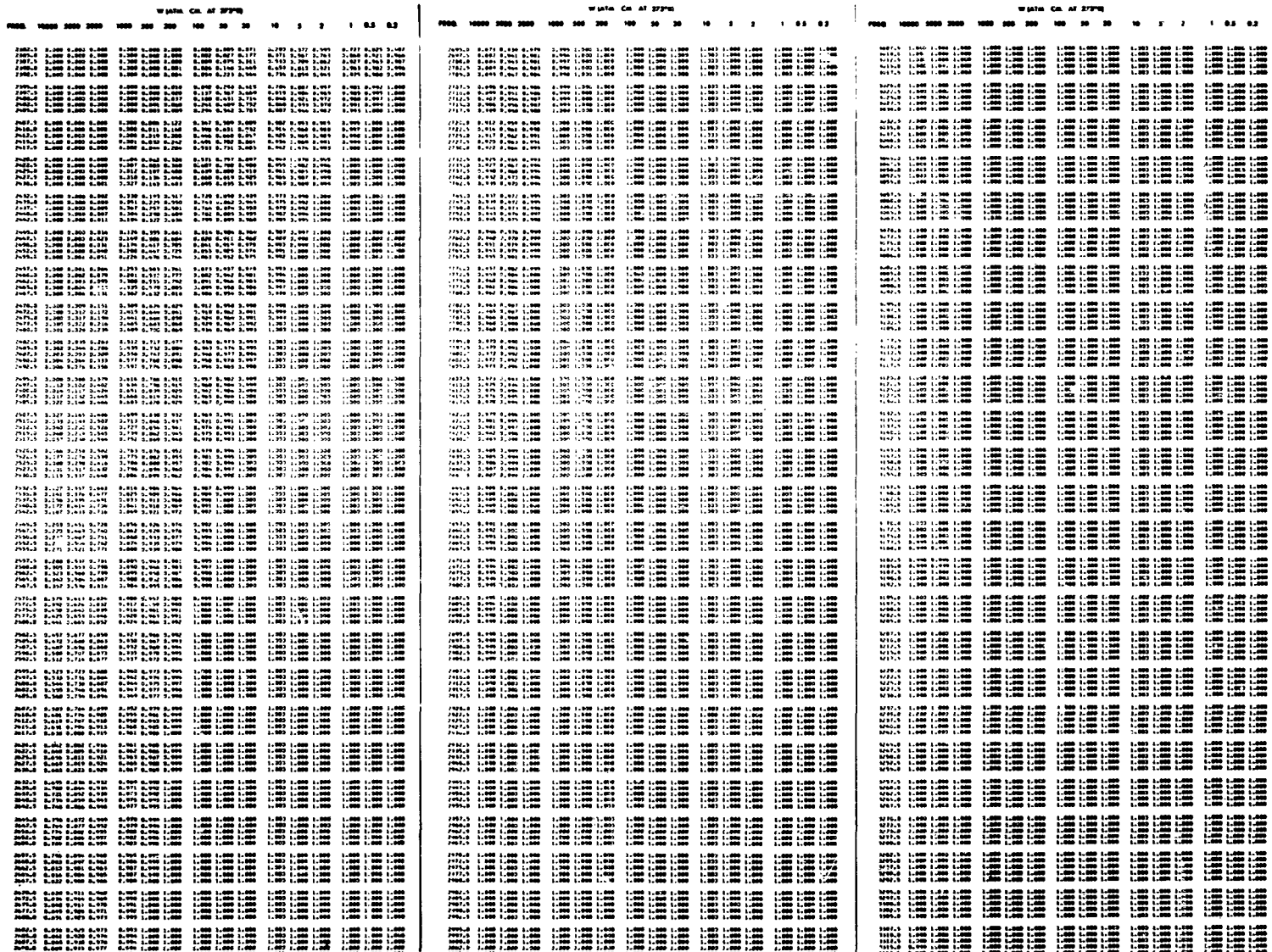


CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

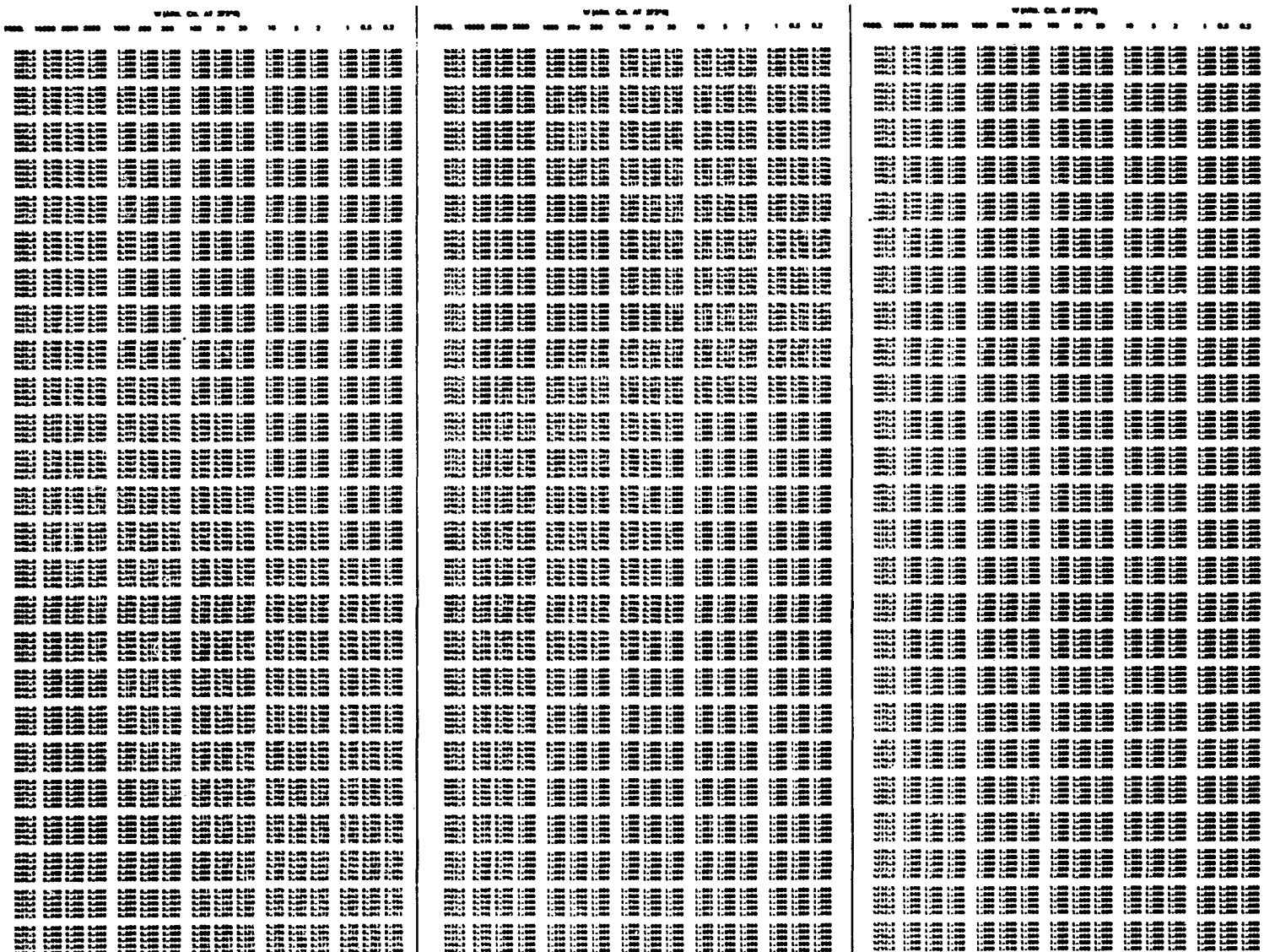
T=200° K

CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=200° K



CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE
T=200°K

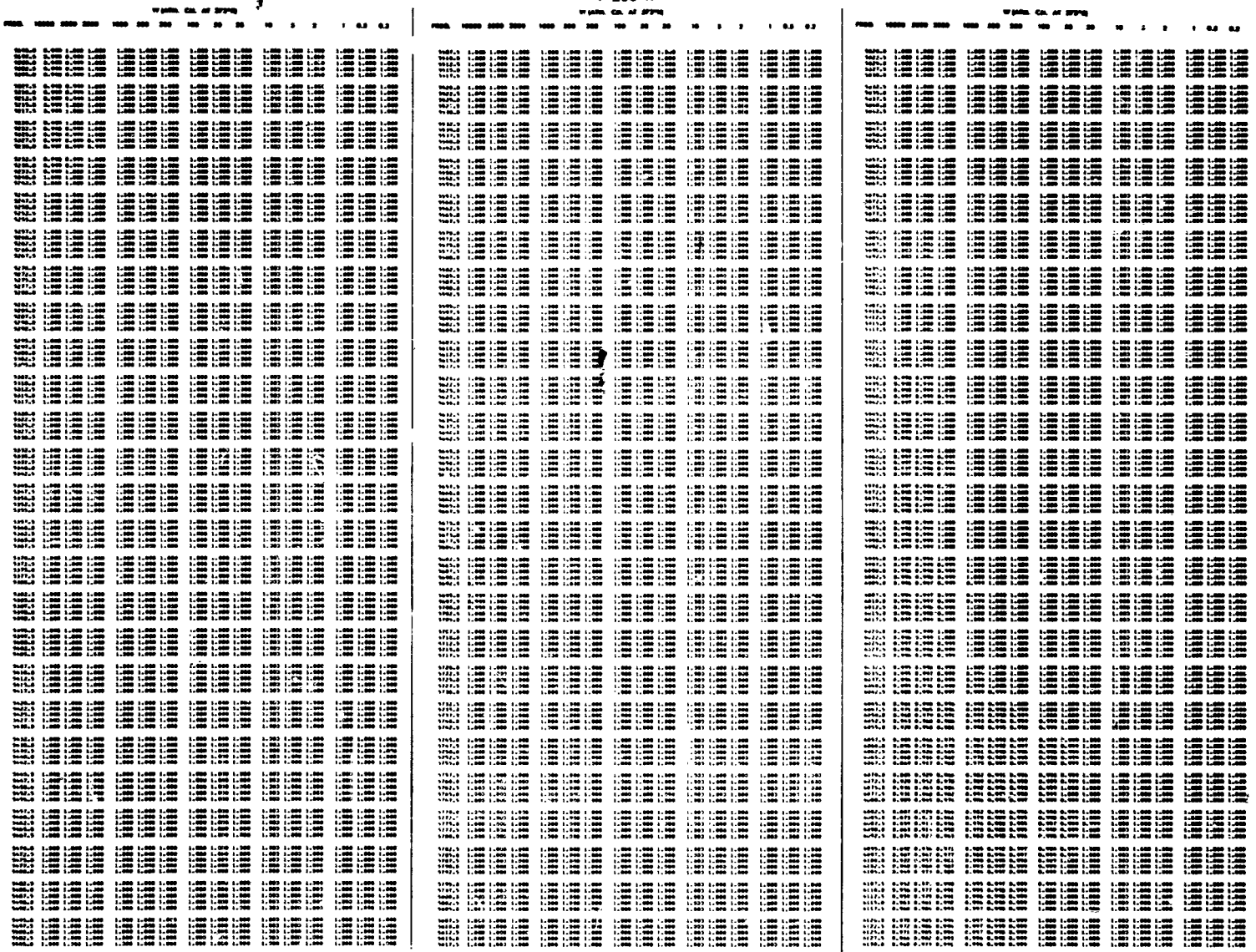


CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T-200° K

CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=200° K



CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

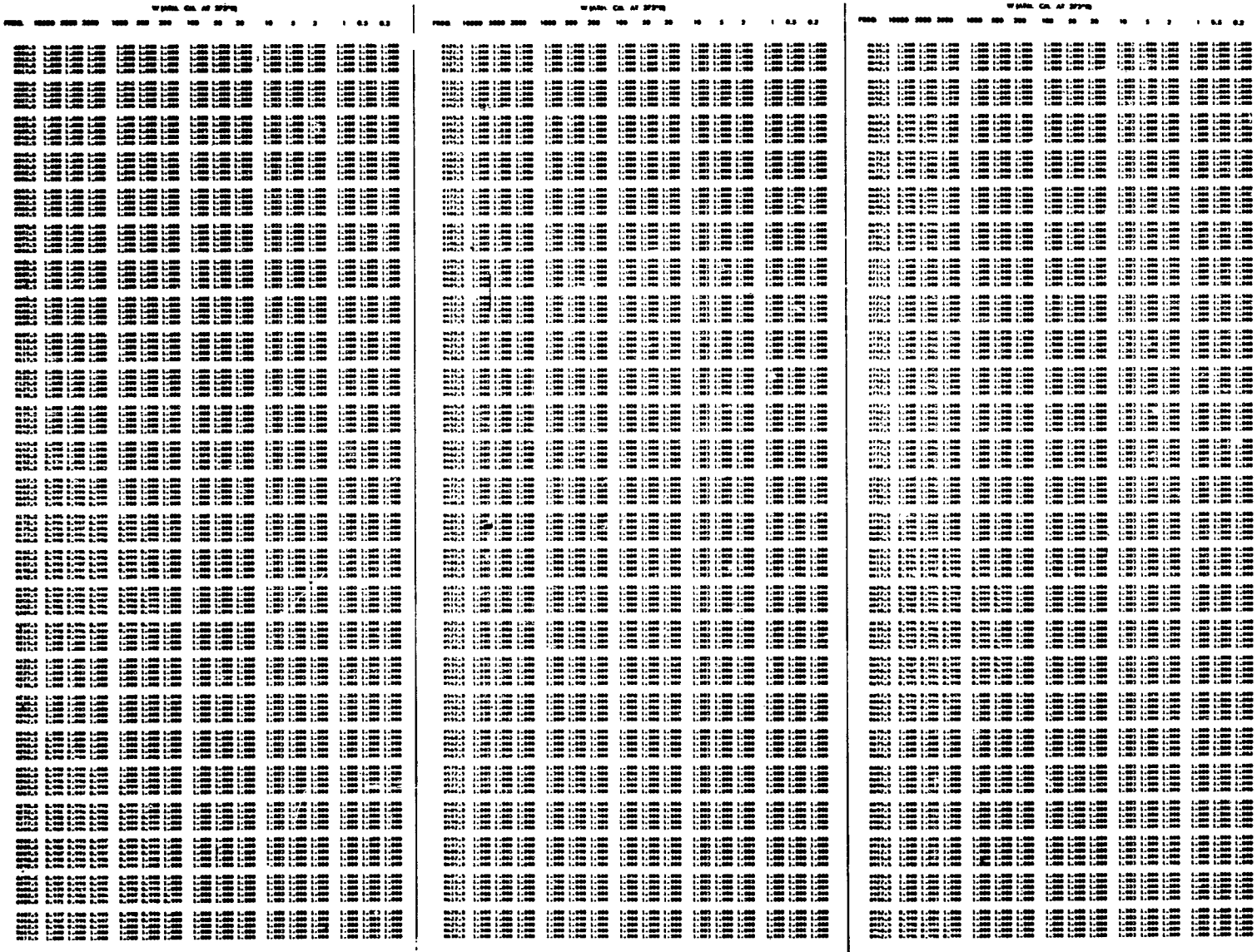
T=200° K

CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=200° K

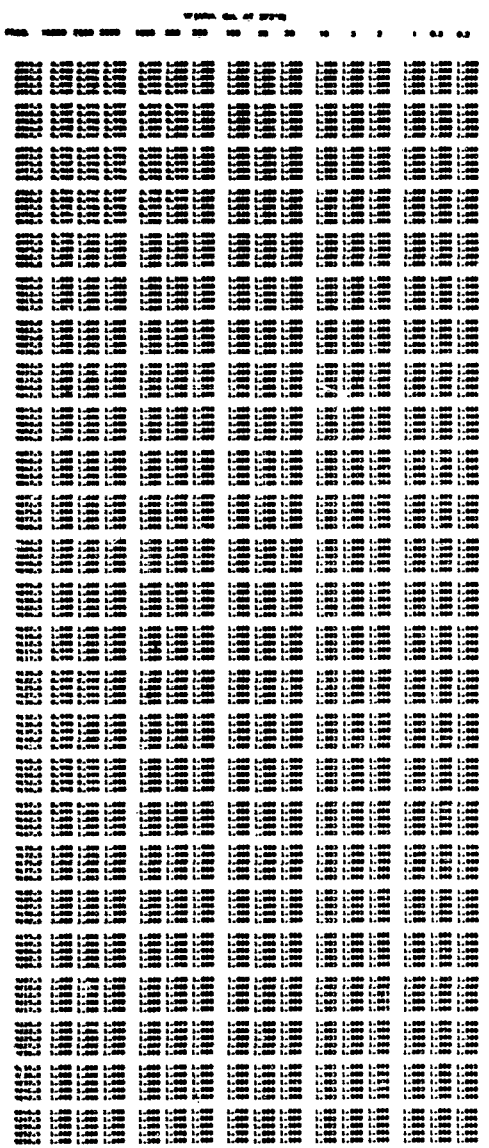
CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

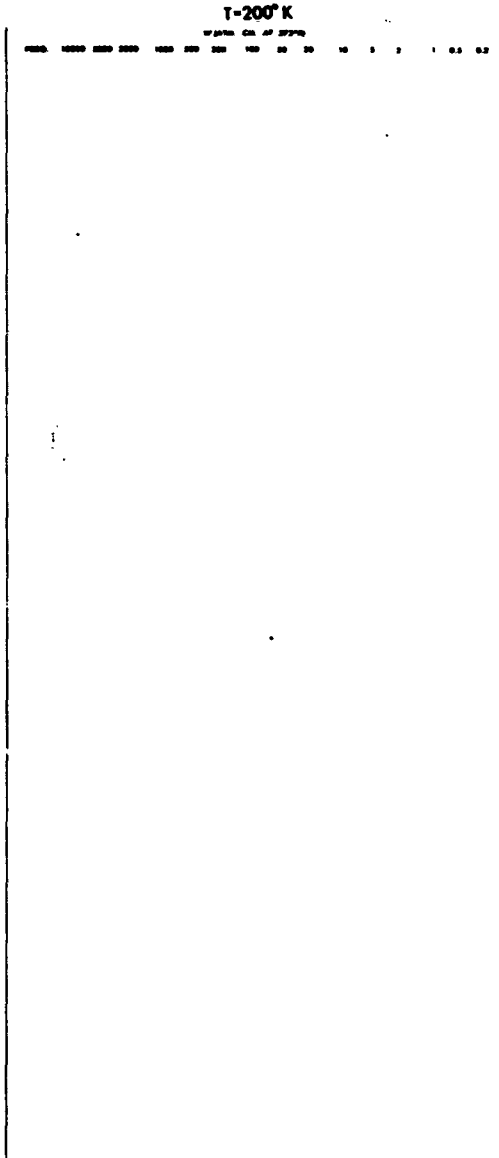
T=200° K

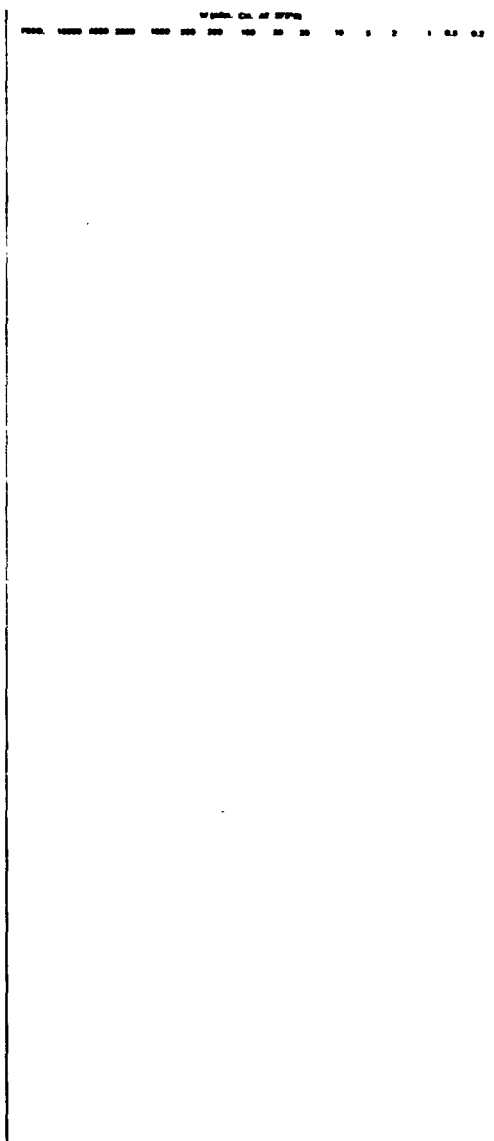


CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=200° K

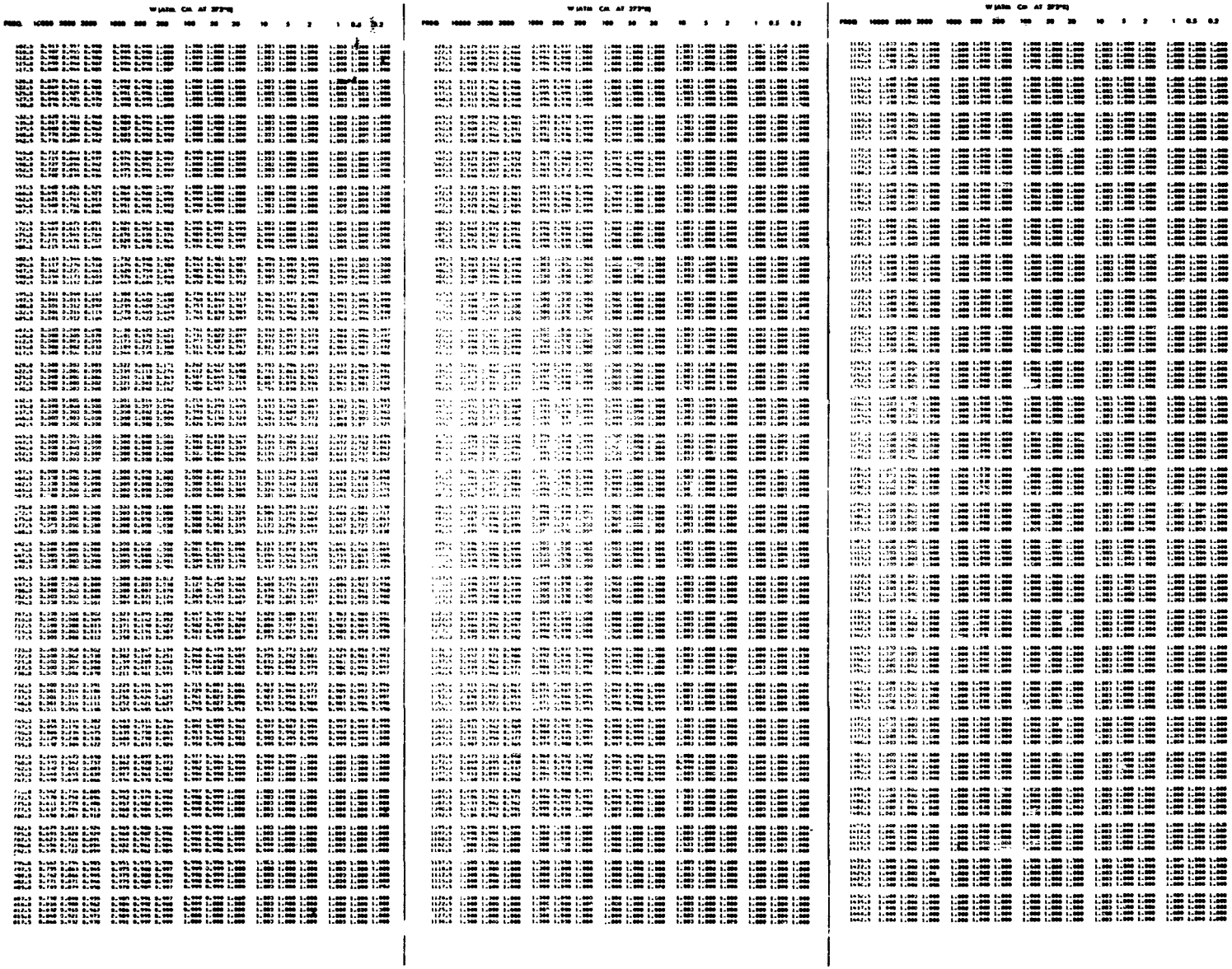




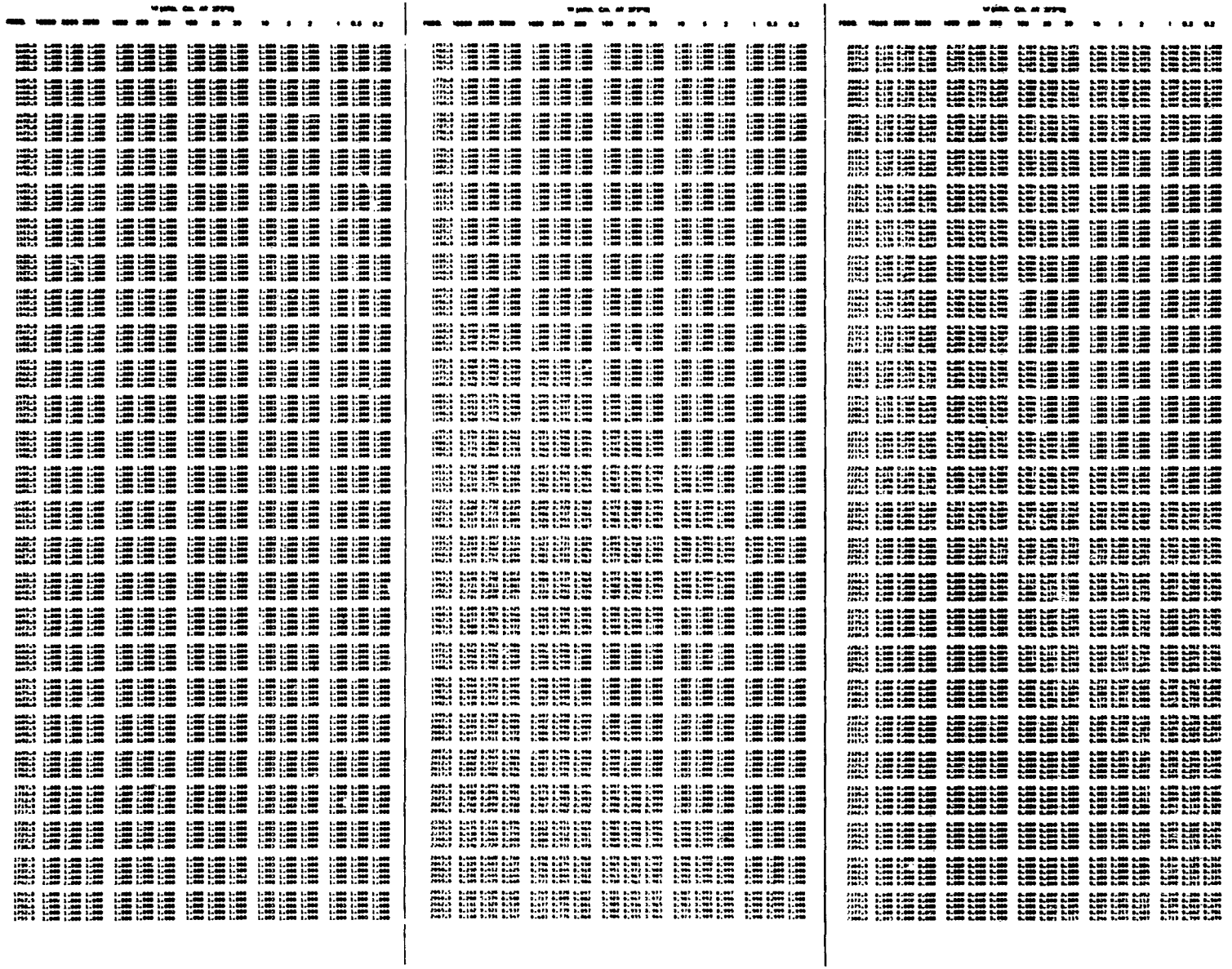


CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

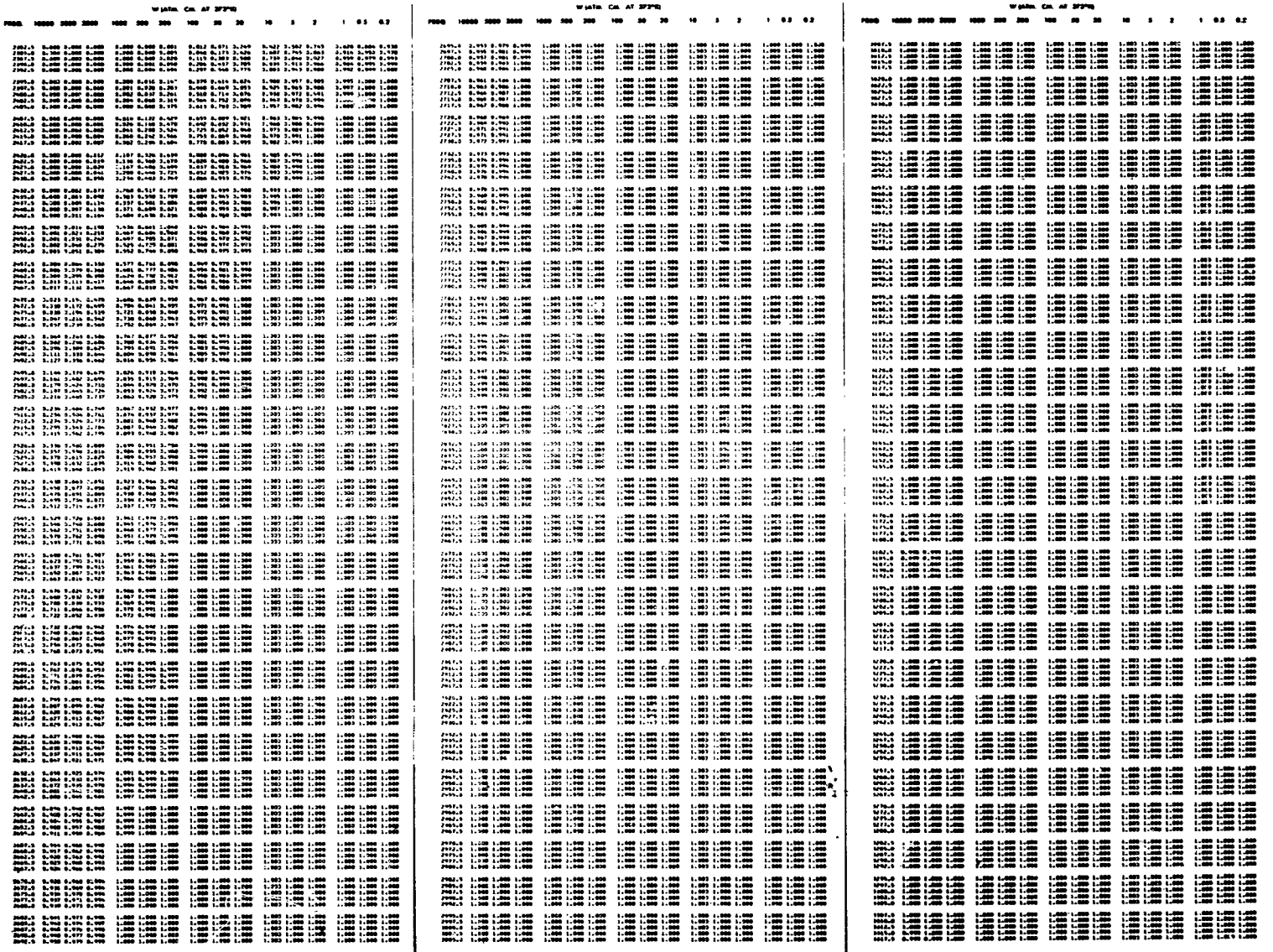
T=200°K



CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE
T=200° K



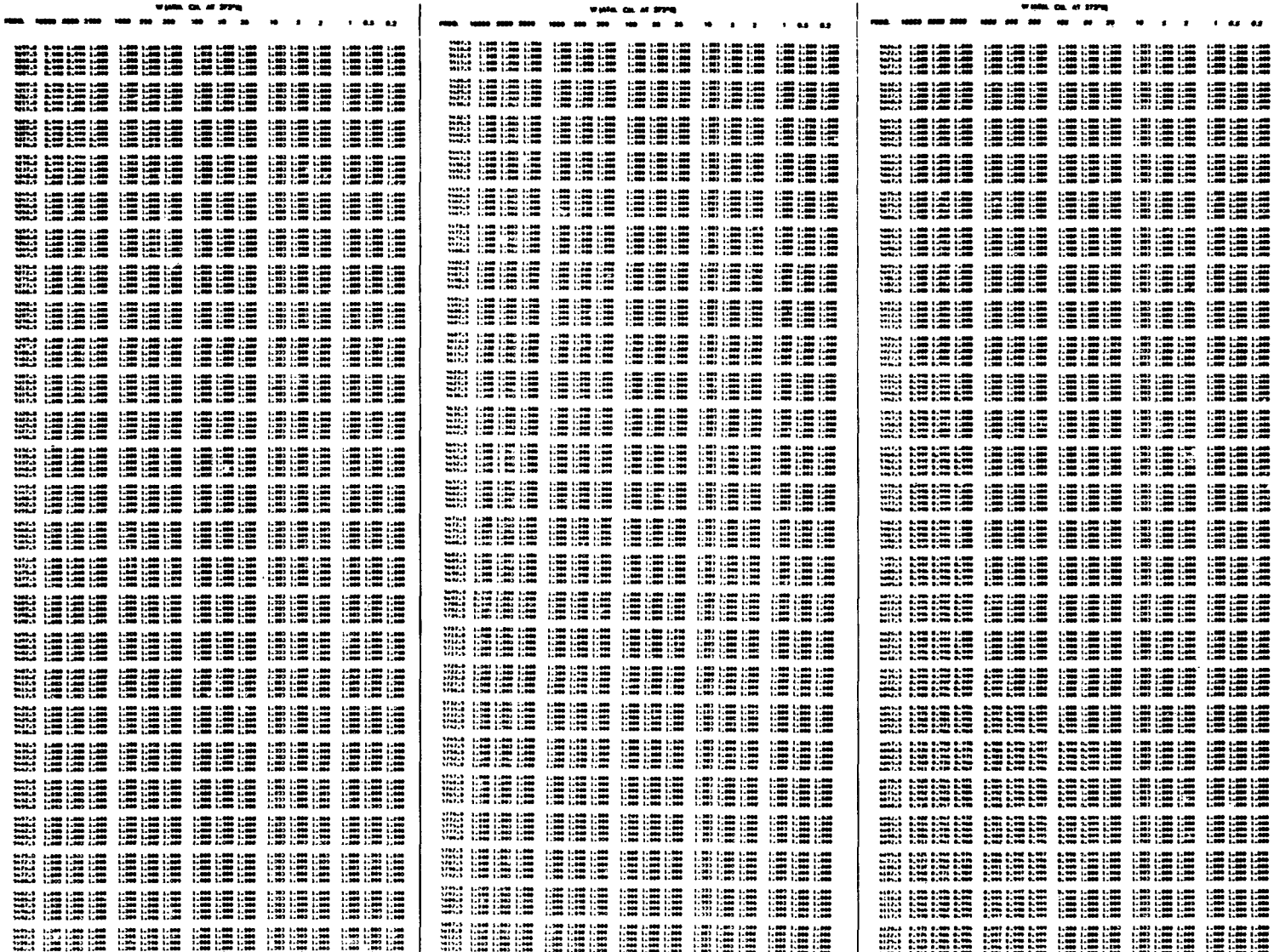
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE
T=200° K



CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE
T=200° K

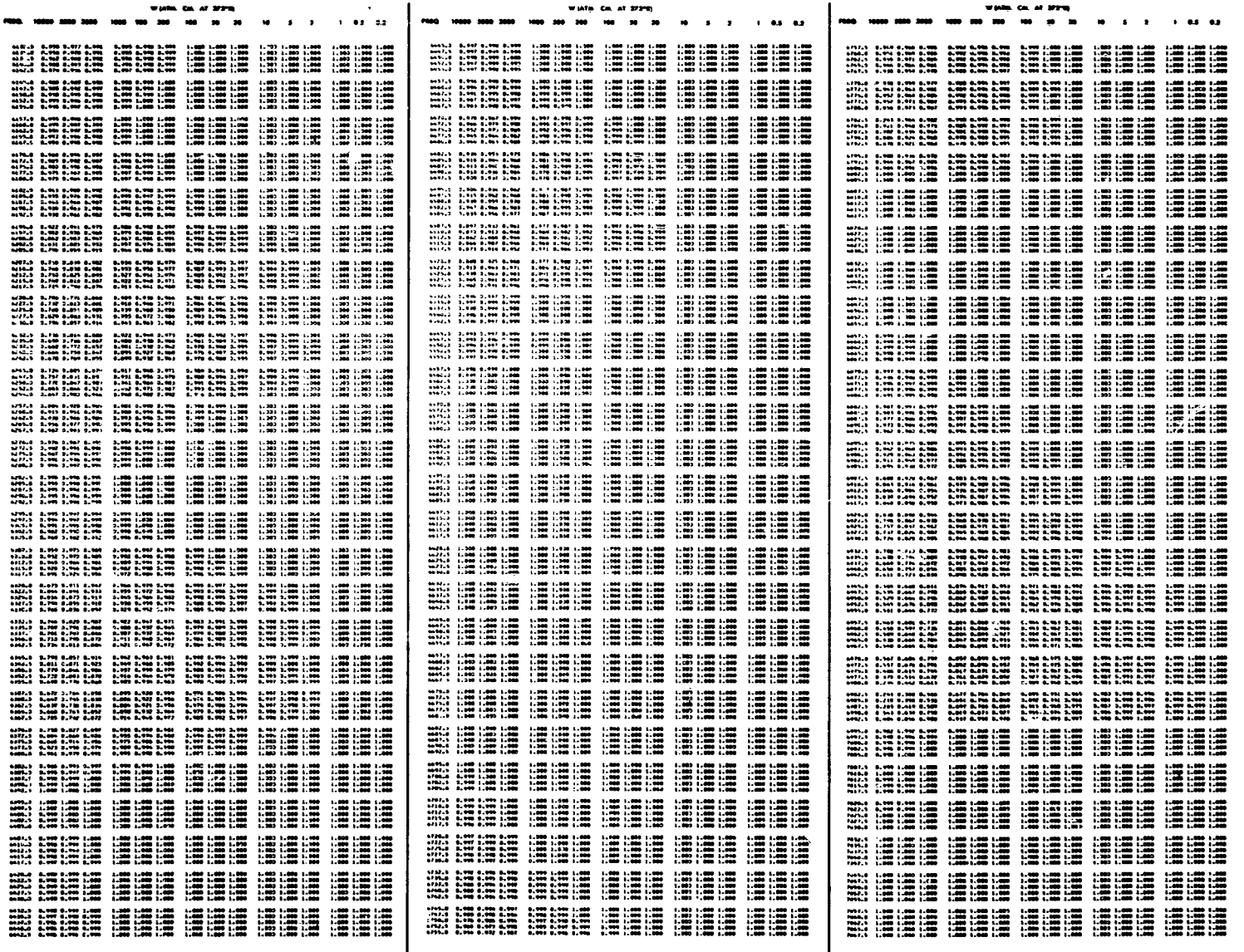
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE
T-200° K

CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE
T=200° K

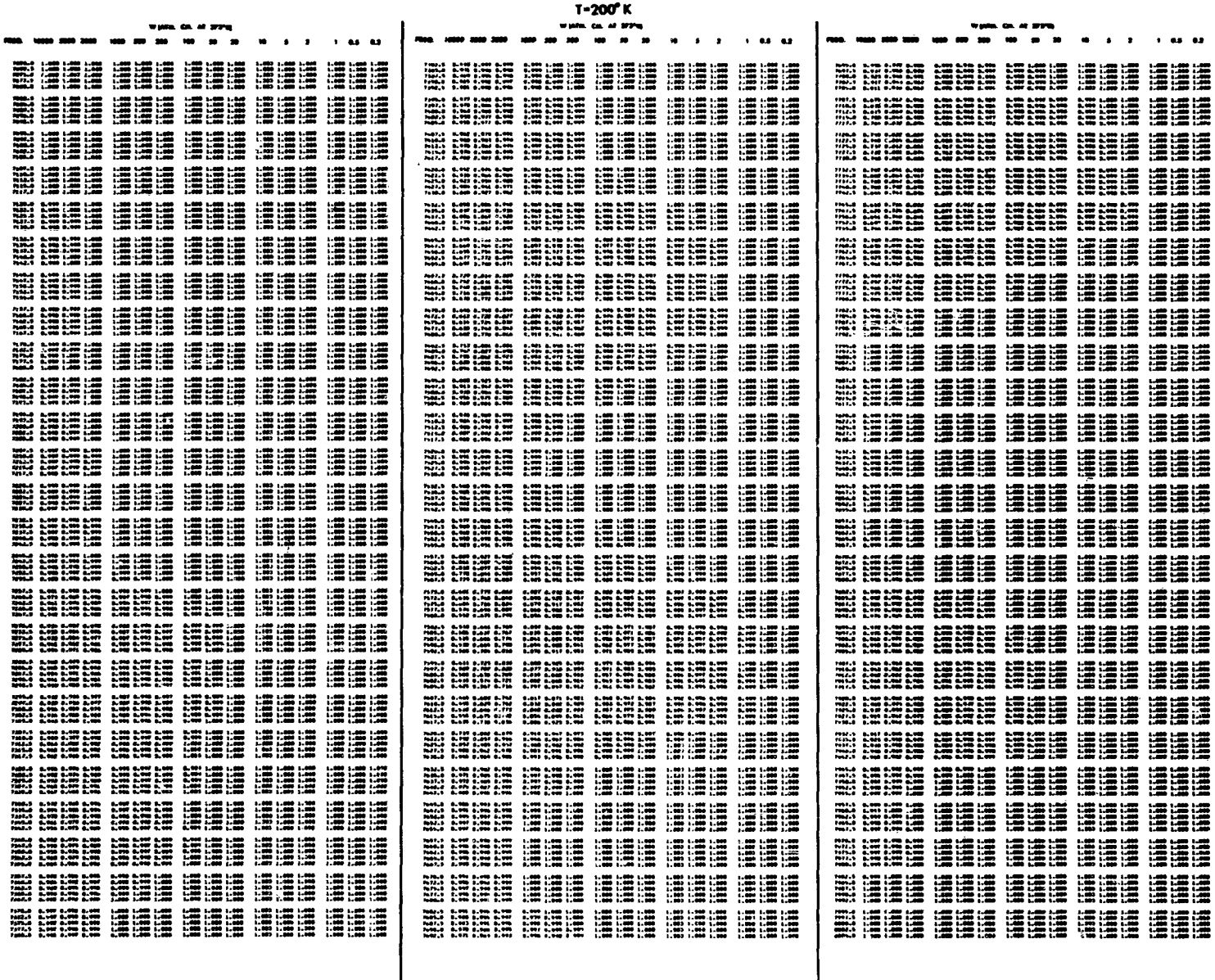


CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=200° K

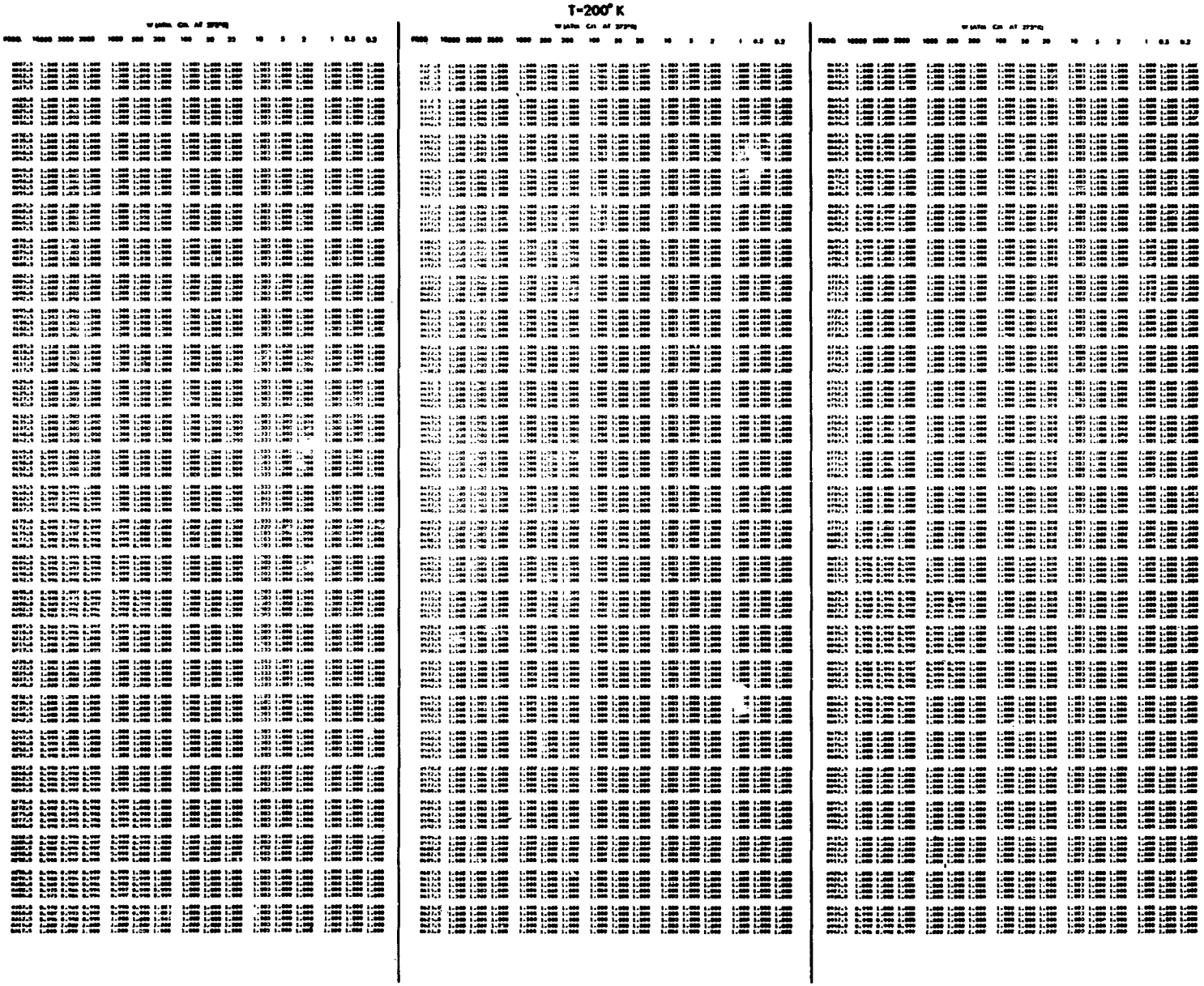


CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE
T-200° K



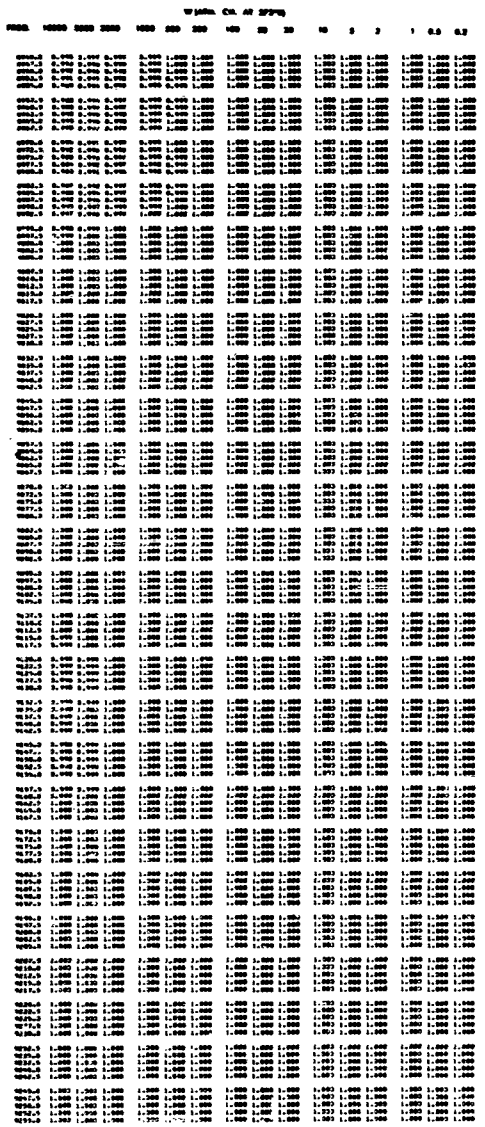
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

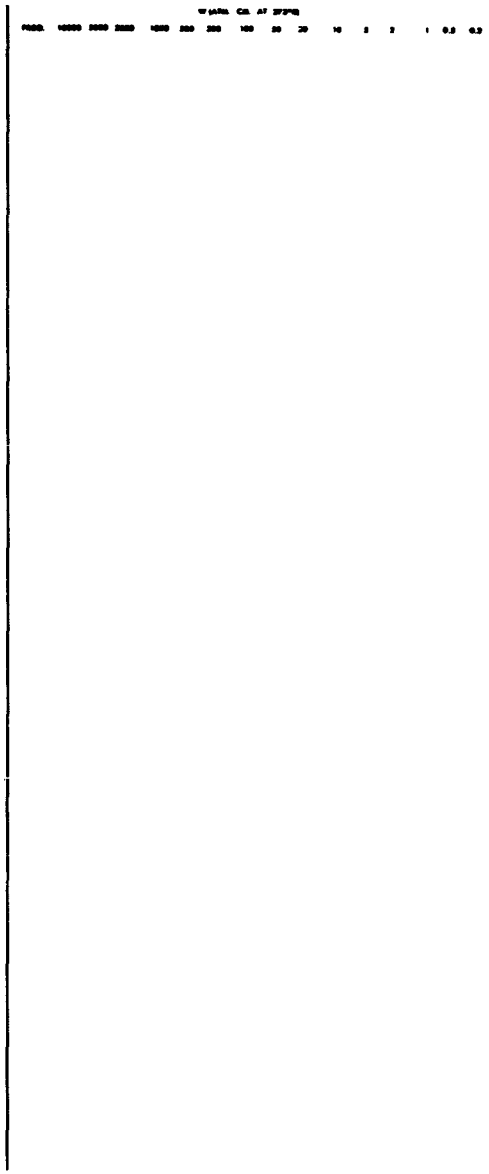
T=200° K

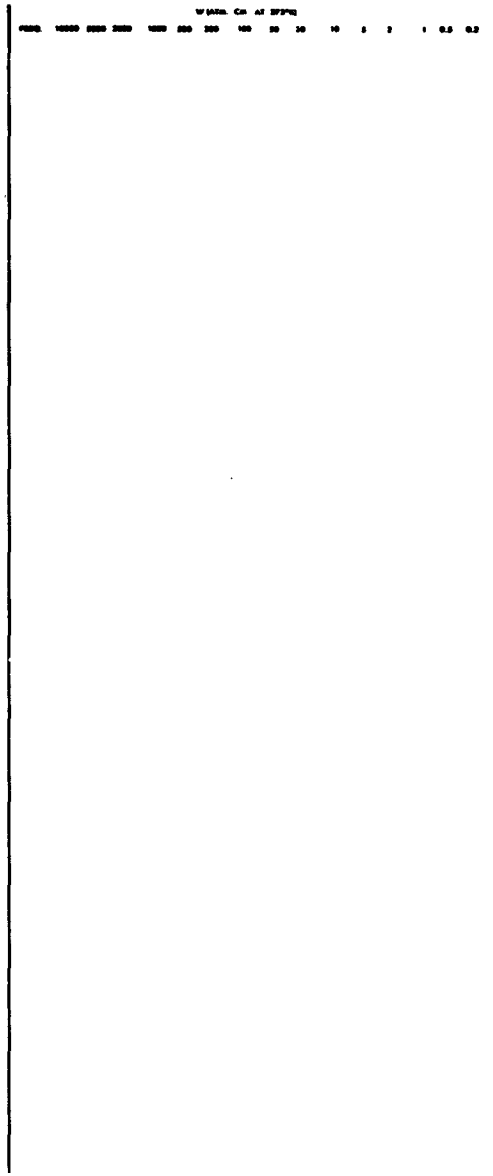


CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=200° K







CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T-200° K

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE
T=200° K

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

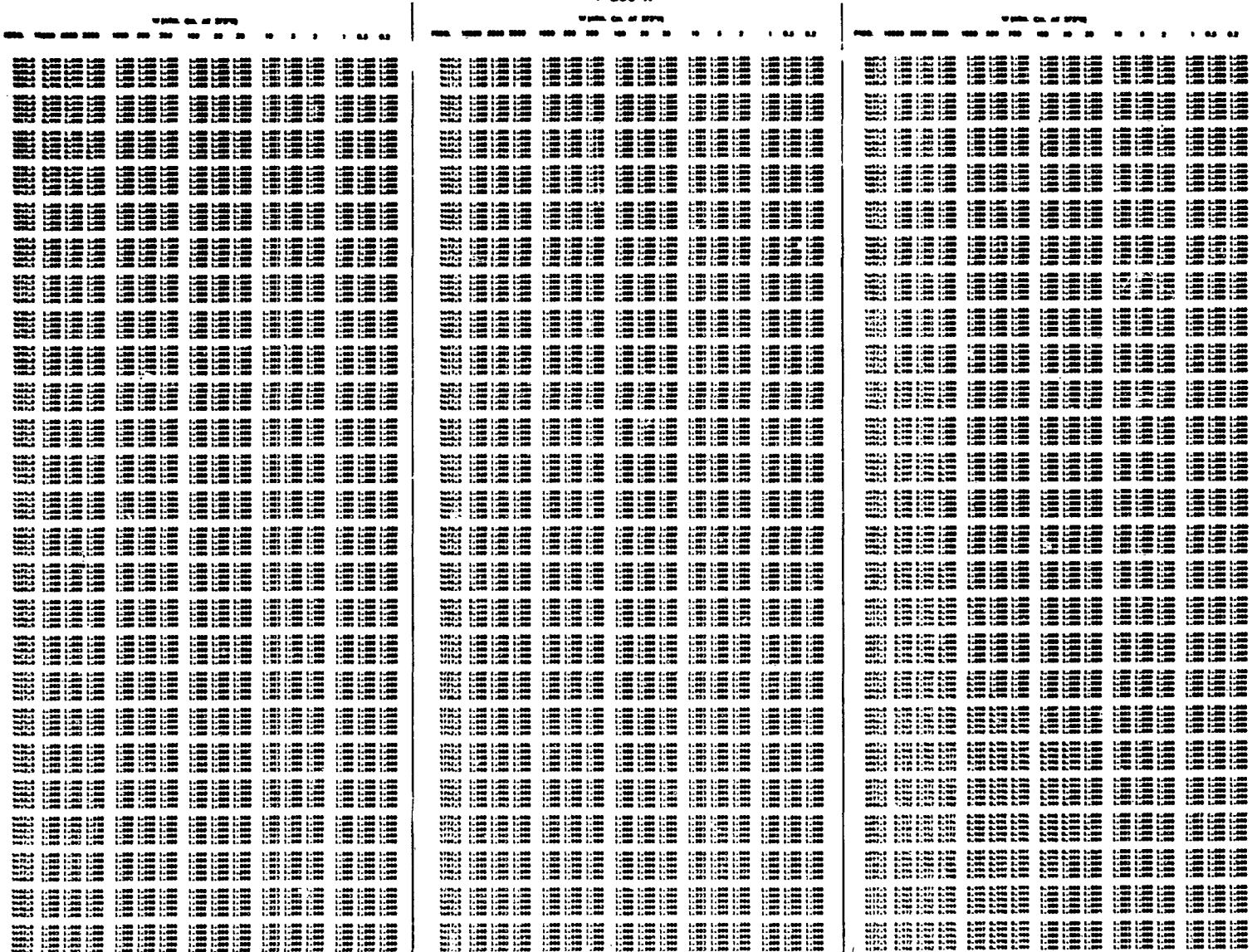
T=200° K

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE
T=200° K

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T-200° K

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE
T=200° K



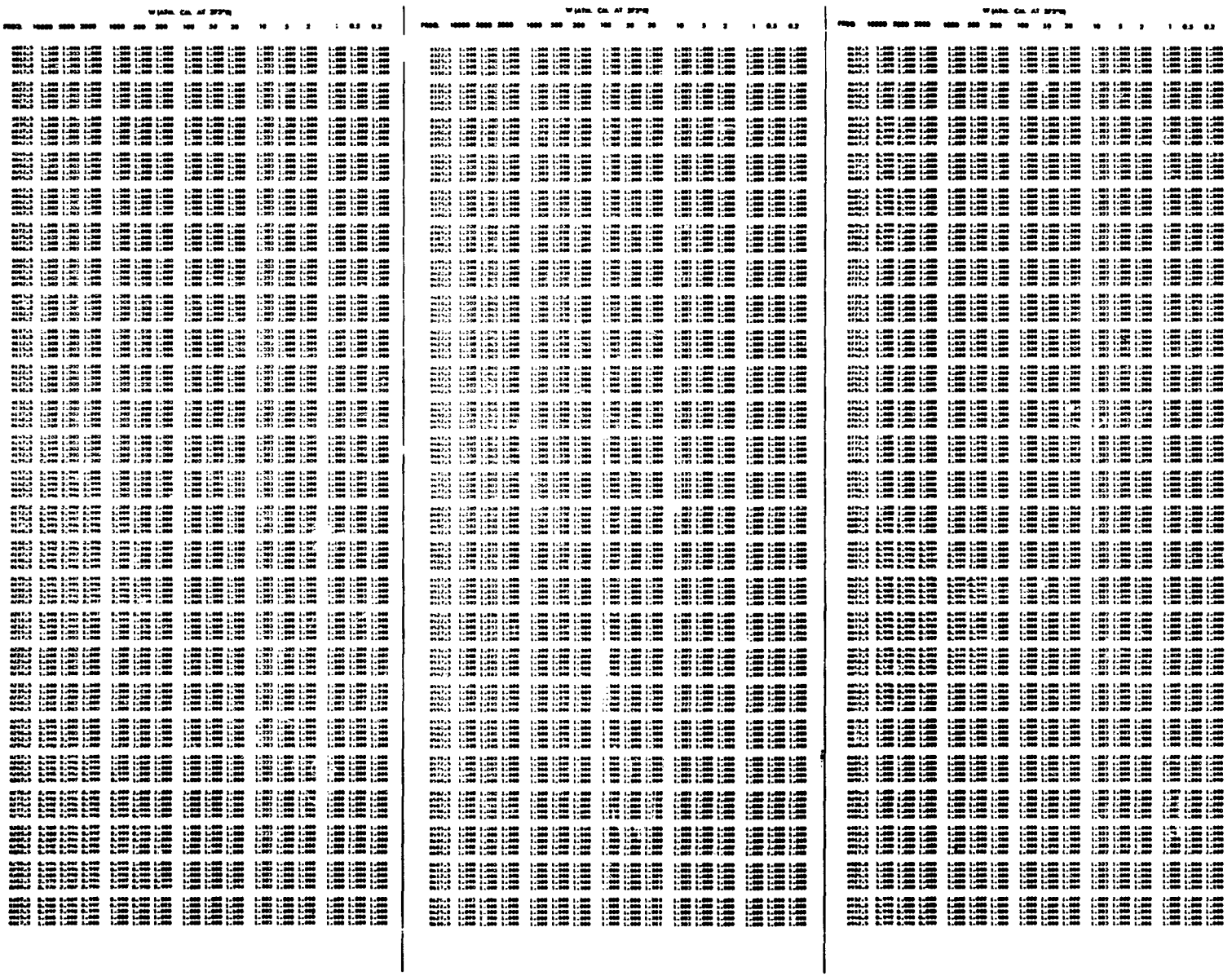
CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T=200° K

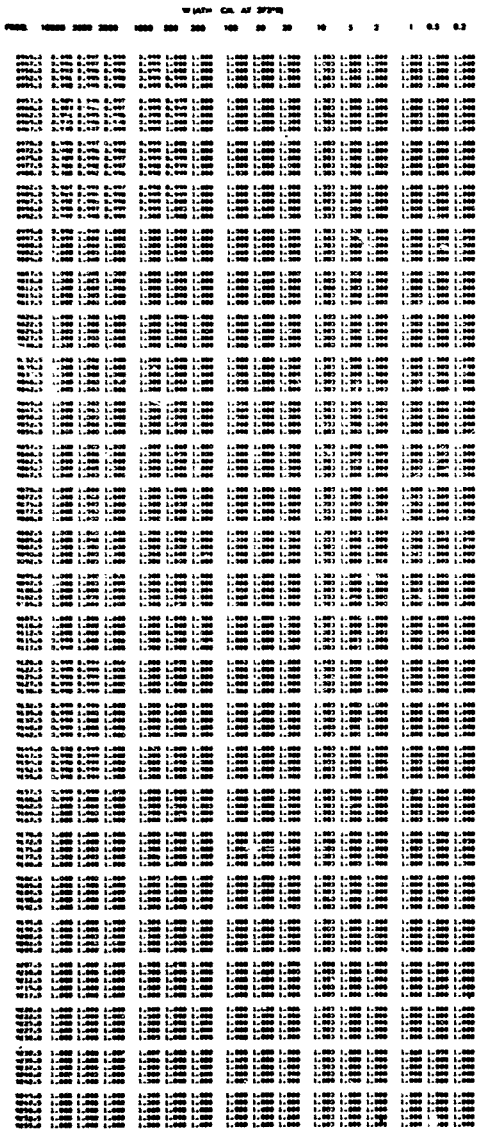
CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE
T-200° K

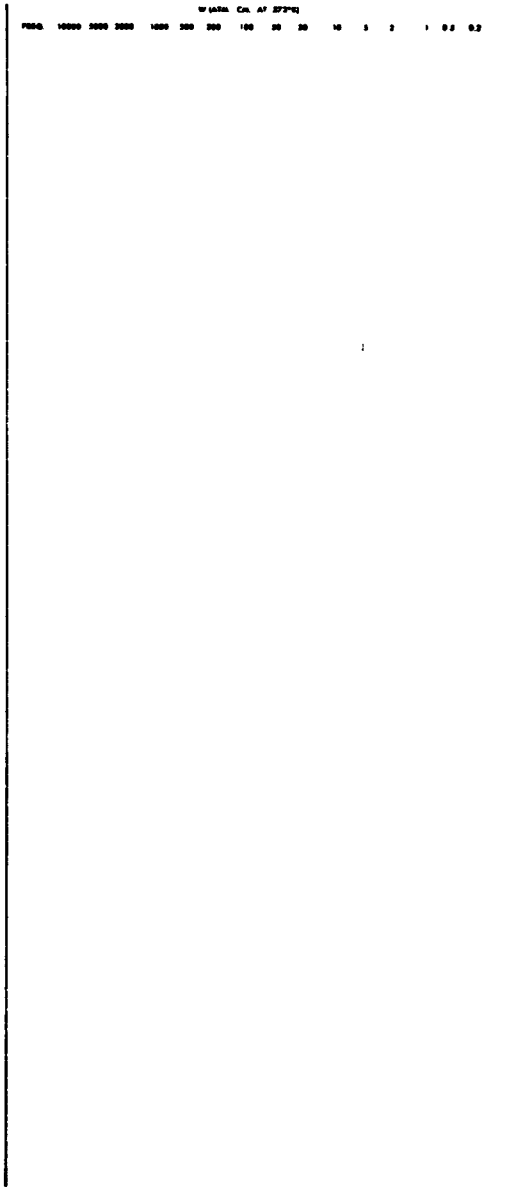
CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

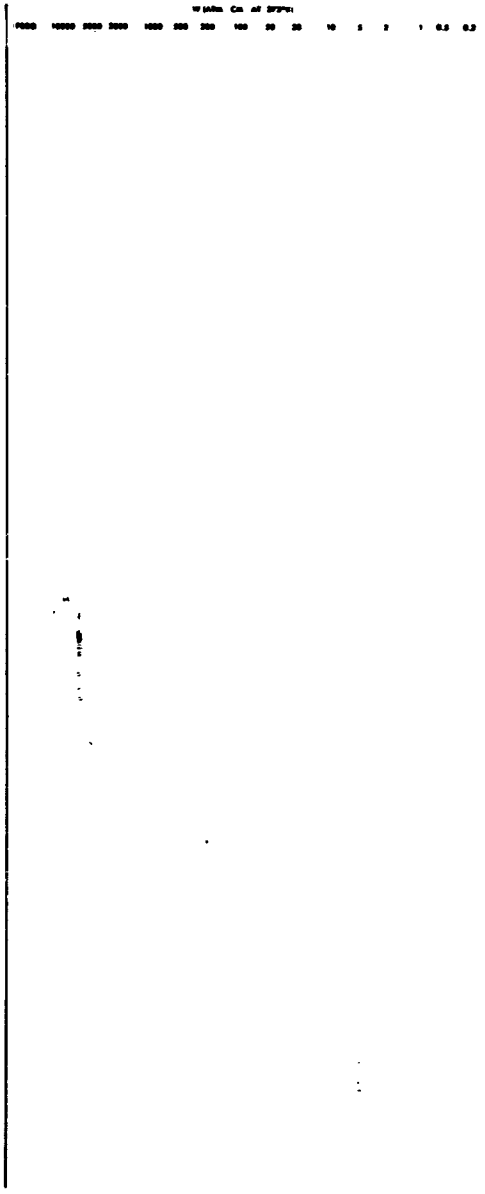
T=200° K



CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE
T=200° K







CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T=200° K

CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T-200° K

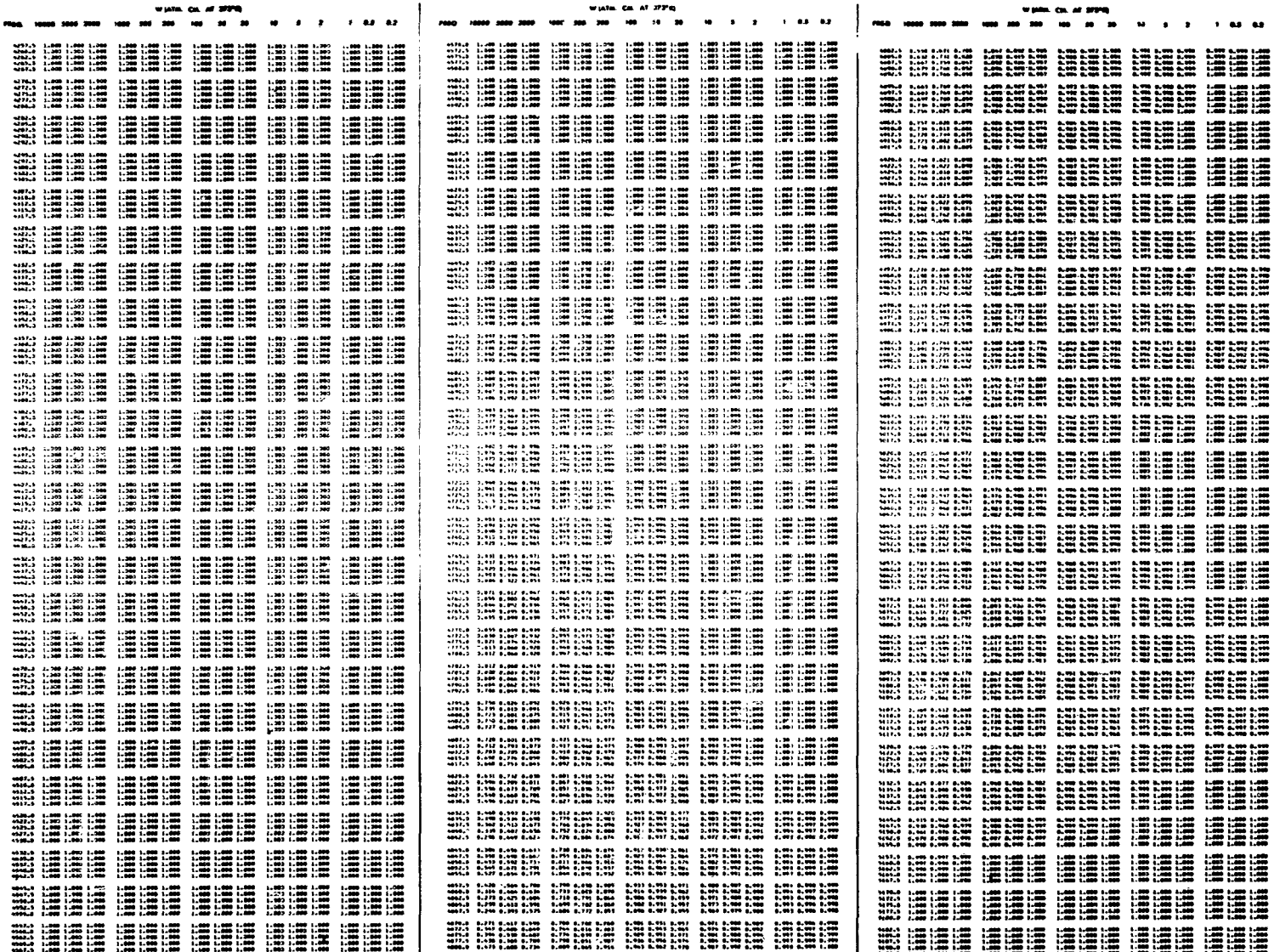
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T=200° K

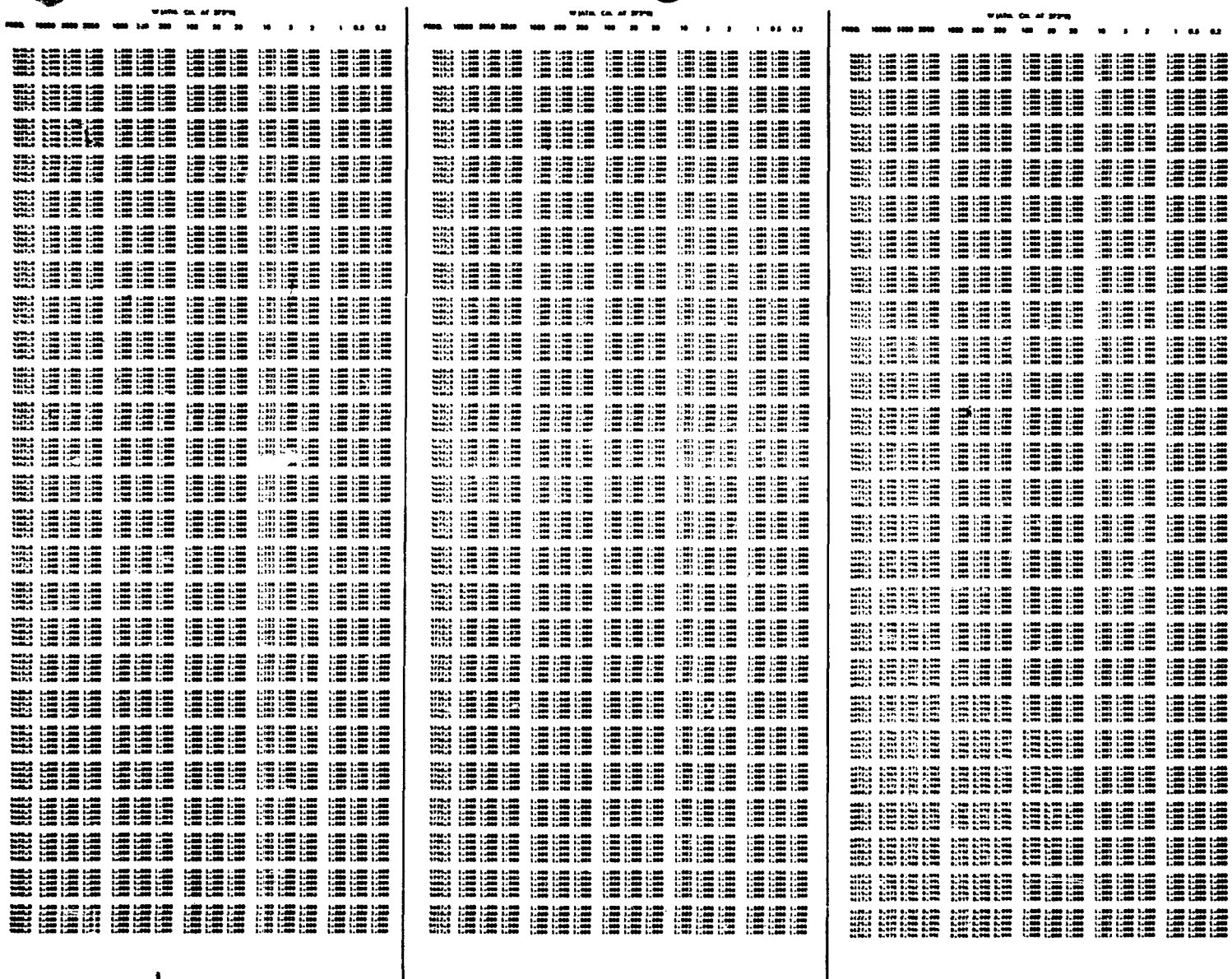
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T-200° K

CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

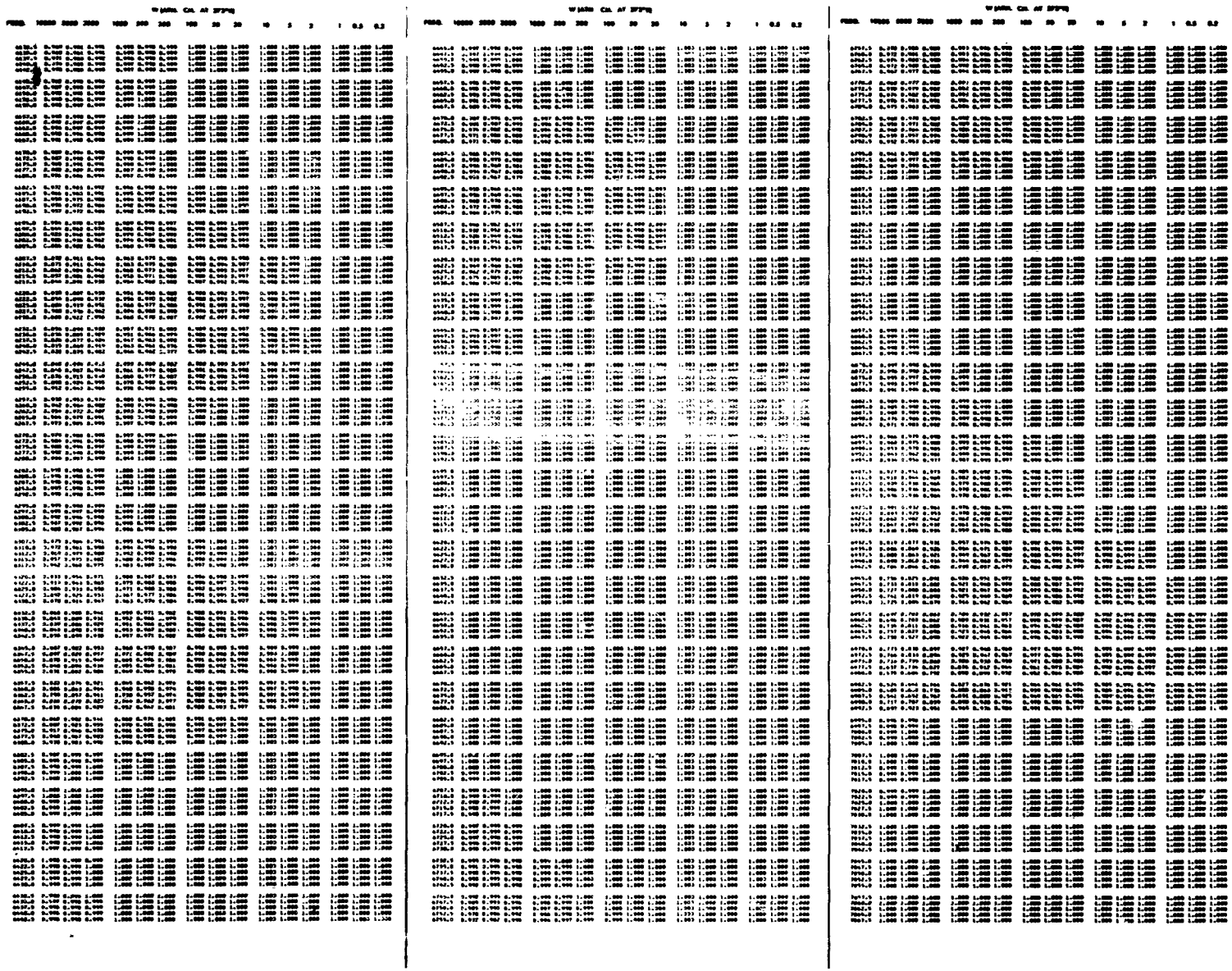
T=200° K



CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T=200° K



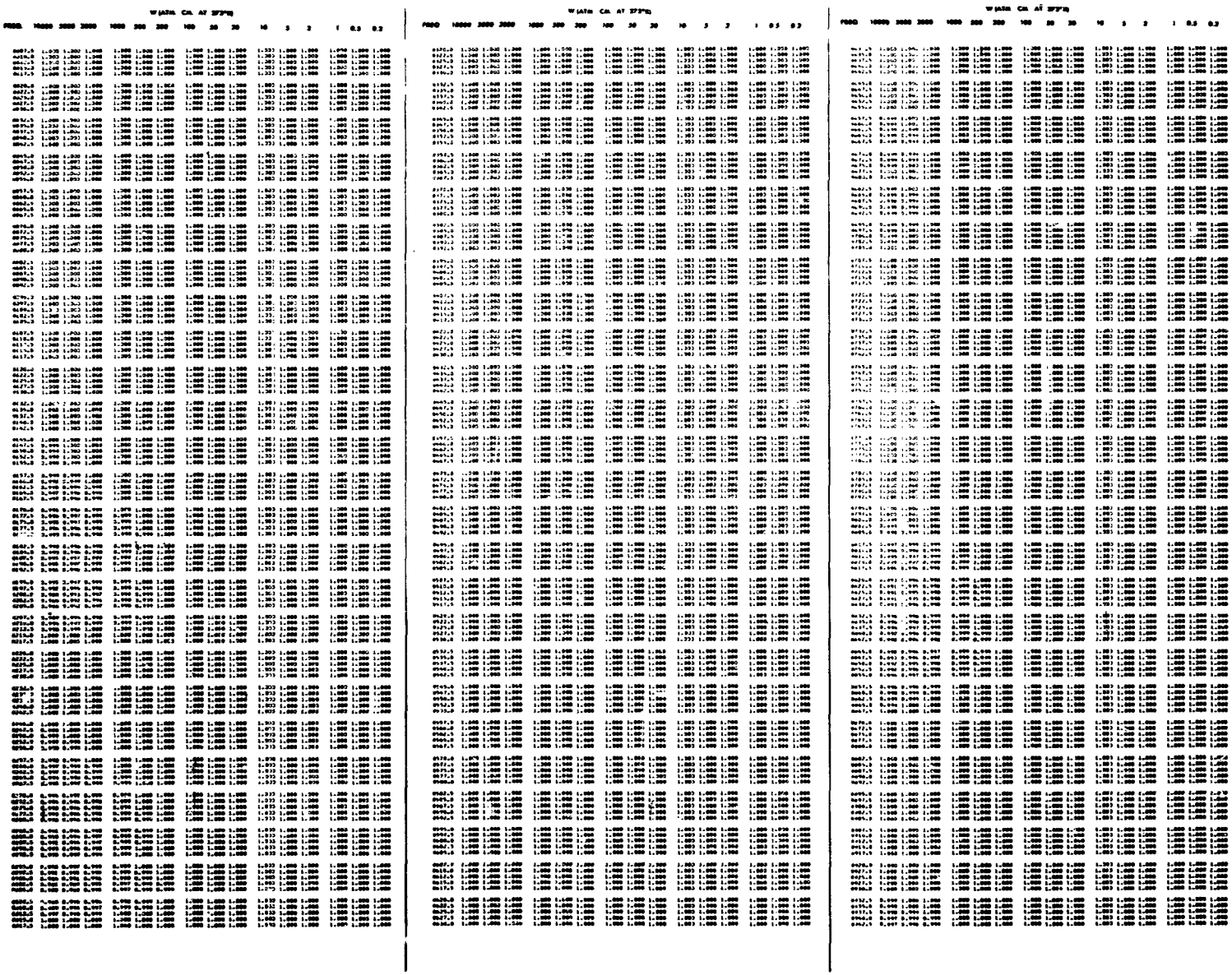
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T=200° K



CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T-200°K

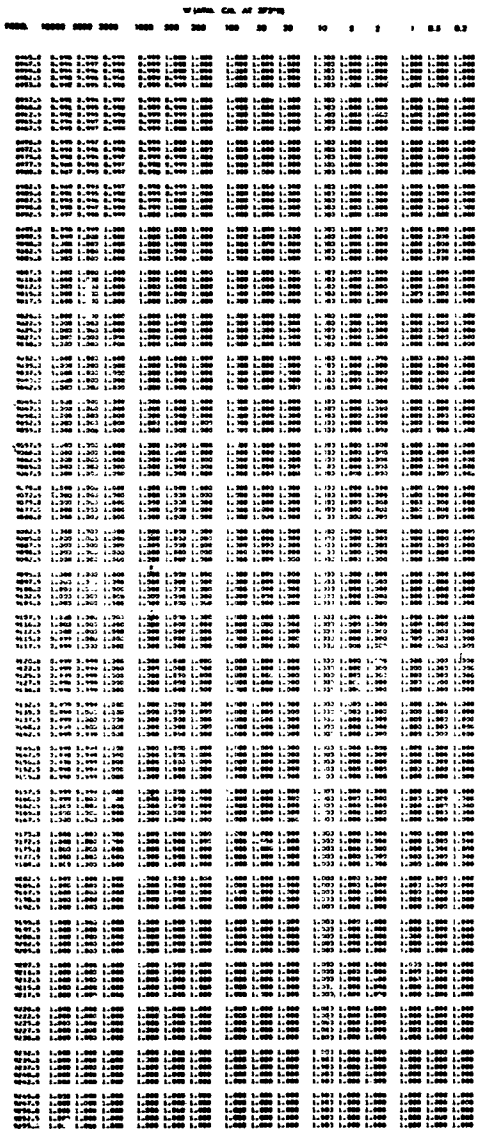
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

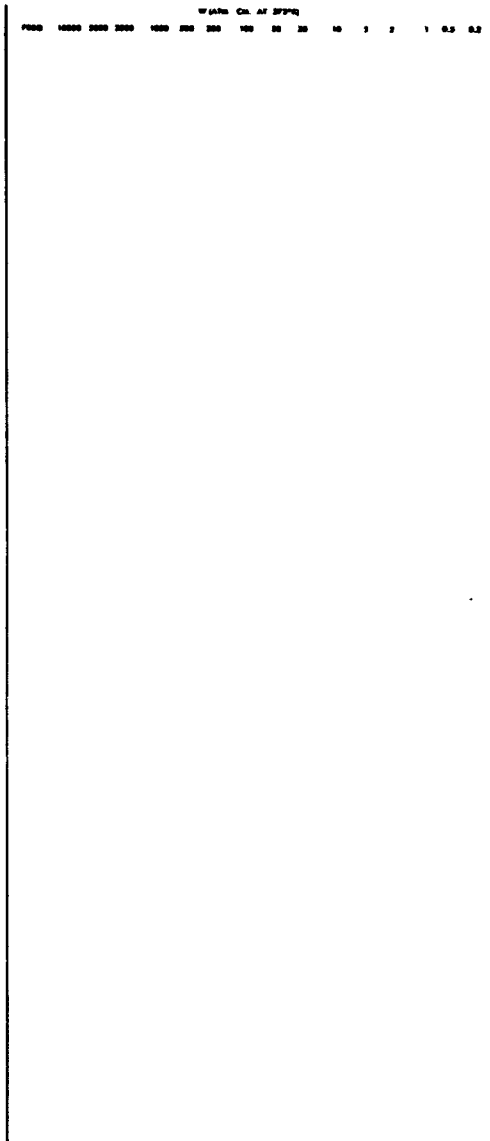
T=200° K



CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

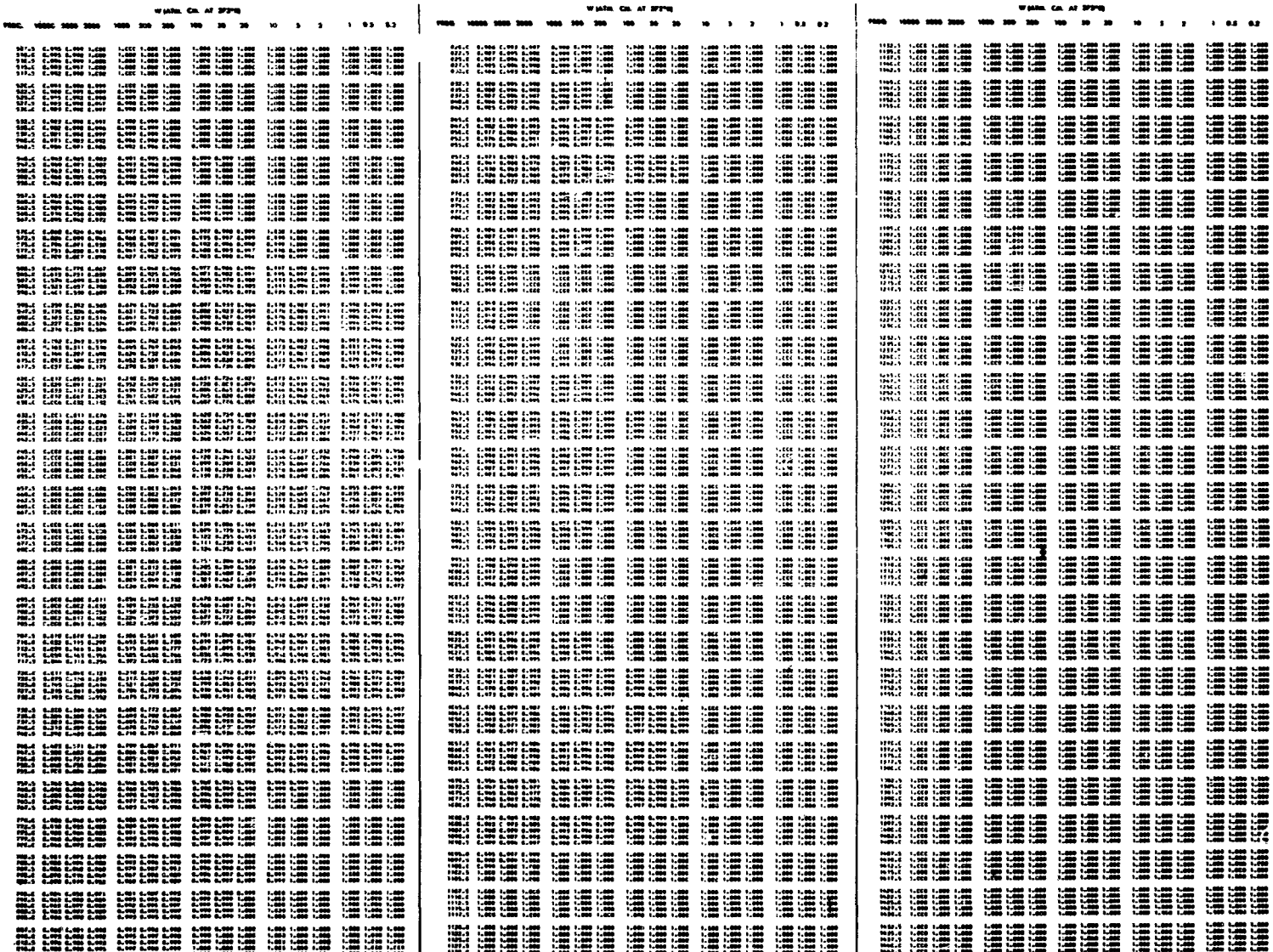
T=200° K





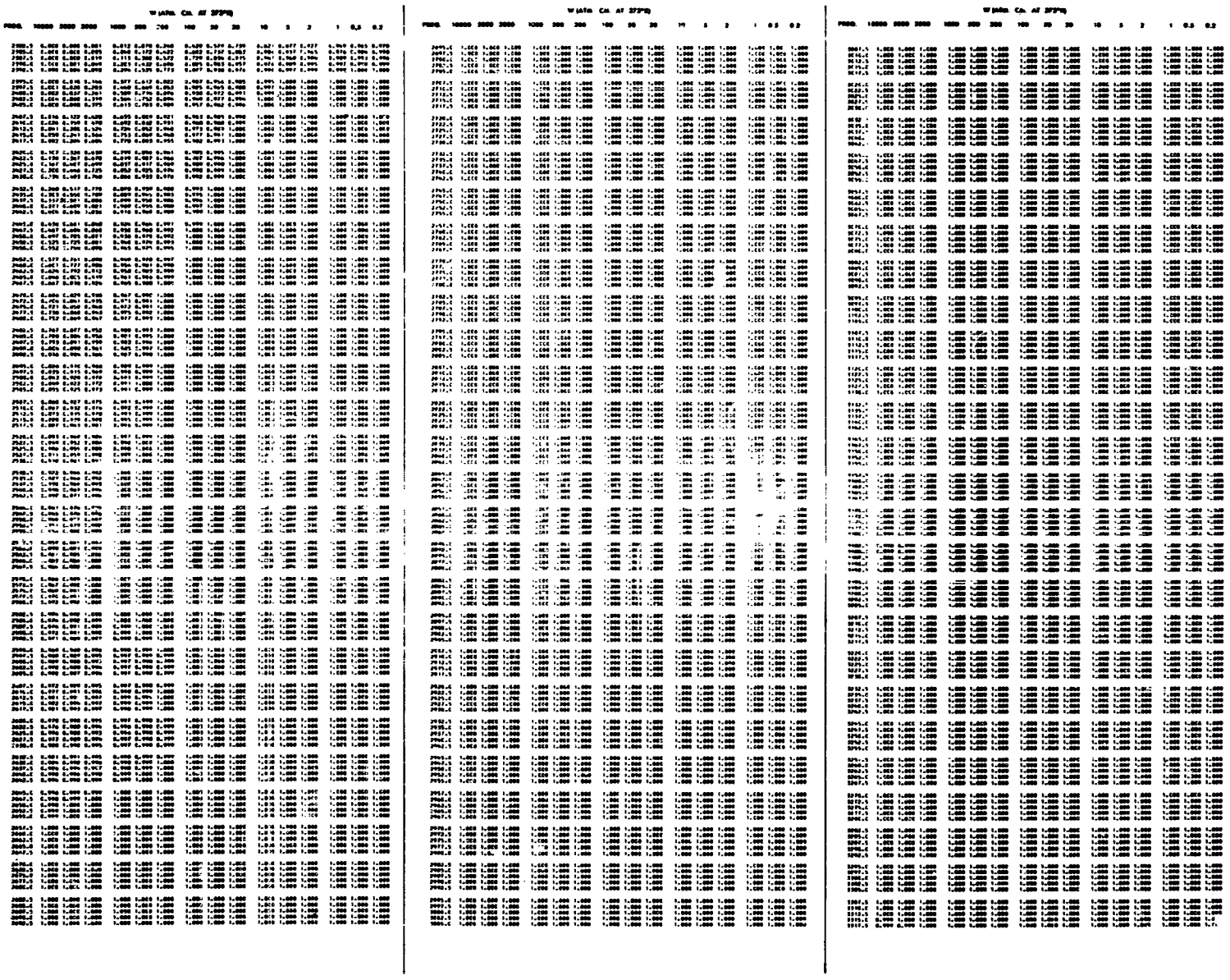
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T=200° K



CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE
T-200° K

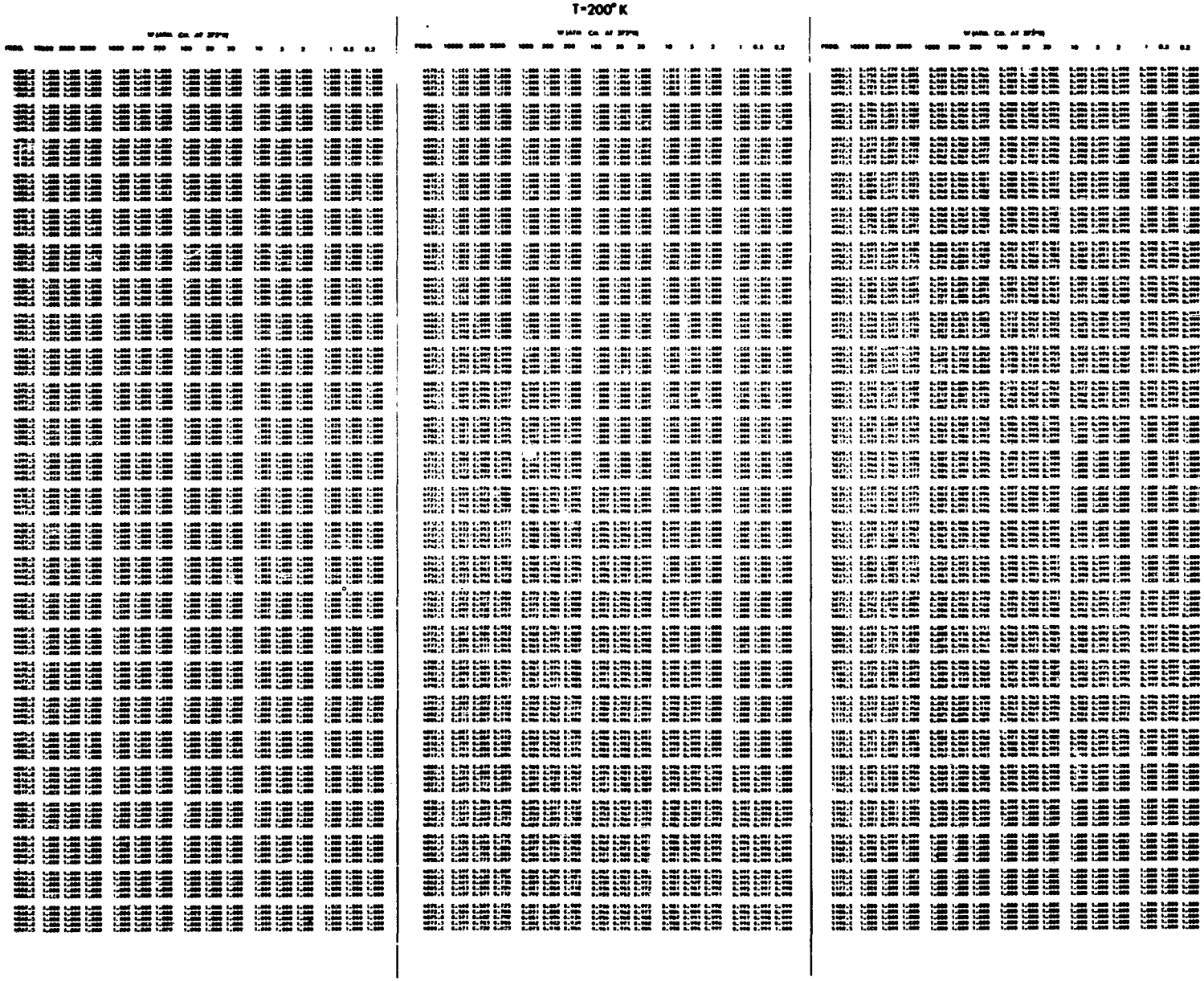
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE
T=200° K



CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

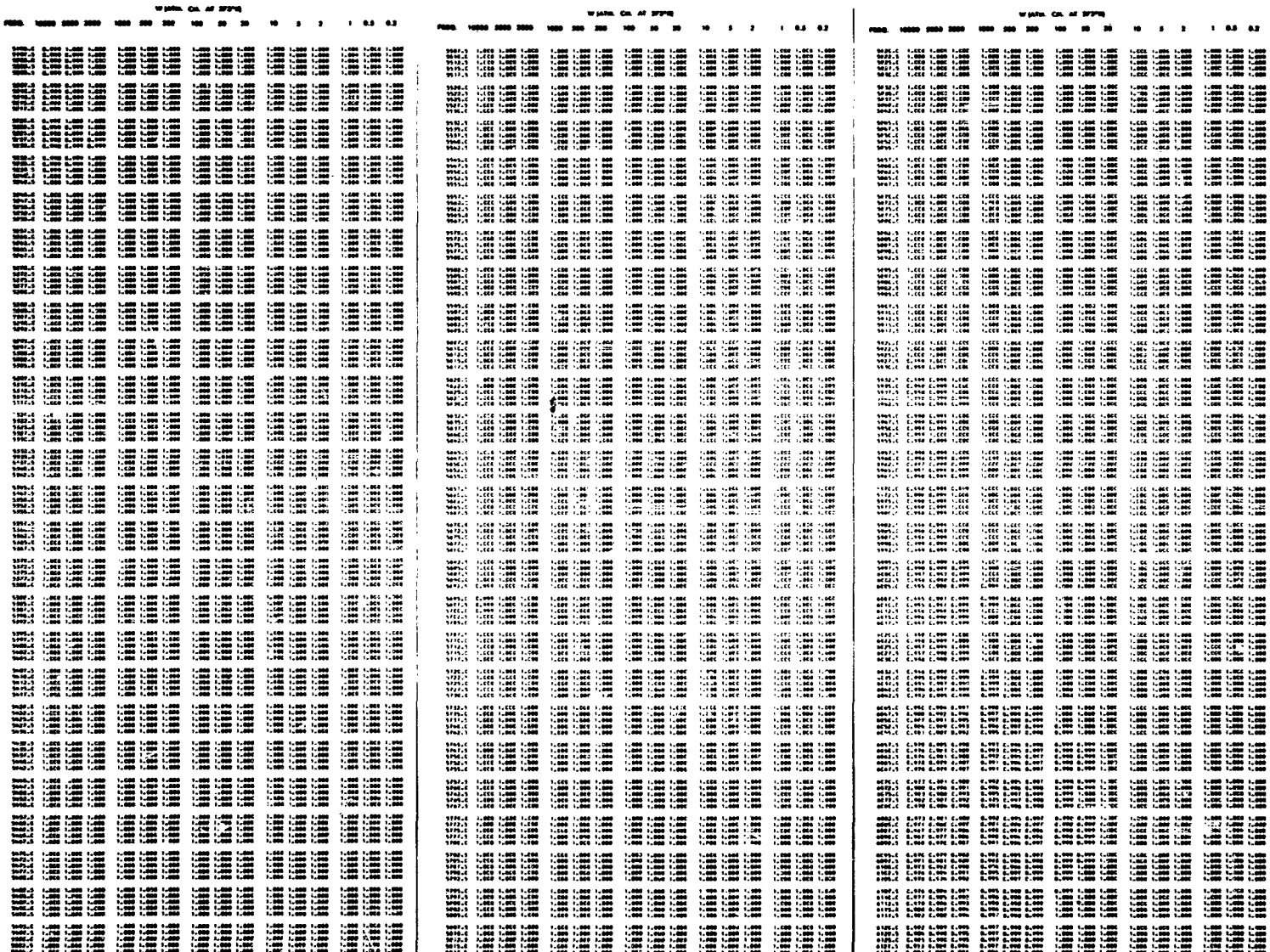
T=200° K

CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE
T=200°K

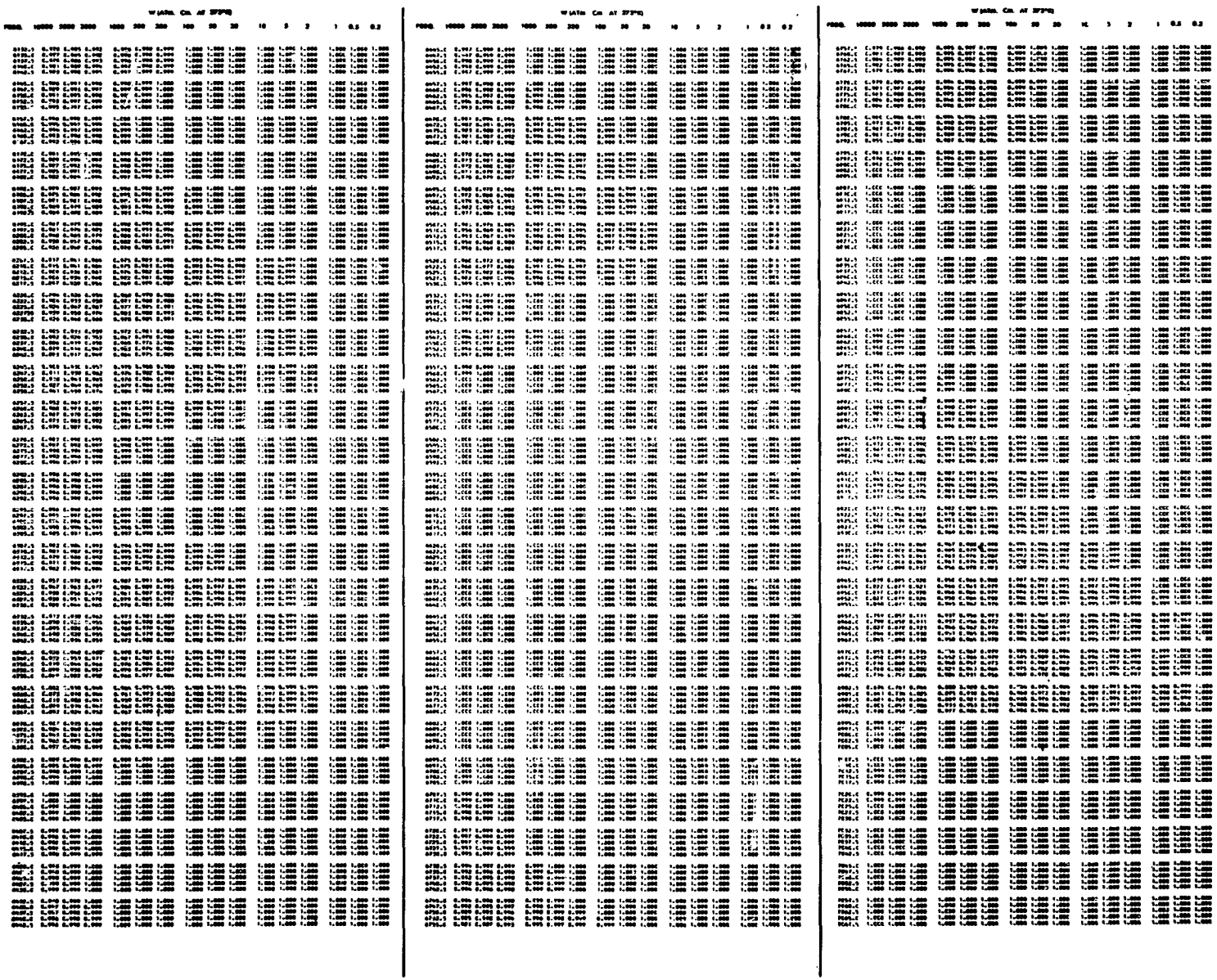


CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T=200° K



CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE
T=200° K



CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T-200° K

CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T-200° K

CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE
T-200° K

CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE
T=200°K

CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE
T-200° K

CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T=200° K

CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE
T-200°K

CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T-200° K

CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

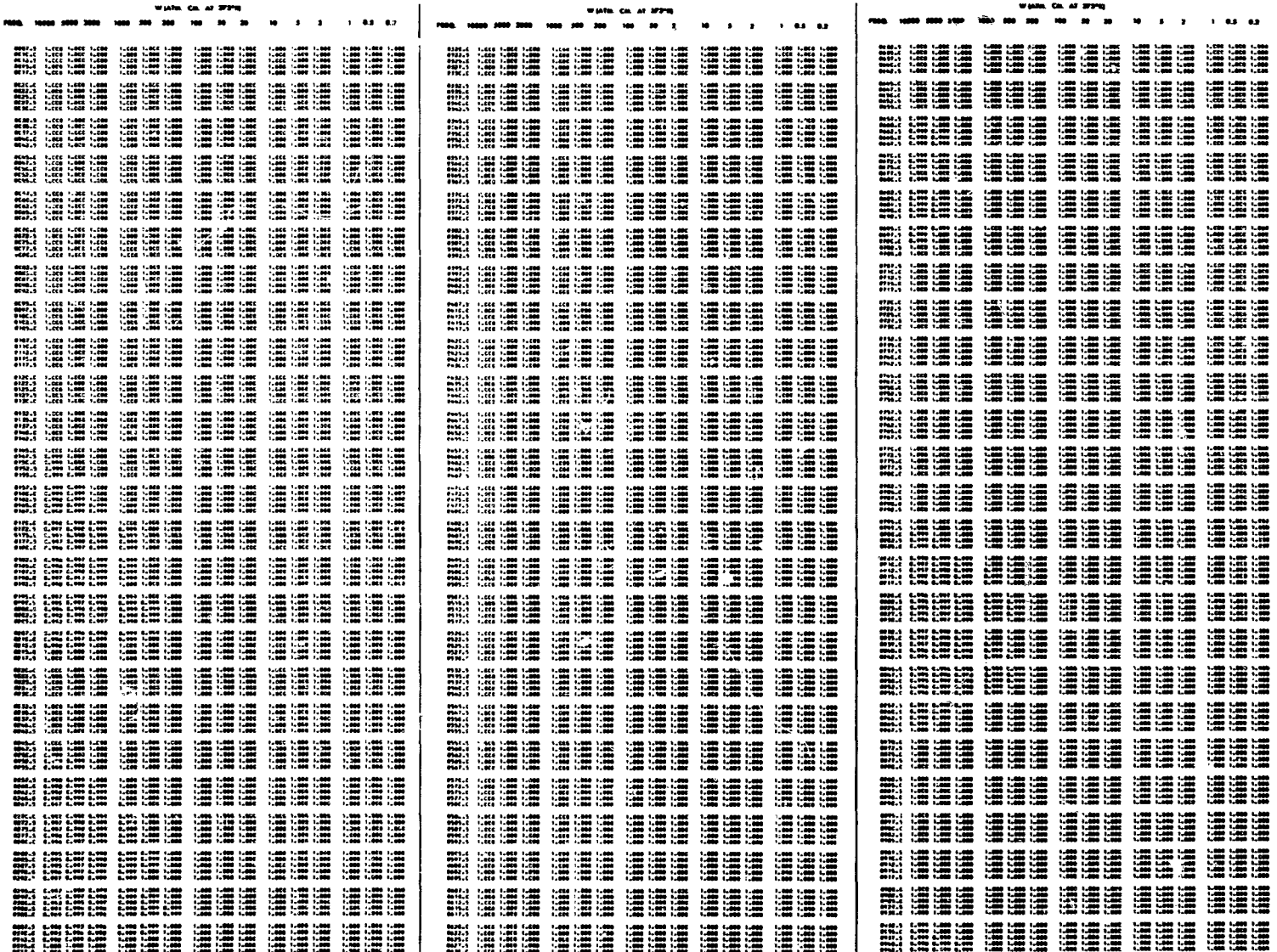
T-200° K

CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T-200° K

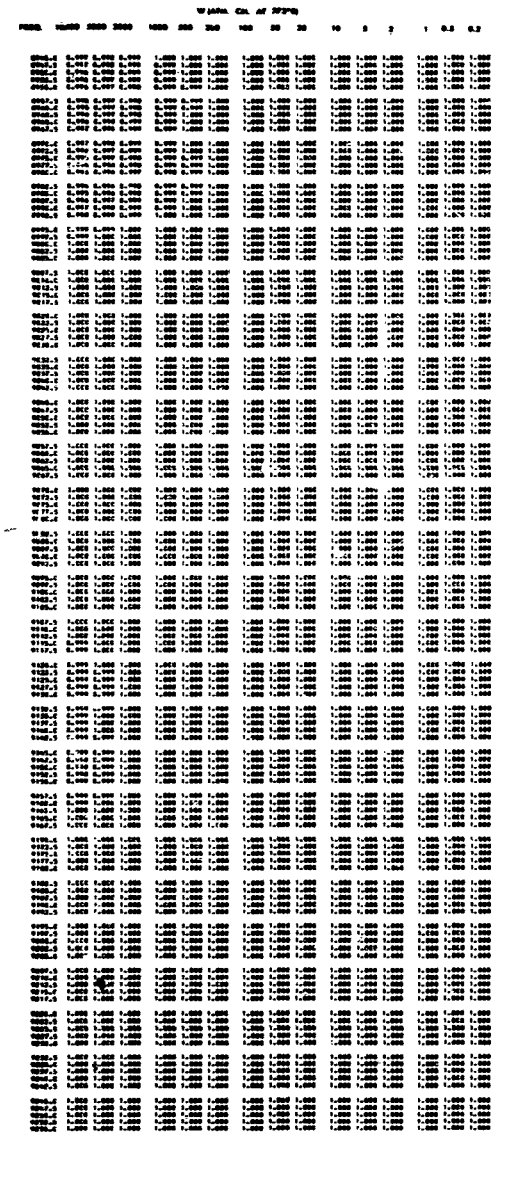
CARBON DIOXIDE AT 0.01 ATM[illegible]ERE PRESSURE
T-200° K

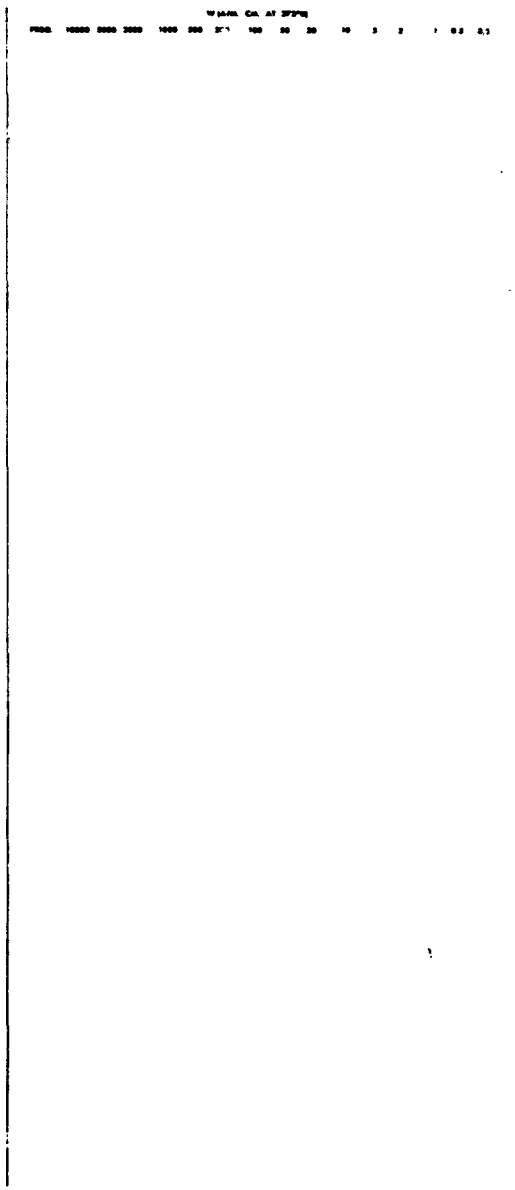
CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE
T=200° K

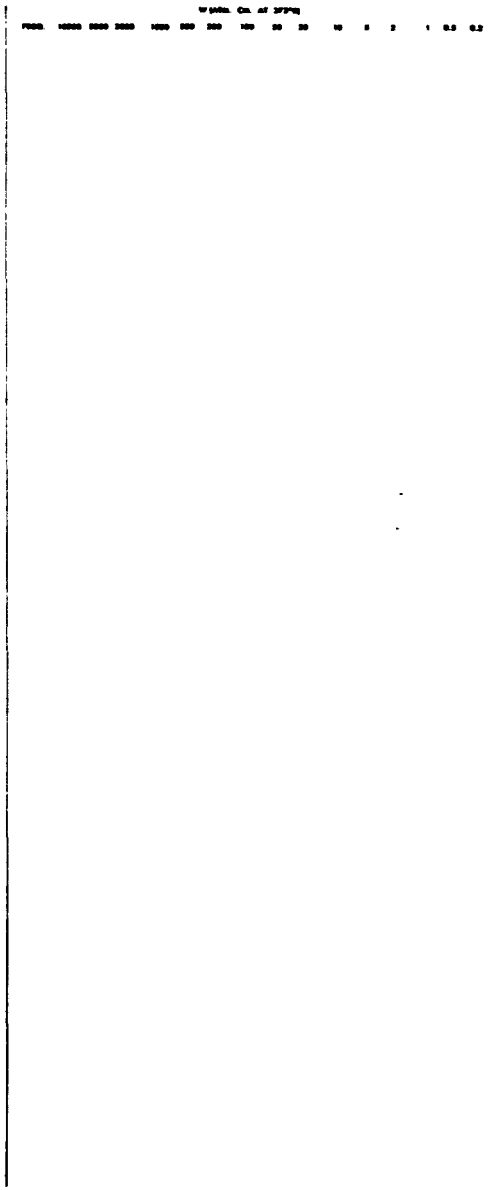


CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T=200° K







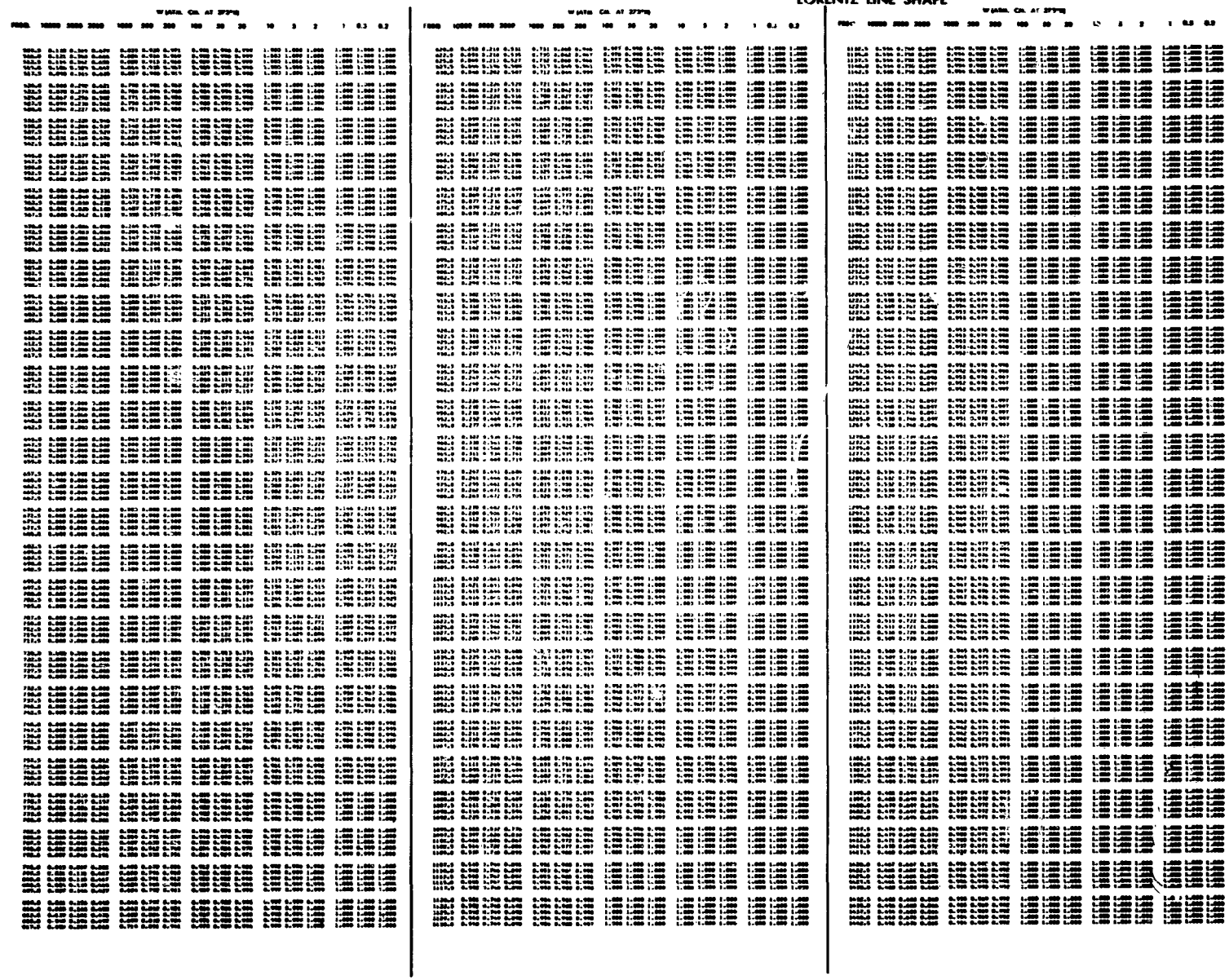
APPENDIX D

CARBON DIOXIDE TRANSMISSIONS BASED ON THE LORENTZ LINE SHAPE AT 1.0 ATMOSPHERE PRESSURE

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 300°K

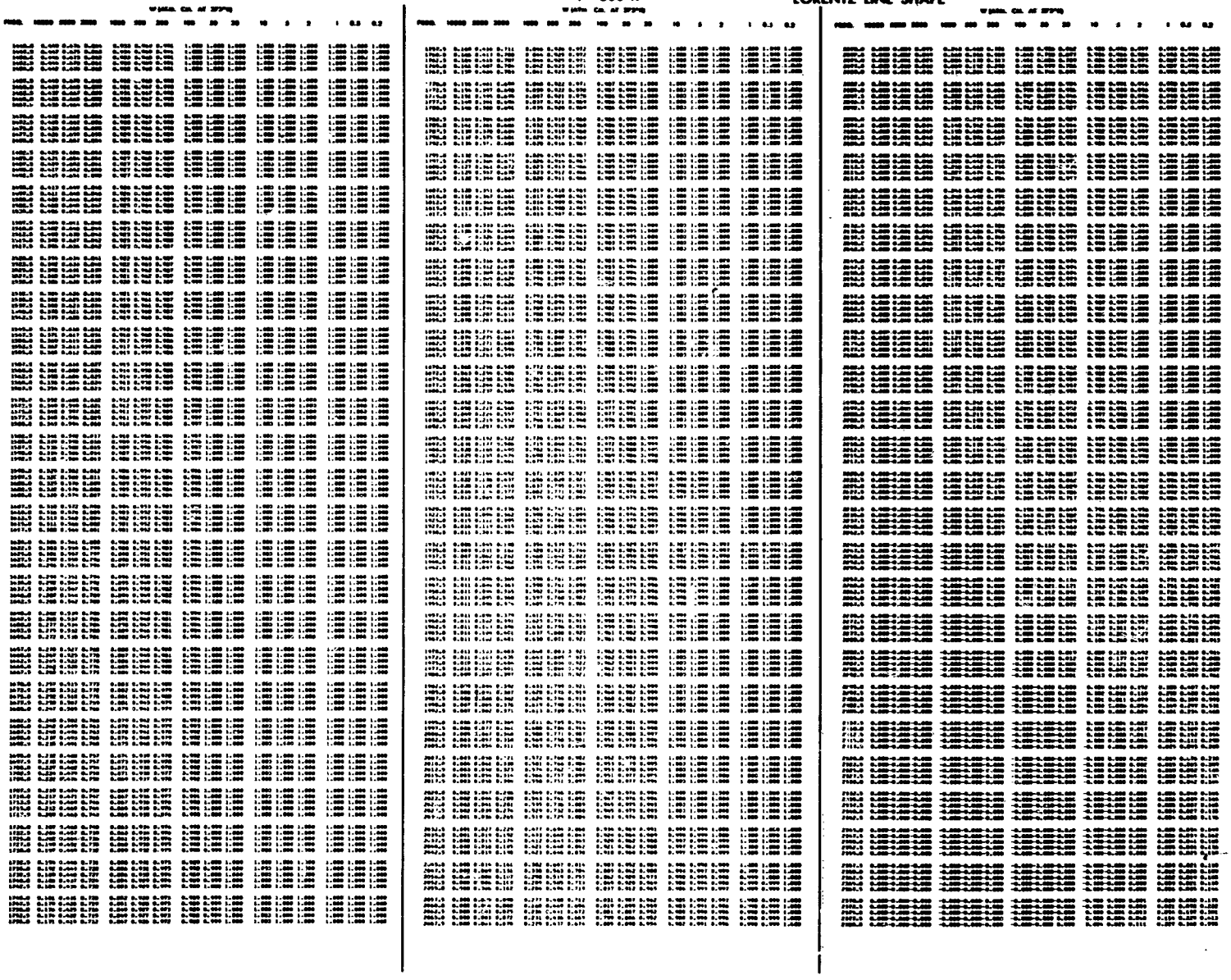
LORENTZ LINE SHAPE



CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 300°K

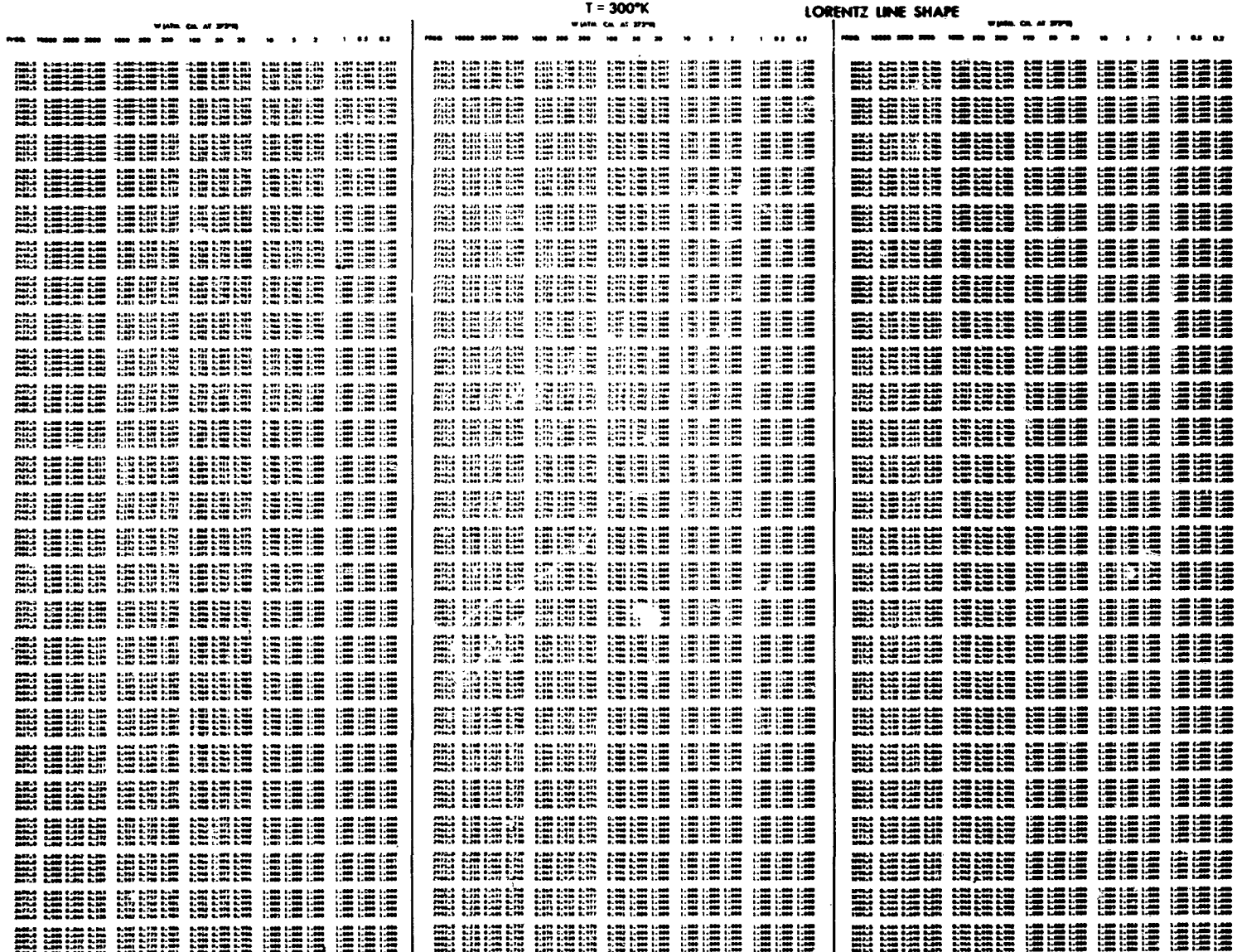
LORENTZ LINE SHAPE



CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 300°K

LORENTZ LINE SHAPE



CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 300°K

LORENTZ LINE SHAPE

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 300°K

LORENTZ LINE SHAPE

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 309°K

LORENTZ LINE SHAPE

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

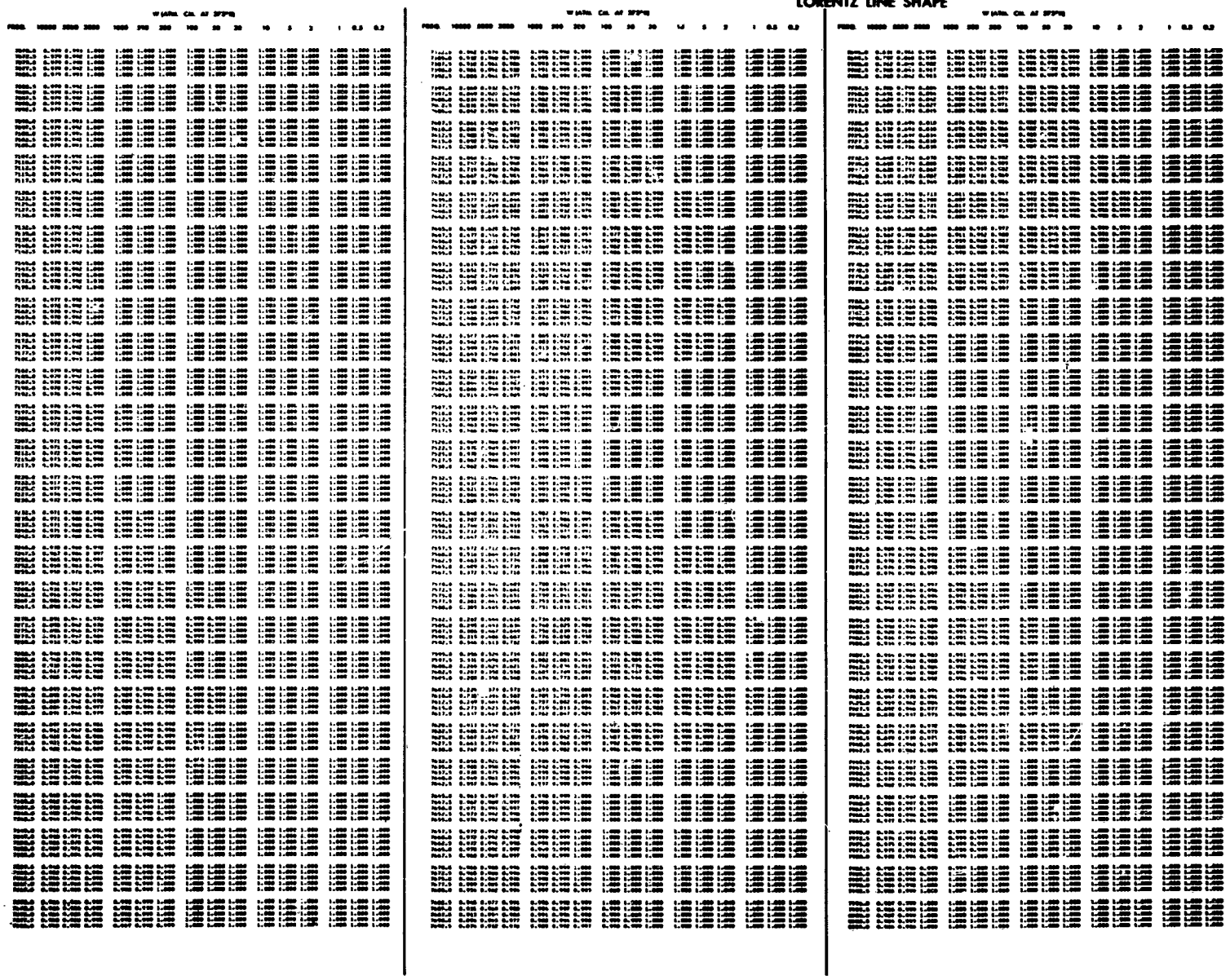
T = 300°K

LORENTZ LINE SHAPE

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 300°K

LORENTZ LINE SHAPE

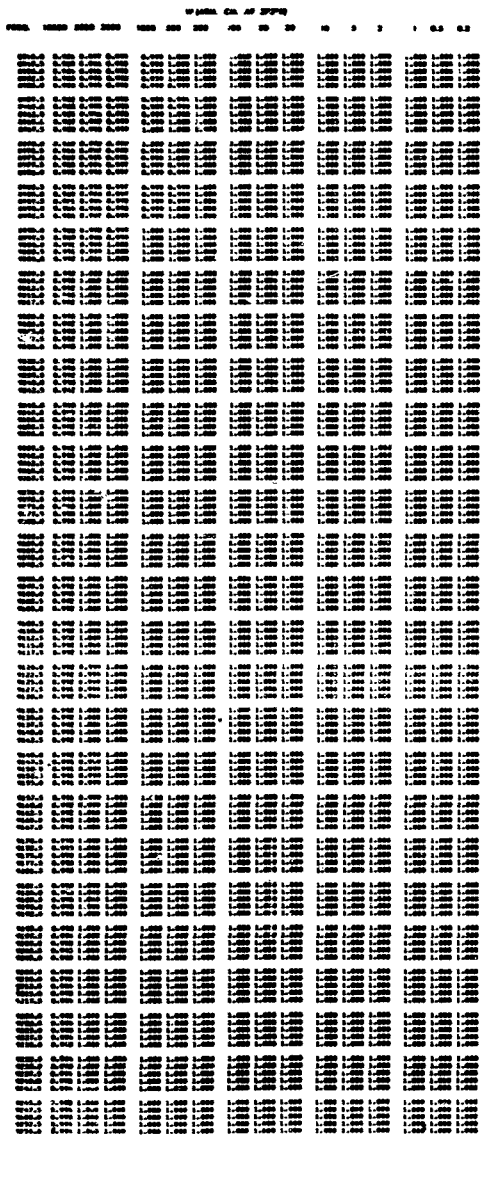


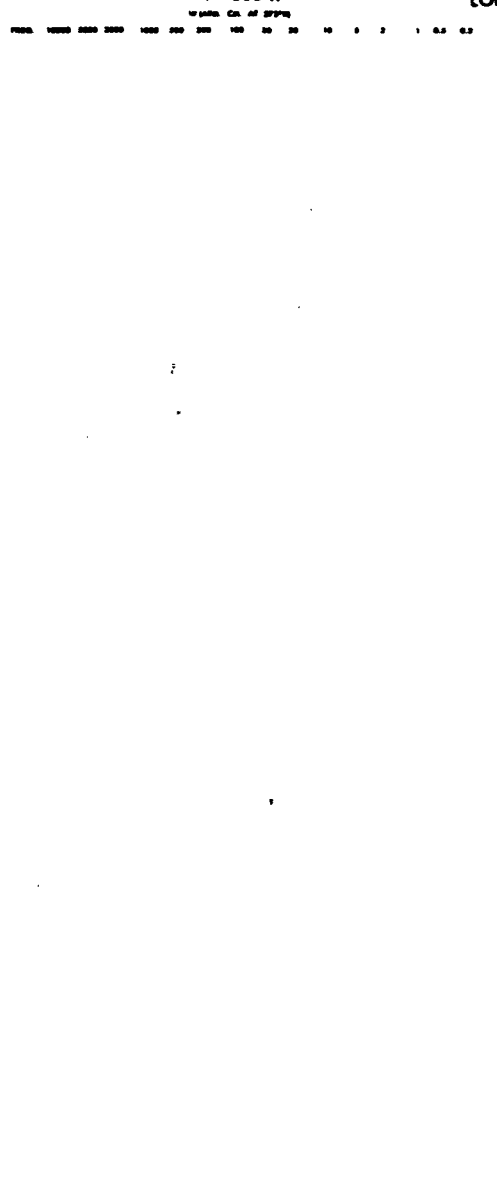
CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE
T = 300°K
LORENTZ LINE SHAPE

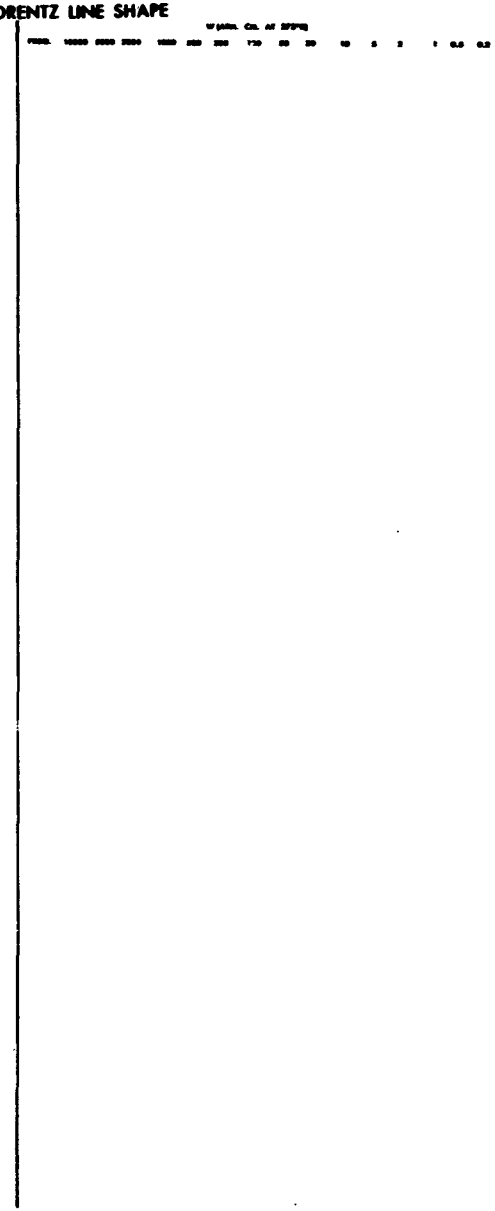
CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T = 300°K

LORENTZ LINE SHAPE







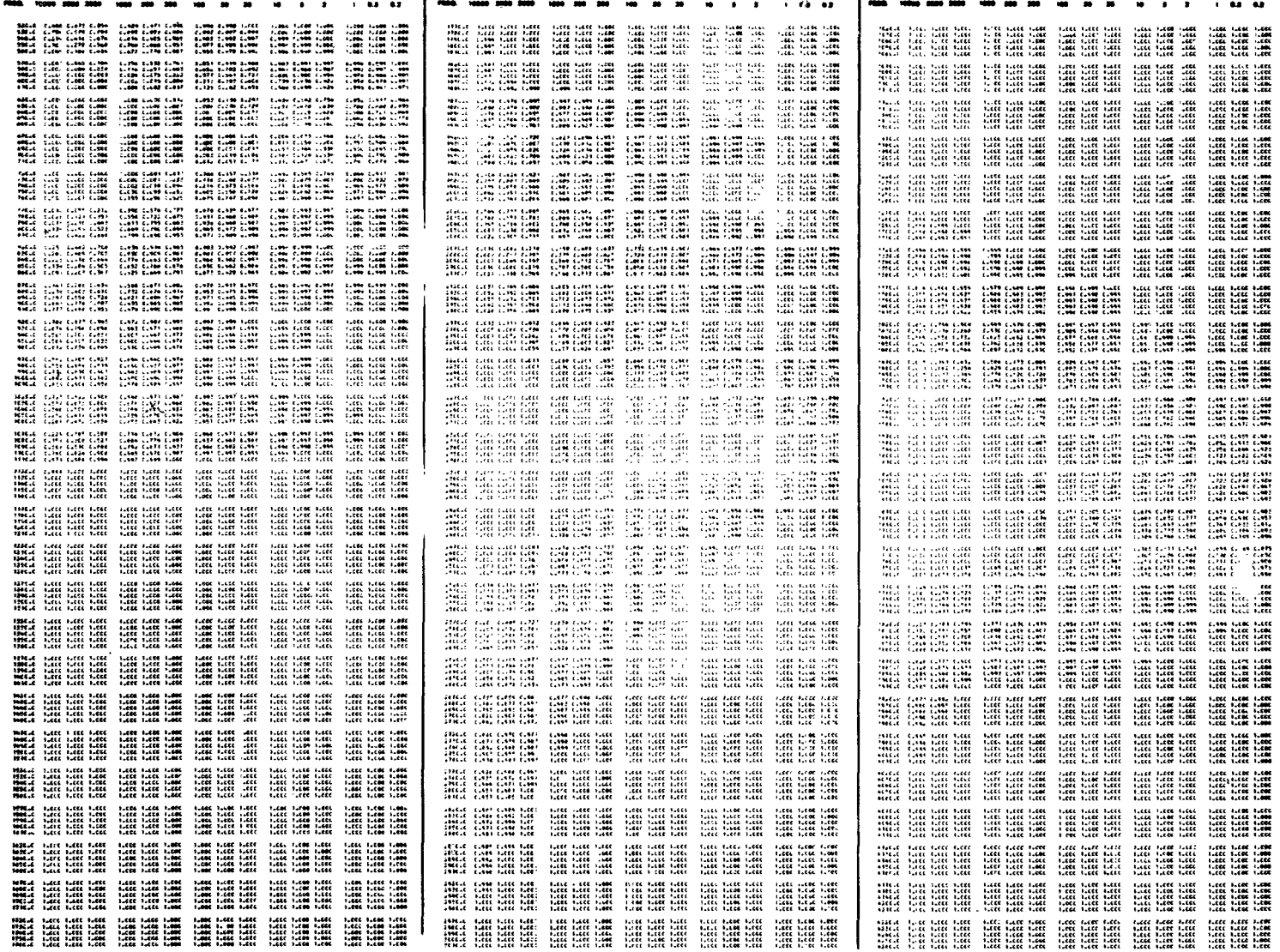
APPENDIX E

CARBON DIOXIDE TRANSMISSIONS AVERAGED OVER 20 cm^{-1} WITH ENTRIES EVERY 10 cm^{-1}

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=300° K

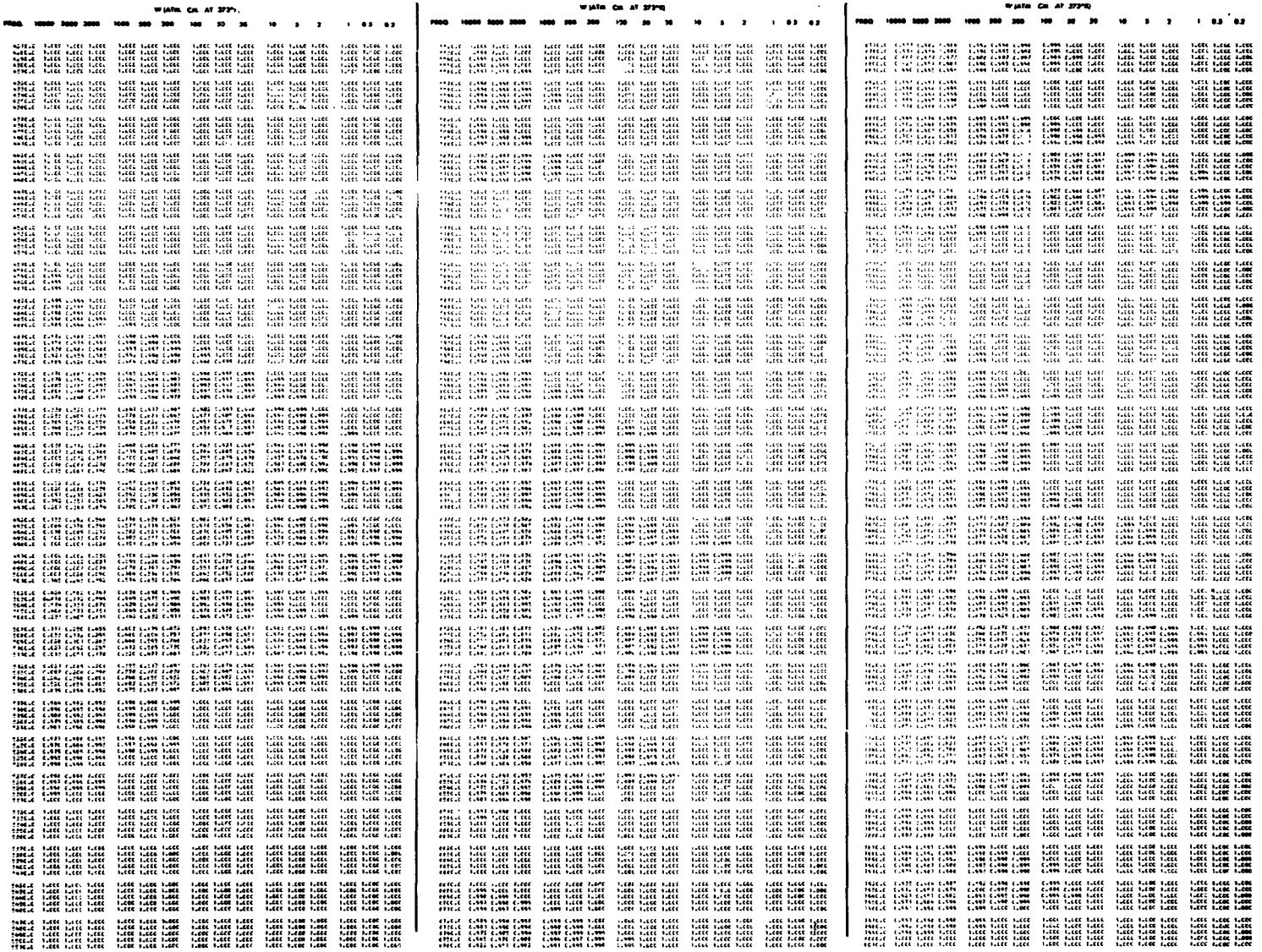
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=300° K

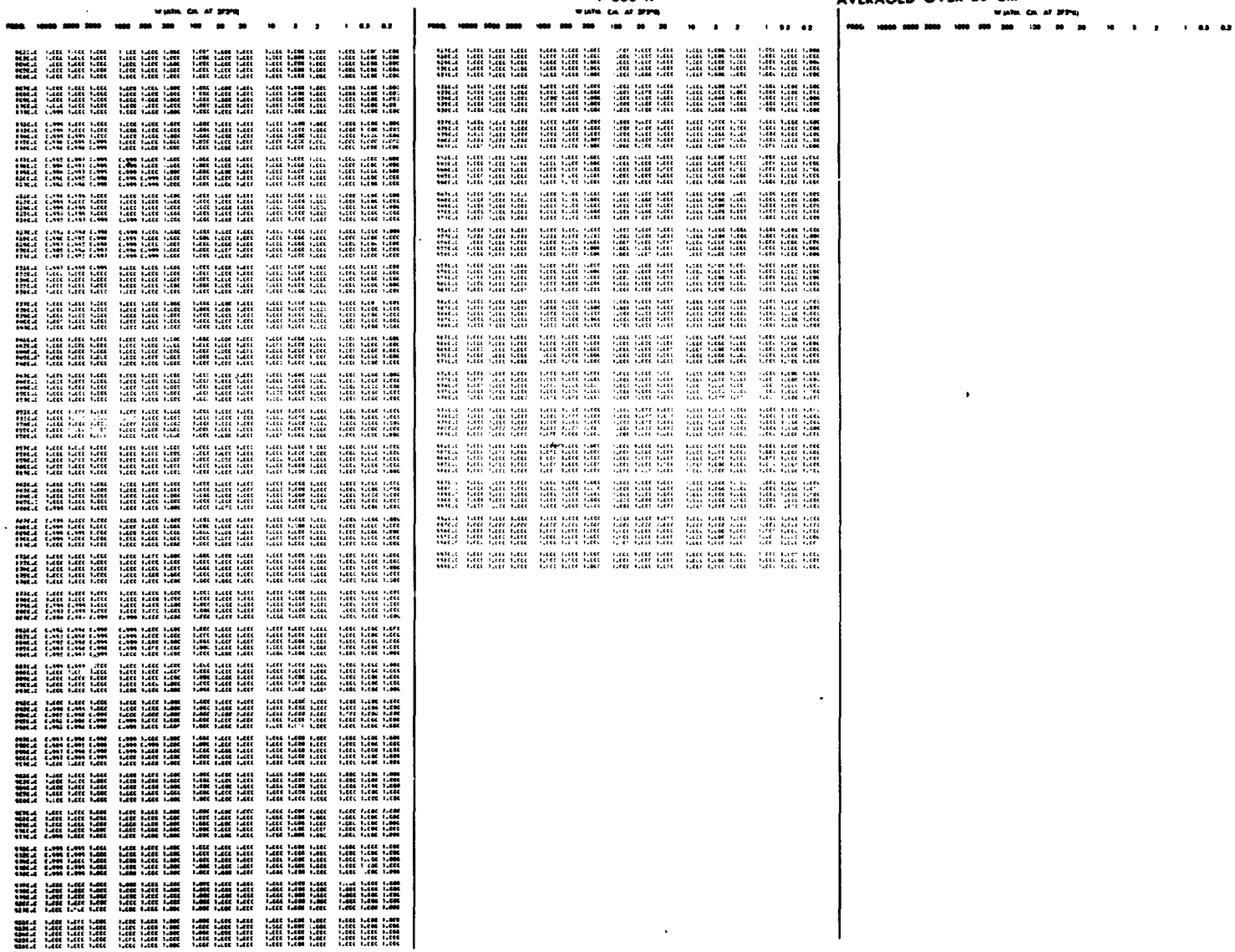
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=300° K

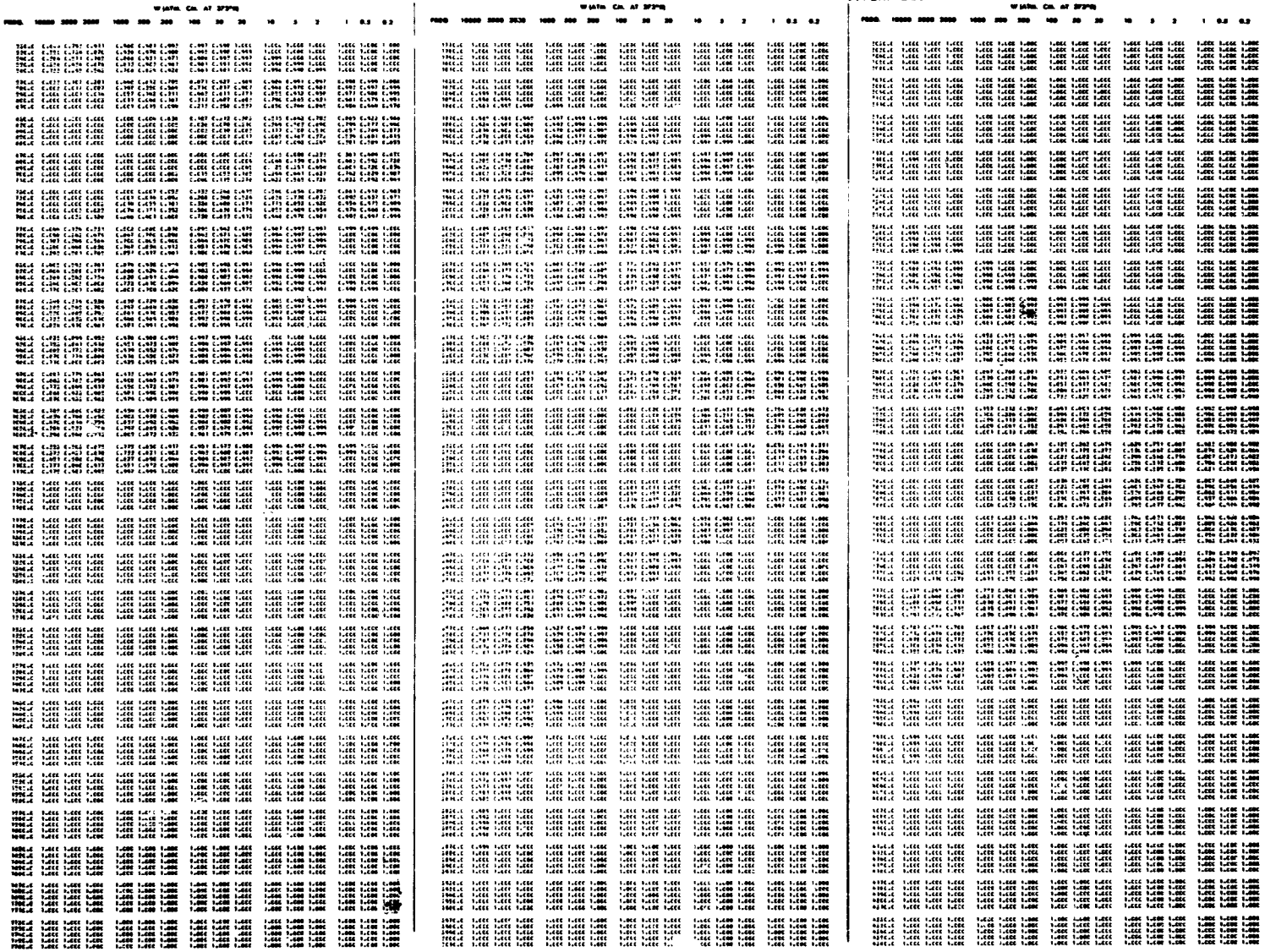
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=300° K

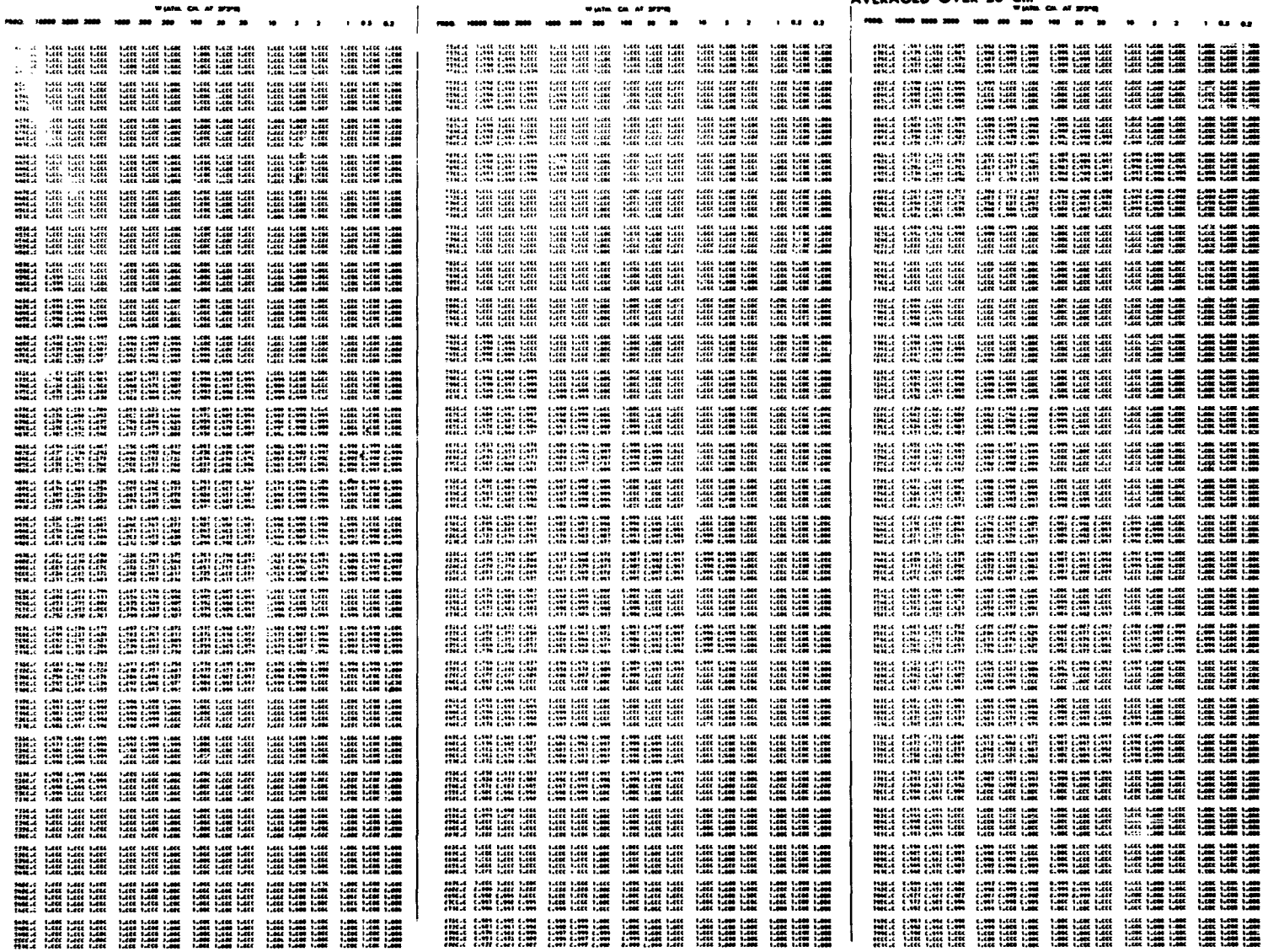
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=300° K

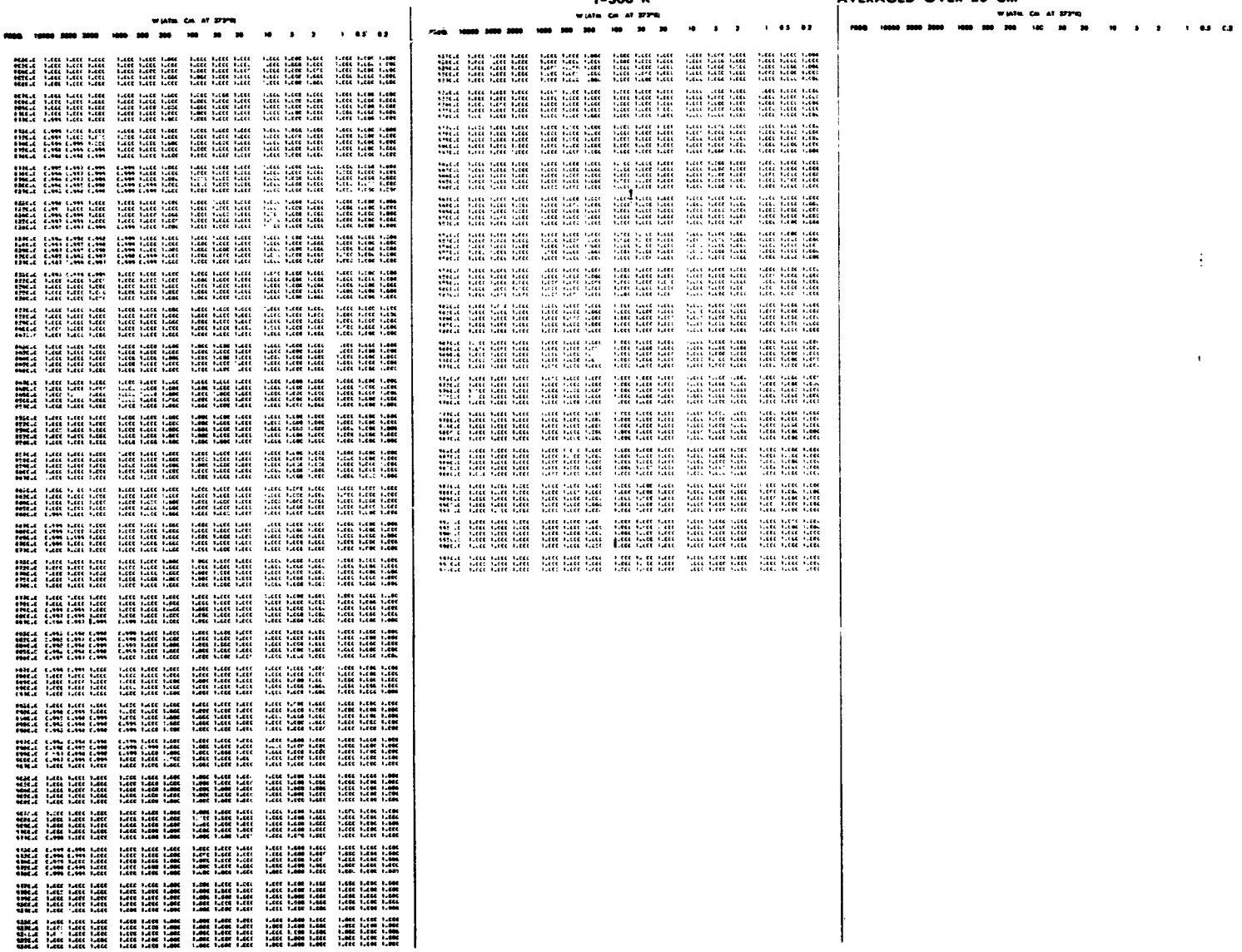
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=300° K

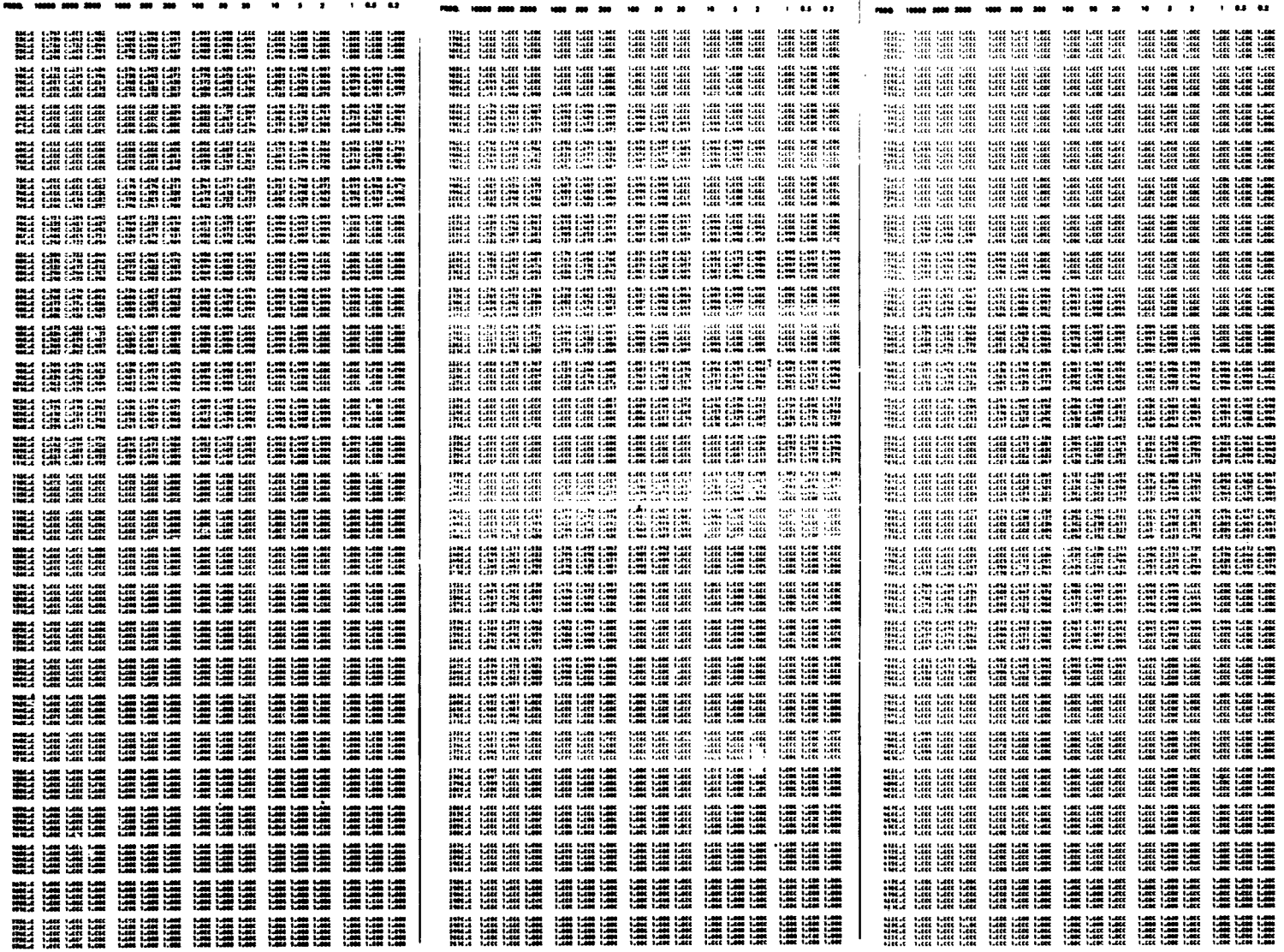
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=300° K

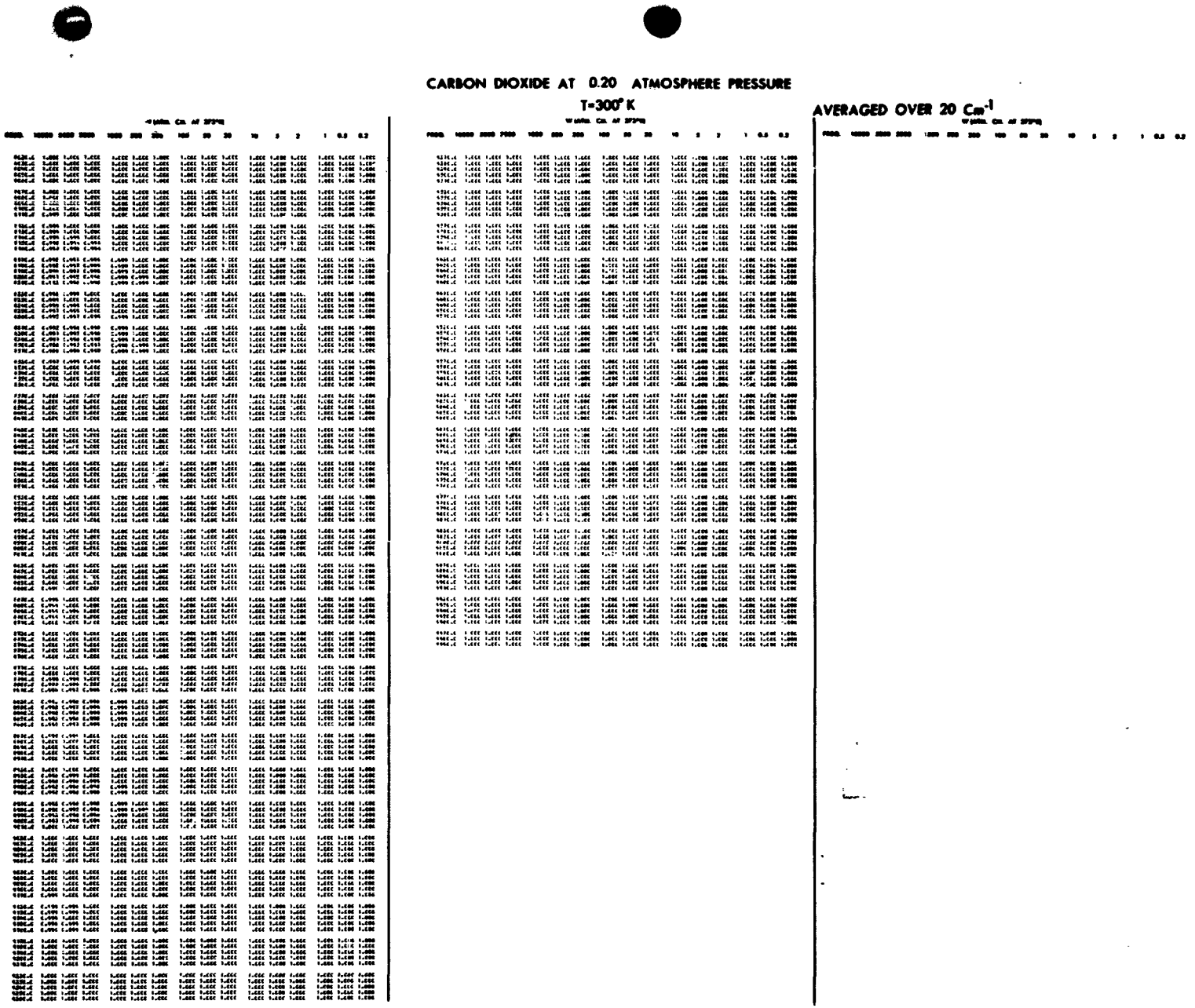
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=300° K

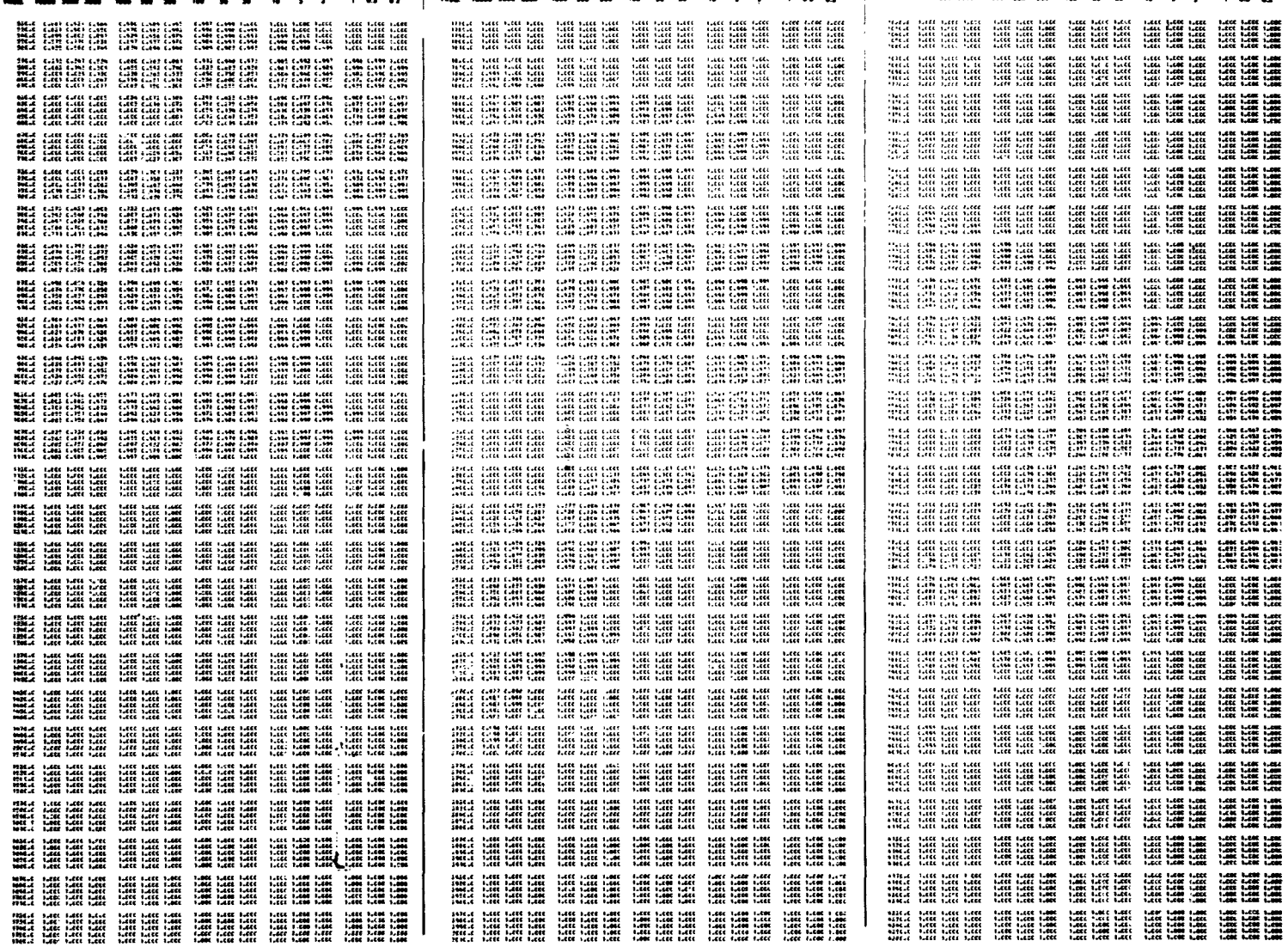
AVERAGED OVER 20 Cm^{-1}


CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE
T=300° K
AVERAGED OVER 20 Cm-1

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T=300° K

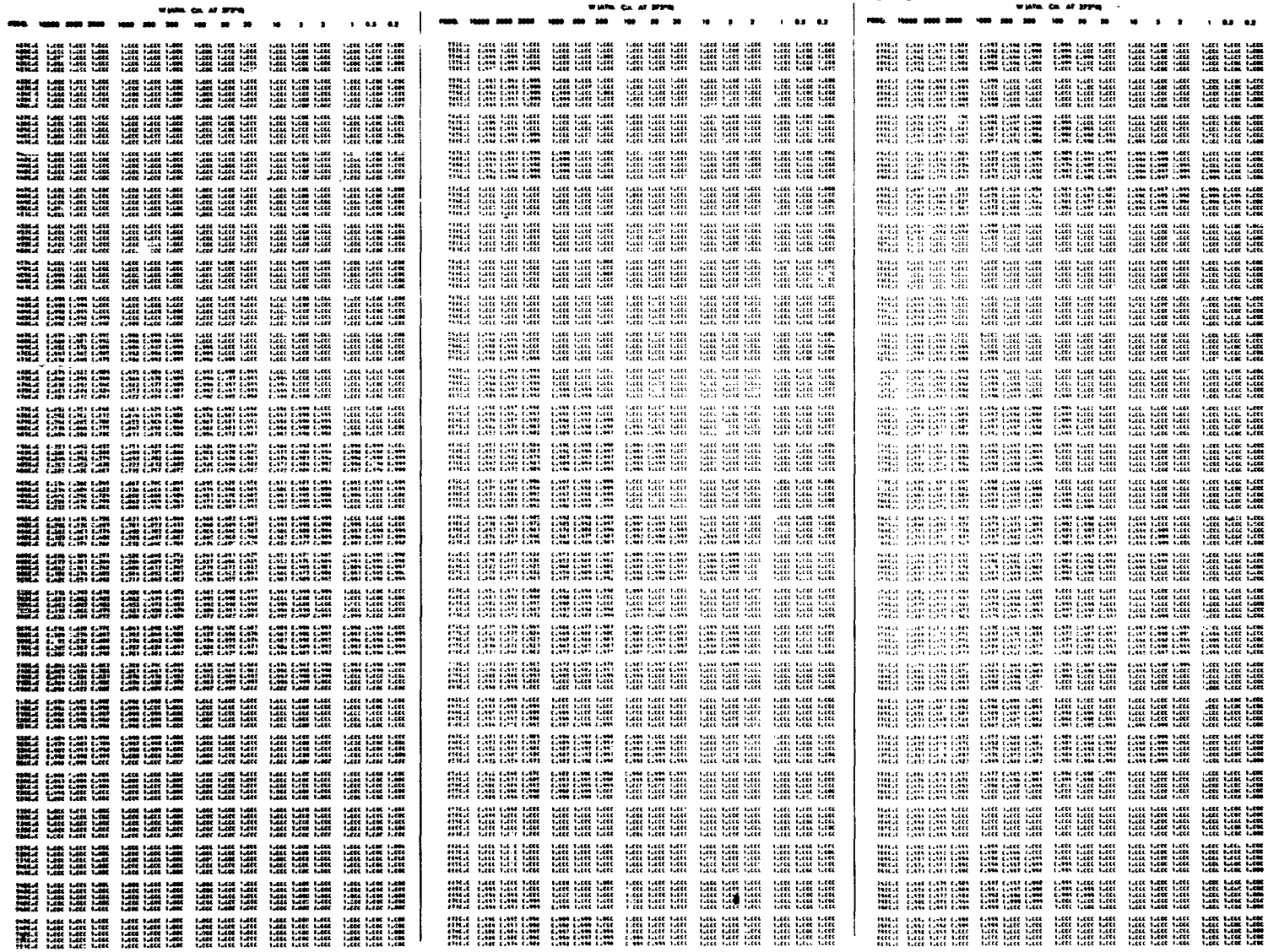
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T=300° K

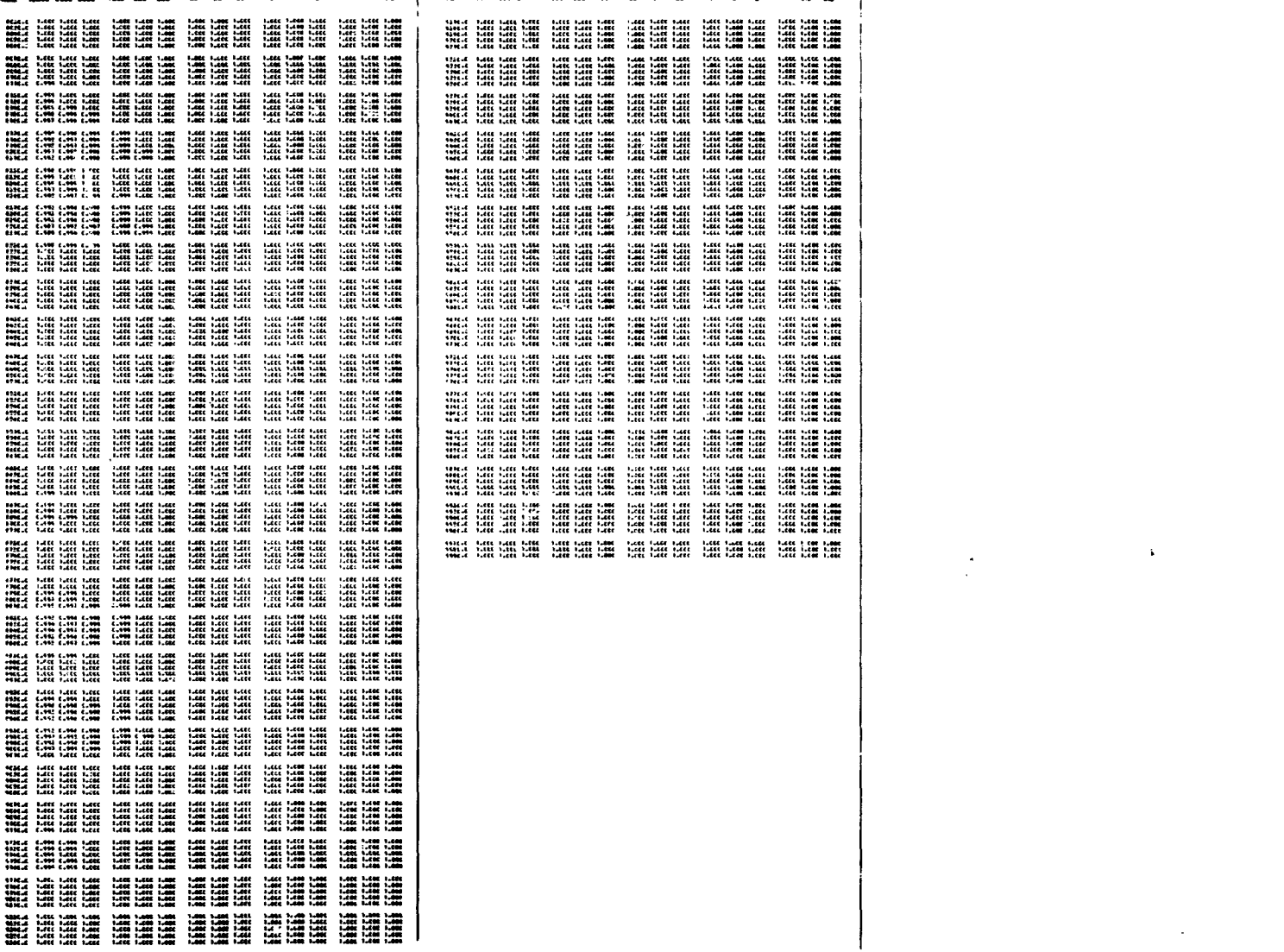
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T=300° K

AVERAGED OVER 20 Cm^{-1}

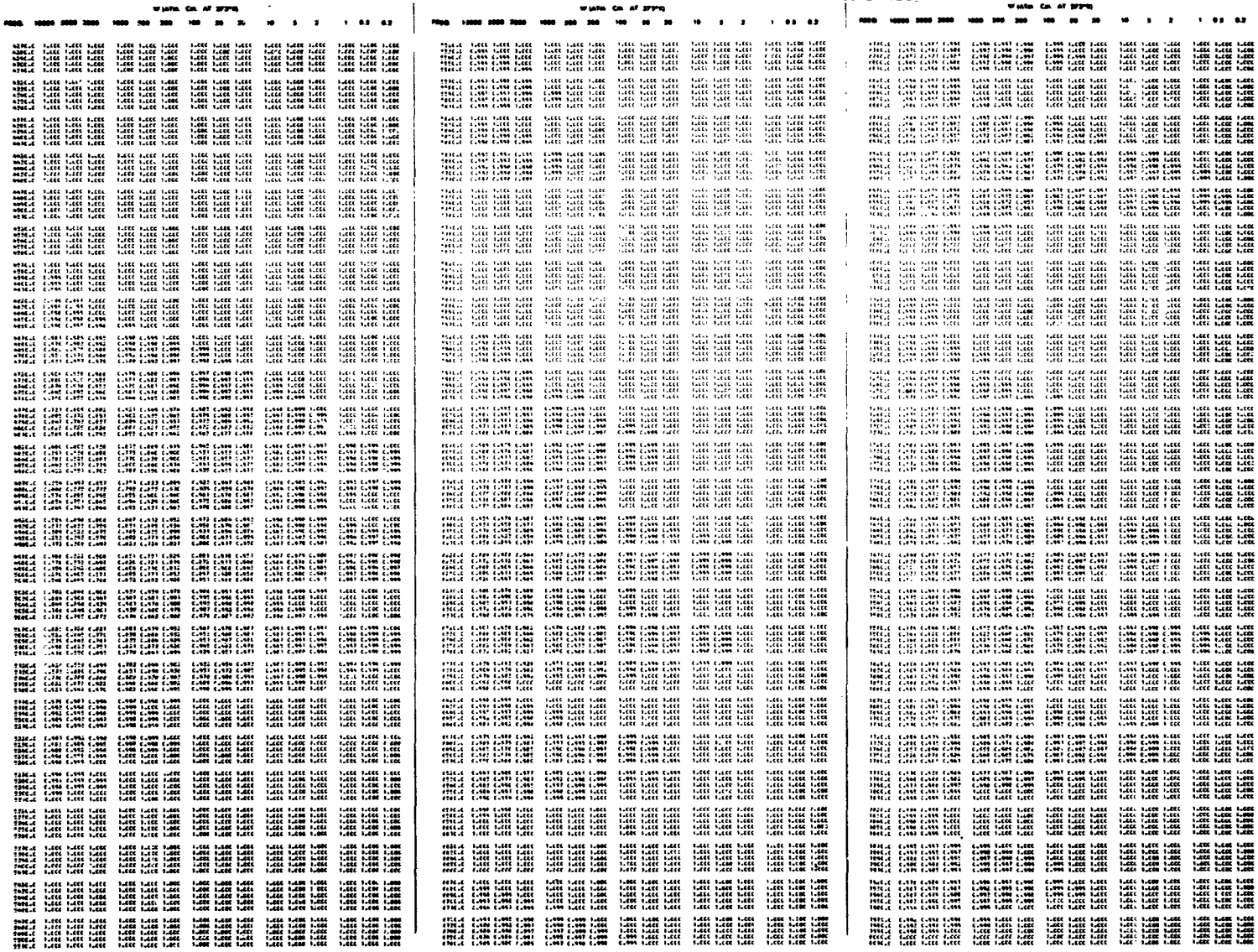


CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T=300° K
AVERAGED OVER 20 Cm⁻¹

CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T=300° K

AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T=300° K
AVERAGED OVER 20 Cm-1

CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T=300° K

AVERAGED OVER 20 Cm^{-1}

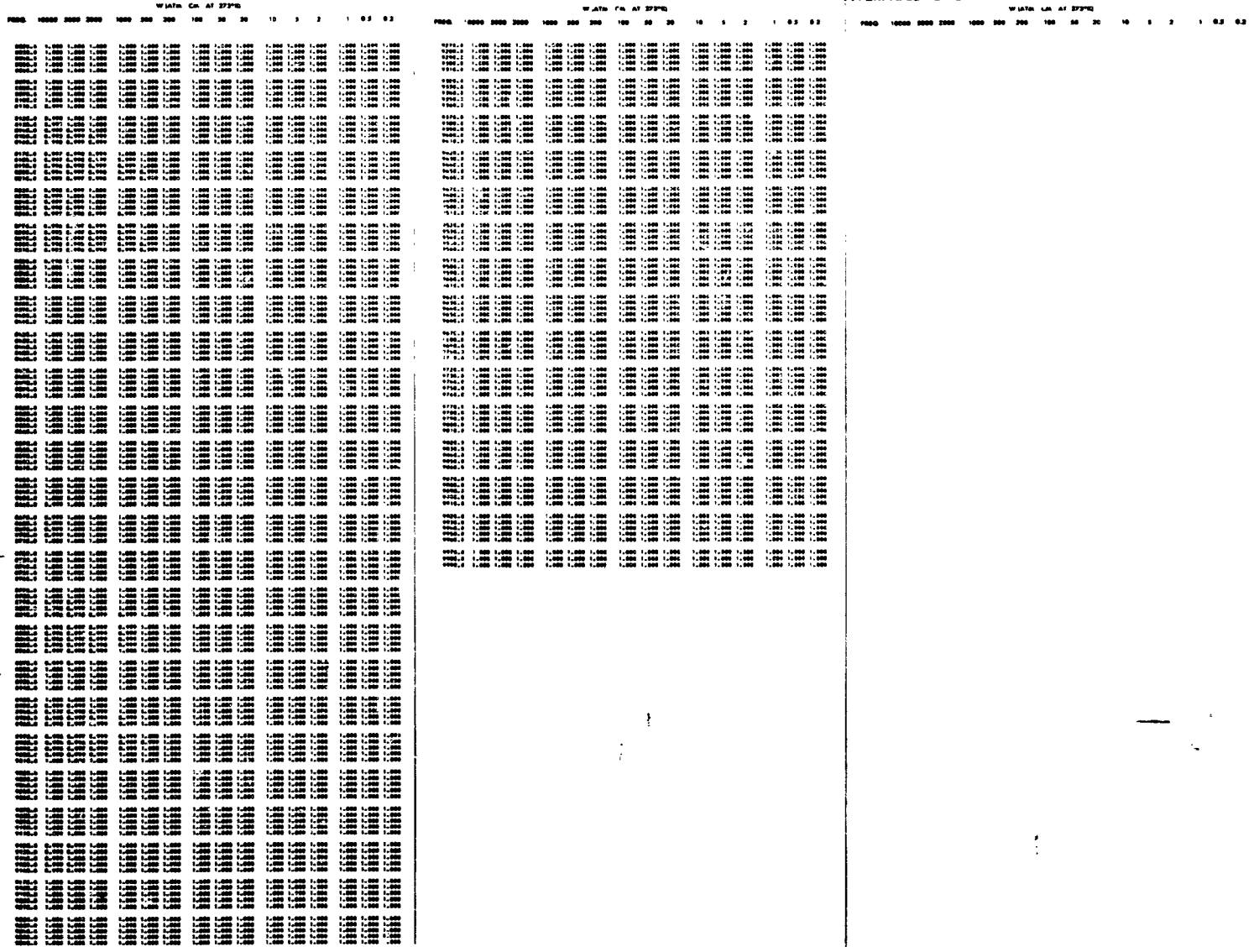
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE
T=300° K

AVERAGED OVER 20 Cm^{-1}

CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T=300° K

AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE
T-300° K
AVERAGED OVER 20 Cm-1

CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE
T-300° K

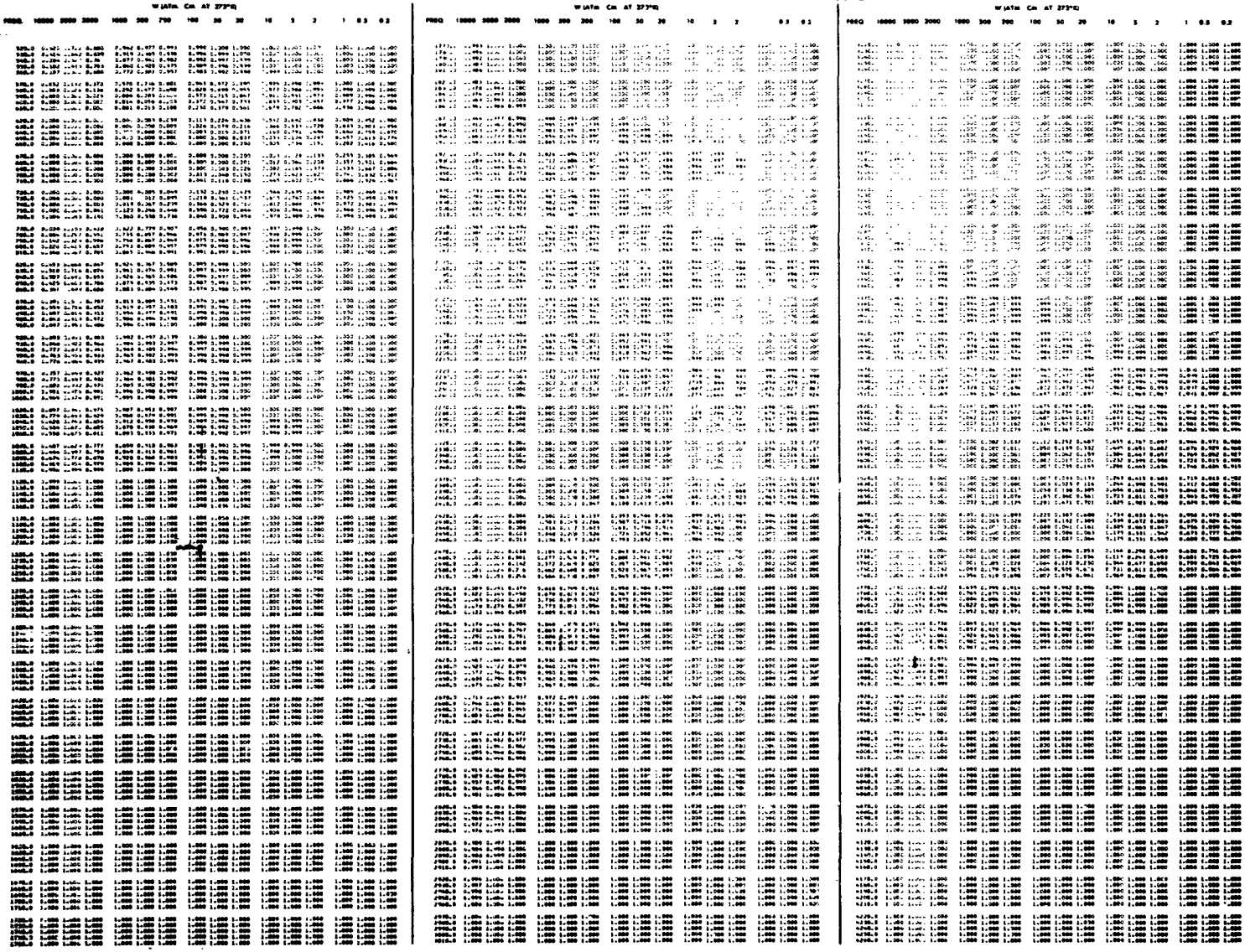
AVERAGED OVER 20 Cm^{-1}

CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE
T=300° K

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=250° K

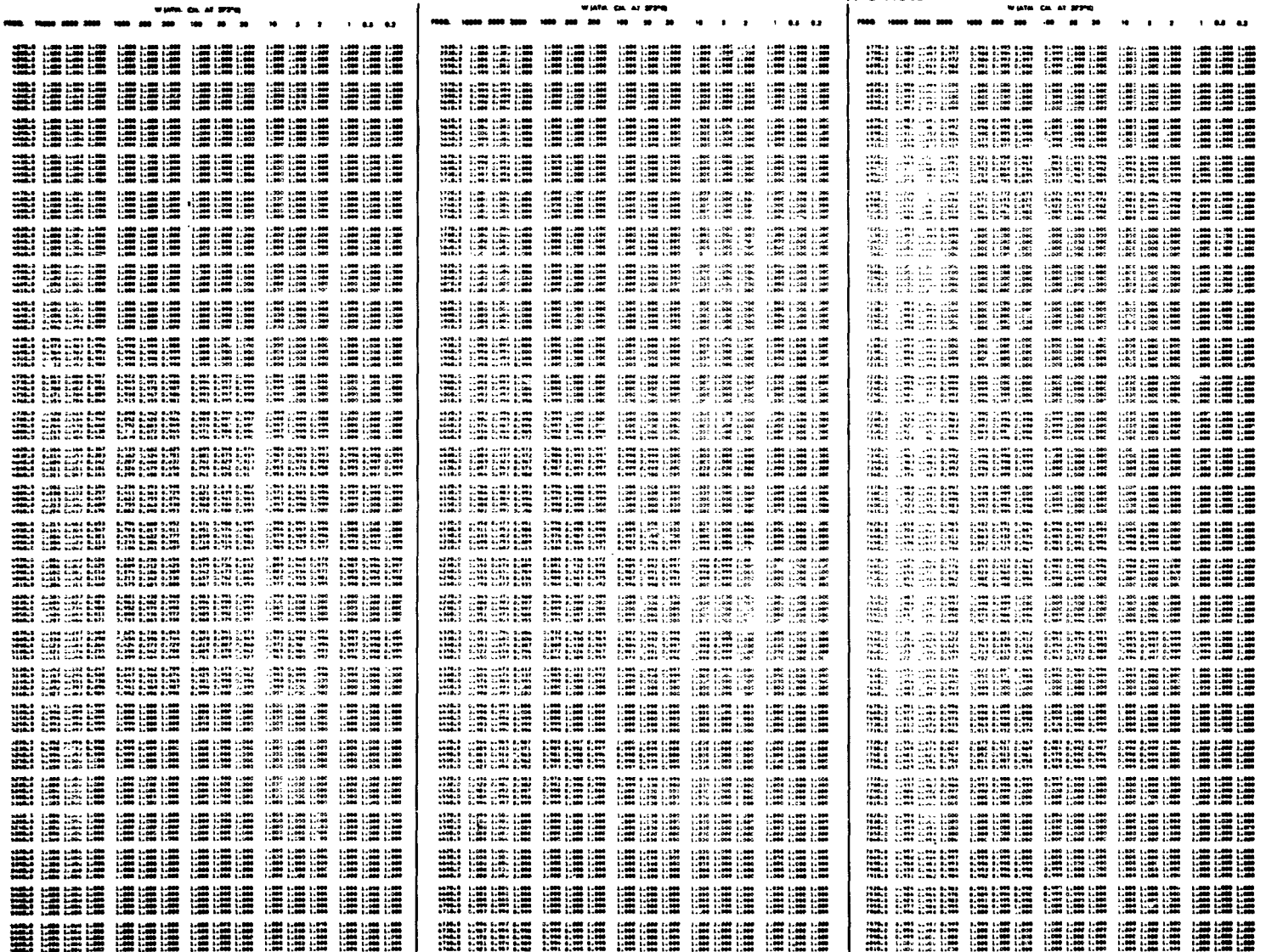
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=250° K

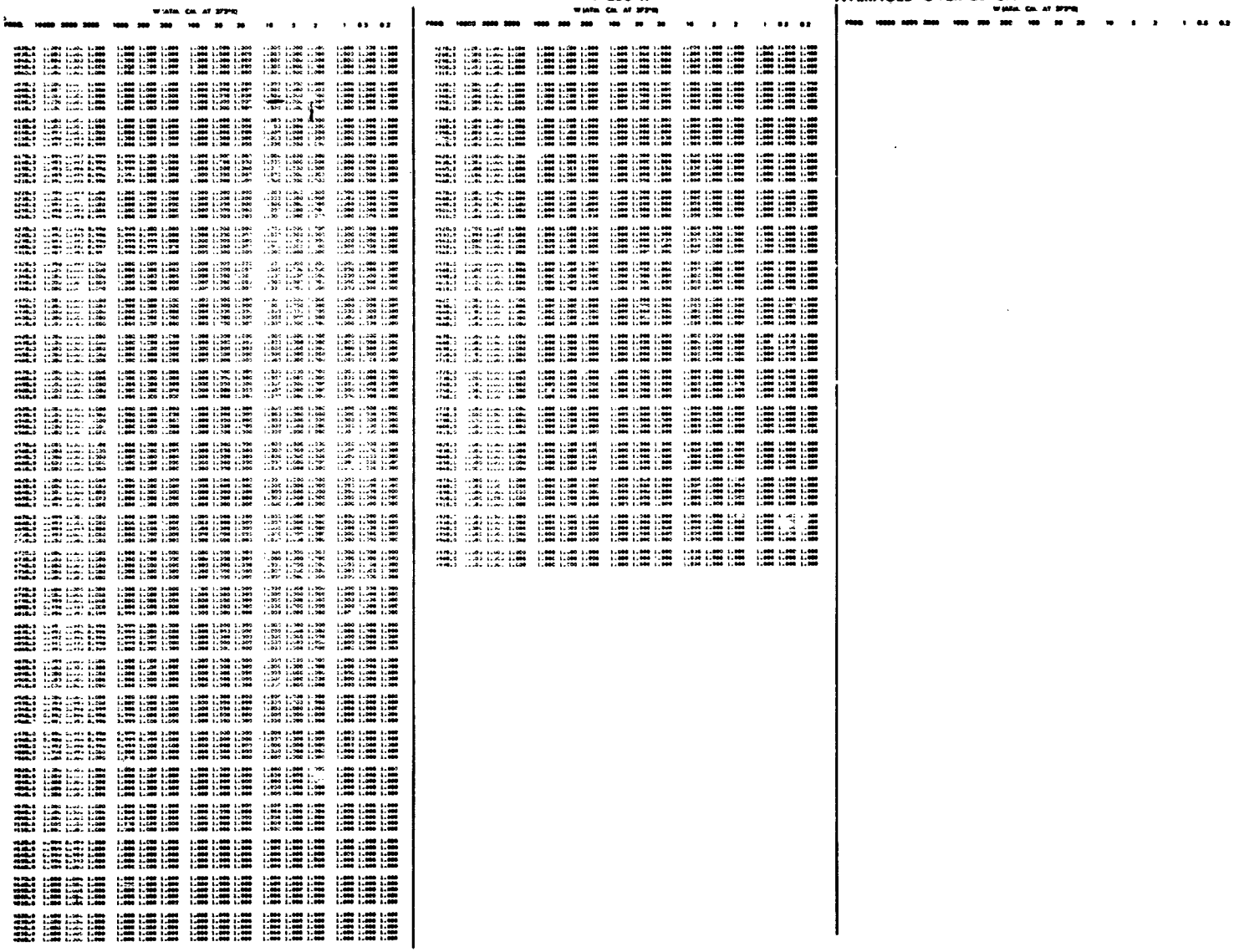
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=250° K

AVERAGED OVER 20 Cm^{-1}



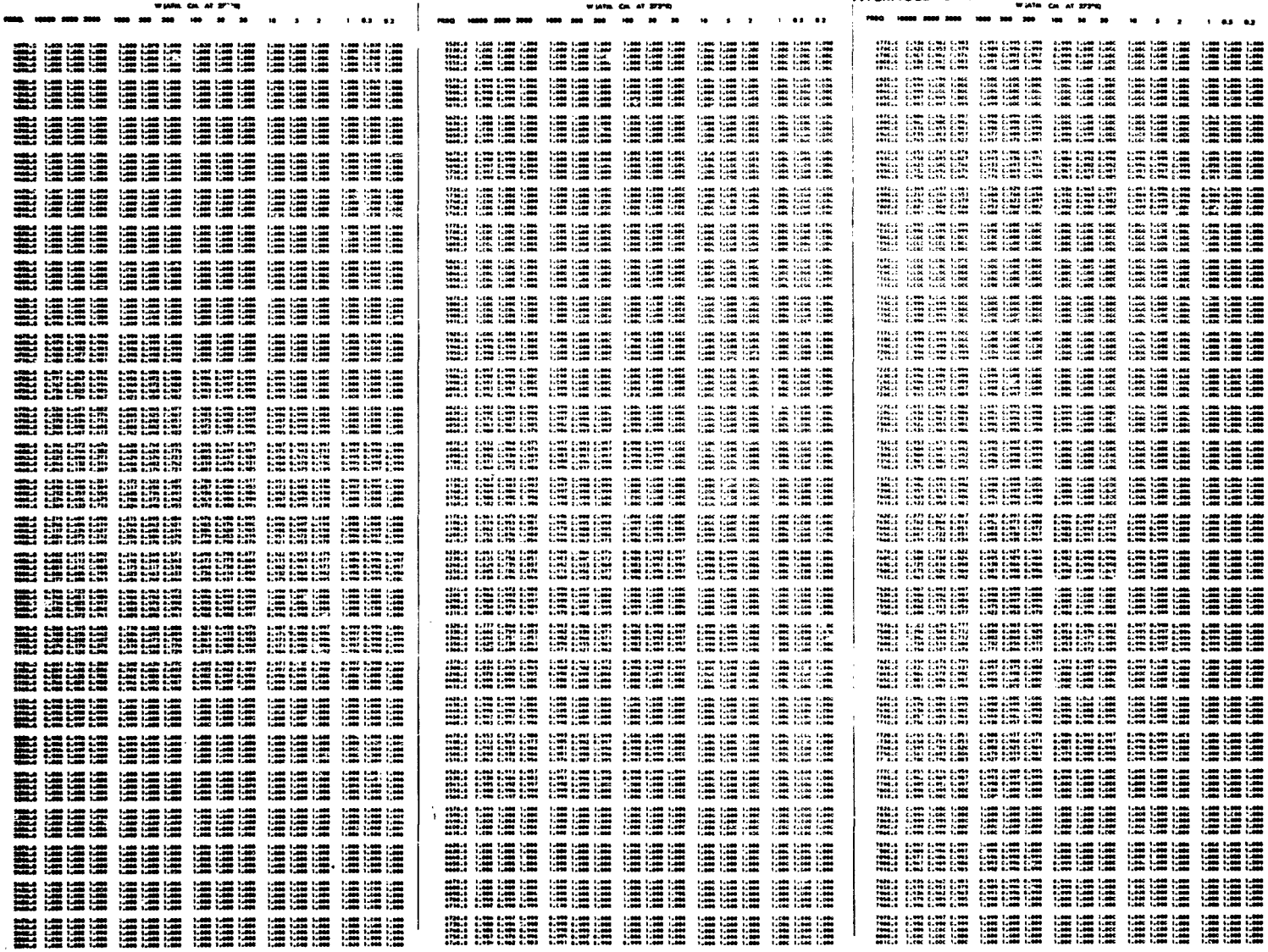
CARBON DIOXIDE AT 0.90 ATMOSPHERE PRESSURE
T=250°K

AVERAGED OVER 20 Cm^{-1}

CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=250° K

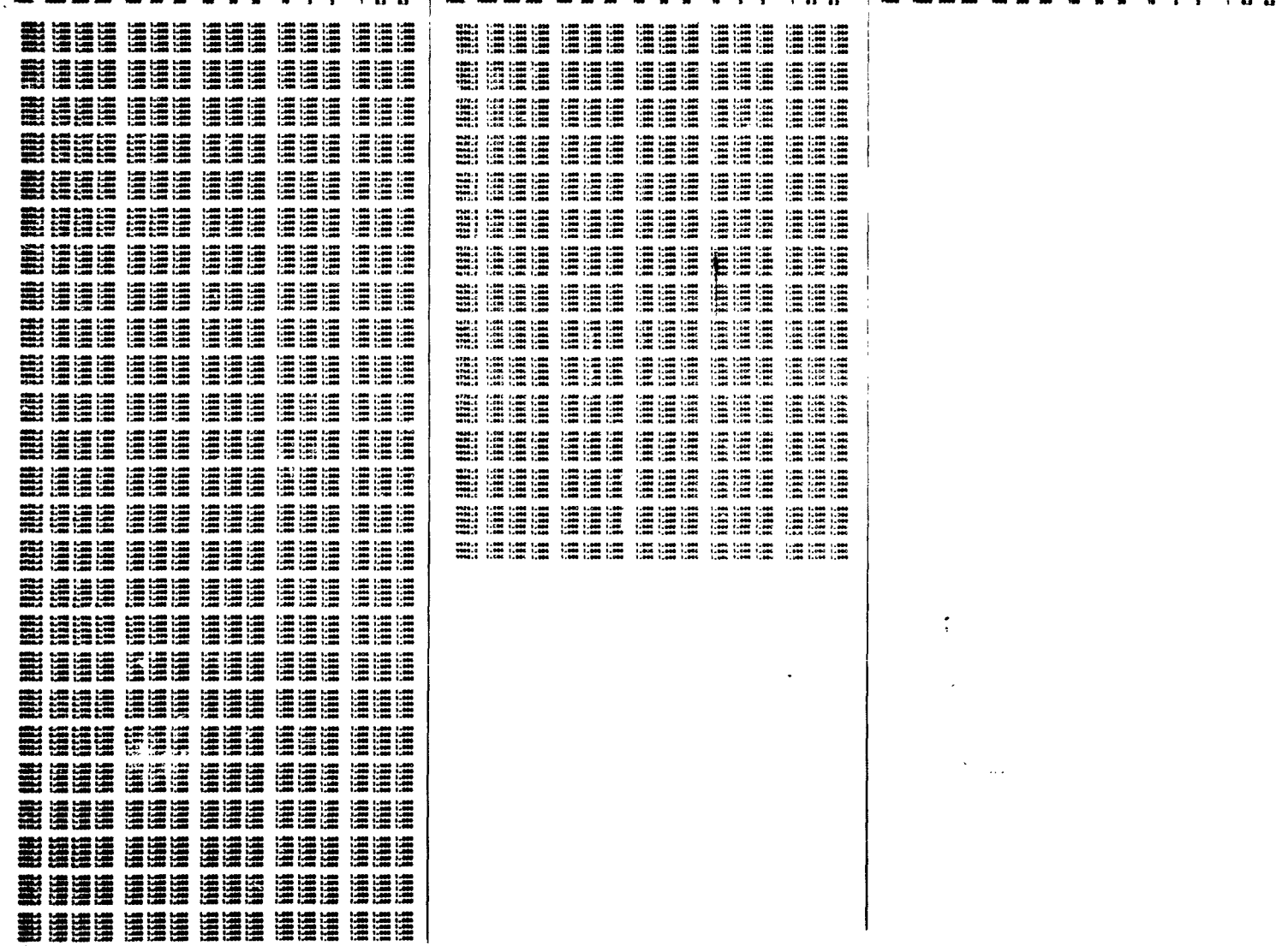
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=250° K

AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

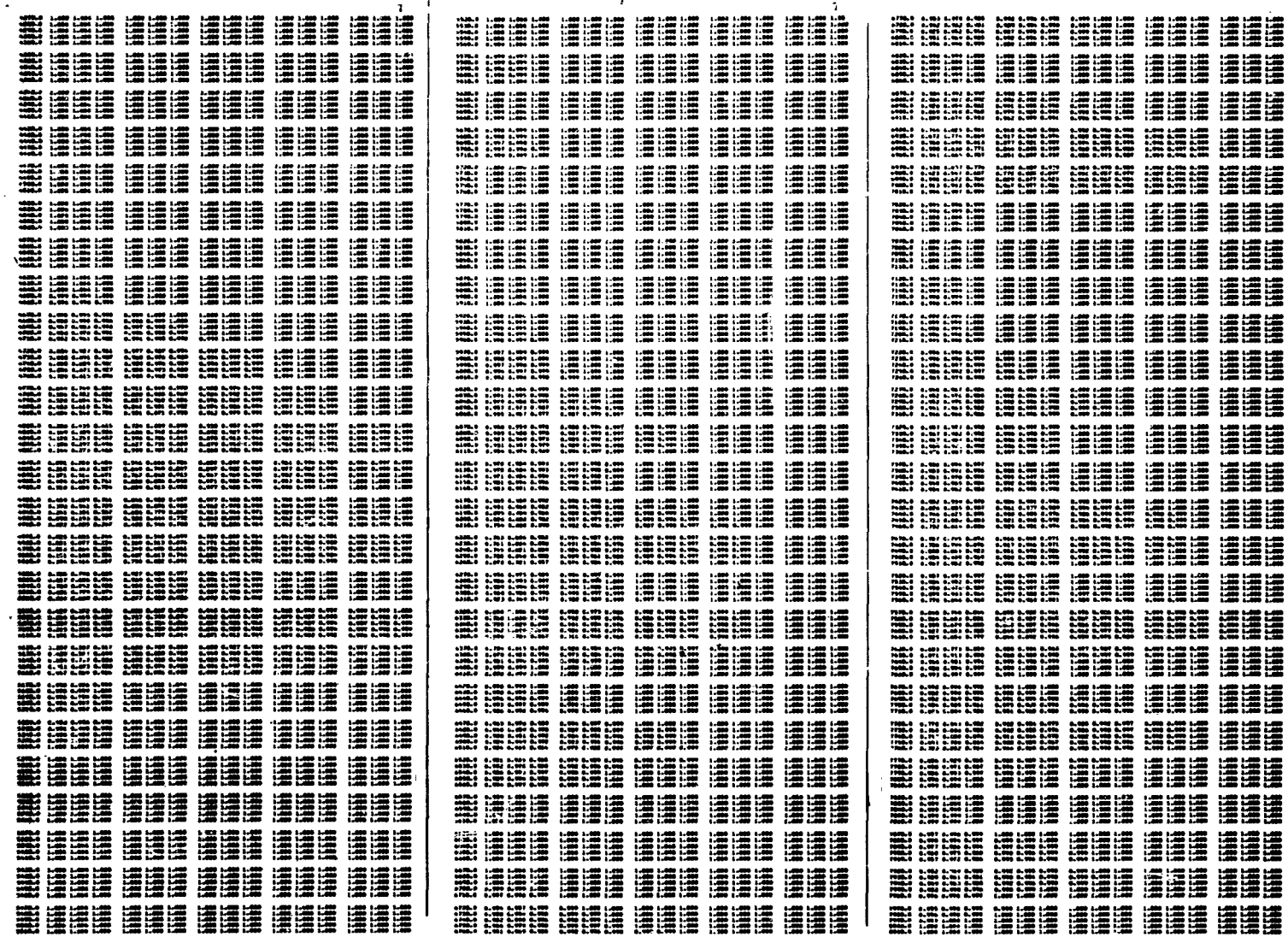
T=250° K

AVERAGED OVER 20 Cm^{-1}

CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=250° K

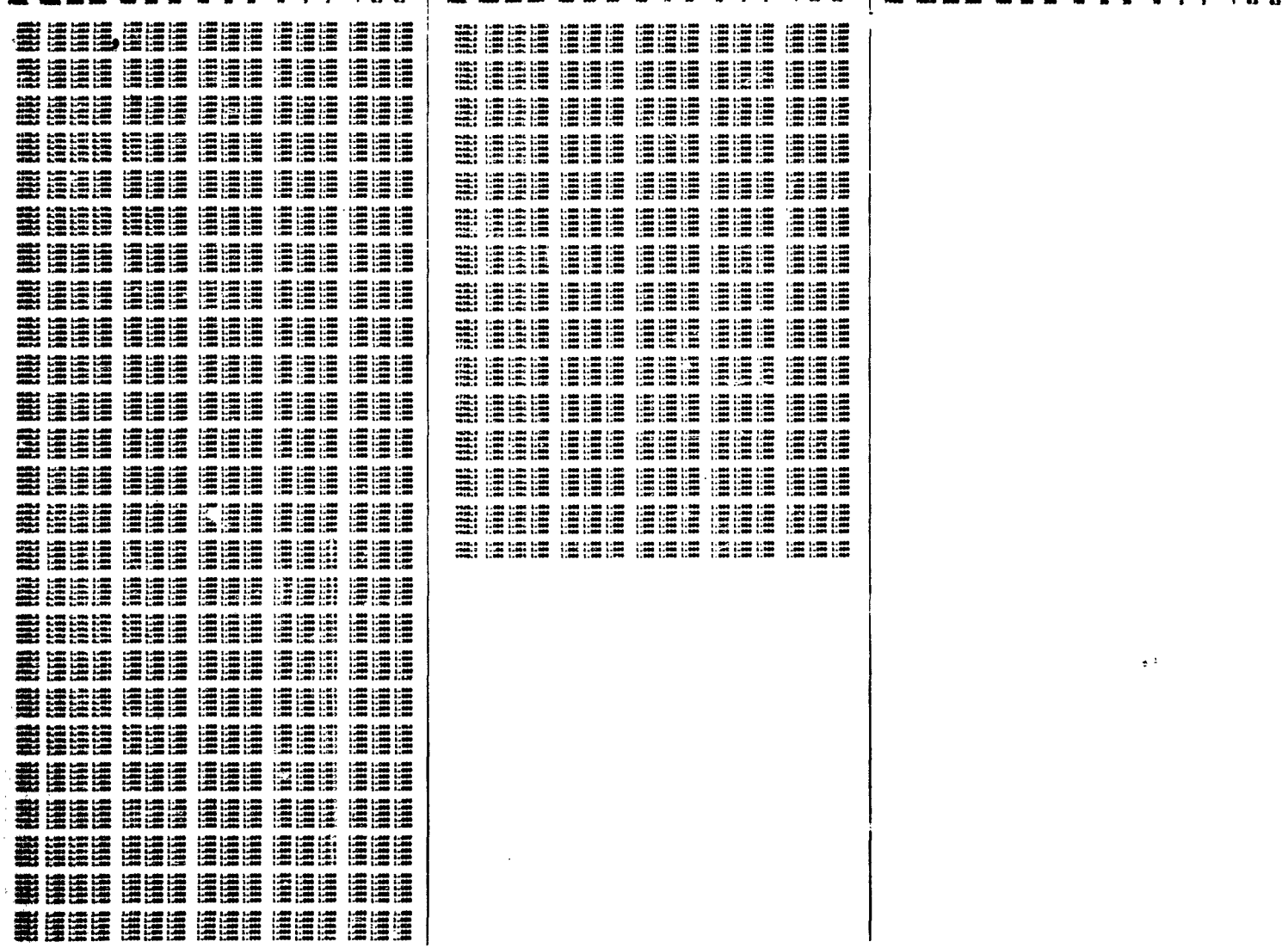
AVERAGED OVER 20 Cm^{-1}

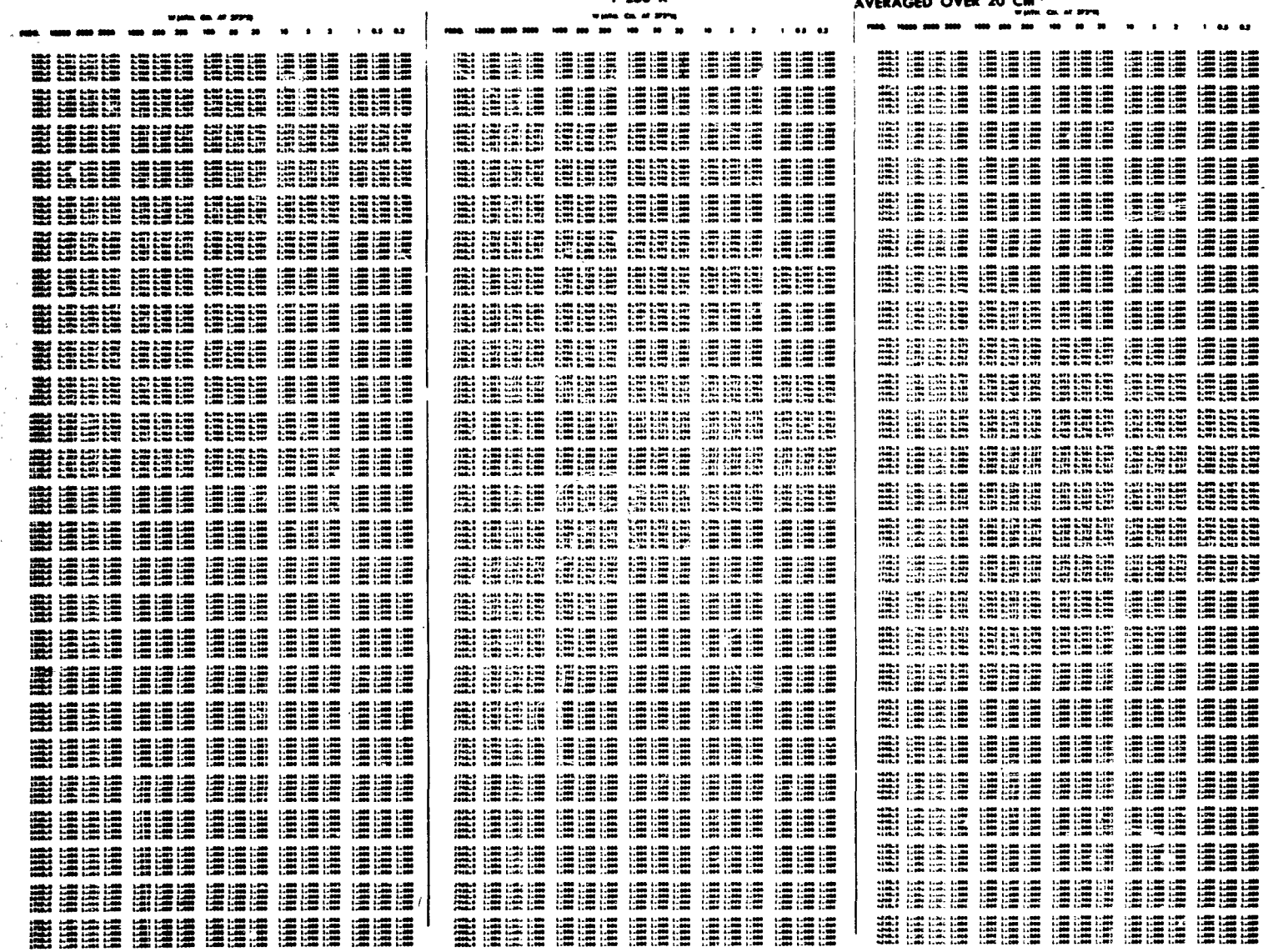


CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=250° K

AVERAGED OVER 20 Cm^{-1}

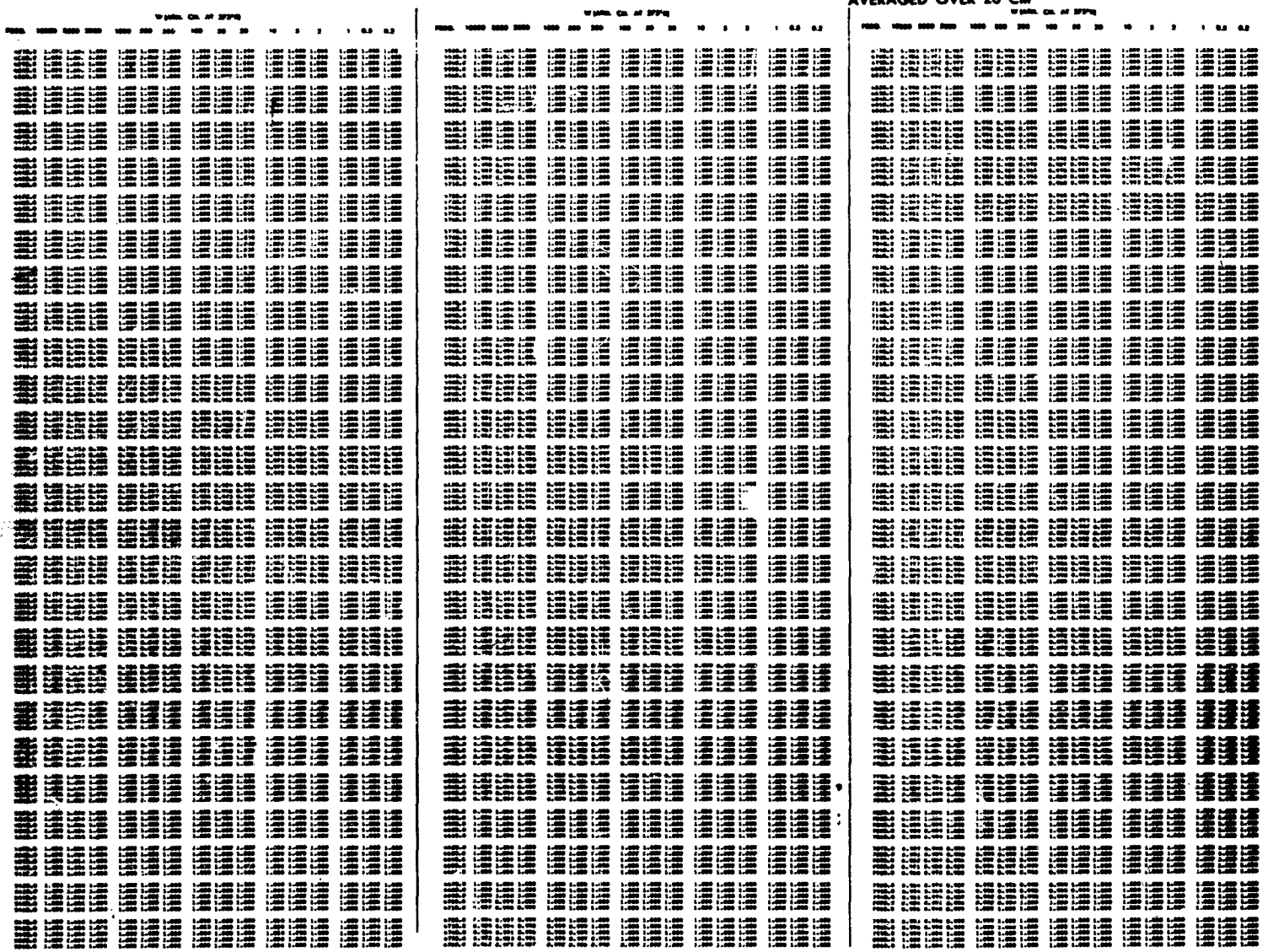



CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE
T=250° K
AVERAGED OVER 20 Cm-1

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T=250° K

AVERAGED OVER 20 Cm^{-1}

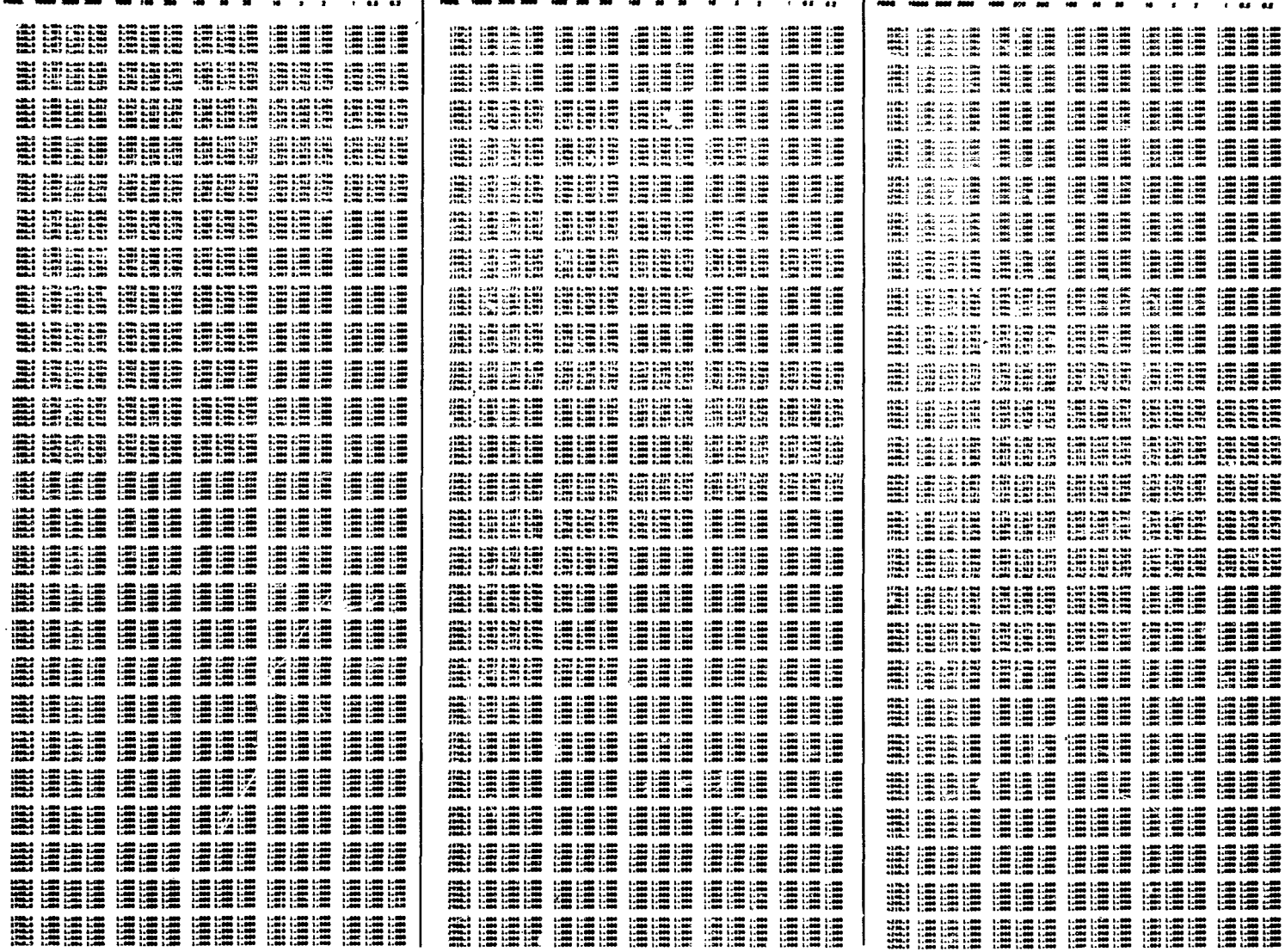


AVERAGED OVER 20 Cm^{-1}
CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE
T-250° K

CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T=250° K

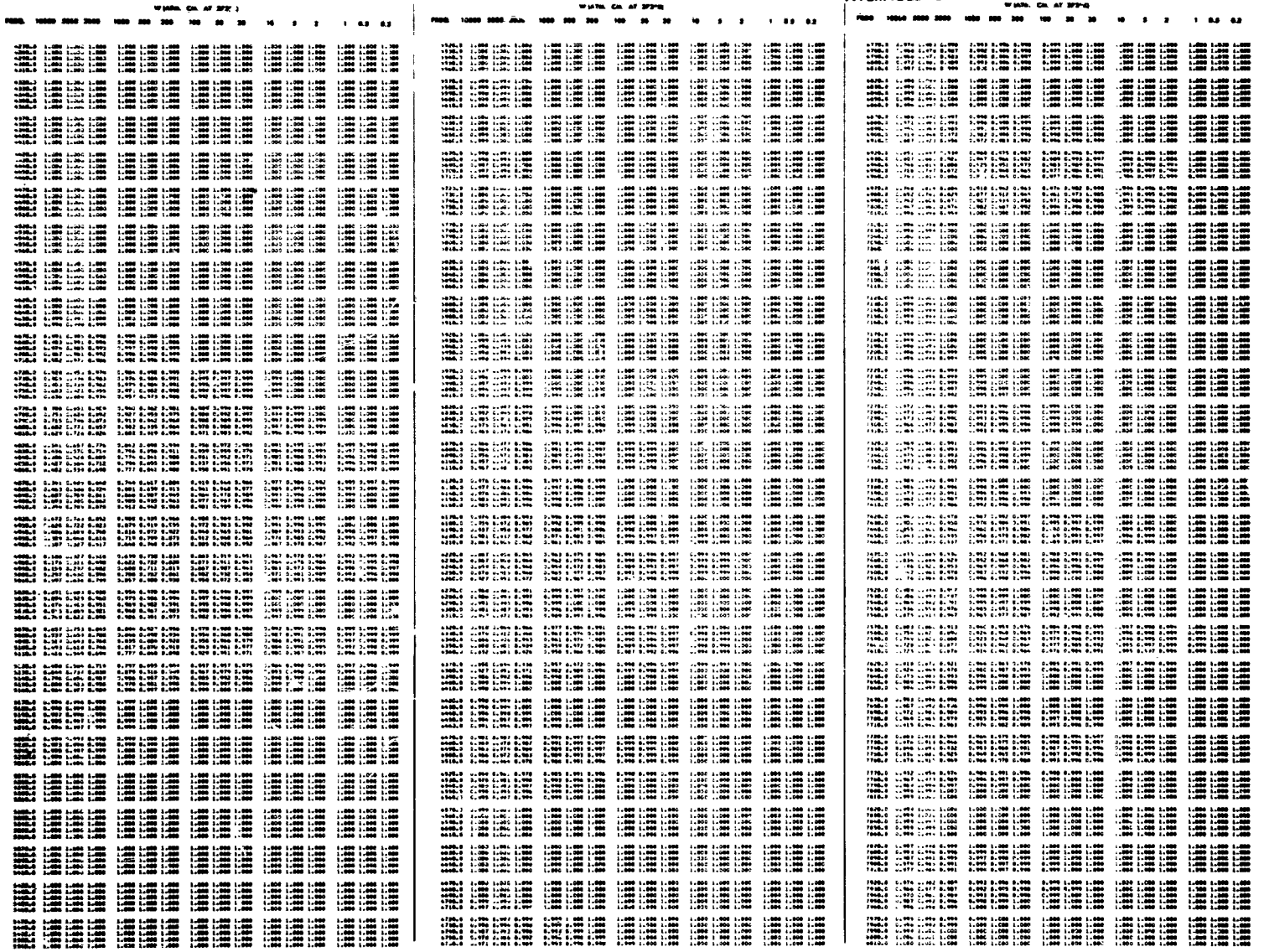
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T=250° K

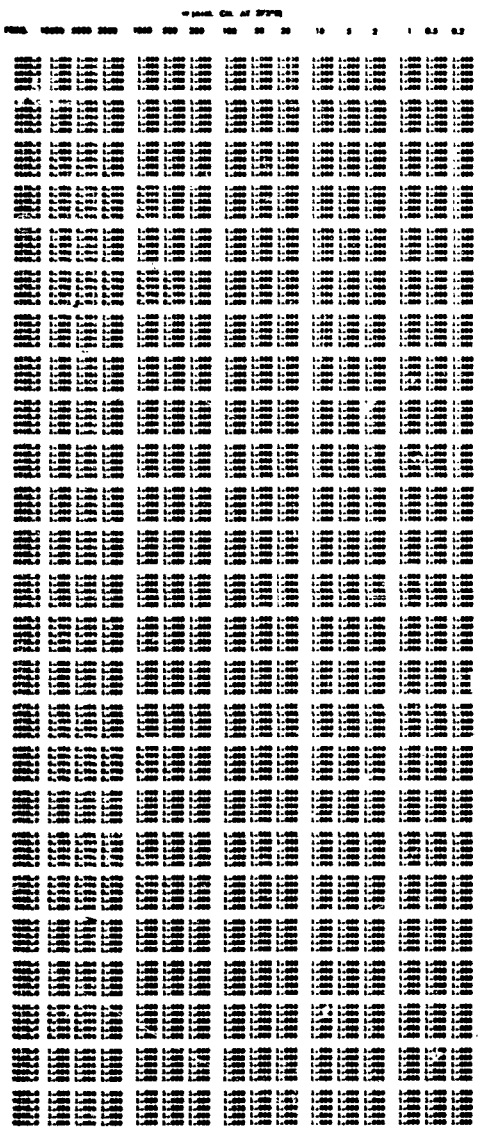
AVERAGED OVER 20 Cm^{-1}

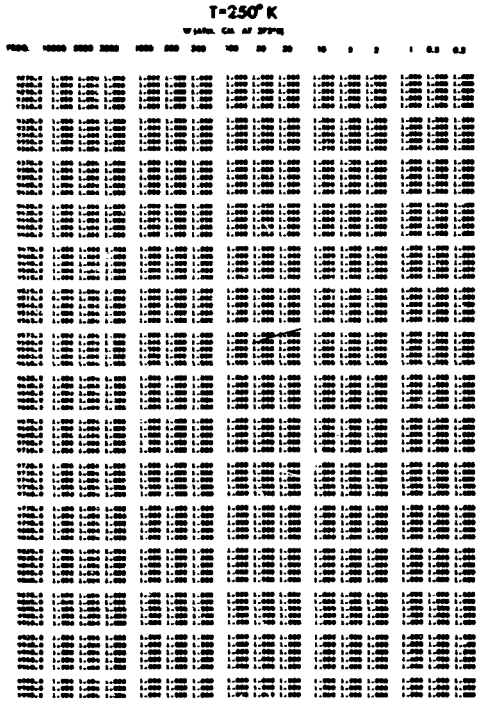


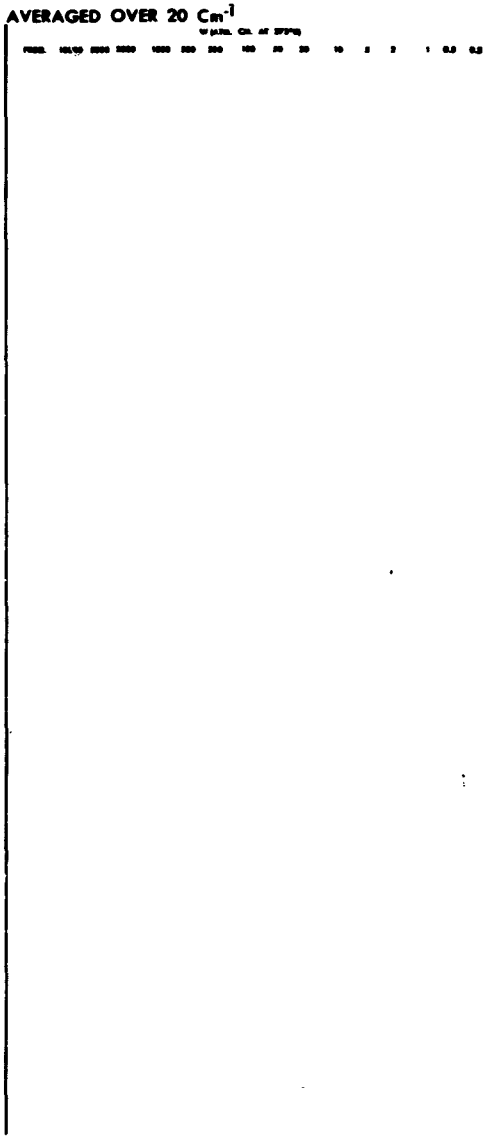
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T=250° K

AVERAGED OVER 20 Cm^{-1}

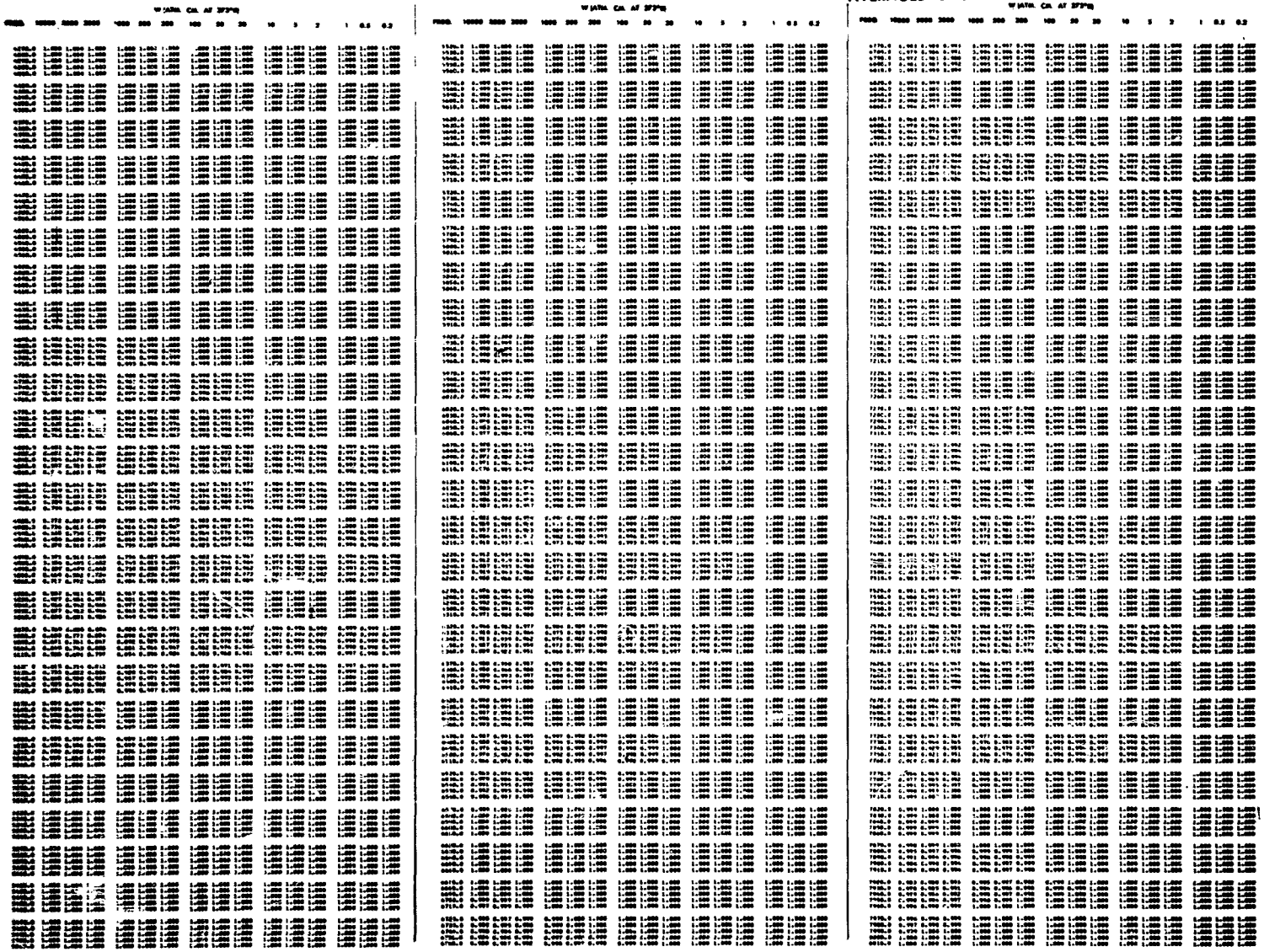






CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE
T-250° K
AVERAGED OVER 20 Cm⁻¹

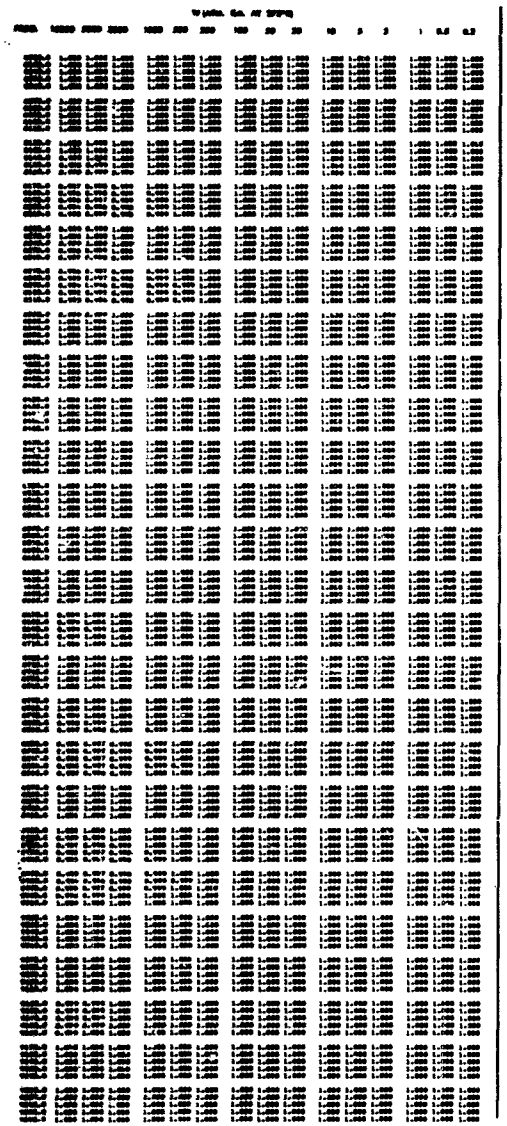
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE
T=250° K
AVERAGED OVER 20 Cm^{-1}

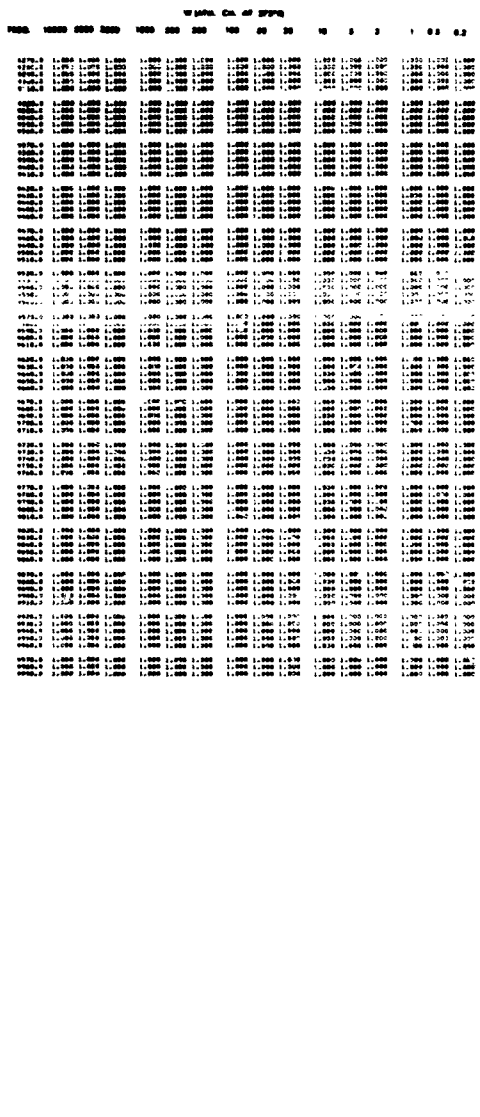


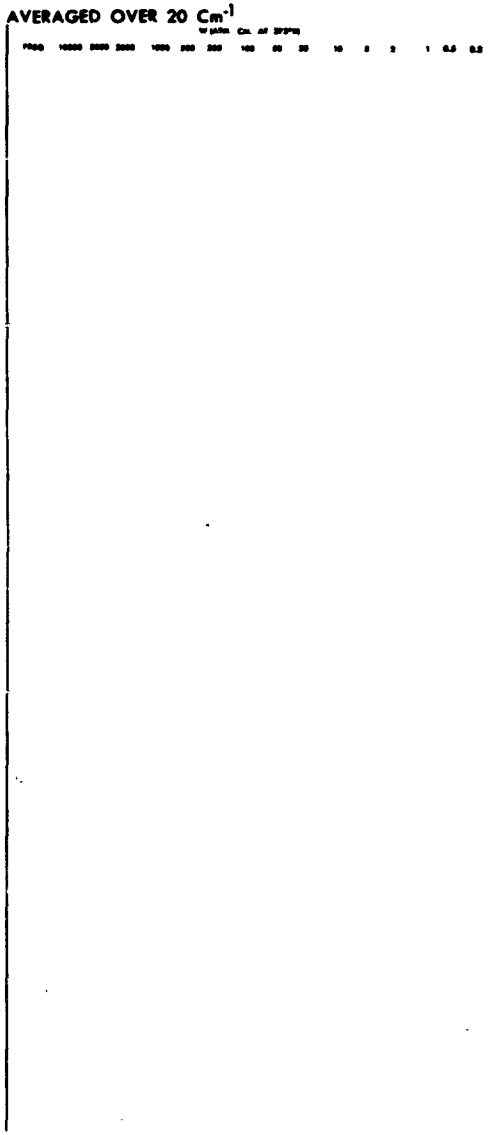
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T=250° K

AVERAGED OVER 20 Cm^{-1}





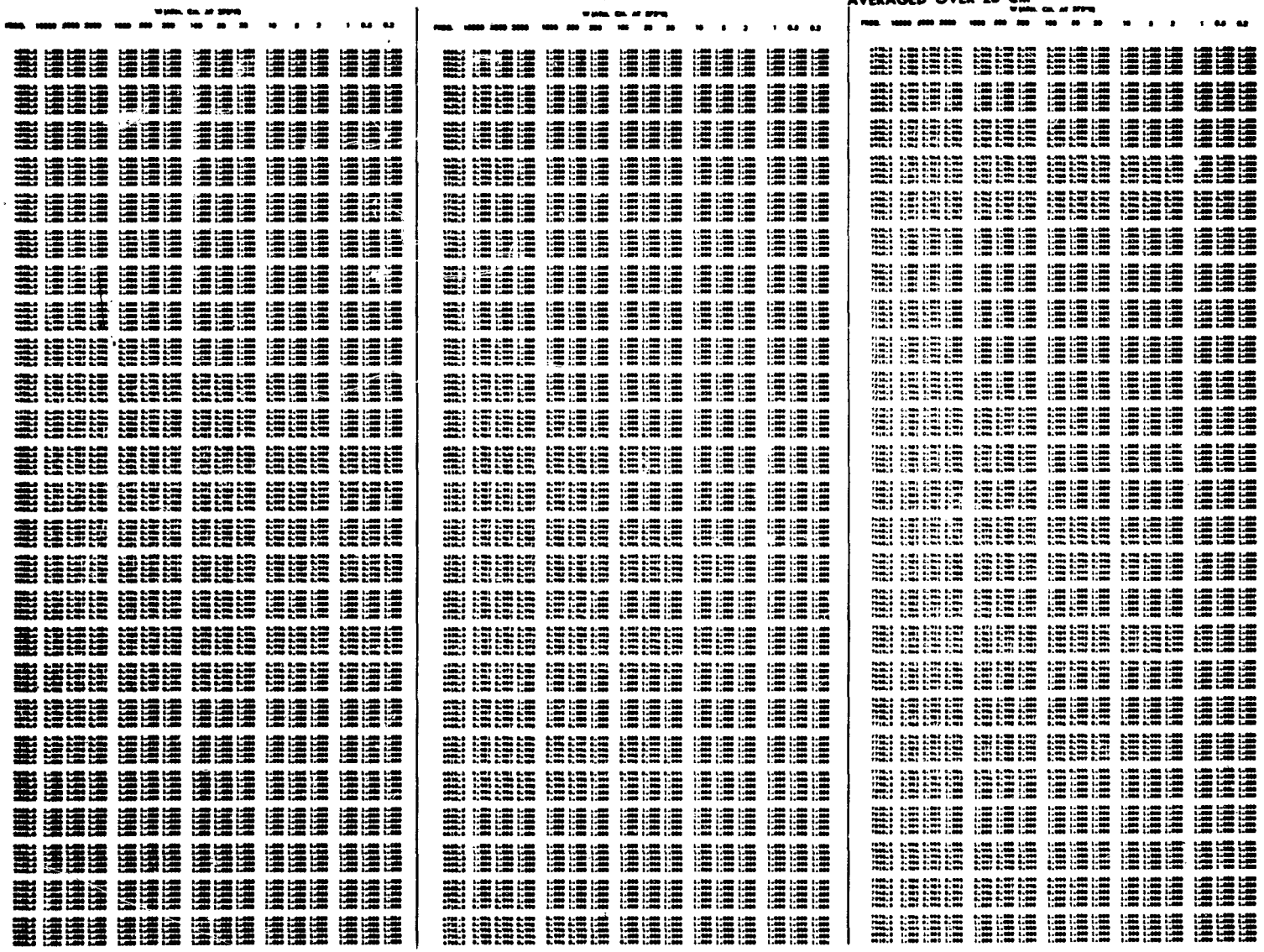


CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T=250° K

AVERAGED OVER 20 Cm^{-1}

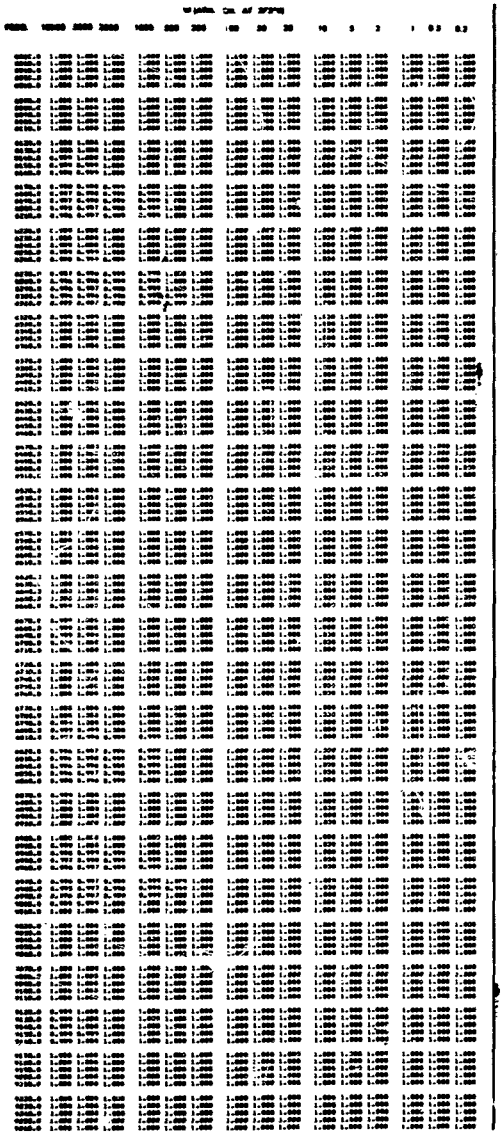
CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE
T=250° K
AVERAGED OVER 20 Cm^{-1}

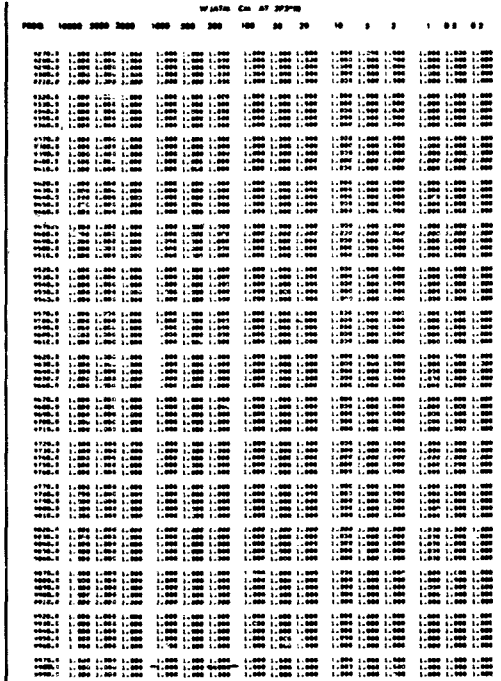


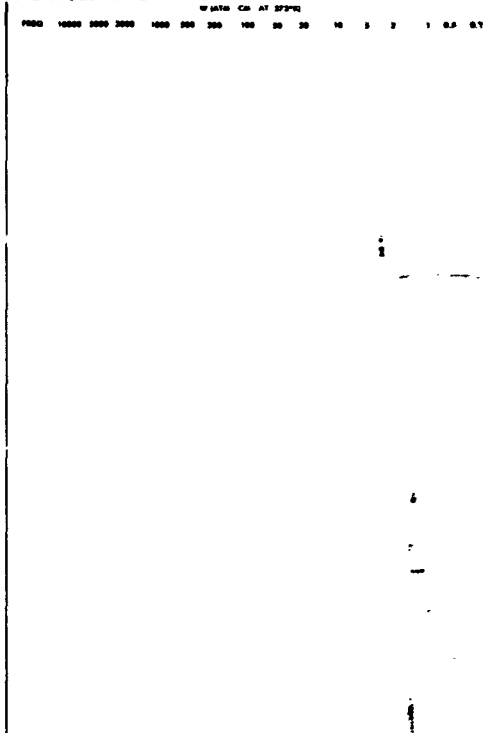
CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T=250° K

AVERAGED OVER 20 Cm^{-1}



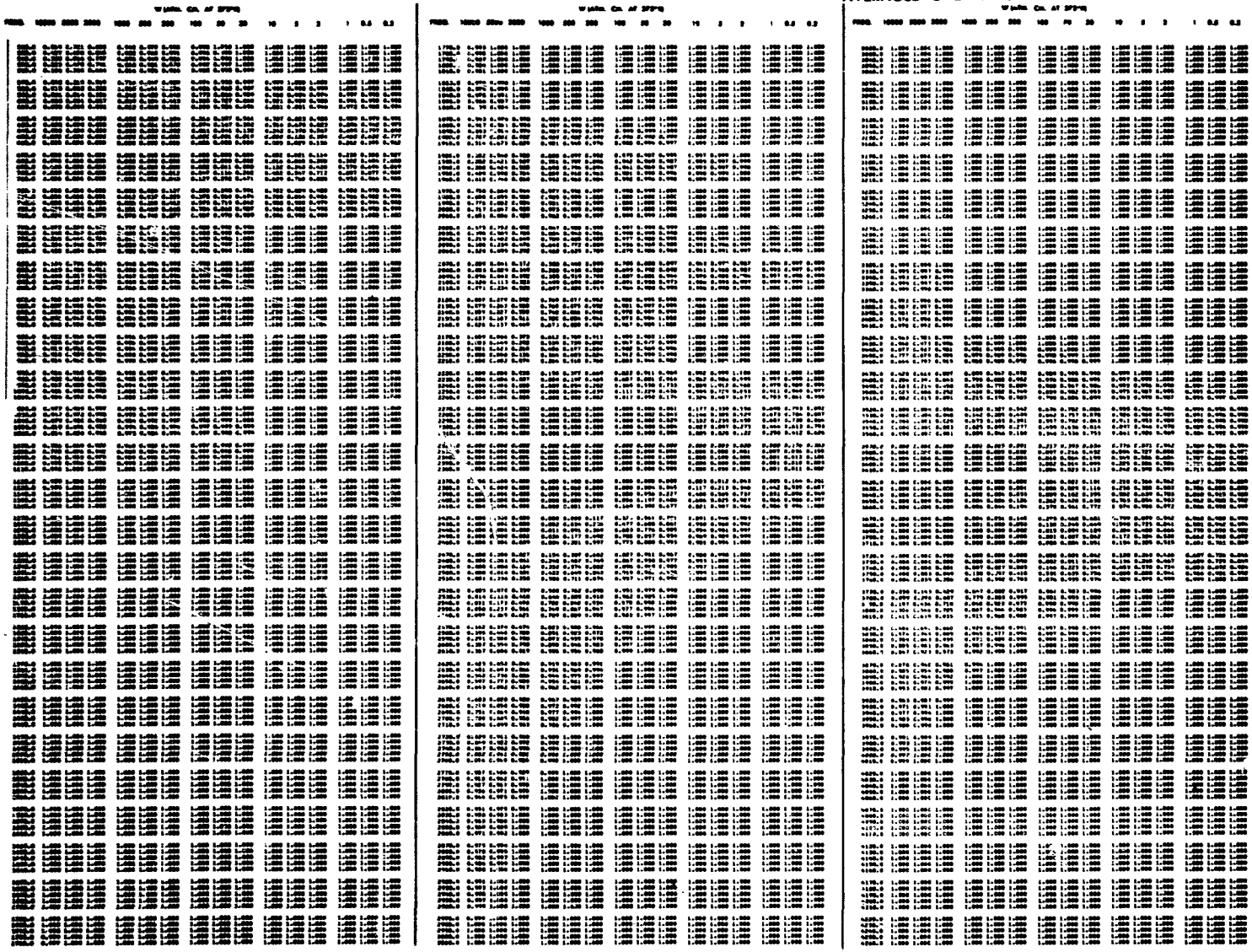




CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=200° K

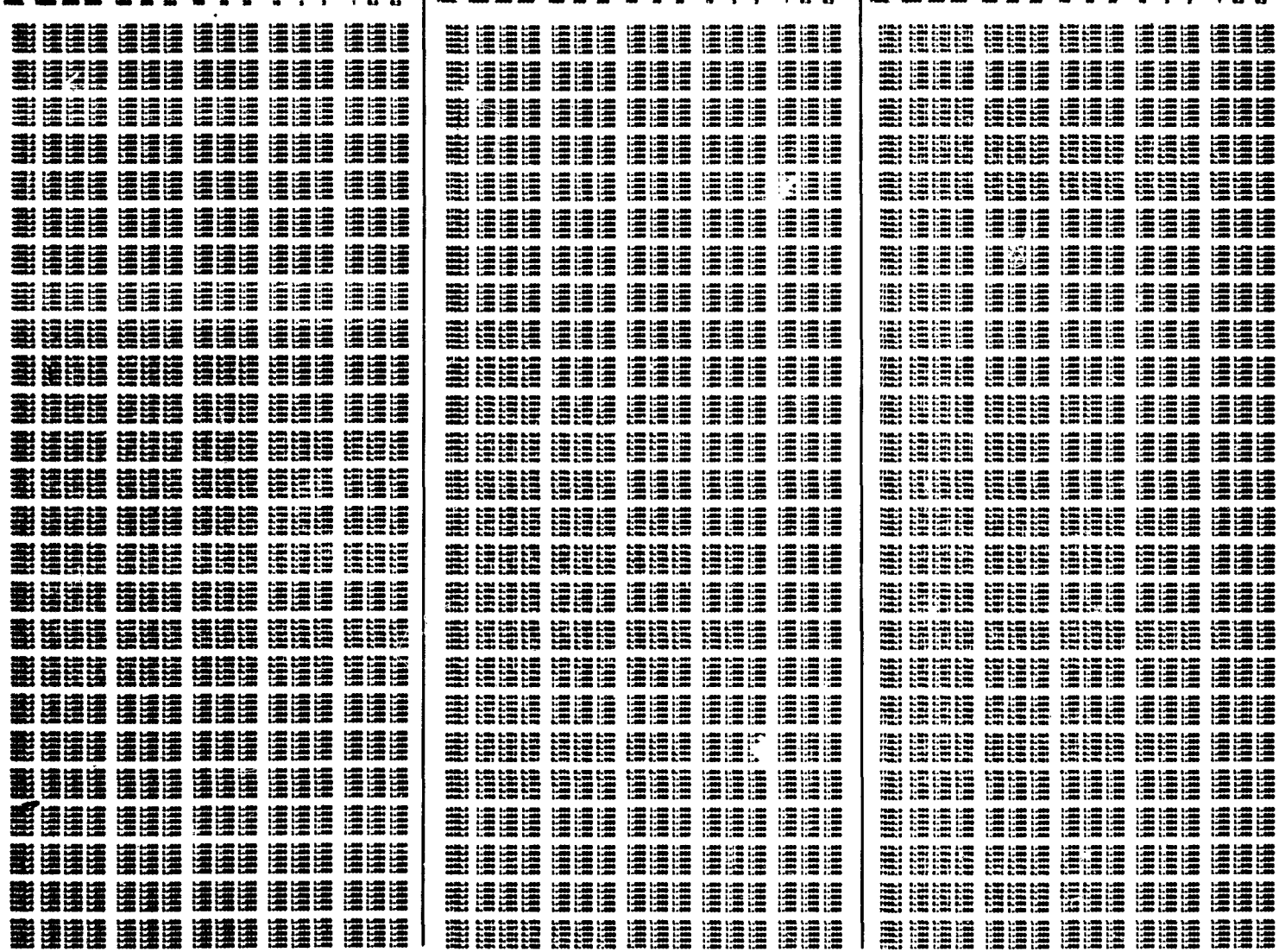
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=200° K

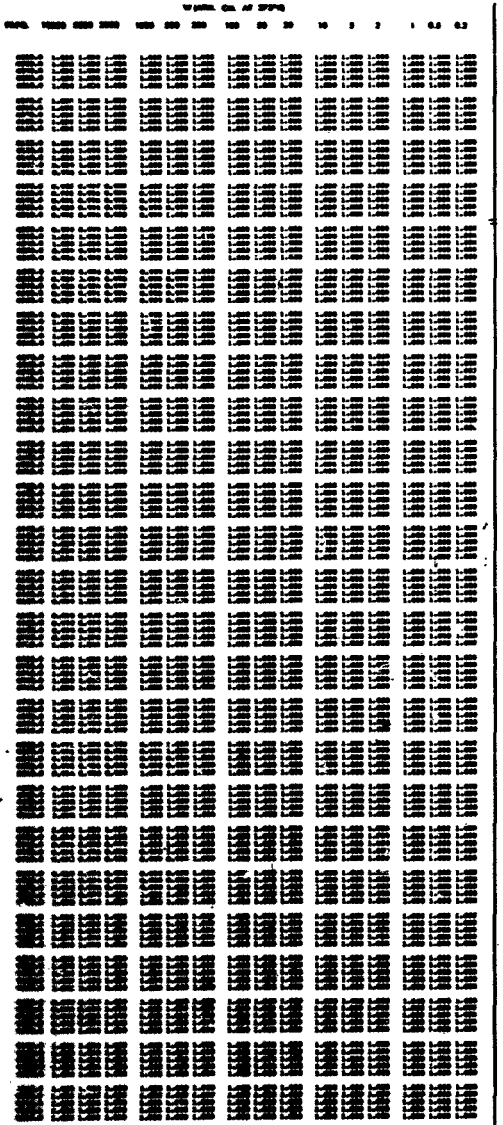
AVERAGED OVER 20 Cm^{-1}

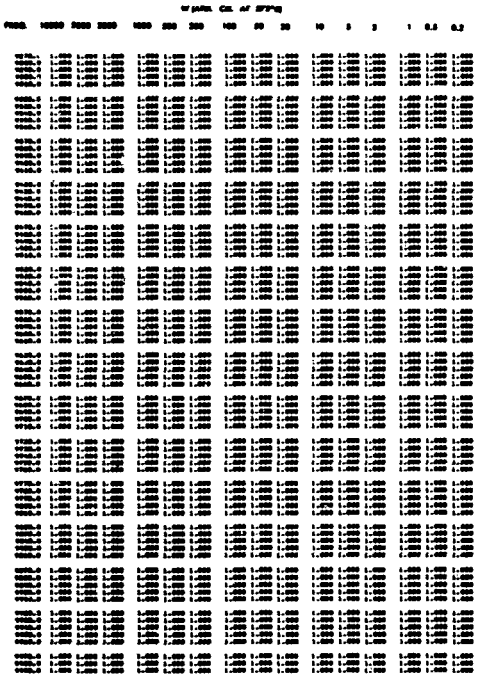


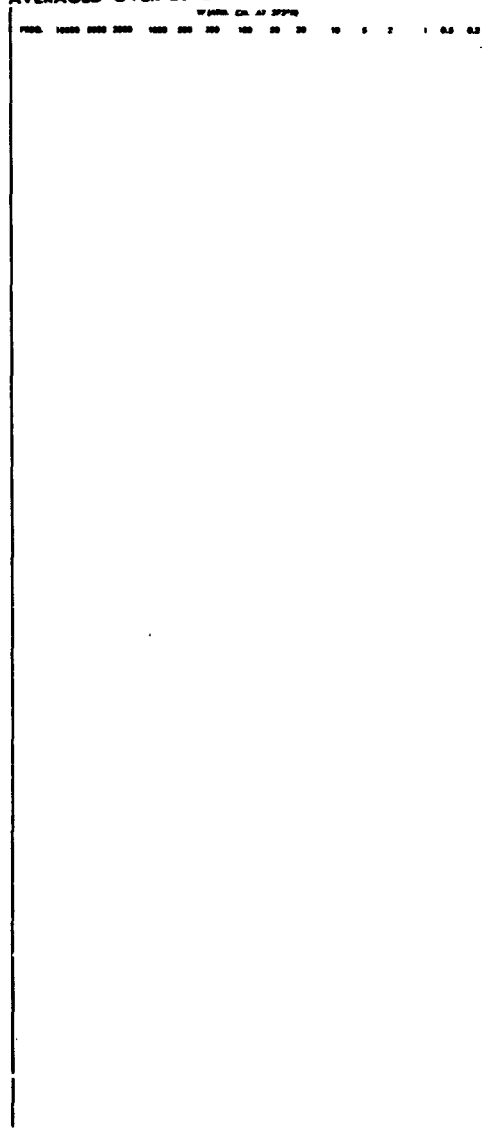
CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=200° K

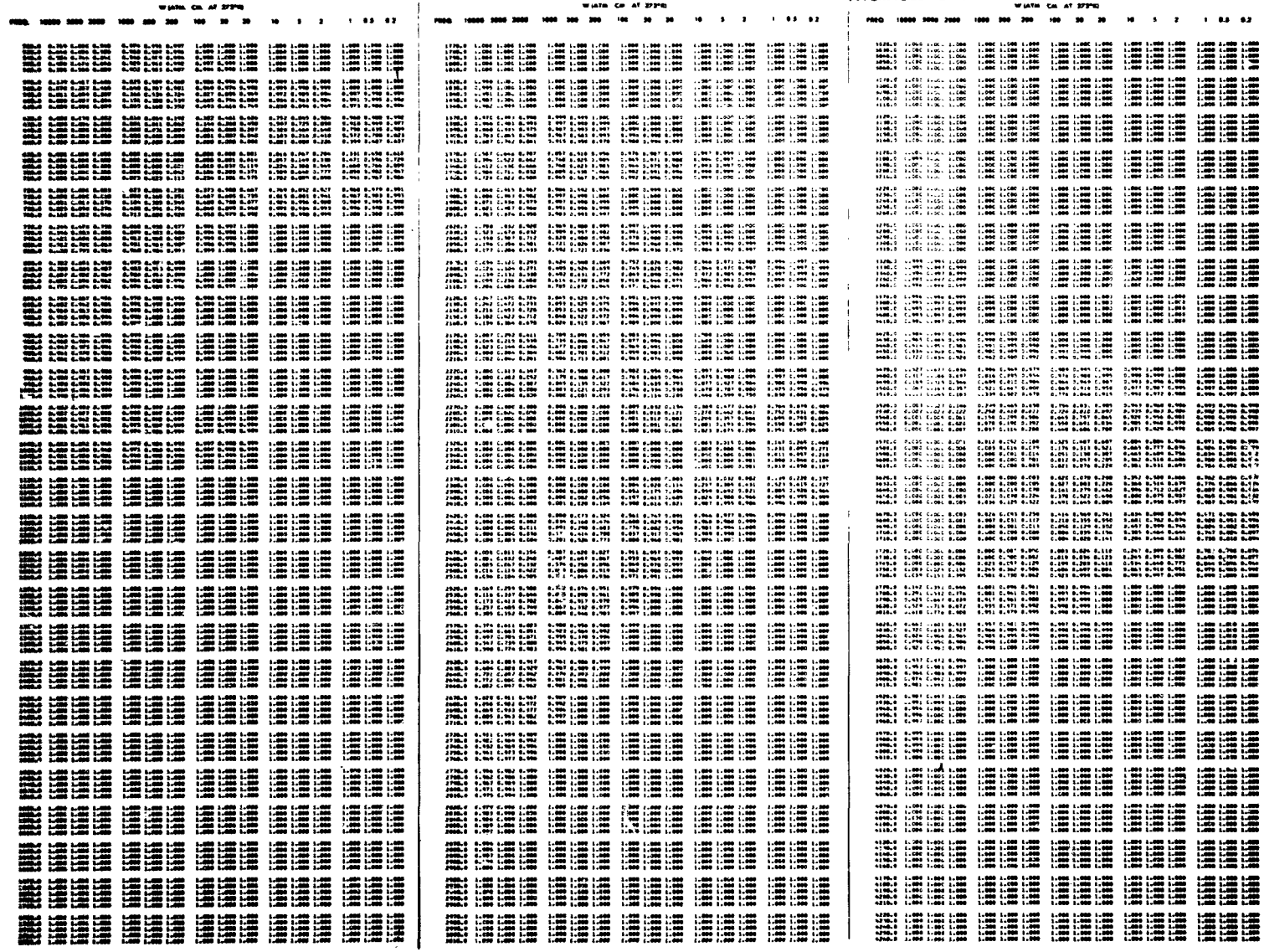
AVERAGED OVER 20 Cm^{-1}







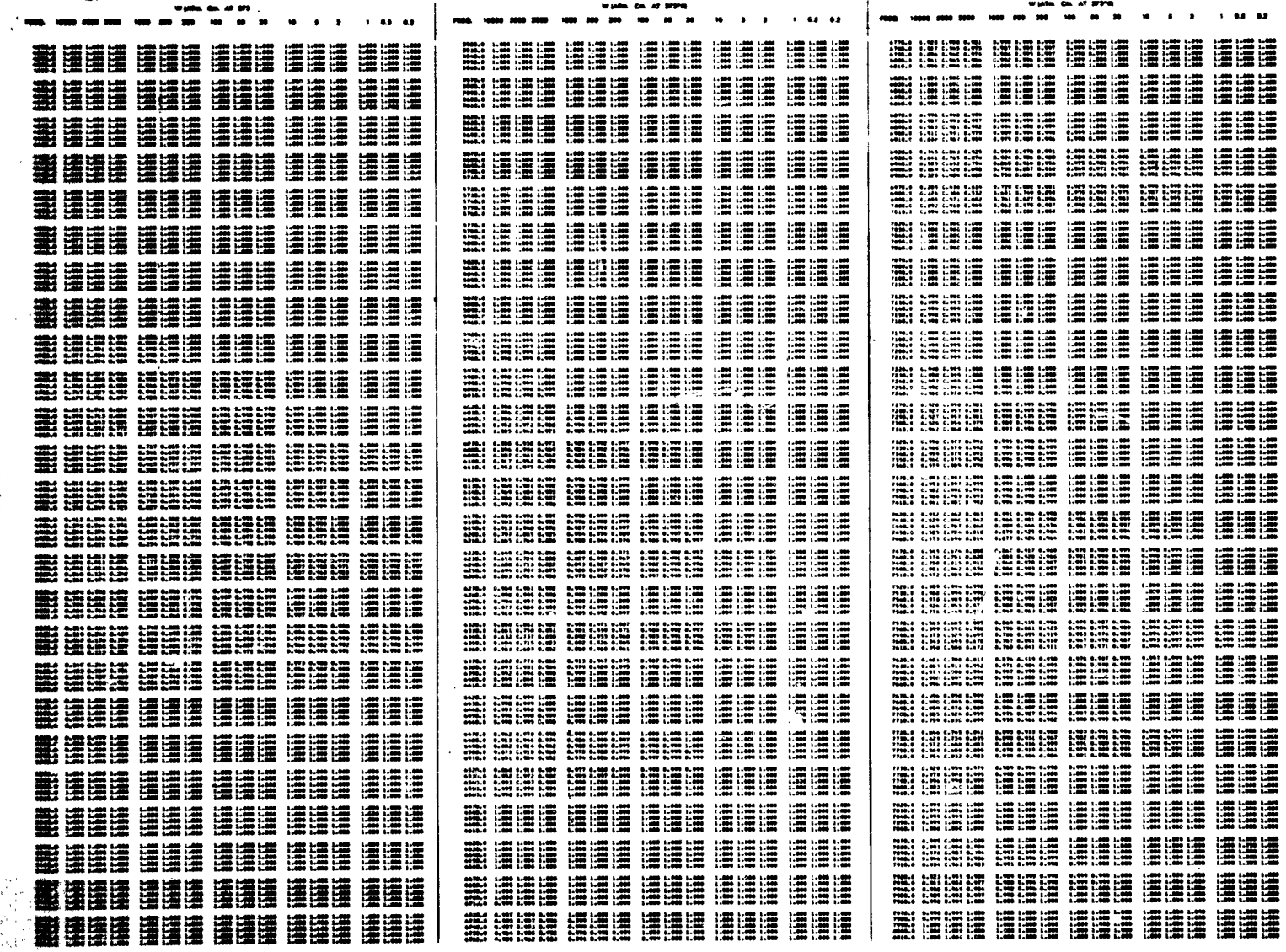
CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE
T=200° K
AVERAGED OVER 20 Cm^{-1}



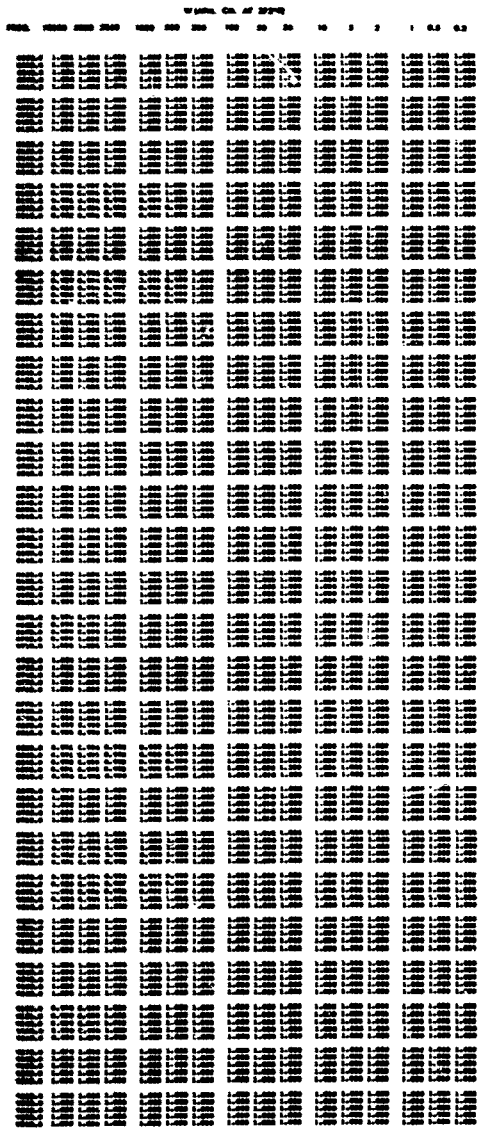
CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

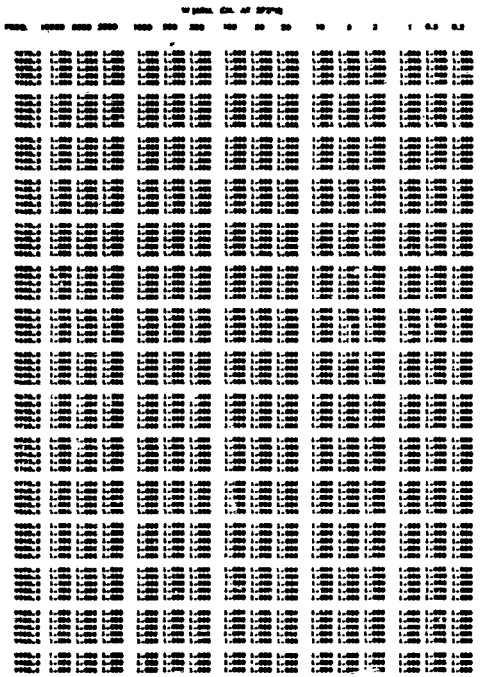
T=200° K

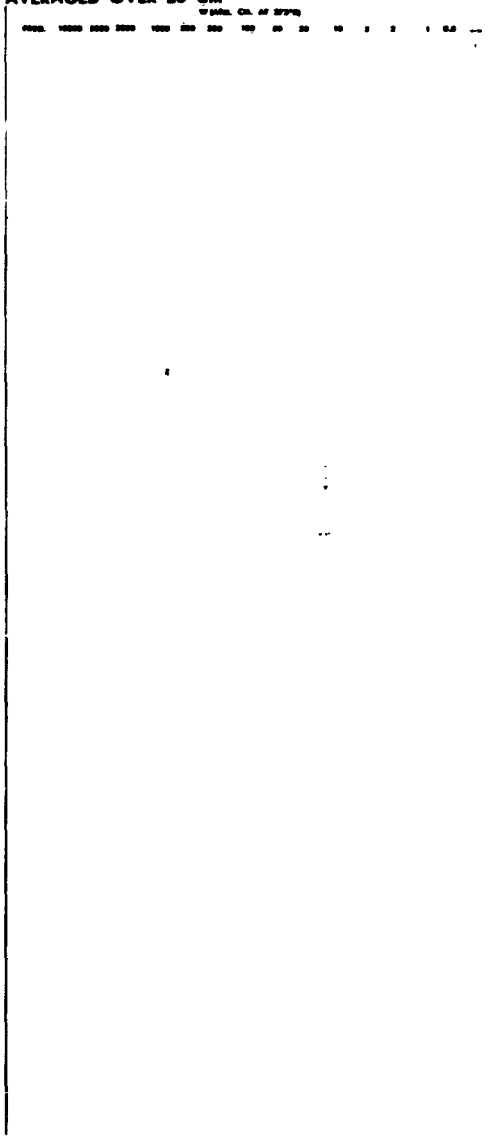
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE
T=200° K
AVERAGED OVER 20 Cm^{-1}







CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

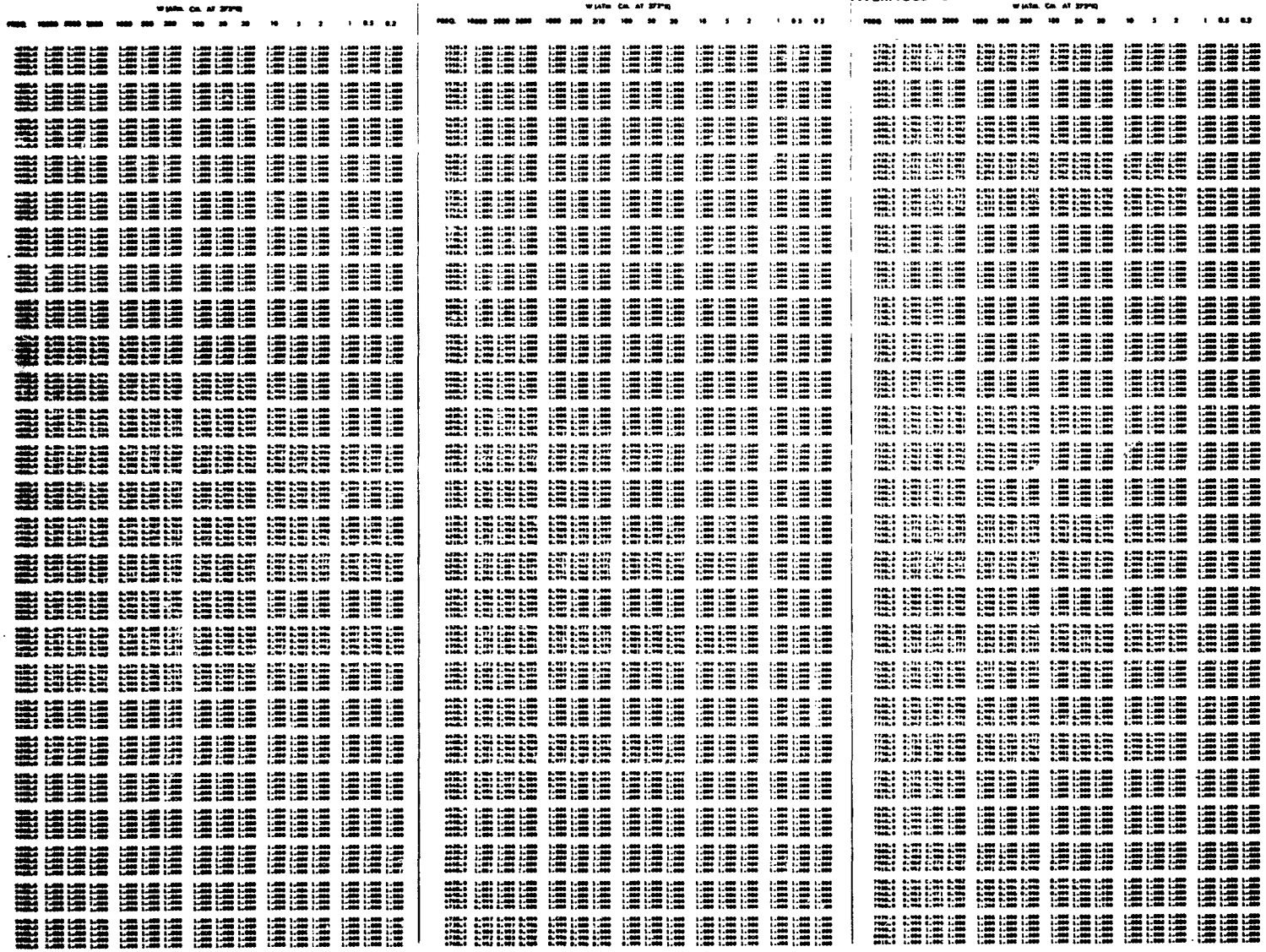
T-200° K

AVERAGED OVER 20 Cm^{-1}

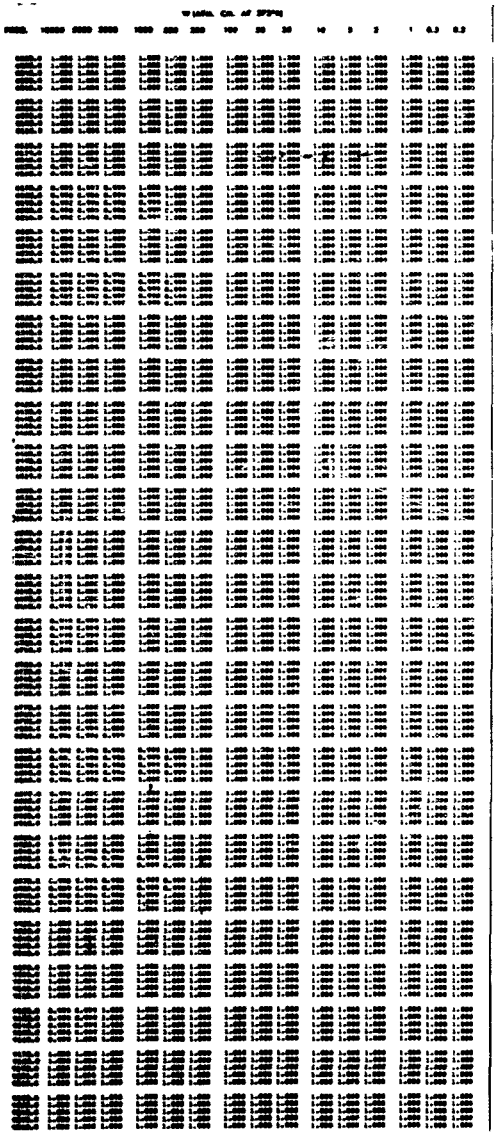
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

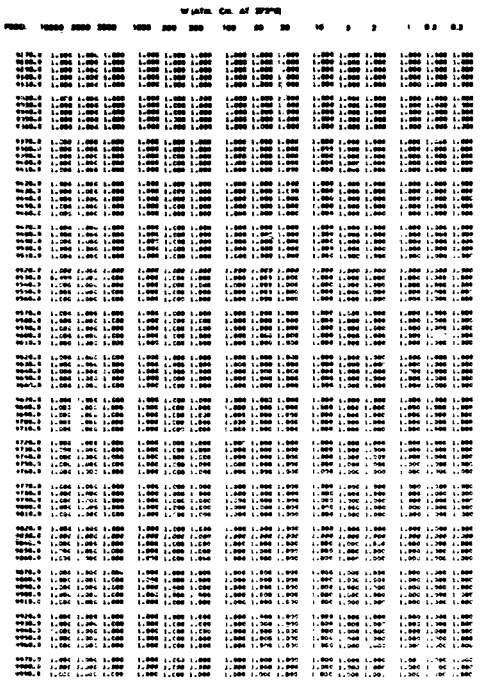
T=200° K

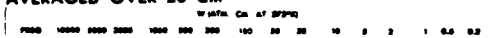
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE
T=200° K
AVERAGED OVER 20 Cm^{-1}







CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

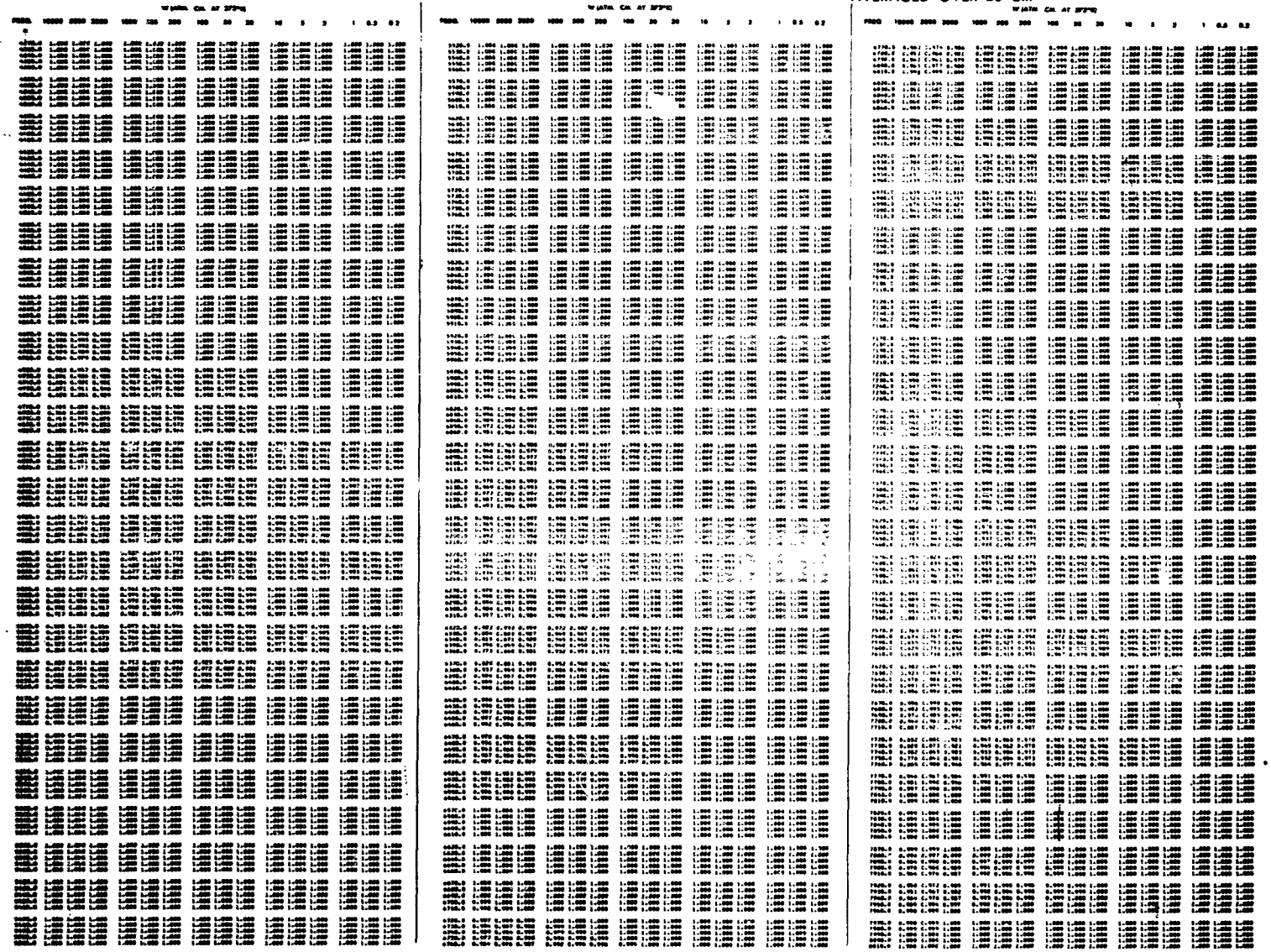
T-200° K

AVERAGED OVER 20 Cm^{-1}

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T=200° K

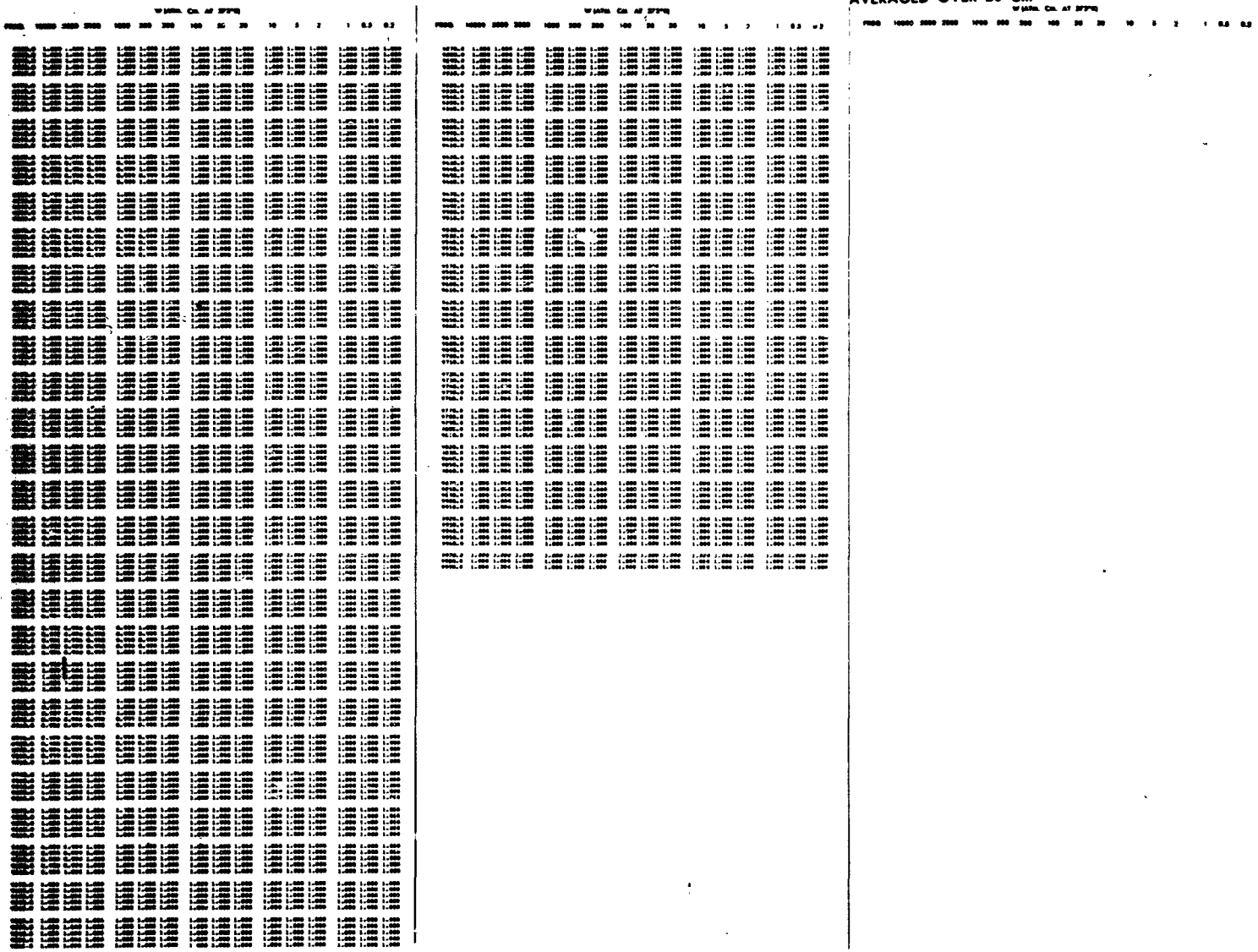
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

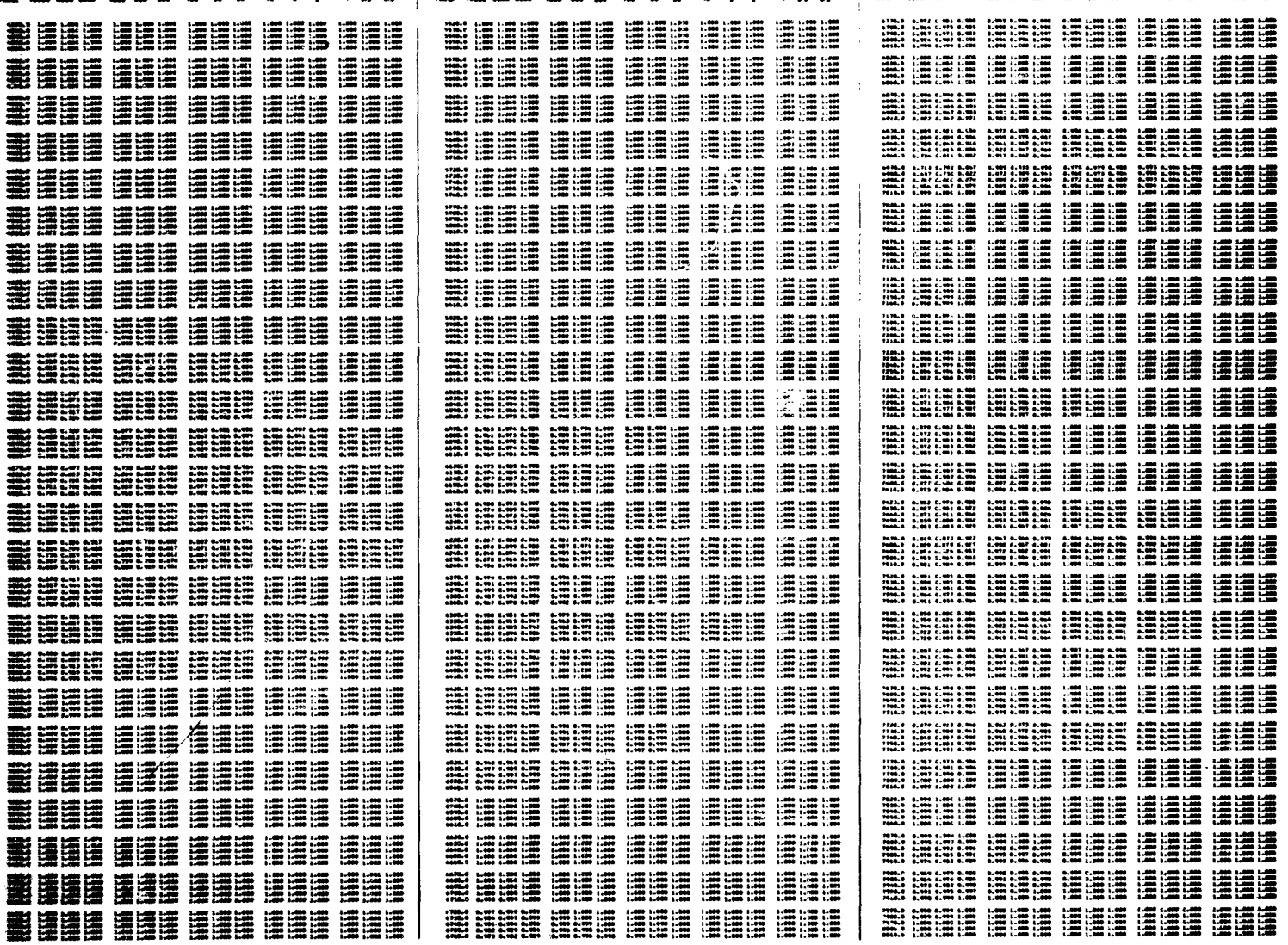
T=200° K

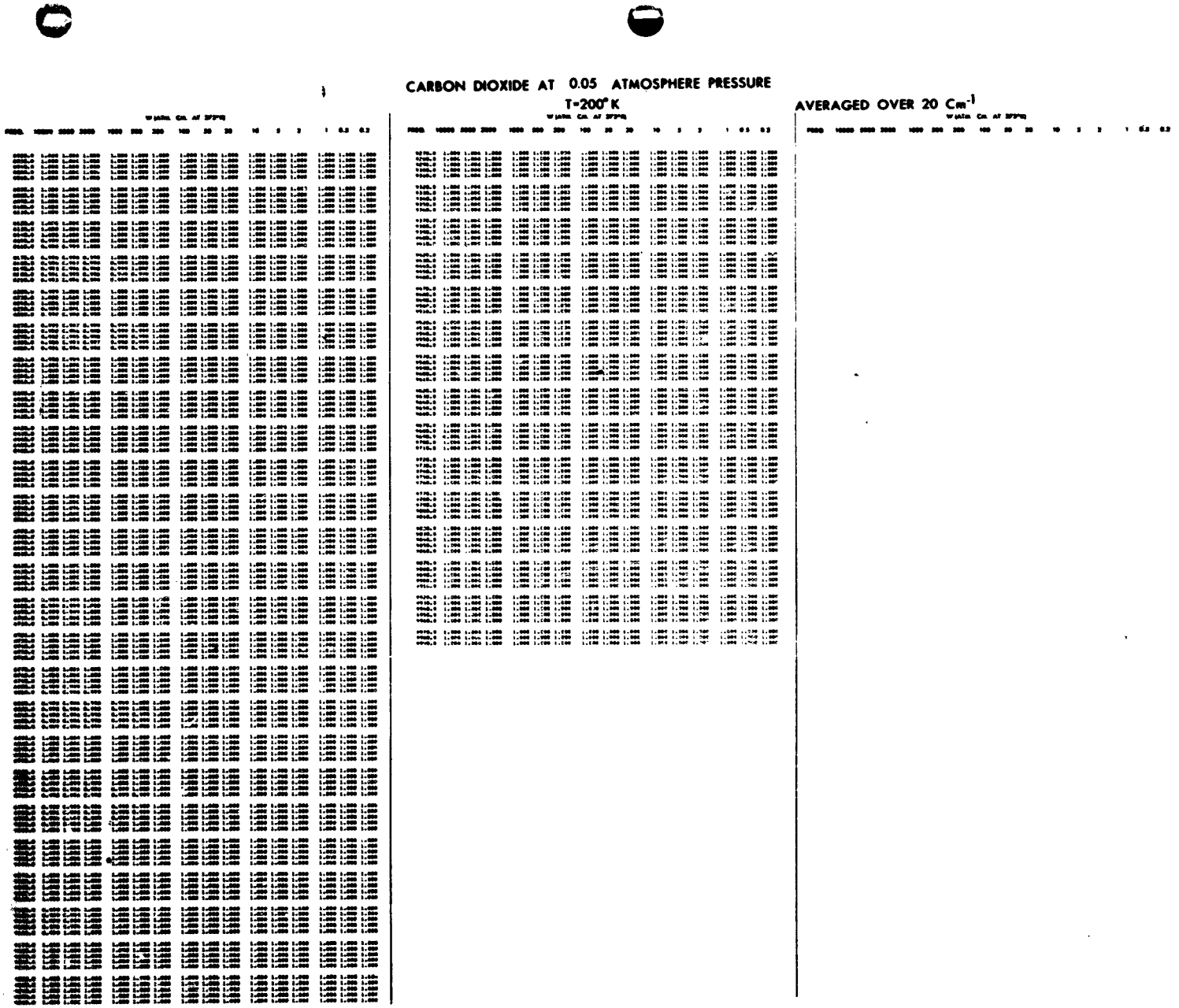
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T-200° K
AVERAGED OVER 20 Cm-1

CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T=200° K
AVERAGED OVER 20 Cm^{-1}

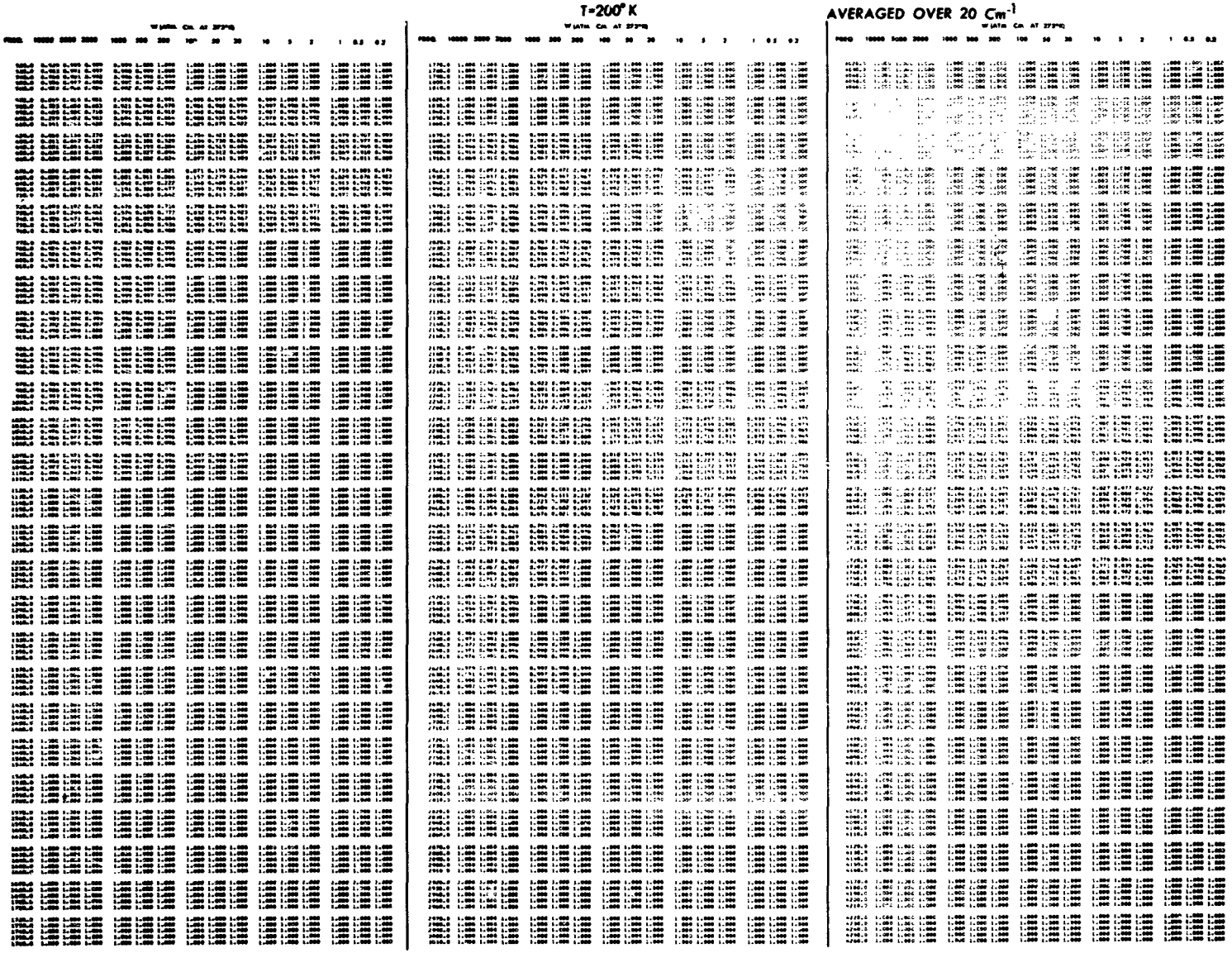



CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T=200°K
AVERAGED OVER 20 Cm-1

CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T=200° K

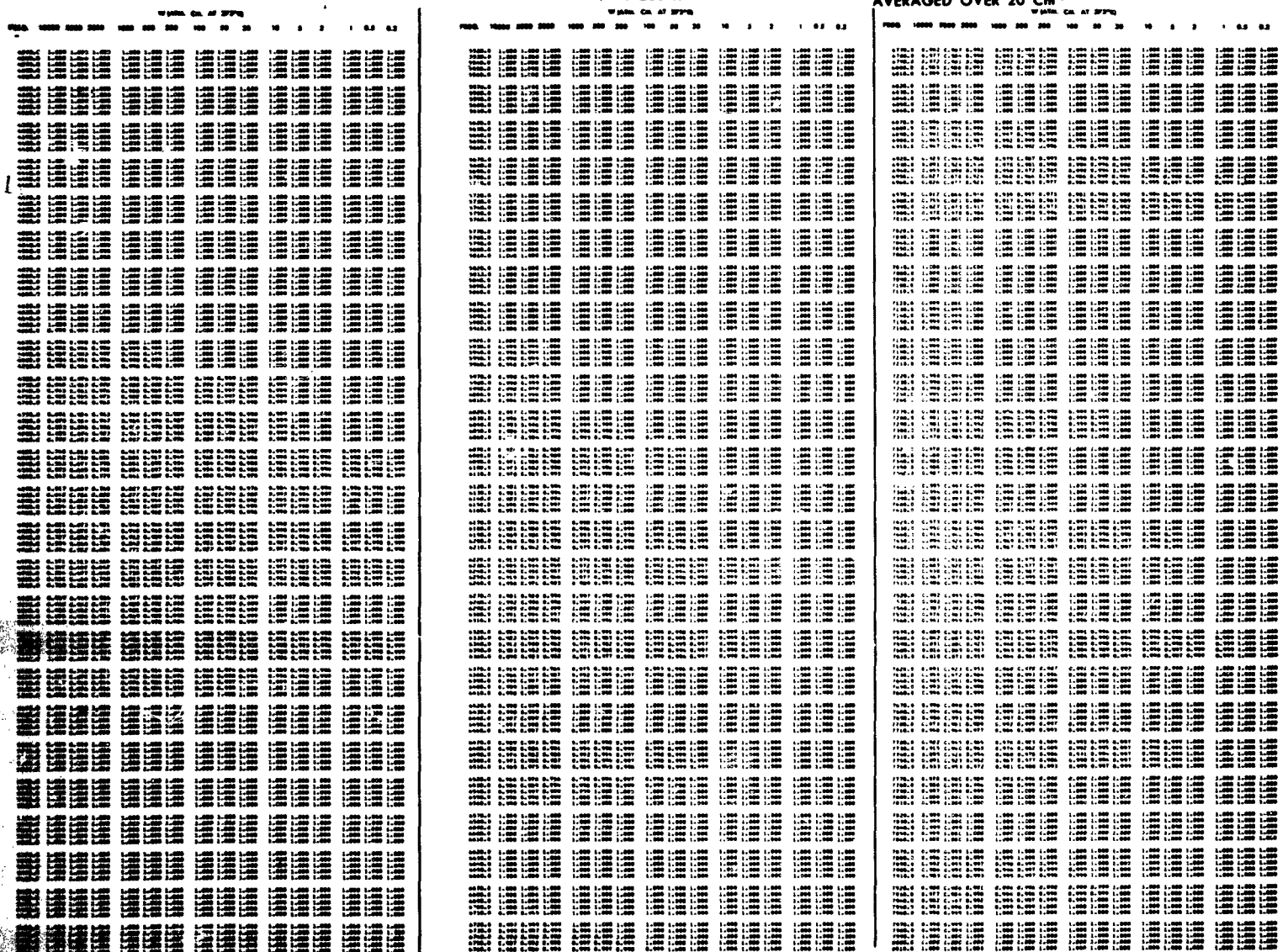
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

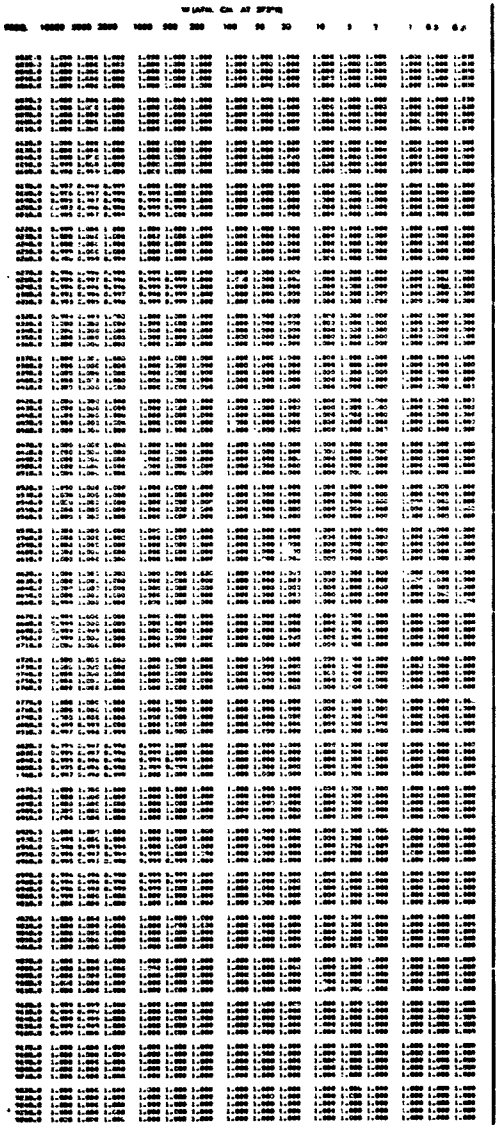
T=200° K

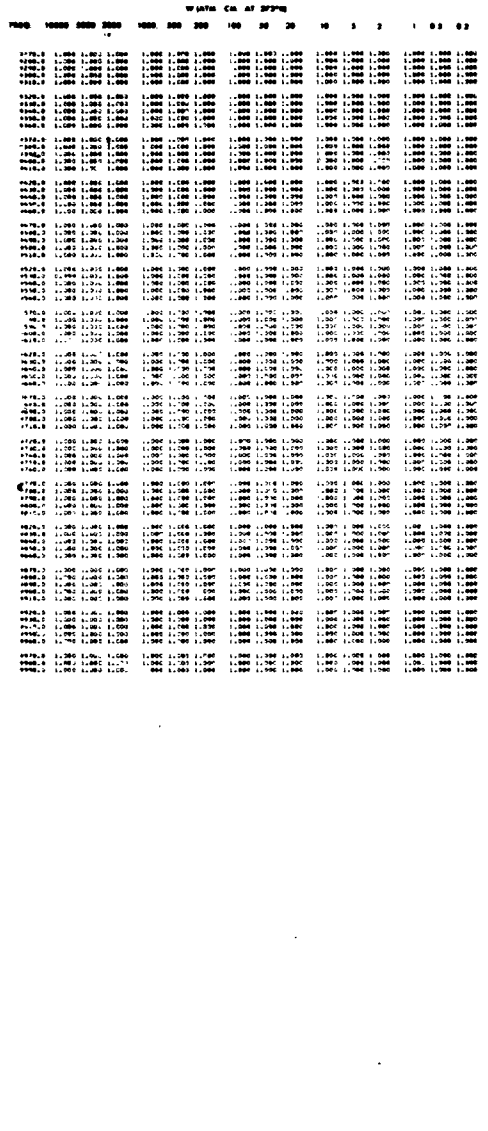
AVERAGED OVER 20 Cm^{-1}



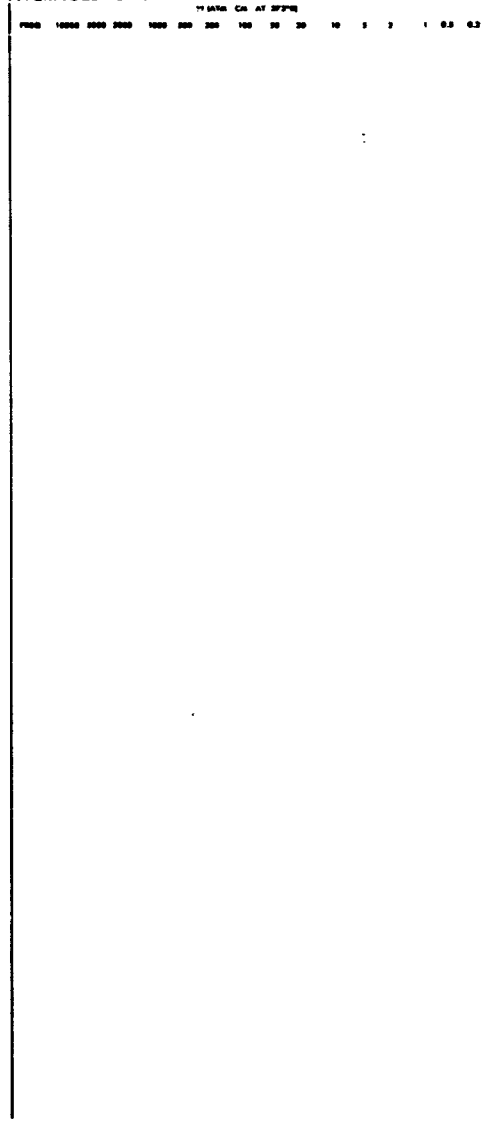
CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T=200° K





AVERAGED OVER 20 Cm^{-1}



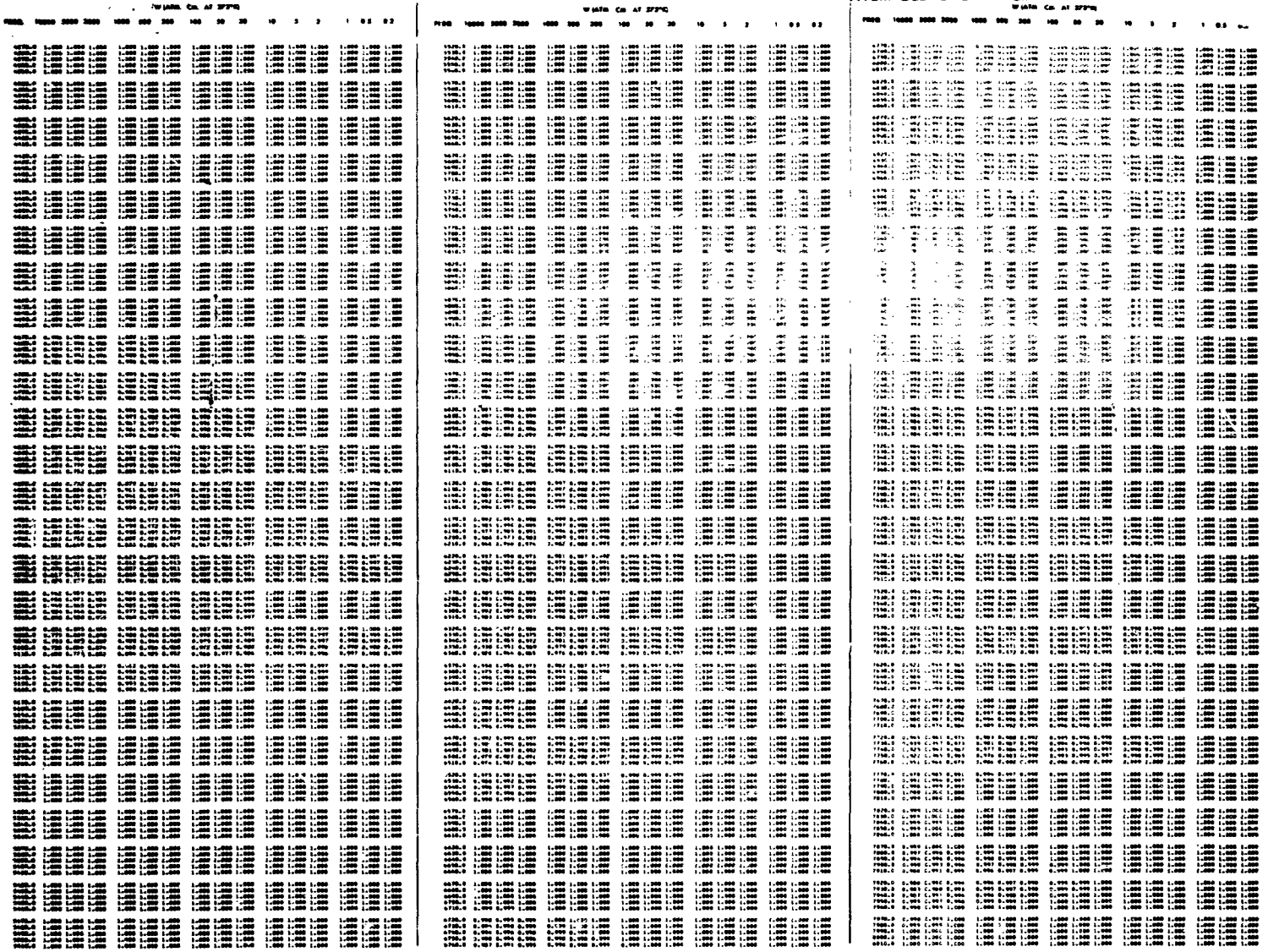
CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE
T=200° K

AVERAGED OVER 20 Cm^{-1}

CARBON DIOXIDE ΔT 0.01 ATMOSPHERE PRESSURE

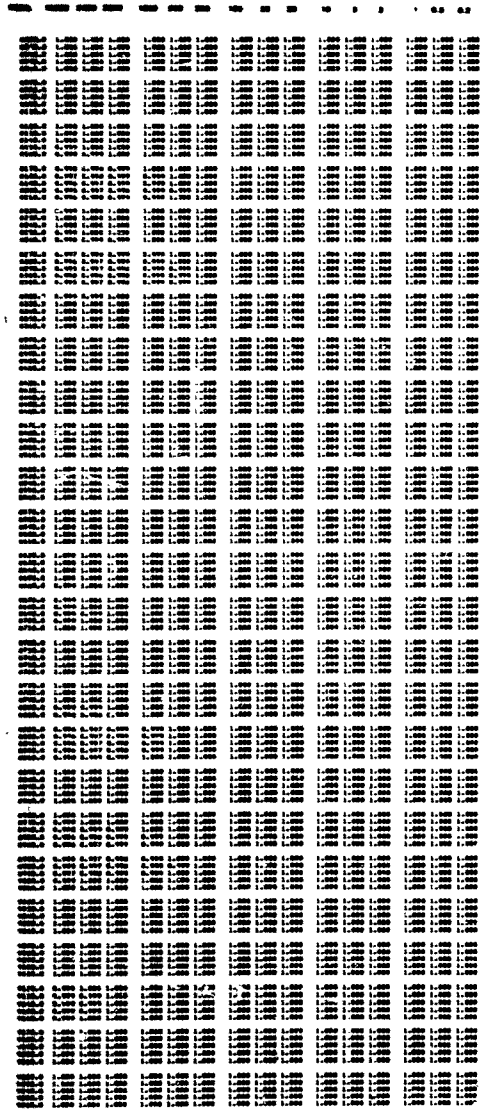
T=200° K

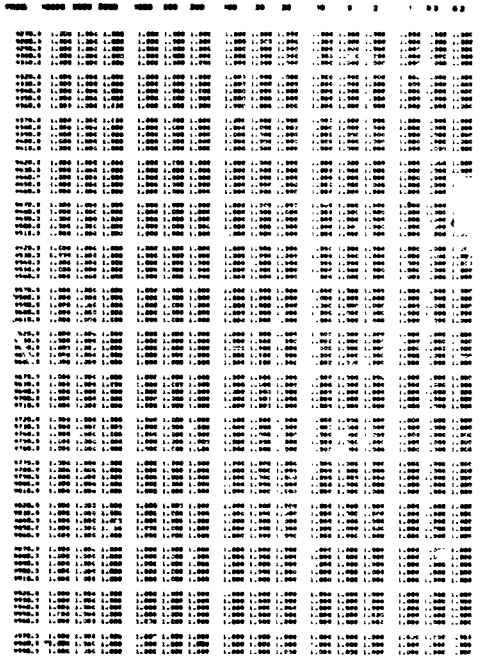
AVERAGED OVER 20 Cm^{-1}



CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE
T=200° K

AVERAGED OVER 20 Cm^{-1}





APPENDIX F

CARBON DIOXIDE TRANSMISSIONS AVERAGED OVER 50 cm^{-1} WITH ENTRIES EVERY 25 cm^{-1}

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

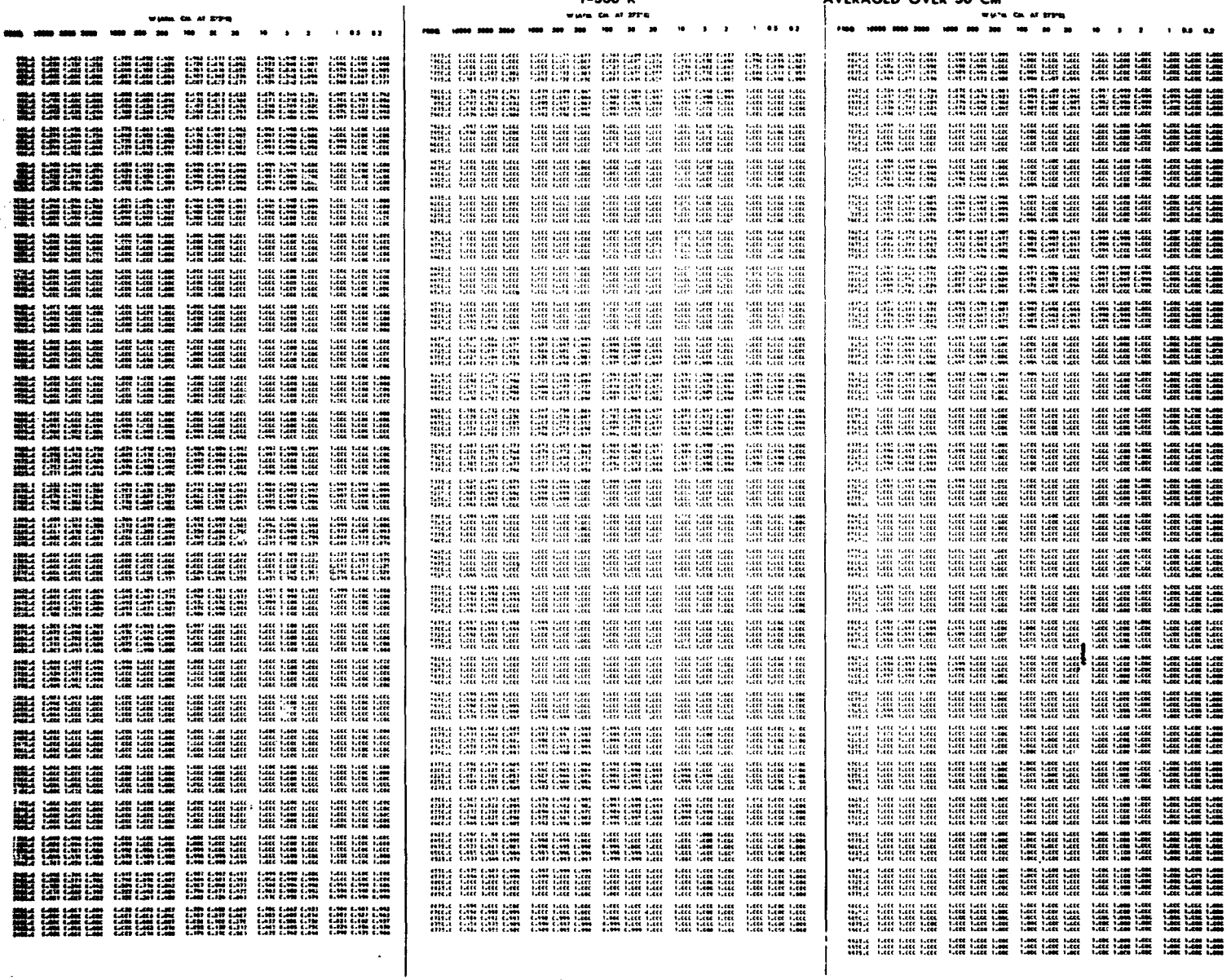
T=300° K

AVERAGED OVER 50 Cm^{-1}

CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=300° K

AVERAGED OVER 50 Cm^{-1}



CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE
T-300° K

AVERAGED OVER 50 Cm^{-1}

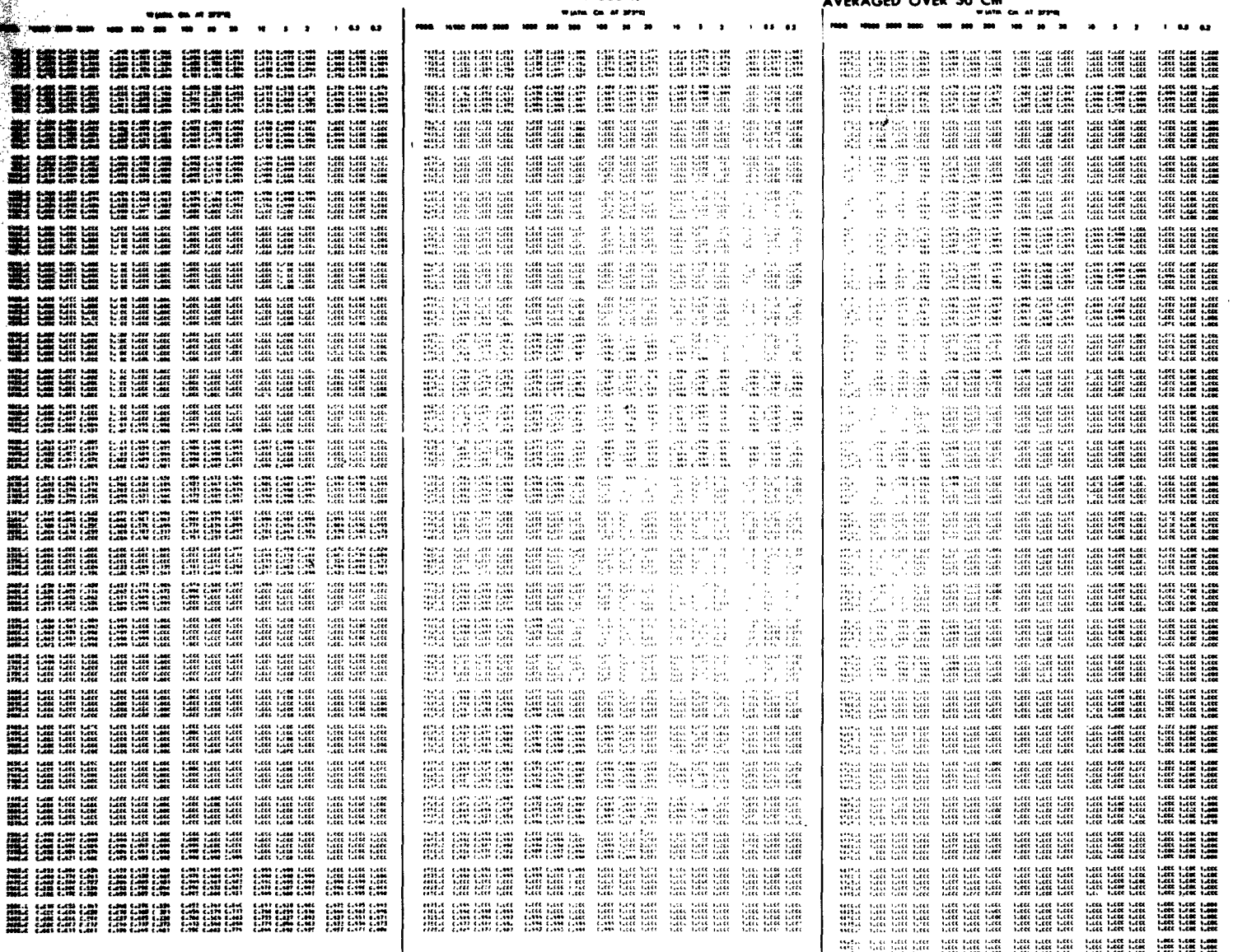
AVERAGED OVER 50 Cm⁻¹

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE
T-300° K

CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T=300° K

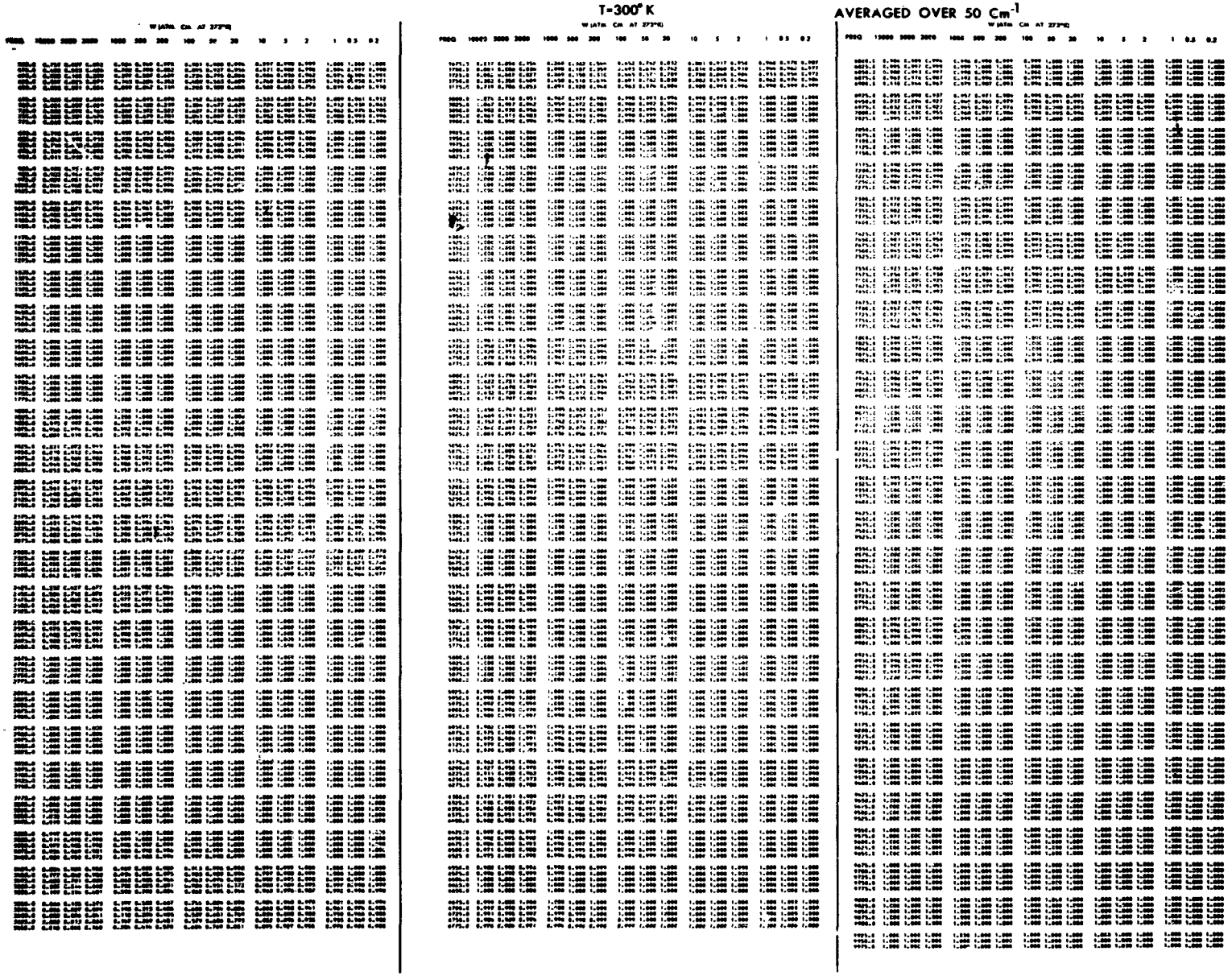
AVERAGED OVER 50 Cm^{-1}



CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T=300° K

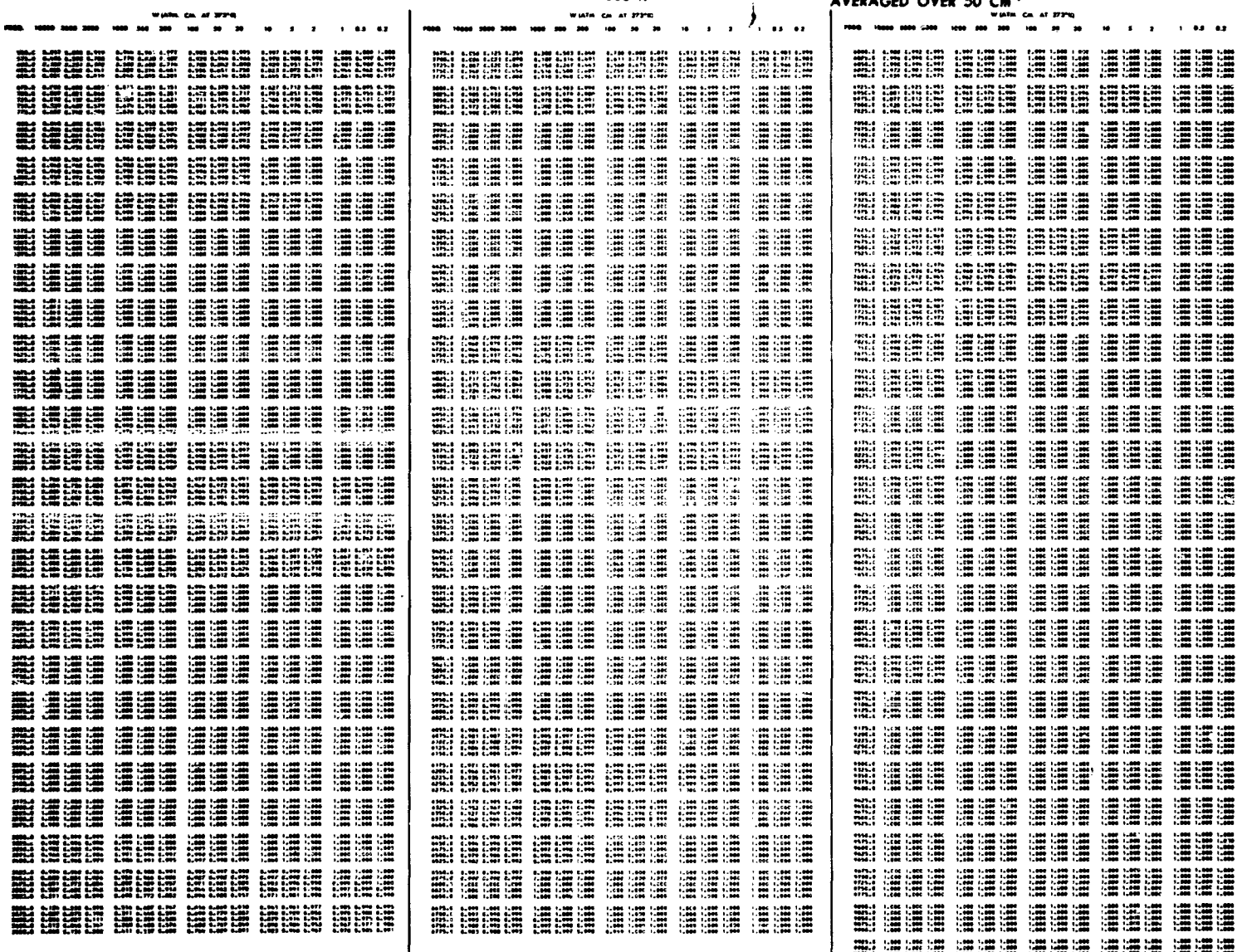
AVERAGED OVER 50 Cm^{-1}



CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T=300° K

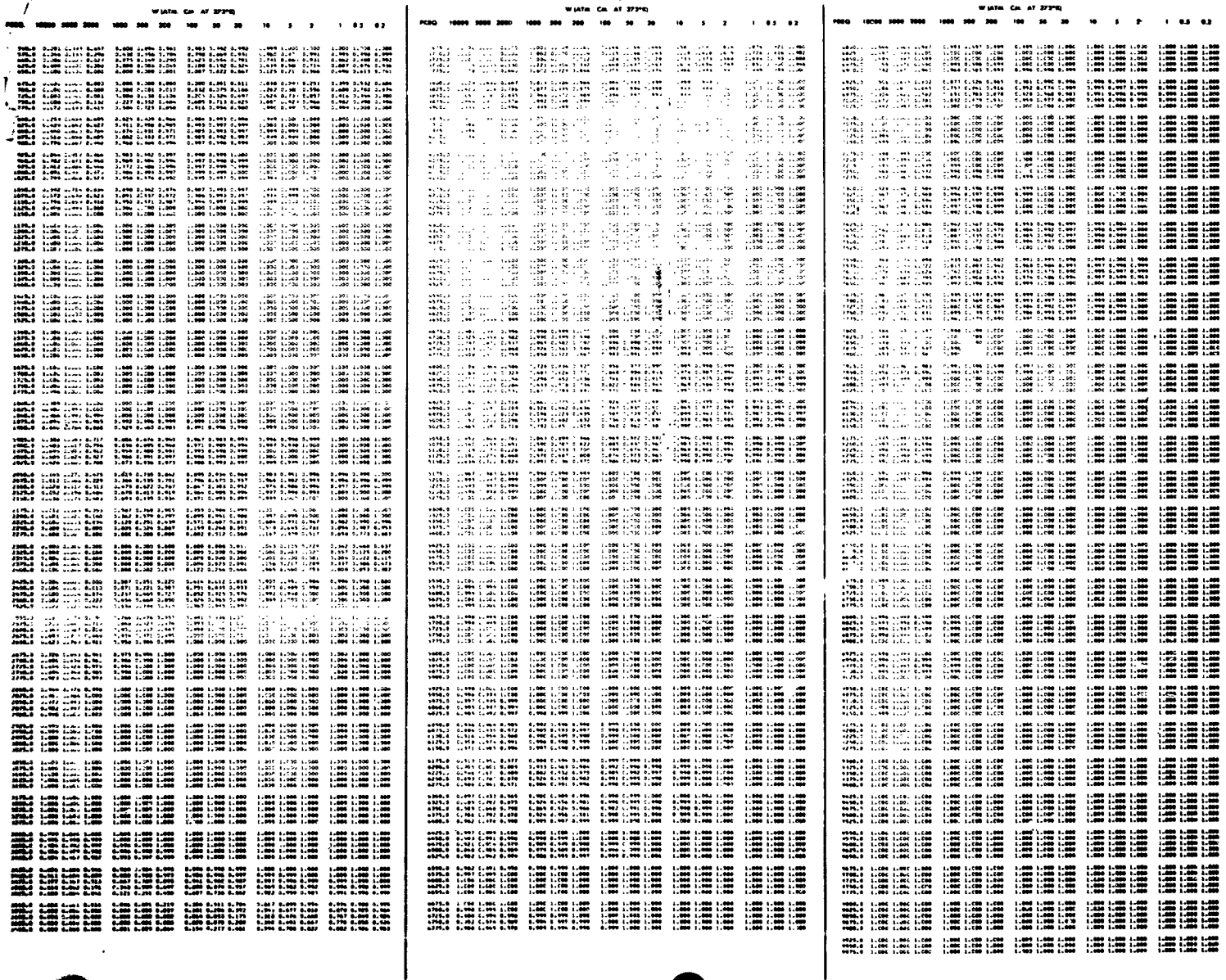
AVERAGED OVER 50 Cm^{-1}



CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=250° K

AVERAGED OVER 50 Cm^{-1}



CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

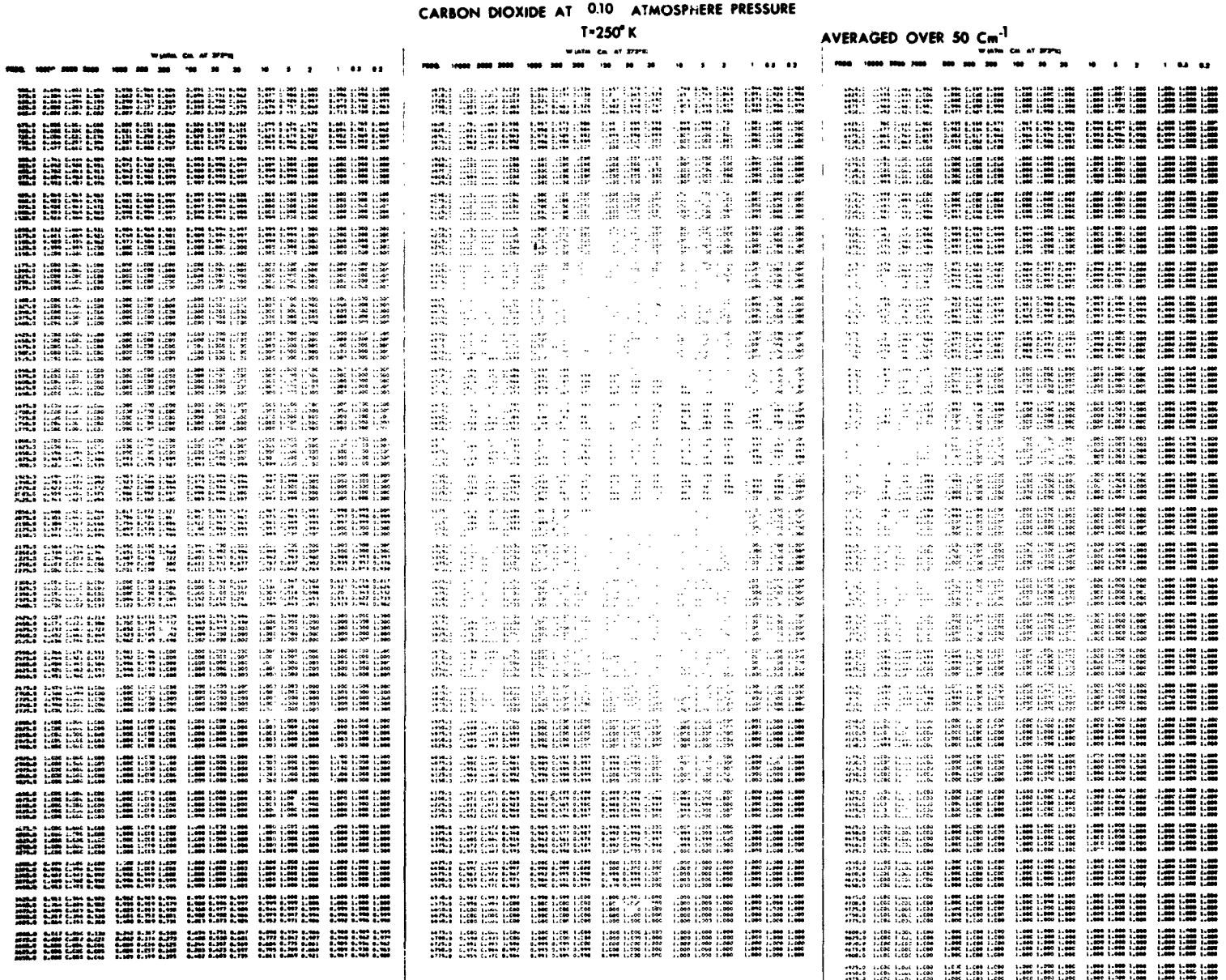
T=250° K

AVERAGED OVER 50 Cm^{-1}

CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=250° K

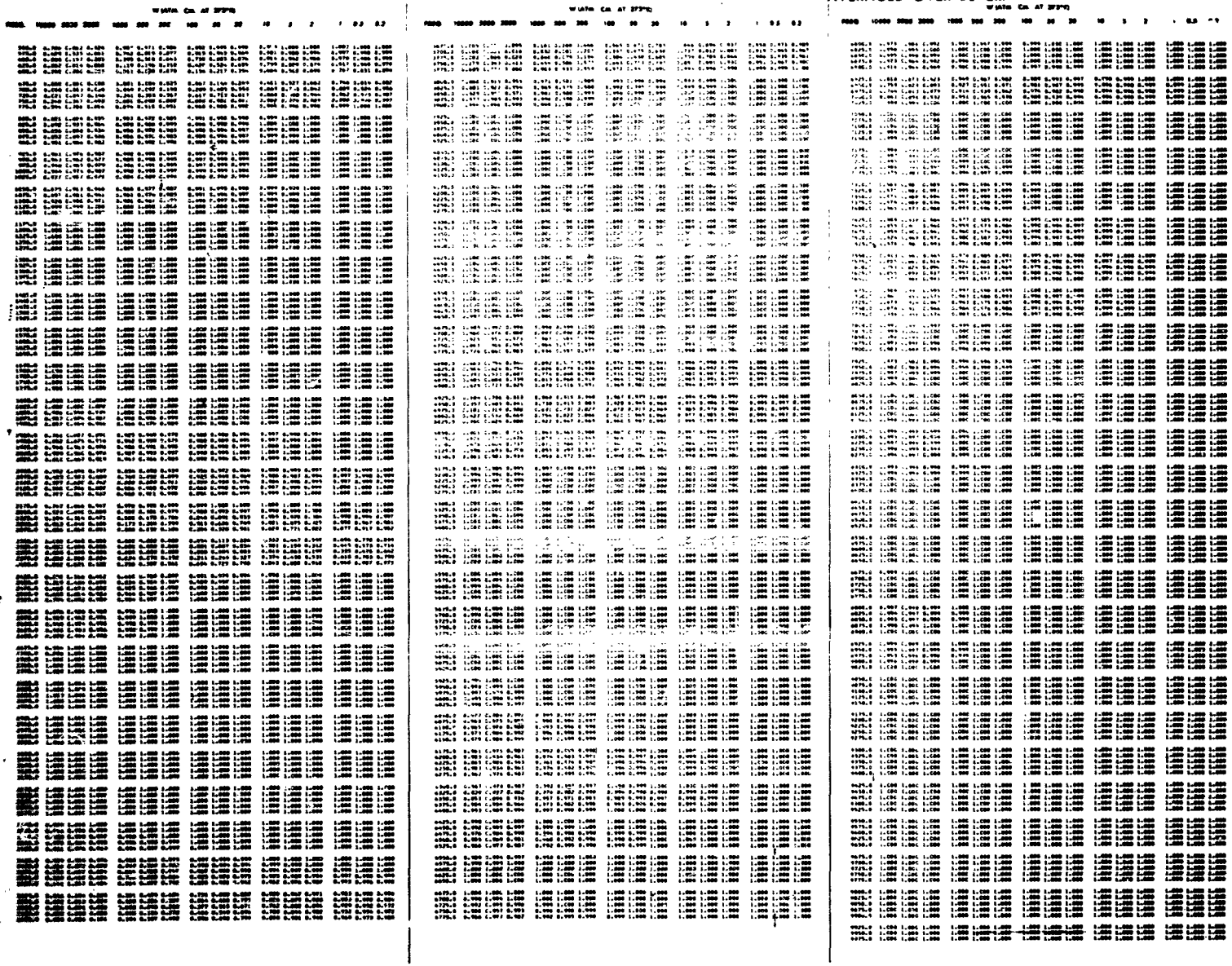
AVERAGED OVER 50 Cm^{-1}


CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE
T=250° K
AVERAGED OVER 50 Cm-1

CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T=250° K

AVERAGED OVER 50 Cm^{-1}



CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE
T-250° K

AVERAGED OVER 50 Cm^{-1}

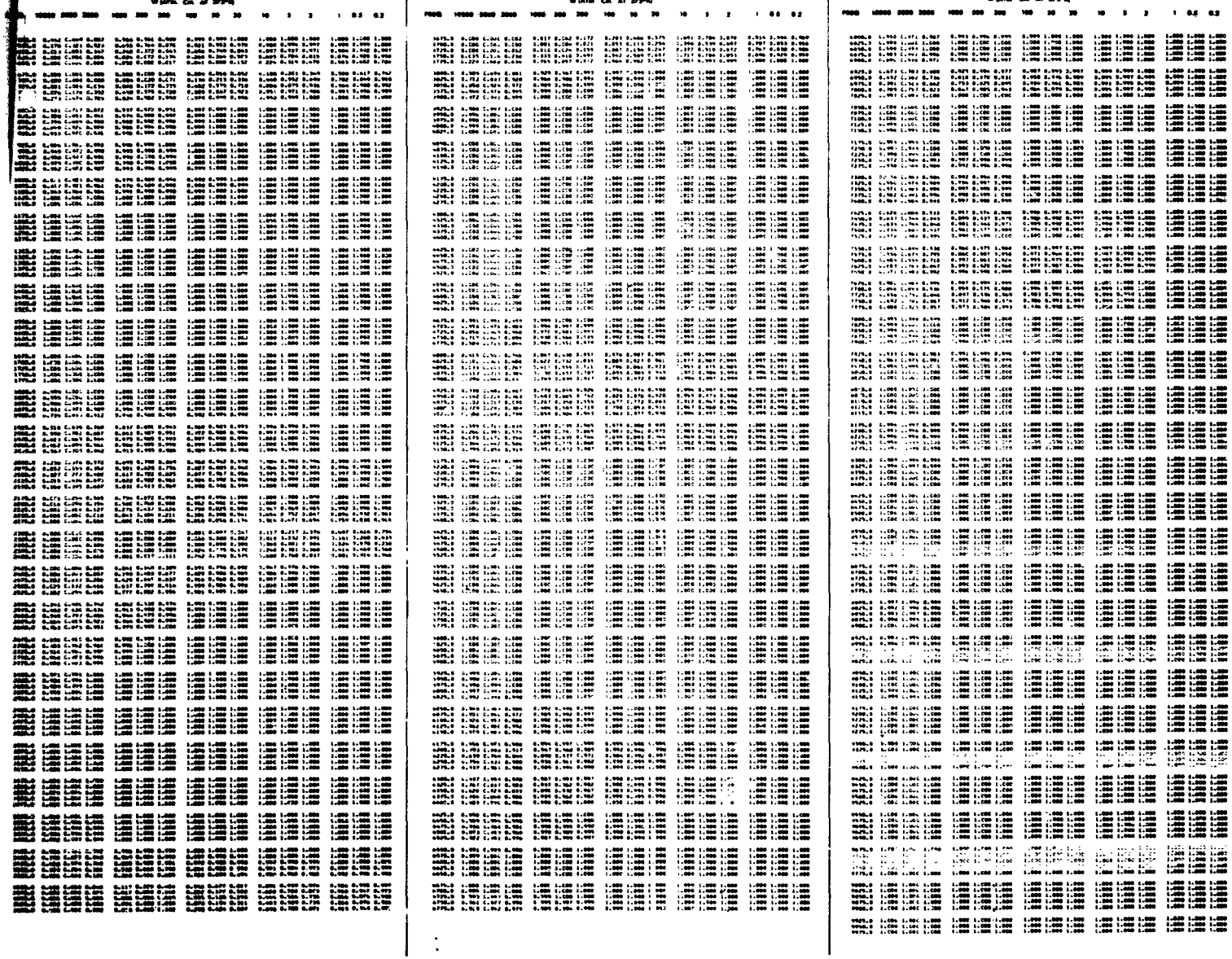
CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE
T=250° K
AVERAGED OVER 50 Cm-1

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T-200° K

AVERAGED OVER 50 Cm^{-1}

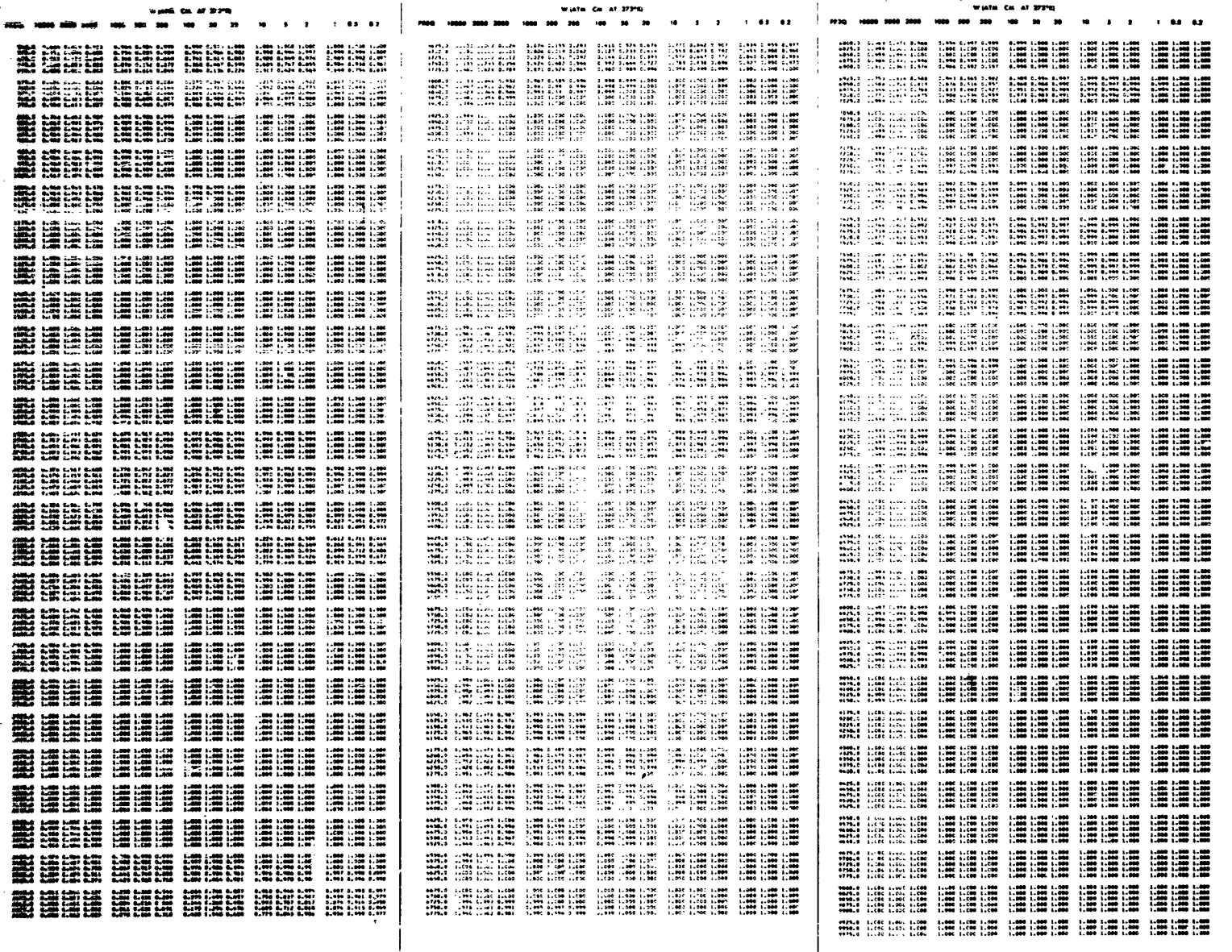
CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE
T=200° K
AVERAGED OVER 50 Cm^{-1}



CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

T=200° K

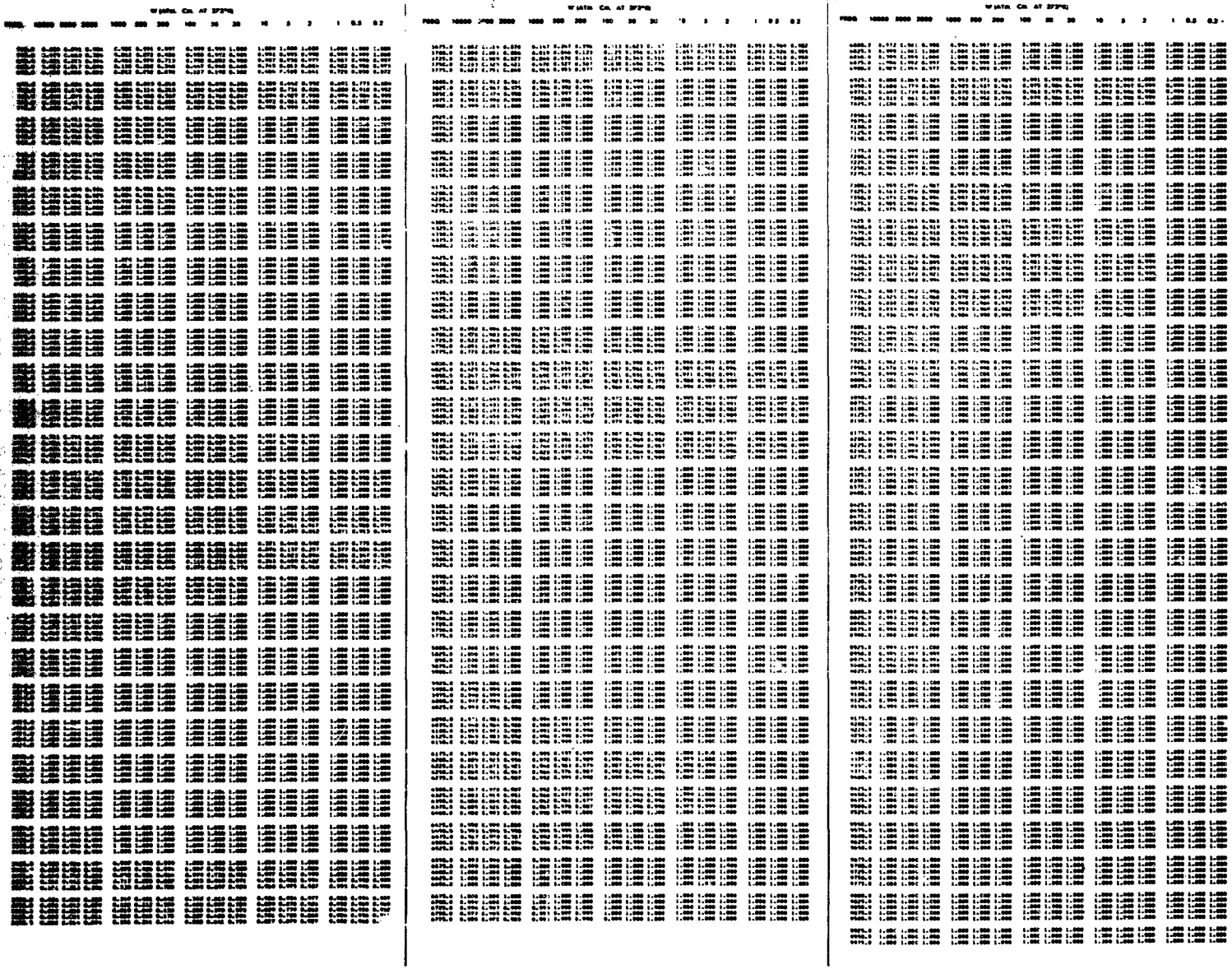
AVERAGED OVER 50 Cm^{-1}



CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T=200° K

AVERAGED OVER 50 Cm^{-1}

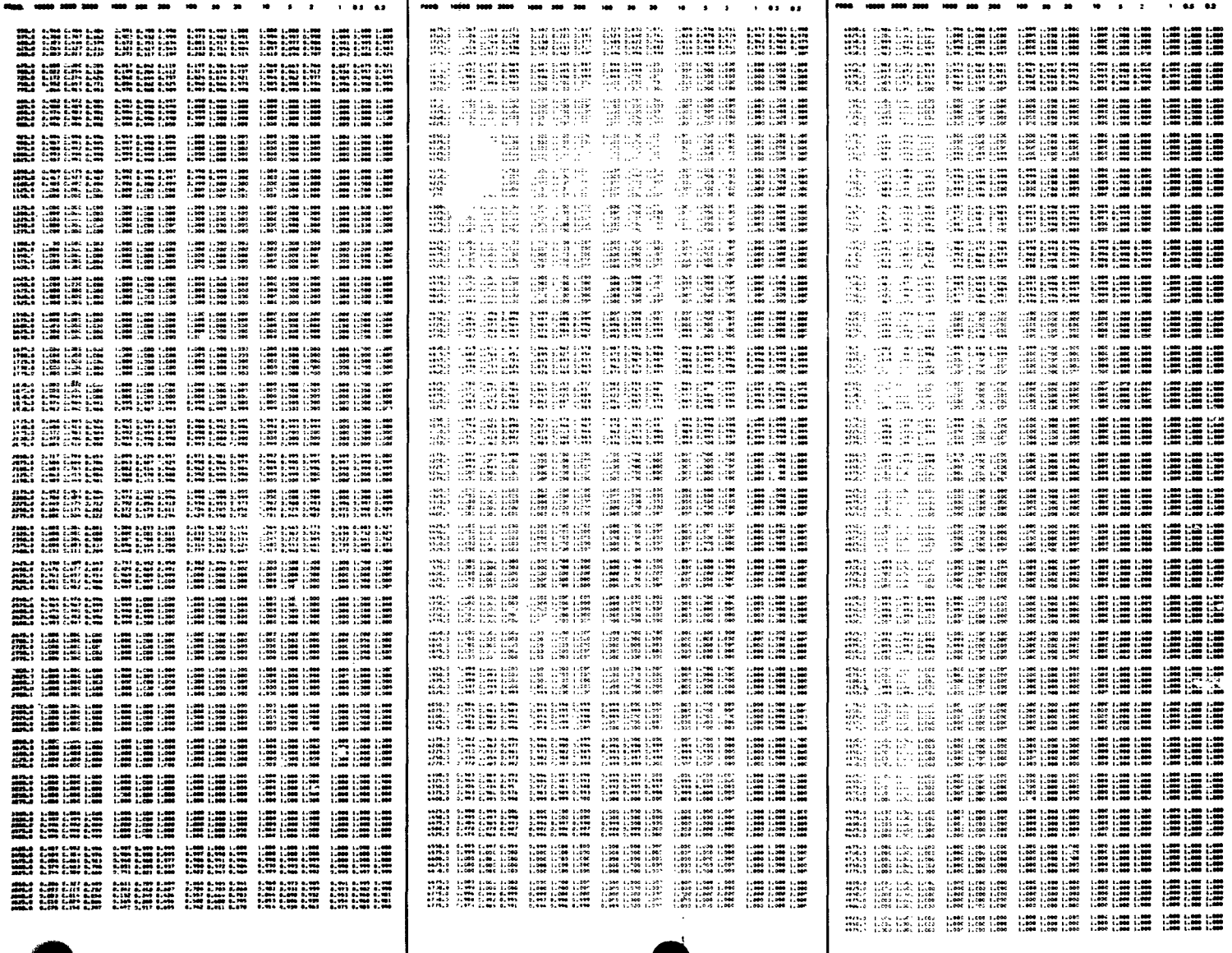


CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE
T=200° K
AVERAGED OVER 50 Cm^{-1}

CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T=200° K

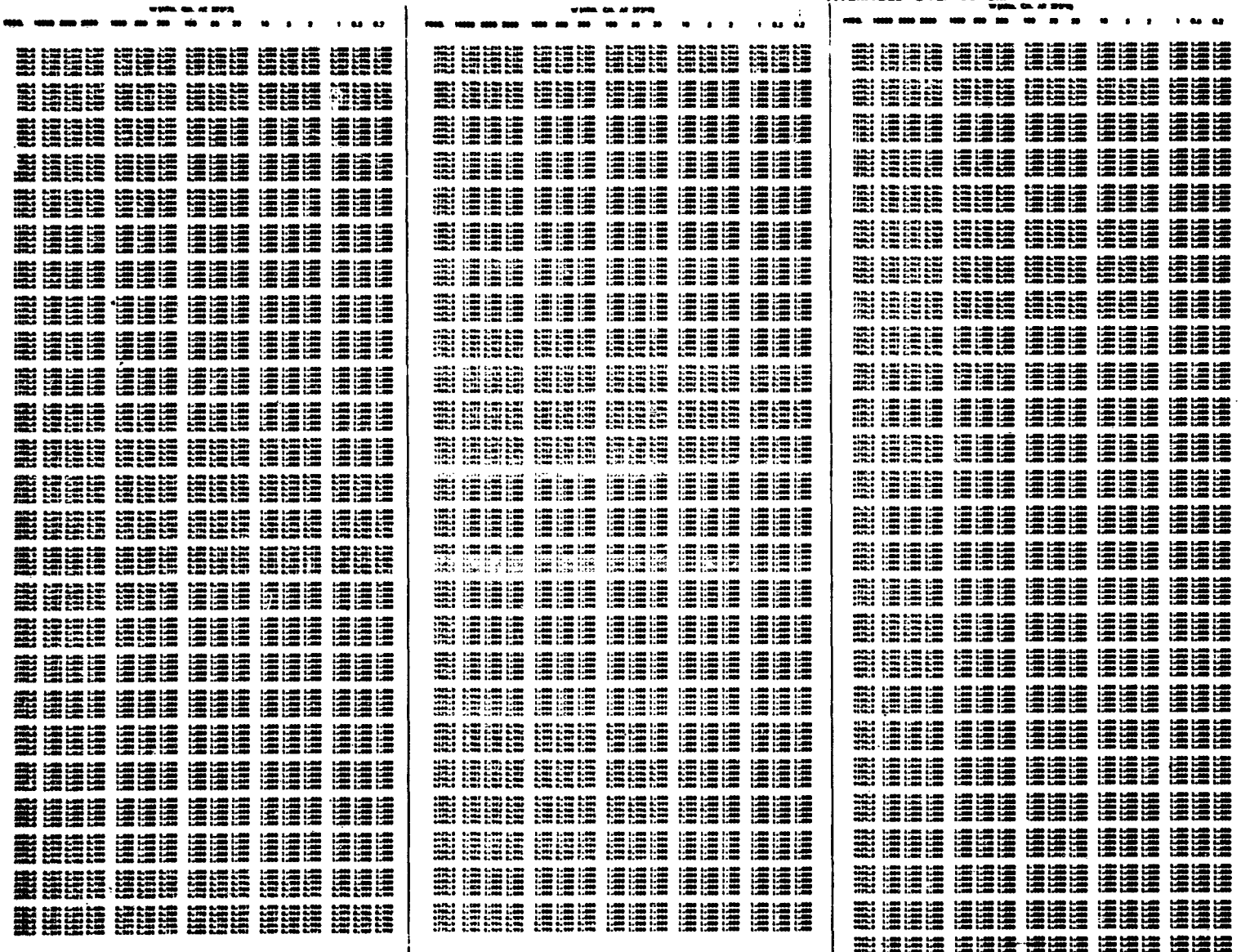
AVERAGED OVER 50 Cm^{-1}



CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE

T=200° K

AVERAGED OVER 50 Cm^{-1}



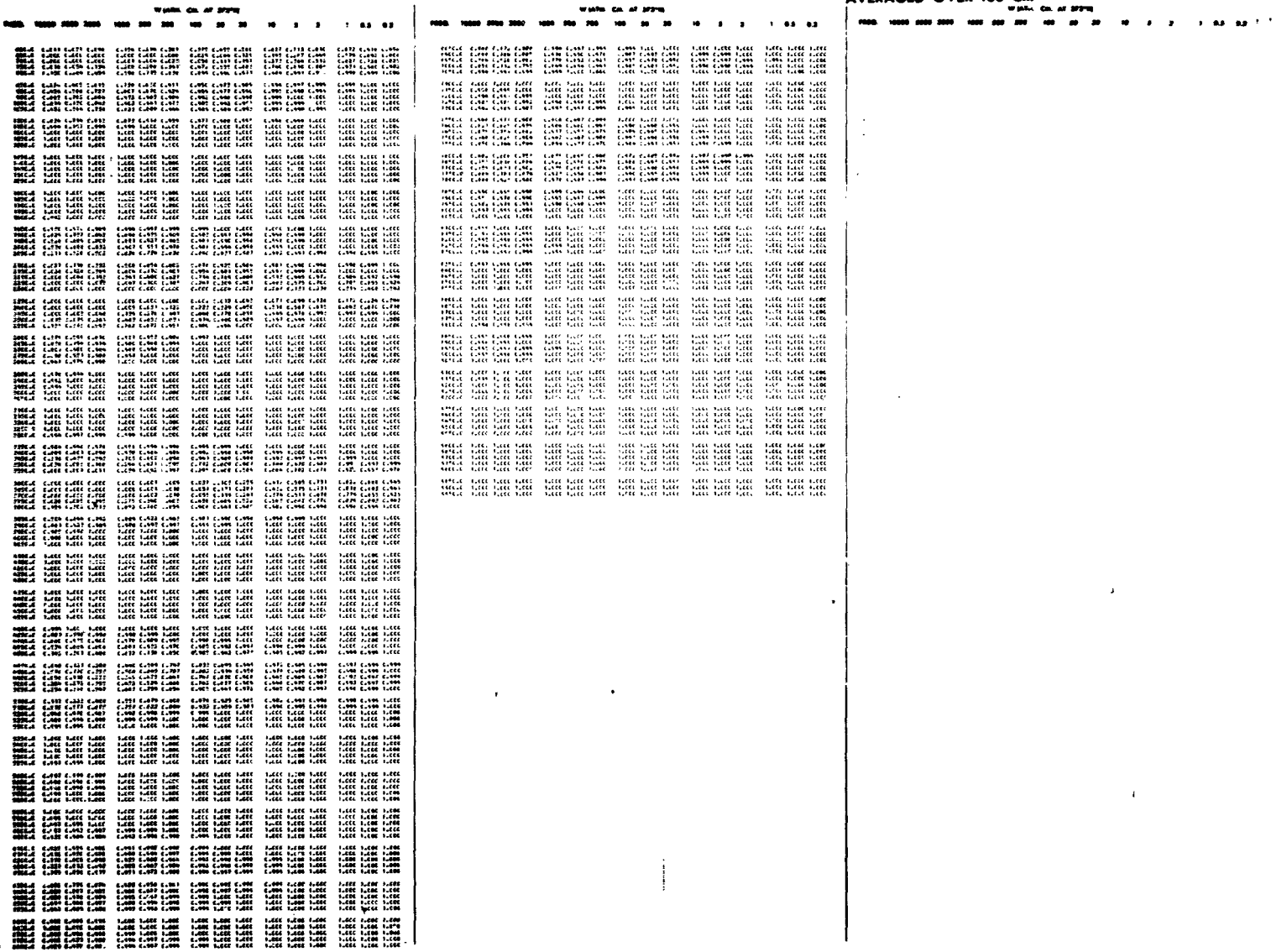
APPENDIX G

CARBON DIOXIDE TRANSMISSIONS AVERAGED OVER 100 cm^{-1} WITH ENTRIES EVERY 50 cm^{-1}

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=300° K

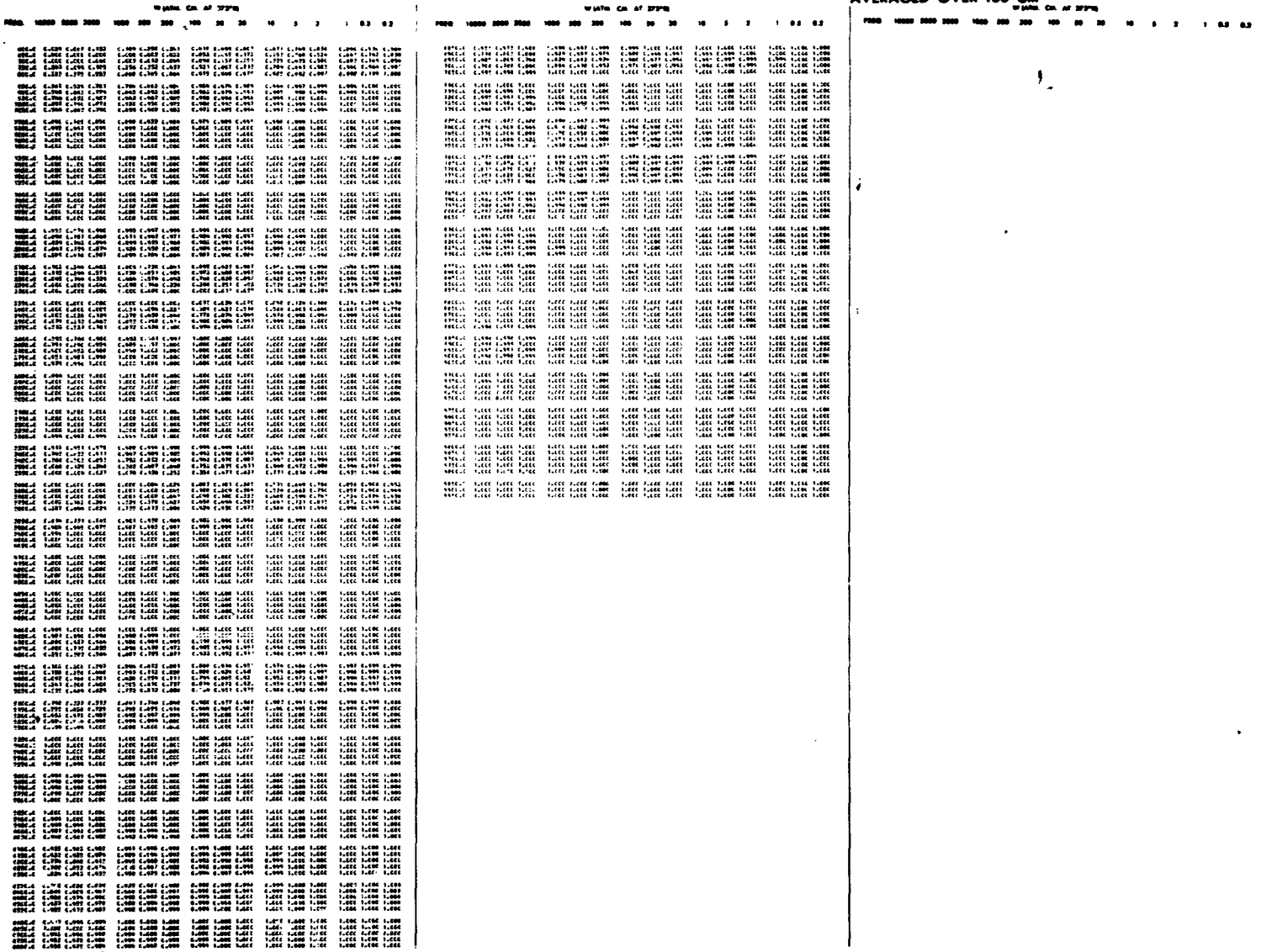
AVERAGED OVER 100 Cm^{-1}



CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE

T=300° K

AVERAGED OVER 100 Cm^{-1}



AVERAGED OVER 100 Cm⁻¹
CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE
T=300° K

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T=300° K

AVERAGED OVER 100 Cm^{-1}

CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

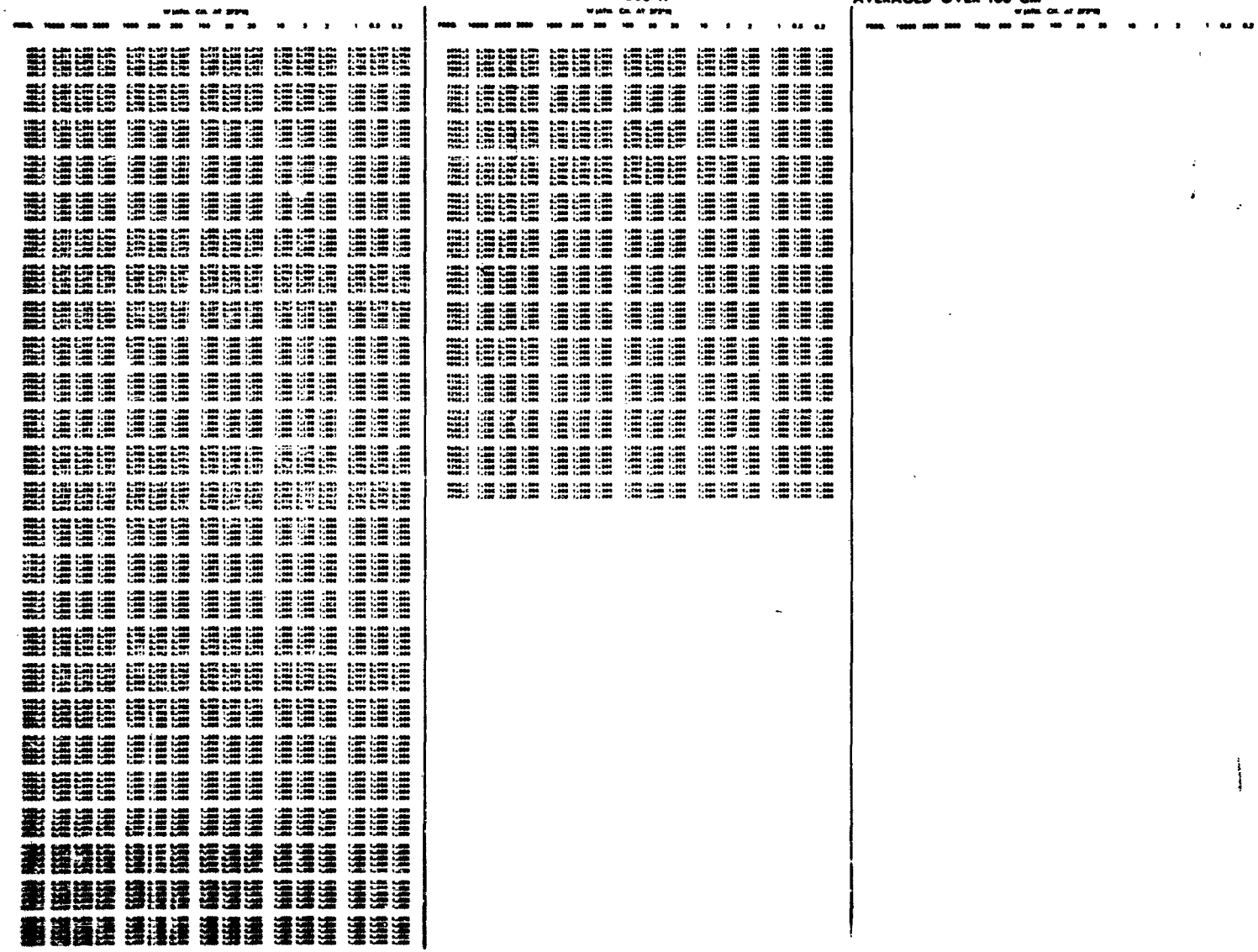
T=300° K

AVERAGED OVER 100 Cm^{-1}

CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE

T=300° K

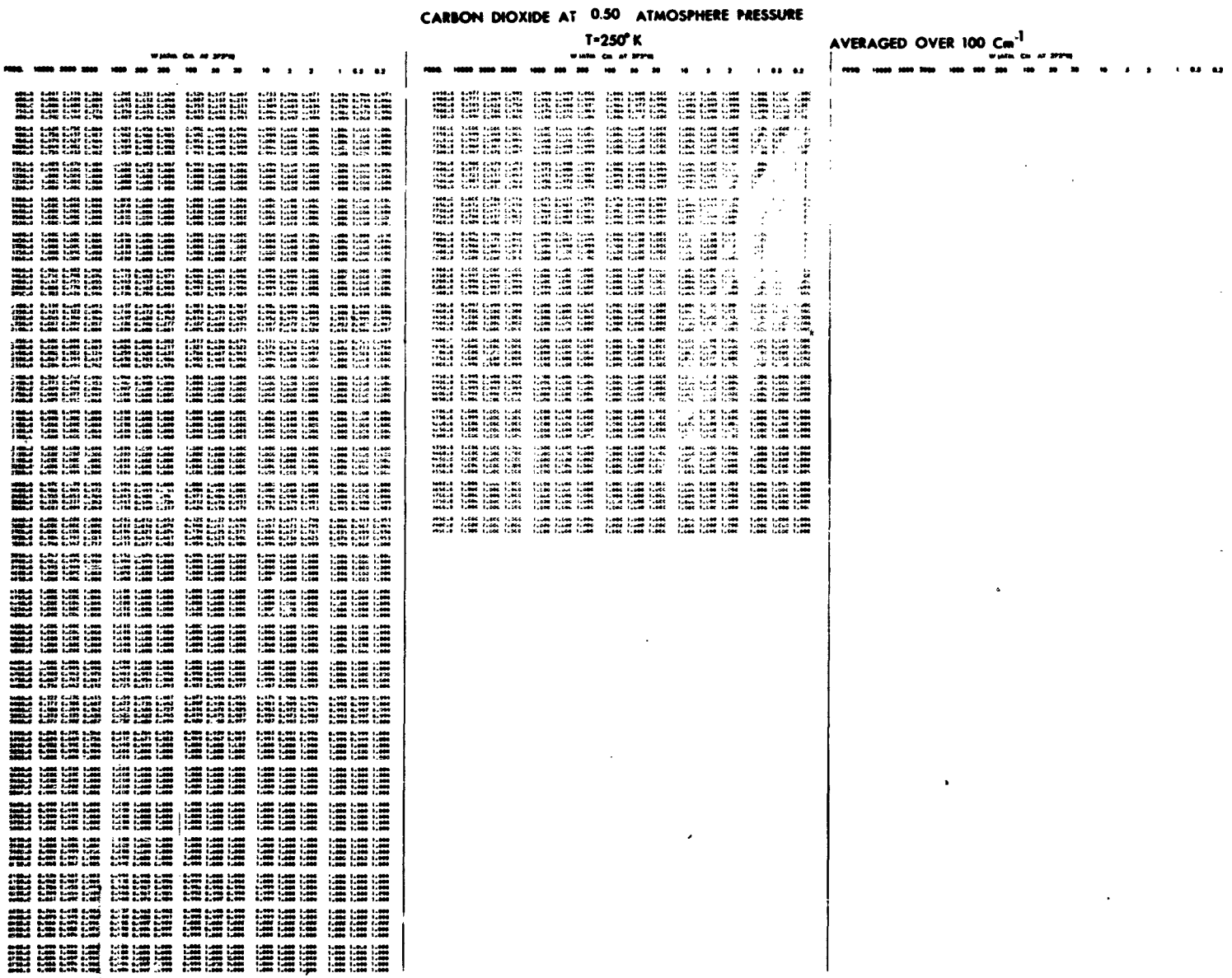
AVERAGED OVER 100 Cm^{-1}


CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE
T=300° K
AVERAGED OVER 100 Cm-1

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE

T=250° K

AVERAGED OVER 100 Cm^{-1}


CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE
T=250° K
AVERAGED OVER 100 Cm-1

CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE

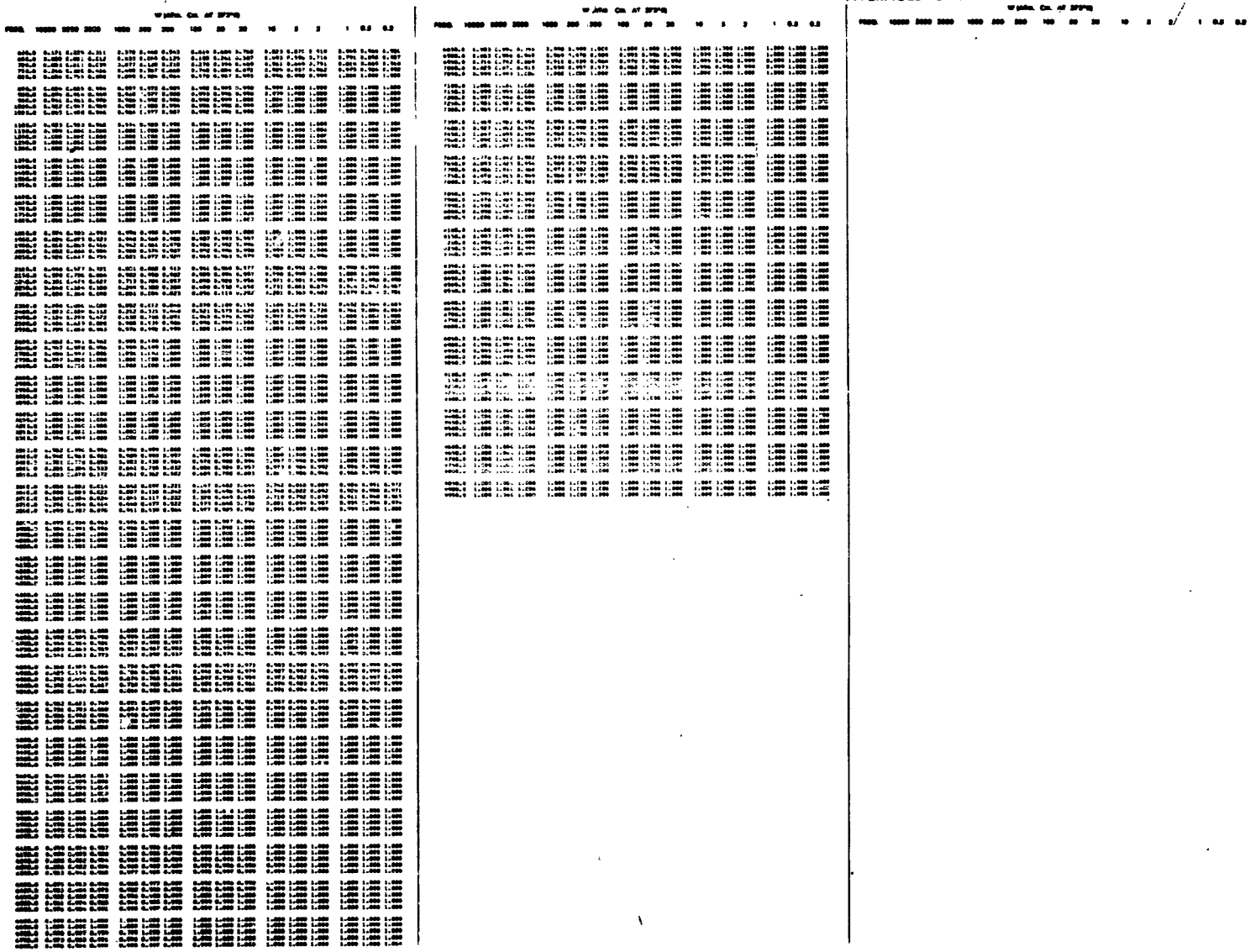
T=250° K

AVERAGED OVER 100 Cm^{-1}

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T=250° K

AVERAGED OVER 100 Cm^{-1}



CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

T-250° K

AVERAGED OVER 100 Cm^{-1}

CARBON DIOXIDE AT 0.02 ATMOSPHERE PRESSURE
T=250° K
AVERAGED OVER 100 Cm⁻¹

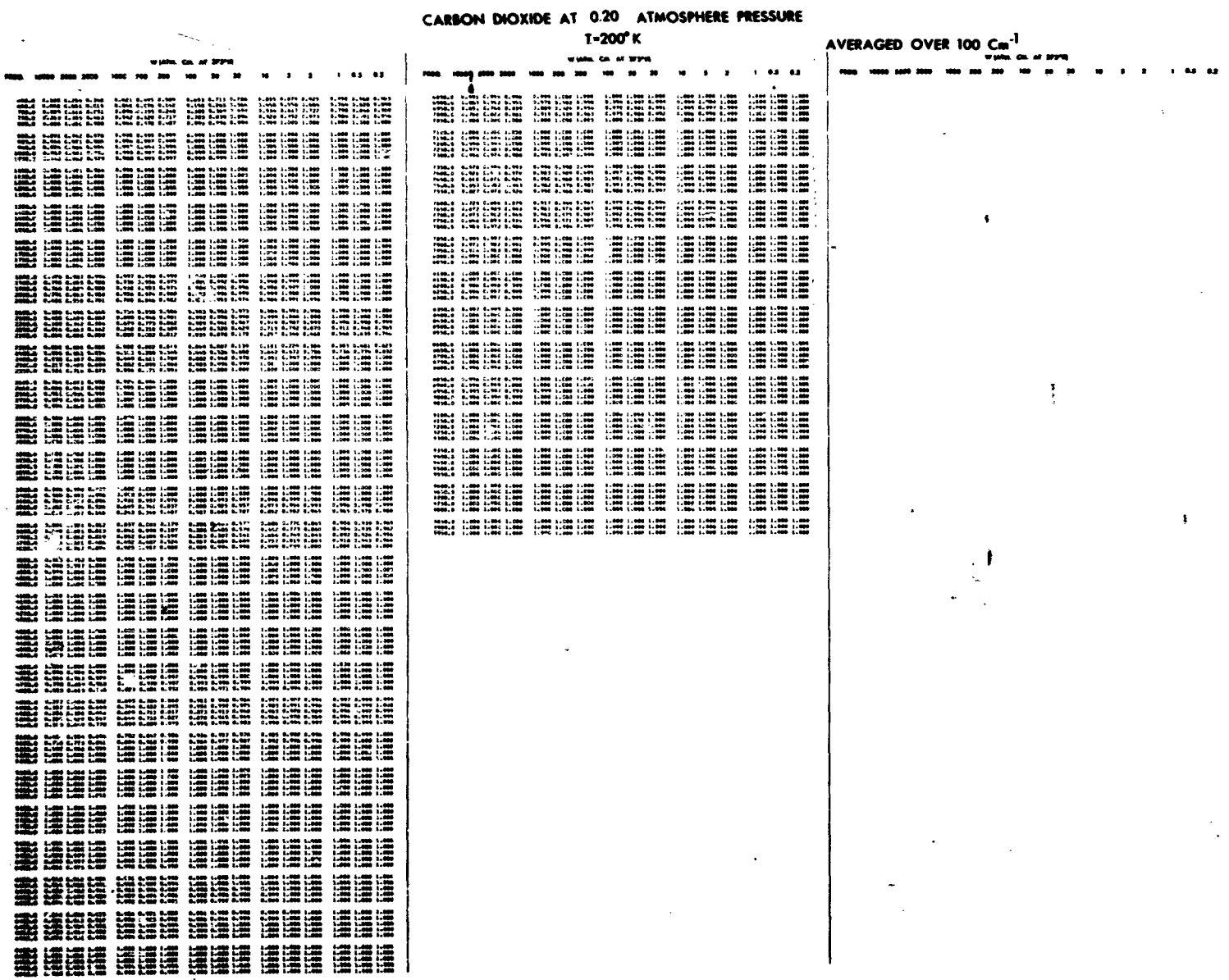
CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE
T=250° K

AVERAGED OVER 100 Cm^{-1}

CARBON DIOXIDE AT 1.00 ATMOSPHERE PRESSURE
T=200° K
AVERAGED OVER 100 Cm^{-1}

AVERAGED OVER 100 cm⁻¹

CARBON DIOXIDE AT 0.50 ATMOSPHERE PRESSURE
T=200° K


CARBON DIOXIDE AT 0.20 ATMOSPHERE PRESSURE
T=200° K
AVERAGED OVER 100 Cm-1

CARBON DIOXIDE AT 0.10 ATMOSPHERE PRESSURE

T=200°K

AVERAGED OVER 100 Cm^{-1}

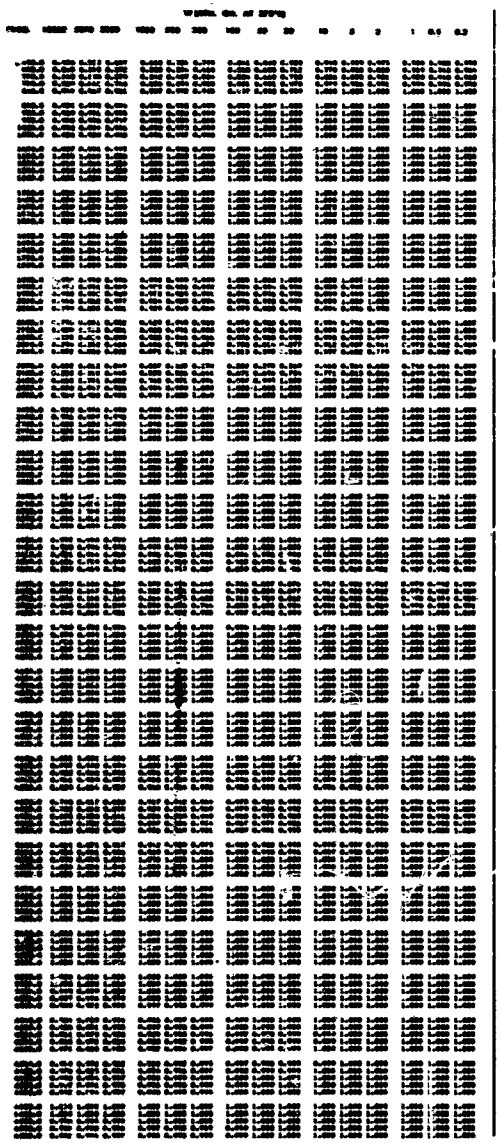
CARBON DIOXIDE AT 0.05 ATMOSPHERE PRESSURE

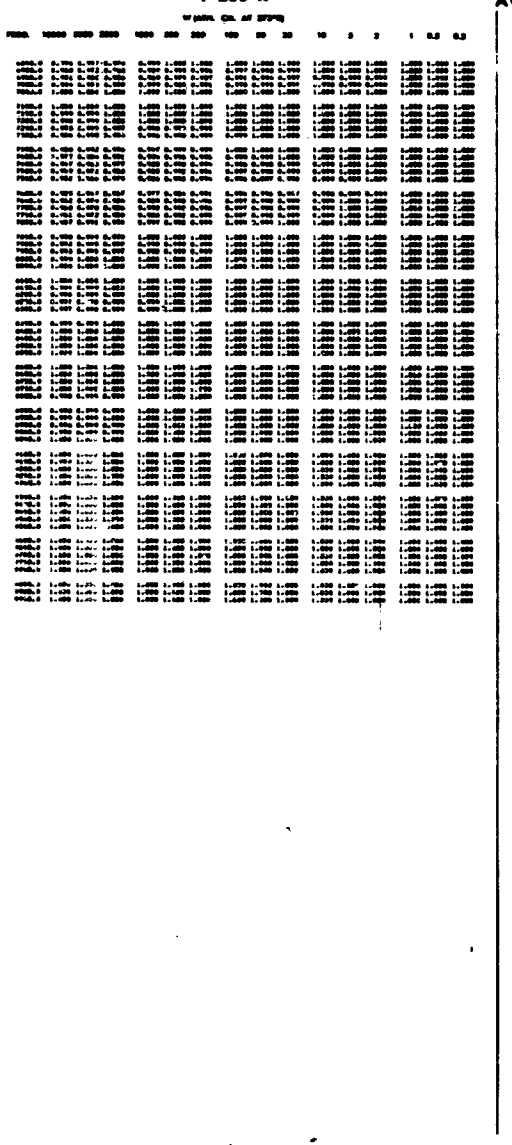
T=200°K

AVERAGED OVER 100 Cm^{-1}

CARBON DIOXIDE AT 0.01 ATMOSPHERE PRESSURE
T=200° K

AVERAGED OVER 100 Cm^{-1}





Space Systems Division, Air Force Systems Command, Los Angeles, California

Rpt. No. SSD-TDR-62-127 - Volume III. INFRARED TRANSMISSION STUDIES, VOLUME III: THE INFRARED ABSORPTION OF CARBON DIOXIDE

Final Report, Volume III, 31 January 1963

408 p., incl. tables and illus.

Unclassified Report

The infrared absorption of carbon dioxide has been calculated over a wide range of path length pressure, and temperature from 500 to 10,000 cm^{-1}. The results are presented in extensive tables which give the transmission

UNCLASSIFIED

1. Absorption
2. Carbon Dioxide
3. Infrared Spectroscopy

I AF 04(695)-96

II Aeronutronic Division, Ford Motor Company, Newport Beach, California

III V. R. Stull
P. J. Wyatt
G. N. Plass

UNCLASSIFIED

Space Systems Division, Air Force Systems Command, Los Angeles, California

Rpt. No. SSD-TDR-62-127 - Volume III. INFRARED TRANSMISSION STUDIES, VOLUME III: THE INFRARED ABSORPTION OF CARBON DIOXIDE

Final Report, Volume III, 31 January 1963

408 p., incl. tables and illus.

Unclassified Report

The infrared absorption of carbon dioxide has been calculated over a wide range of path length pressure, and temperature from 500 to 10,000 cm^{-1}. The results are presented in extensive tables which give the transmission

UNCLASSIFIED

1. Absorption
2. Carbon Dioxide
3. Infrared Spectroscopy

I AF 04(695)-96

II Aeronutronic Division, Ford Motor Company, Newport Beach, California

III V. R. Stull
P. J. Wyatt
G. N. Plass

UNCLASSIFIED

Space Systems Division, Air Force Systems Command, Los Angeles, California

Rpt. No. SSD-TDR-62-127 - Volume III. INFRARED TRANSMISSION STUDIES, VOLUME III: THE INFRARED ABSORPTION OF CARBON DIOXIDE

Final Report, Volume III, 31 January 1963

408 p., incl. tables and illus.

Unclassified Report

The infrared absorption of carbon dioxide has been calculated over a wide range of path length pressure, and temperature from 500 to 10,000 cm^{-1}. The results are presented in extensive tables which give the transmission

UNCLASSIFIED

1. Absorption
2. Carbon Dioxide
3. Infrared Spectroscopy

I AF 04(695)-96

II Aeronutronic Division, Ford Motor Company, Newport Beach, California

III V. R. Stull
P. J. Wyatt
G. N. Plass

UNCLASSIFIED

Space Systems Division, Air Force Systems Command, Los Angeles, California

Rpt. No. SSD-TDR-62-127 - Volume III. INFRARED TRANSMISSION STUDIES, VOLUME III: THE INFRARED ABSORPTION OF CARBON DIOXIDE

Final Report, Volume III, 31 January 1963

408 p., incl. tables and illus.

Unclassified Report

The infrared absorption of carbon dioxide has been calculated over a wide range of path length pressure, and temperature from 500 to 10,000 cm^{-1}. The results are presented in extensive tables which give the transmission

UNCLASSIFIED

1. Absorption
2. Carbon Dioxide
3. Infrared Spectroscopy

I AF 04(695)-96

II Aeronutronic Division, Ford Motor Company, Newport Beach, California

III V. R. Stull
P. J. Wyatt
G. N. Plass

UNCLASSIFIED

over intervals of 5 cm^{-1} and also averaged over larger intervals. The calculated data representing the intensity, position, and number of spectral lines in a given frequency interval is tabulated in a form which is useful for further transmission calculations. All lines from all isotopic species having an intensity greater than 10^{-8} of the strongest line in an absorption region were included in the calculation. The transmission values were calculated from the quasi-random model which simulates the actual frequency and intensity distributions of spectral lines better then previous models.

over intervals of 5 cm^{-1} and also averaged over larger intervals. The calculated data representing the intensity, position, and number of spectral lines in a given frequency interval is tabulated in a form which is useful for further transmission calculations. All lines from all isotopic species having an intensity greater than 10^{-8} of the strongest line in an absorption region were included in the calculation. The transmission values were calculated from the quasi-random model which simulates the actual frequency and intensity distributions of spectral lines better then previous models.

over intervals of 5 cm^{-1} and also averaged over larger intervals. The calculated data representing the intensity, position, and number of spectral lines in a given frequency interval is tabulated in a form which is useful for further transmission calculations. All lines from all isotopic species having an intensity greater than 10^{-8} of the strongest line in an absorption region were included in the calculation. The transmission values were calculated from the quasi-random model which simulates the actual frequency and intensity distributions of spectral lines better then previous models.

over intervals of 5 cm^{-1} and also averaged over larger intervals. The calculated data representing the intensity, position, and number of spectral lines in a given frequency interval is tabulated in a form which is useful for further transmission calculations. All lines from all isotopic species having an intensity greater than 10^{-8} of the strongest line in an absorption region were included in the calculation. The transmission values were calculated from the quasi-random model which simulates the actual frequency and intensity distributions of spectral lines better then previous models.