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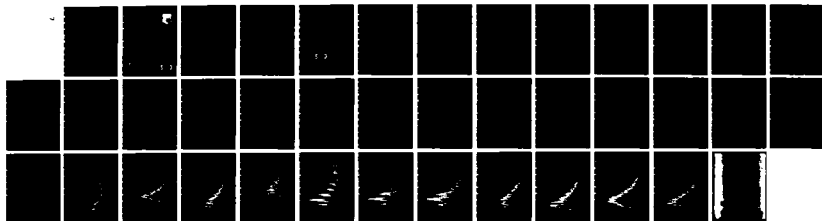
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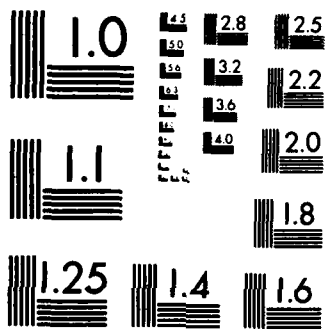
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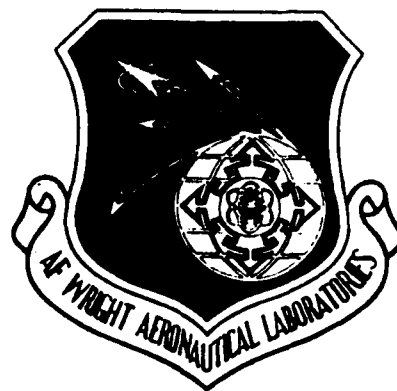


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CO<sub>2</sub> v<sub>3</sub> FUNDAMENTAL BAND 4.5 μm LASER POTENTIAL

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March 1984

Final Report for Period 5/2/83 to 3/26/84

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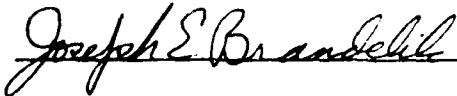
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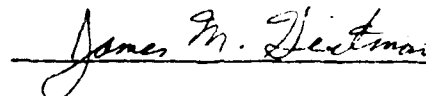
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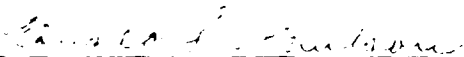


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## Section I

### INTRODUCTION AND BACKGROUND

Since 1976, a number of new lasing transitions have been reported on infrared bands of the  $\text{CO}_2$  molecule, in addition to the  $10.4 \mu\text{m}$   $(001) \rightarrow (100)$  and  $9.4 \mu\text{m}$   $(001) \rightarrow (02^{\circ}0)$  transitions. These include the  $(100) \rightarrow (01^1_0)$  cascade band at  $14 \mu\text{m}$ ,<sup>1-3</sup> the  $(101) \rightarrow (011)$  difference band at  $17 \mu\text{m}$ ,<sup>4</sup> the  $(00n) \rightarrow (1,0,n-1)$  and  $(00n) \rightarrow (0,2,n-1)$  sequence bands in the  $9-11 \mu\text{m}$  region,<sup>5-7</sup> and the  $(10^{\circ}1, 02^{\circ}1) \rightarrow (10^{\circ}0, 02^{\circ}0)$  cascade bands at  $4.3 \mu\text{m}$ .<sup>8-10</sup>

It was pointed out by Reid and Siemsen<sup>6</sup> that the inversion on the  $(00n) \rightarrow (0,2, n-1)$  sequence bands is created in an electric glow discharge for conditions in which the  $\text{CO}_2 \nu_3$  mode temperature (as measured between  $00^{\circ}2$  and  $00^{\circ}1$ ) is  $\sim 4000^{\circ}\text{K}$ , while the gas translational temperature is kept at  $\sim 250^{\circ}\text{K}$  by wall-cooling the discharge with a dry-ice methanol mixture. Such conditions favor vibration-vibration (V-V) collisional pumping of the higher anharmonic vibrational states  $(00n)$  of the  $\nu_3$  mode. This V-V pumping mechanism<sup>11</sup> is responsible for the population inversions among the anharmonic vibrational states of carbon monoxide in the  $5 \mu\text{m}$  CO infrared laser.<sup>12</sup> Accordingly, it was suggested in Ref. 6 that a partial inversion among the higher  $(00n)$  states of the  $\text{CO}_2 \nu_3$  mode, sufficient to create lasing on the  $(0,0,n \rightarrow 0,0,n-1)$   $\text{CO}_2 \nu_3$  band, might exist in such a cooled electric discharge.

Quite recently, Dang, Reid, and Garside<sup>13</sup> measured the detailed vibrational population distribution of the  $\text{CO}_2 \nu_3$  mode  $(00n)$  states from  $n = 0$  to  $n = 9$  in a cooled glow discharge, and demonstrated that the distribution is indeed V-V pumped in accordance with the theoretical model of Ref. 11. These results are reviewed below.

Initial attempts to obtain lasing on such anharmonic  $(0,0,n \rightarrow 0,0,n-1)$  transitions<sup>6,13</sup> in  $\text{CO}_2$  discharges have been unsuccessful. As the wavelength of such transitions extends from  $4.3 \mu\text{m}$  to at least  $4.7 \mu\text{m}$  (see Section 2, Table 1), such laser action is attractive for several avionics applications. In the present program, a broader investigation of the laser potential of this system was undertaken. A principal program task was to verify and extend the

results of Ref. 13. In Ref. 13, Dang, et al. only measured the  $\nu_3$  populations from  $(00^0_1)$  to  $(00^0_9)$ . The measurement technique used, tunable diode laser absorption, precluded measurement above  $(00^0_9)$ , as the diode could not be tuned to sufficiently long wavelengths corresponding to the absorption band for these higher components. In the present experiments, the primary diagnostic is infrared emission spectroscopy. Significant populations of levels above  $(00^0_9)$  can be detected. A second program task was investigation of the effect of discharge operating parameters (gas temperature, flow velocity, gas mixture, current) on the partial inversion in the  $\nu_3$  states. Finally, attempts were made to achieve laser oscillation under the most favorable pumping conditions. These efforts were unsuccessful.

Section II, following, reviews the previous experimental findings important for the present project, and presents gain calculations for the system. Section III gives the measurements of populations, and the results of both parametric studies of the discharge operation and laser oscillation attempts. A summary and conclusions are in Section IV.

## Section II

### CO<sub>2</sub> ( $\nu_3$ ) MODE POPULATION DISTRIBUTIONS AND CALCULATED SMALL SIGNAL GAIN

Dang, et.al.<sup>13</sup> have performed detailed vibrational population distribution measurements of the CO<sub>2</sub>  $\nu_3$  mode (00n) states from n = 0 to n = 9, in a 10 cm long x 1 cm bore, wall-cooled discharge tube. The tube was operated at a relatively fast pump rate, 840 ml/min NTP, to minimize CO<sub>2</sub> dissociation. The CO<sub>2</sub> (00n) populations were measured by absorption of a tunable diode laser beam; this probe beam was directed down the axis of the discharge tube, and was restricted to a diameter of 2 mm in the center of the discharge tube bore by use of an iris. Further details are given in Ref. 13.

Figure 1 shows the CO<sub>2</sub> (00n) populations measured by Dang, et.al.<sup>13</sup> with this technique. The discharge conditions are shown on the figure; this case represents the most highly pumped partial population inversion achieved. Measurements were made only up to level n = 9, since the diode laser could not be tuned to the wavelengths of transitions above (0,0,9)  $\rightarrow$  (0,0,10); it appears probable that the V-V pumped plateau extends to considerably higher quantum levels.

Shown on Fig. 1 is the analytical V-V pumped distribution function of Treanor, et.al.<sup>11</sup> (solid line); the agreement with the measured populations for  $0 \leq n \leq 9$  is excellent. This analytical function is calculated for the measured translational temperature of  $T_{\text{trans}} = 350^\circ\text{K}$  and for the measured vibrational "temperature"  $T_{V_3}^*$  of  $2850^\circ\text{K}$  defined by the measured ratio of the (000) and (001) populations,

$$T_{V_3}^* = \frac{E(0,0,1) - E(0,0,0)}{k \ln [N(0,0,0) - N(0,0,1)]}$$

For these conditions, the theory predicts the minimum of the V-V pumped analytical solution to occur at  $V = 12$ , as shown on the figure. Beyond this minimum, the analytic theory of Treanor, et.al.<sup>11</sup> predicts a total inversion, as shown by the solid-line curve; however, it has been well established that vibrational-to-translational (V-T) energy transfer processes generally inhibit such creation

of total inversions, and that the actual distribution function beyond the minimum at  $V = 12$  can be approximated by the form  $N_V \approx \text{CONSTANT} \times V^{-1}$ .<sup>14</sup> This form is shown for  $V \geq 12$  as the dashed line in Fig. 1; it forms a reasonable prediction of the distribution that would be measured by an experimental diagnostic giving access to the states  $V > 9$ .

On the basis of this predicted distribution function for the higher anharmonic  $\text{CO}_2$  ( $00n$ ) states, it is possible to estimate the small signal gain that can be achieved on  $(0,0,n) \rightarrow (0,0,n-1)$  transitions. Figure 2 shows such a calculation for the peak of a Doppler-broadened gain profile. The small-signal gain expression used is that of Patel;<sup>15</sup> it is written out explicitly on the figure. The gains for the  $(0,0,16) \rightarrow (0,0,15)$  band component are calculated for the distribution of Fig. 1 and for the  $\text{CO}_2$  concentration of the Dang, et.al., experiment ( $P_{\text{CO}_2} = 0.31$  torr). Gain is plotted against  $J'$ , the rotational quantum number of the upper level in the transition. The sources of the molecular constants and transition probabilities used in this estimate are also shown on the figure. Gains are plotted for 350°K, the temperature of the experiment, and for two lower temperatures, 250° and 150°K.\* It can be seen that gain is very slight for the 350°K temperature of the experiment of Ref. 13, even on the  $(0,0,16) \rightarrow (0,0,15)$  band; gain is smaller or non-existent for the lower-order transitions. This conclusion is in accordance with the results reported by Dang, et.al., who were unable to measure any gain on the  $(00^9) \rightarrow (00^8)$  transition for these conditions.

While Fig. 2 indicates that gain is considerably higher at kinetic temperatures of 150°K and 250°K than for 350°K, it is important to realize that these results are all based on the distribution of Fig. 1, which was measured at 350°K. Theory and experiments in several V-V pumped molecular species<sup>16</sup> indicates that a more strongly pumped population distribution is created for the same power input at the lower kinetic temperatures. Such distributions can be predicted with some confidence on the basis of the analyses

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\* The  $\text{CO}_2$  vapor pressure at 150°K is  $> 1$  mm Hg.

already cited.<sup>11,14</sup> Such distributions are shown in Fig. 3. As indicated on the figure, the distributions are calculated for  $T_{V_3}^* = 2850^\circ\text{K}$ , the value measured in Ref. 13, but for  $T_{\text{TRANS}} = 150^\circ\text{K}$  and  $250^\circ\text{K}$ , as well as  $350^\circ\text{K}$ . The  $350^\circ\text{K}$  distribution is the same as that inferred previously (Fig. 1); the more highly populated inversions predicted by theory for the two lower temperatures are apparent.

Small signal gains calculated from the distributions of Fig. 3 are displayed in Fig. 4 ( $250^\circ\text{K}$ ) and Fig. 5 ( $150^\circ\text{K}$ ). For the  $250^\circ\text{K}$  case, gain approach  $1\% \text{ cm}^{-1}$  for the higher band components; for  $150^\circ\text{K}$ , gain on all bands above  $(00^05) \rightarrow (00^04)$  exceeds  $1\% \text{ cm}^{-1}$ , approaching  $10\% \text{ cm}^{-1}$  for the higher band components. It is also noteworthy that partial inversion occurs on increasing lower band components as the temperature is lowered; for the  $150^\circ\text{K}$  case, high gain is predicted from  $4.5 \mu\text{m}$  to above  $5.0 \mu\text{m}$  (cf. Table 1).

Finally, it should be noted that the recent observation of extreme V-V pumping of the  $\text{CO}_2 \nu_3$  mode of Ref. 13 is not the only observation of such pumping in a triatomic molecule. Several years ago, Picard-Bersellini and Rossetti measured quite analogous pumping of the  $\text{N}_2\text{O } \nu_3$  mode asymmetric stretch populations in  $\text{N}_2/\text{N}_2\text{O}$  mixtures in a mixing discharge tube.<sup>17</sup> This independent observation in a different triatomic species strongly supports the inferences drawn in Ref. 13.

Table 1

CO<sub>2</sub>  $\nu_3$  BAND WAVELENGTHS

$V_3$	$E_{0,0^0,V_3}$ (cm <sup>-1</sup> )	$\tilde{\nu}_{0,0^0,V_3 \leftrightarrow 0,0^0,V_3-1}$ (cm <sup>-1</sup> )	$\lambda_{0,0^0,V_3 \leftrightarrow 0,0^0,V_3-1}$ ( $\mu$ m)
0	0	--	--
4	9,248	2275.	4.396
7	15,922.	2200.	4.545
10	22,370.	2125.	4.706
13	28594.	2050.	4.878
16	34592.	1975.	5.063
20	42240.	1875.	5.333

### Section III EXPERIMENTS

Experiments were conducted in a flowing gas discharge tube, with 150 cm of active length. In the course of the program two different tube diameters were used, 2 cm and 1 cm I.D. Premixed gases are fed into the tube through a central injection port, and are pumped through exhaust ports at each end. There is a central grounded electrode, and a positive electrode at each end. Accordingly, two discharge loops of 75 cm length are struck in the tube. The system is resistively ballasted in standard fashion, and powered by a Universal Voltronics 70 kV/110 ma regulated D.C. supply equipped with a saturable core reactive current limiter. The gases are pumped by a 500 liter/min mechanical pump.  $\text{CaF}_2$  windows at each tube end allow spontaneously emitted endlight to be focussed into a scanning monochromator. The tube is equipped with a trough for liquid-nitrogen or dry ice/methanol wall-cooling baths along the entire active discharge length.

All spectra were taken with a 1/2 meter monochromator, equipped with a 300 line/m.m., 4  $\mu$ m blaze grating, and an InSb detector. Radiative signal was chopped at 800 Hz and amplified by a PAR 124 phaselock amplifier in standard fashion.

#### 1 LARGE BORE TUBE

Figures 6-9 show typical endlight infrared emission spectra obtained from operation of the 2 cm I.D. tube. The molecular band spectra shown in these figures are the  $\nu_3$ ,  $(0,0^\circ,n) \rightarrow (0,0^\circ,n-1)$  band of  $\text{CO}_2$  and the  $\Delta V = 1$  fundamental band of CO. The CO is created by  $\text{CO}_2$  dissociation in the discharge.

The experimental discharge conditions for each of Figs. 6-9 are given in Table 2.

Table 2  
OPERATING PARAMETERS, 2 cm DIAMETER TUBE MEASUREMENTS

FIG.	FLOW VELOCITY m/sec	P <sub>CO<sub>2</sub></sub>	P <sub>N<sub>2</sub></sub> TORR	P <sub>He</sub>	CURRENT mA	COOLING <sup>*</sup>
6	0.18	0.7	4.2	9.6	25	dry ice
7	10.1	0.15	1.5	17.0	22.5	room temperature
8	57.7	0.1	0.5	15.0	30.0	dry ice
9	46.4	0.3 <sup>**</sup>	0.6	14.9	22.5	liquid nitrogen

\* This column indicates the type of wall cooling bath. In Figures 7-9, gases were precooled additionally by passing through a dry ice methanol trap before injection into the discharge tube.

\*\* In this run, some CO<sub>2</sub> was being condensed on the discharge tube walls.

Figure 6 shows the IR spectrum for a relatively slow flow. The structure from 4.35  $\mu\text{m}$  to 4.45  $\mu\text{m}$  is the CO<sub>2</sub>  $\nu_3$  band. The structure beyond 4.45  $\mu\text{m}$  is almost entirely the CO fundamental band. It is interesting to note that almost all of the (001) and (002) emission is absorbed by atmospheric CO<sub>2</sub> in the optical path. The strong CO emission is evidence of almost complete CO<sub>2</sub> dissociation. The CO<sub>2</sub>  $\nu_3$  Einstein "A" coefficients exceed those of the CO fundamental by almost an order of magnitude.

Figures 7-9 show the IR spectrum for much faster gas flows. The almost total inhibition of CO formation, in contrast to Fig. 6, is evident. Figures 7-9 show the effect of decreasing translational temperature; in Fig. 7, the tube walls are at room temperature, in Fig. 8, they are at 193°K, and in Fig. 9, at 77°K.

Two features in the spectra are observed as the wall temperature is lowered. One is that the CO<sub>2</sub>  $\nu_3$  band components extend to longer wavelengths with decreasing temperature. In the case of Fig. 7, the room temperature case, there is little emission beyond 4.50  $\mu\text{m}$ , and the intensity drops perceptibly beyond 4.4  $\mu\text{m}$ . In the case of Fig. 9, the coldest run, emission extends to



almost  $4.7 \mu\text{m}$ , and the intensity beyond  $4.5 \mu\text{m}$  is generally much greater with respect to the shorter wavelength emission,  $\lambda < 4.50 \mu\text{m}$ .

A second feature created by the decreasing temperature is that the structure of the various band components becomes more evident. Particularly in Fig. 9, the alternating intensity rise and fall caused by the overlapping of the P and R branches of the successive  $(0,0^{\circ},v) \rightarrow (0,0^{\circ},v-1)$  band components is apparent. This effect is obscured at the higher temperatures, where more rotational states are populated. These additional rotational lines tend to fill in the emission spectra, obscuring the band structure.

## 2 COMPARISON WITH COMPUTED SYNTHETIC SPECTRA

The Calspan synthetic spectrum computer code<sup>18</sup> was used to generate synthetic spectra for the purposes of comparison with the experimental spectra of Figs. 7-9. Figures 10-12 show these spectra; they were generated for the three V-V pumped distributions theoretically calculated for  $150^{\circ}\text{K}$ ,  $250^{\circ}\text{K}$ , and  $350^{\circ}\text{K}$  translational temperature, as plotted in Fig. 3.

Comparisons of Figs. 10, 11, and 12 shows the very marked increase in the predicted emission from longer wavelengths with decreasing translational-rotational temperature. The experimental spectrum of Fig. 9, the most highly pumped experimental case, has been compared with these theoretical predictions to estimate the magnitude of the partial population inversion achieved. Convenient reference points on the spectra, for the purposes of this comparison, are the emission peaks near  $4.4$  and  $4.6 \mu\text{m}$ ; these represent signal from  $V_3 \approx 4$  and  $V_3 \approx 8$ , respectively. Table 3 shows the ratio of these emission peaks from the optimum experimental spectrum (Fig. 9), and from the three predicted spectra (Figs. 10-12).

Table 3  
Emission Intensity Ratios

Case:	$I_{4.6}/I_{4.4}$
Experimental (Fig. 9)	0.42
Theoretical (Fig. 10)	0.85
Theoretical (Fig. 11)	0.44
Theoretical (Fig. 12)	0.19

It can be seen that the experimental distribution exhibits an emission intensity ratio quite close to that predicted theoretically for a vibrational population distribution with a translational temperature of 250°K (see Fig. 3). This is consistent with the temperature deduced from less direct experimental evidence. Experimental emission spectra such as that of Fig. 9 can be produced when the inlet gases to the discharge tube are precooled by a 193°K heat exchanger, and with the discharge tube walls also cooled to 193°K; cooling the tube walls to 77°K does not significantly increase the long-wavelength emission. Accordingly, it is reasonable to infer a 250°K centerline temperature in the tube, in agreement with the IR emission spectrum data.

Summarizing the results of these studies:

1. At the flow velocities used in the experiment of Dang, et al.<sup>13</sup> ( $< 1$  m/sec), a large fraction of the  $\text{CO}_2$  is dissociated in the 75 cm length of each discharge section of the present experimental device. To ensure that most  $\text{CO}_2$  does not dissociate, much higher flow velocities ( $> 10$  m/sec) must be used. This finding is in accord with the detailed measurements of CO formation in  $\text{CO}_2$  electric discharge lasers performed by Wiegand, et al.<sup>19</sup>
2. Cooling the gas discharge tube with wall baths, in addition to precooled the gases in a cold trap before they are admitted into the tube, results in marked enhancement of the V-V pumping of the  $\text{CO}_2$   $\nu_3$  mode vibrational states. This finding is in agreement with the theoretically predicted  $\text{CO}_2$   $\nu_3$  mode population distributions given in the calculations of Section 2.
3. Populations of the  $\text{CO}_2$   $\nu_3$  states up to  $(0,0^0,10)$  have been measured.

Infrared emission spectra have also been obtained using 1 cm I.D. tube; this smaller diameter was tested to ascertain if lower center-line temperatures could be achieved with wall-cooling than in the 2 cm I.D. system. Figures 13-16 show the endlight emission spectra obtained with this tube; the discharge operating parameters for these cases are given in Table 4.

Table 4  
Operating Parameters

FIG.	FLOW/VELOCITY m/sec	P <sub>CO<sub>2</sub></sub>	P <sub>N<sub>2</sub></sub> TORR	P <sub>He</sub>	CURRENT mA	COOLING
13	147	0.37	1.2	21.4	30	Dry ice
14	129	0.39	0.76	15.7	22.5	Liquid nitrogen
15	147	0.37	1.2	21.4	30	Dry ice
16	169	0.33	1.1	18.6	10	Dry ice

Figures 13 and 14 show the spectra for, respectively, dry ice and liquid nitrogen wall-cooling. No substantial pumping improvement over the 2 cm I.D. tube experiments is noted.

As noted earlier, the emission spectra all show substantial absorption of the CO<sub>2</sub> (001 → 000) and (002 → 001) band components, caused by residual CO<sub>2</sub> in the optical instrumentation train. Since this effect did not impair the usefulness of the IR emission monochromator setup as a diagnostic for  $\nu_3$  mode V-V pumping, complete shrouding and purging of the apparatus was only used in a few runs. Such spectra, obtained with shrouded optics and with dry nitrogen gas purges passing through the shrouds and the monochromator, are given in Figs. 15 and 16. It can be seen that substantial emission due to (002 → 001) and (001 → 000) transitions is recovered, in contrast to the spectra obtained with the unpurged instrumentation. Both Figs. 15 and 16 are for dry ice in alcohol wall cooling baths. It will be noted from Table 4, however, that Fig. 15 is for a current of 30 mA (current density = 38 mA/cm<sup>2</sup>), while Fig. 16 is for a current of 10 mA (current

density = 15 mA/cm<sup>2</sup>). The high current density run (Fig. 15) clearly shows much higher rotational temperature than the low current density case (Fig. 16). Comparison of Fig. 15 with synthetic spectra indicate translational/rotational temperatures > 400°K; in the case of Fig. 16, translational/rotational temperatures ~ 250°K are achieved; Fig. 16 is quite close to the 250°K distribution which gives the synthetic spectrum of Fig. 8. We note that the lower current densities required to prevent translational heating in the 1 cm tube are difficult to achieve at these high flow velocities required to inhibit dissociation. Currents lower than 10 mA gave unstable discharge operation, with a tendency for one or both discharge arms to extinguish. Accordingly, as noted above, no substantial improvement over the 2 cm bore results have been realized. A configuration to eliminate this difficulty to small bore operation is suggested in Section 4.

#### 4 GAIN ESTIMATES AND LASER OSCILLATION EXPERIMENTS

The emission spectra for the "best-pumped" cases of Figs. 9 and 16 correspond closely to the synthetic spectrum of Fig. 11 for the 250°K theoretical distribution of Fig. 3, for states below (0,0°,10). Gains inferred for this distribution are low among these lower states. As shown on Fig. 4, gains on the  $V_3 = 9 \rightarrow 8$  transition range from  $3 \times 10^{-3} \text{ cm}^{-1}$  on  $P_3$ , to  $1 \times 10^{-3} \text{ cm}^{-1}$  on  $P_{27}$ , per torr of  $\text{CO}_2$ . Accordingly, for the  $\text{CO}_2$  pressures run here, maximum anticipated gain is rather low, of the order of 10% per pass in the 150 cm tube.

Tests for laser oscillation were performed in both the 1 cm and 2 cm I.D. tubes. An optical cavity was formed by dielectric-coated mirrors, a max-reflectance mirror with 99.9% reflectance in the 4-5  $\mu\text{m}$  range, and a partially-transmitting mirror with >96% reflectance from 4.5 to 4.8  $\mu\text{m}$ . No  $\text{CO}_2 \nu_3$  laser oscillation was obtained for the conditions giving the optimum pumped distribution of Figs. 9 and 14. Precise alignment was checked using CO in the laser cavity; despite the fact that the optics were unoptimized for CO laser action, ~3 watts c.w. were easily obtained on CO lines.

For both tube diameters, discharge operating parameters (current density,  $\text{CO}_2/\text{N}_2/\text{He}$  partial pressures, flow velocity) were varied over large ranges

around the values giving the pumped emissions of Figs. 9 and 14. We were still unable to force laser oscillation.

## Section IV

### SUMMARY AND CONCLUSIONS

Measurements have been made of the vibrational population distribution of the CO<sub>2</sub> asymmetric stretch mode, in a flowing glow discharge, using quantitative infrared emission spectroscopy of the CO<sub>2</sub>  $\nu_3$  (0,0,V)  $\rightarrow$  (0,0,V-1) bands. These CO<sub>2</sub>  $\nu_3$  states from (001) to (009) are in a V-V pumped distribution at the lower discharge current densities, in agreement with the earlier results of Dang, et al.

It was found that in discharge tubes of length sufficient to yield usable total gain for optimum V-V pumping, a large fraction of the CO<sub>2</sub> dissociated for the flow velocities of Ref. 13. High flow velocities were required to inhibit dissociation.

IR monochromator scans were made in the wavelength region from 4.7  $\mu\text{m}$  to 5.1  $\mu\text{m}$ . The (0,0,11)  $\rightarrow$  (0,0,10) to (0,0,16)  $\rightarrow$  (0,0,15) CO<sub>2</sub>  $\nu_3$  band components lie in this region. No emission from these band components could be detected. If these higher CO<sub>2</sub>  $\nu_3$  states were populated to the extent predicted by the V-V pumped models given in Fig. 3, they would have been readily detectable with the instrumentation used. It is concluded that the CO<sub>2</sub>  $\nu_3$  does not continue to V-V pump strongly above (0,0,10).

With the wall-cooling and pre-cooling methods used for the discharge gases, the minimum center line translational temperatures achieved were  $\sim 250^\circ\text{K}$ , for usable discharge current densities ( $> 15 \text{ mA/cm}^2$ ). At lower current densities, the discharge became unstable. Lower center line translational temperatures (and lower current densities) could be achieved in the present apparatus at slower flow velocities; however, this results in a prohibitively large fraction of CO<sub>2</sub> dissociation. Therefore, the present wall-cooled, 75 cm per arm discharge could not practically be operated below  $\sim 250^\circ\text{K}$ .

Among states CO<sub>2</sub> (0,0,10) to CO<sub>2</sub> (0,0,1) at a 250 $^\circ\text{K}$  translational temperature, maximum gains realized were estimated to be of the order of .05% per cm (on the (009)  $\rightarrow$  (008) P<sub>31</sub> transition). Despite the low estimated gains, laser oscillation tests were conducted. It was not possible to force laser oscillation, although discharge operating parameters were systematically varied in an effort to increase gain.

It is concluded that  $\text{CO}_2 \nu_3$  mode lasing is not achievable in a wall-cooled glow discharge apparatus of the type used in the present study. This is because levels above (0,0,10) do not V-V pump, and lasing among levels (0,0,9) and below requires lower translational/rotational temperatures than can be achieved at the flow rates required to inhibit  $\text{CO}_2$  dissociation.

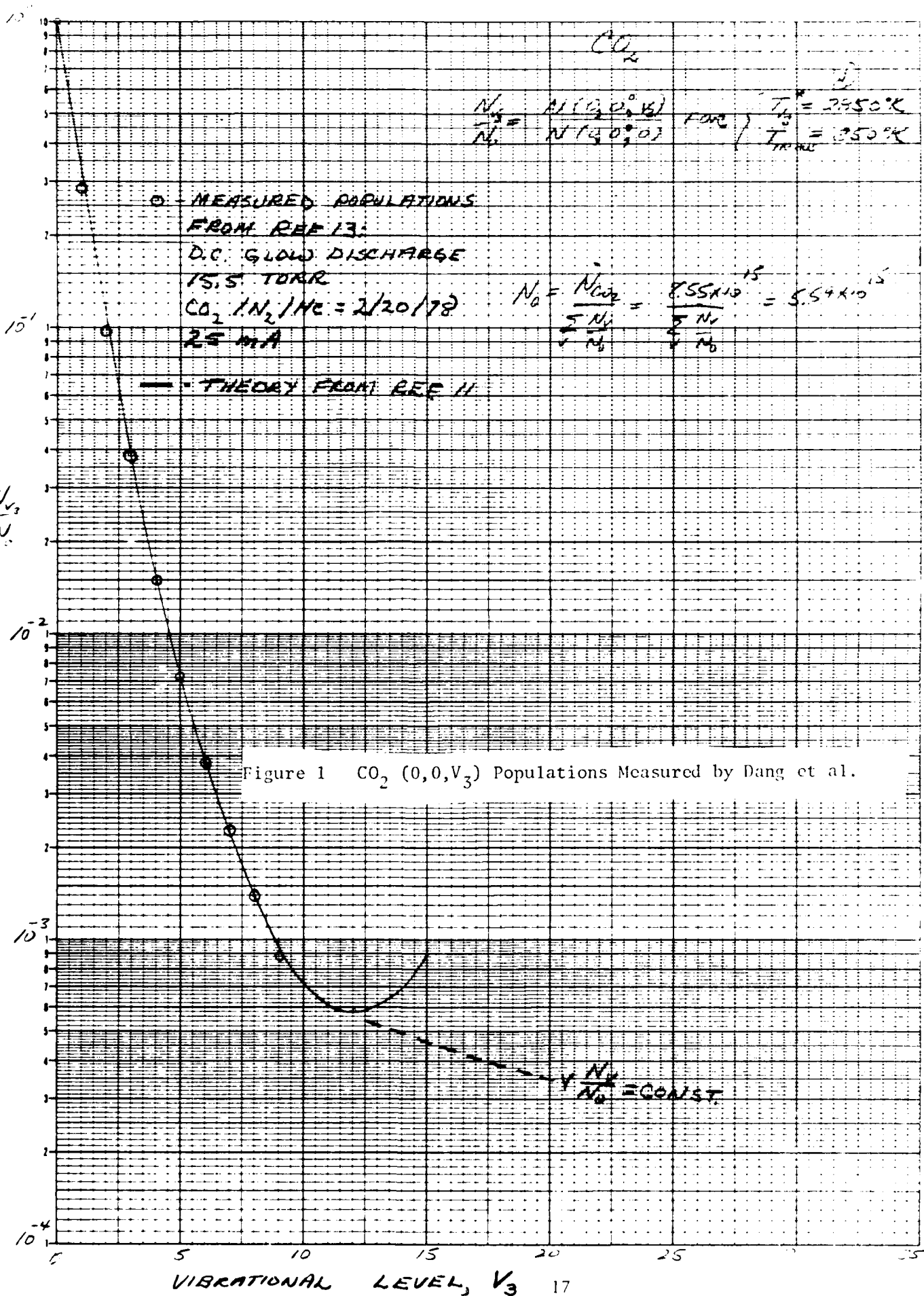
$\text{CO}_2 \nu_3$  mode oscillation may well be achievable in alternate laser geometries. For example, a segmented discharge tube, consisting of several short (15 cm) discharge sections, each having separate gas injection and removal, would allow much lower flow velocities and consequent efficient wall cooling, resulting in lower gas translational/rotational temperatures. At the same time,  $\text{CO}_2$  dissociation would be minimal in each section. A second approach would be to explore aerodynamic expansion methods of gas cooling. Both of these alternatives have the disadvantage of adding to the system complexity, in contrast to single discharge tube devices.

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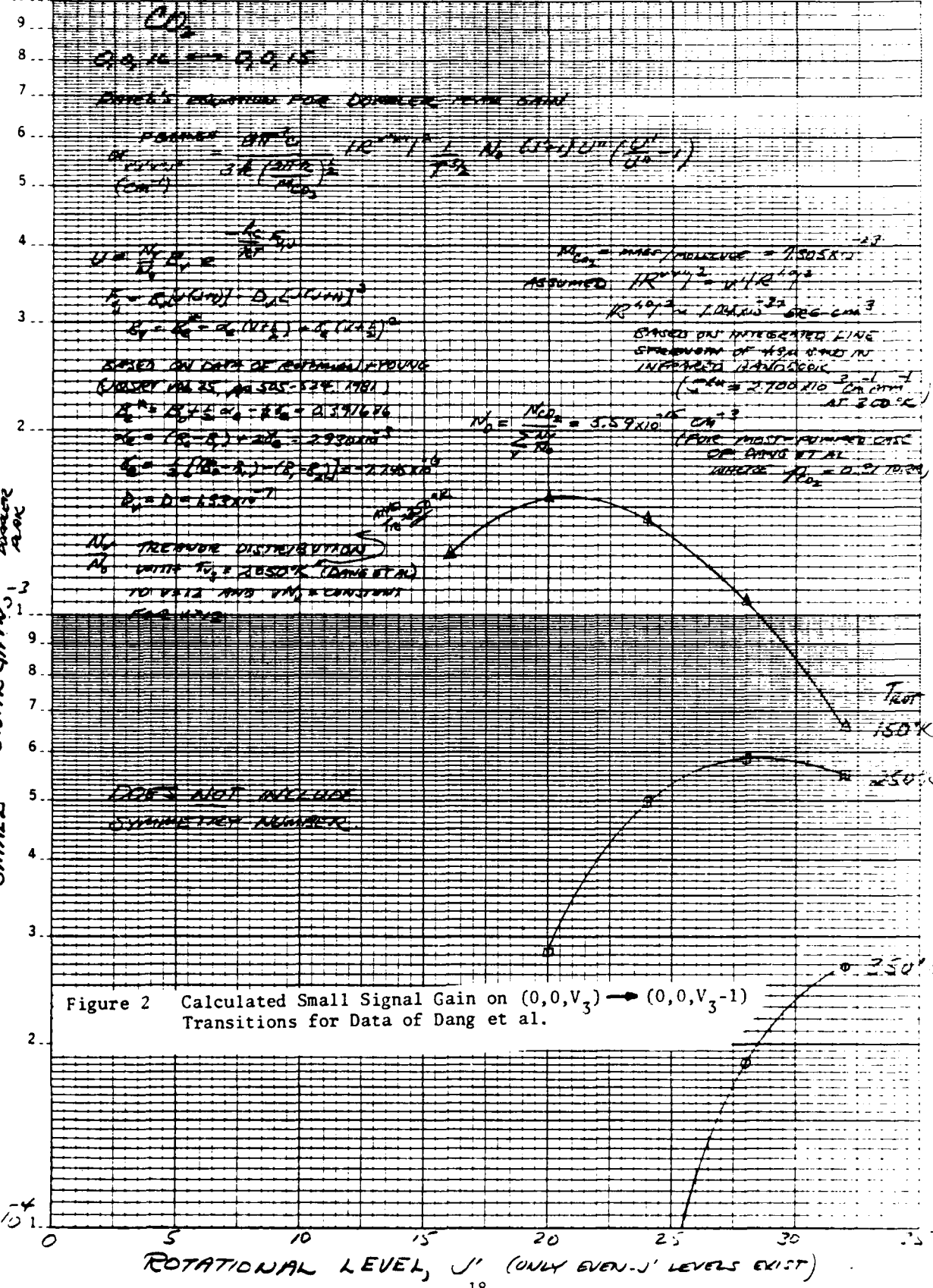
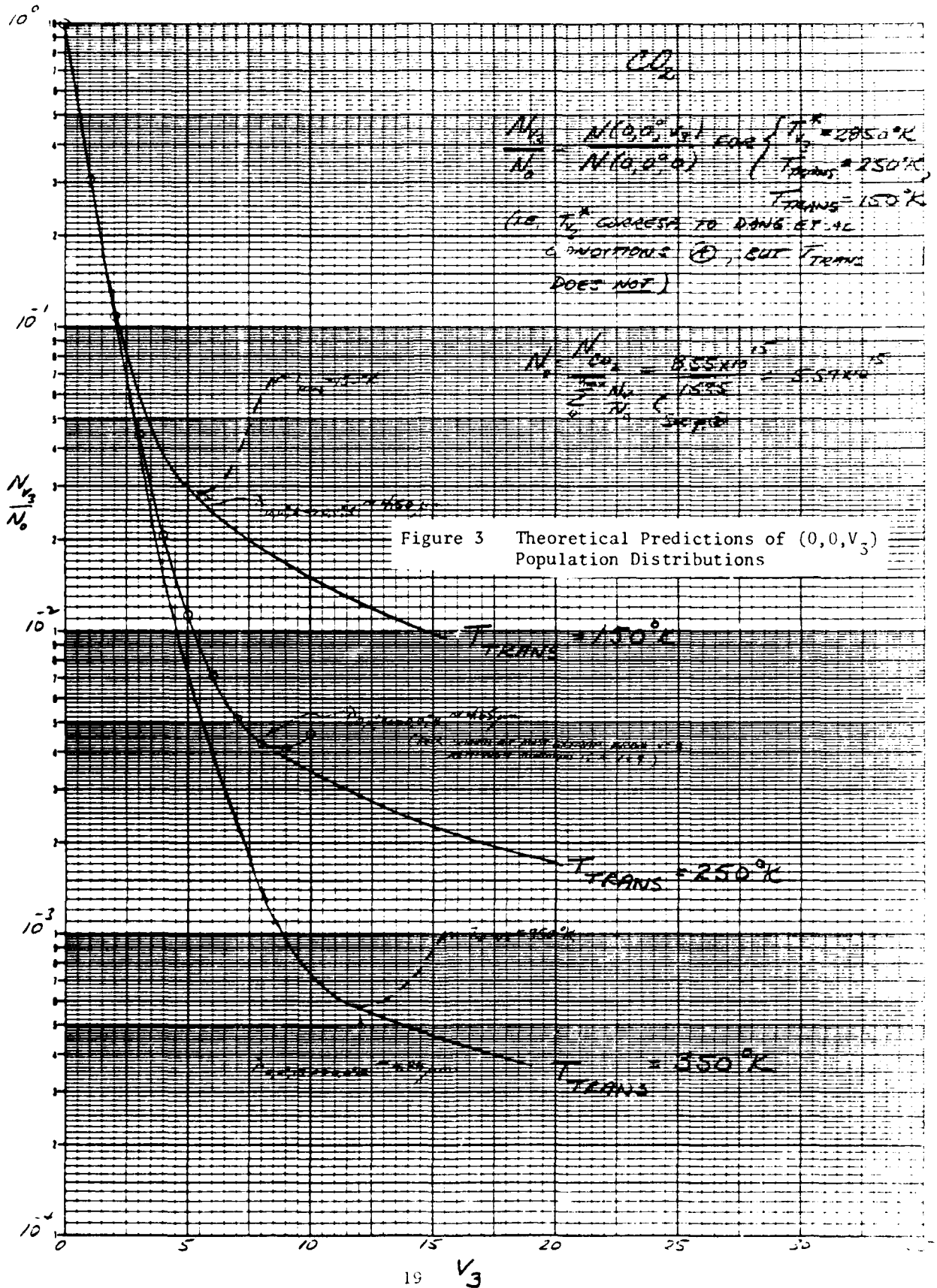


Figure 2 Calculated Small Signal Gain on  $(0,0,V_3) \rightarrow (0,0,V_3-1)$  Transitions for Data of Dang et al.



- FOR  $v_3 = \begin{cases} \text{EVEN} \\ \text{ODD} \end{cases}, j = \begin{cases} \text{EVEN} \\ \text{ODD} \end{cases}$   
 - SYMMETRY NUMBER NOT INCLUDED

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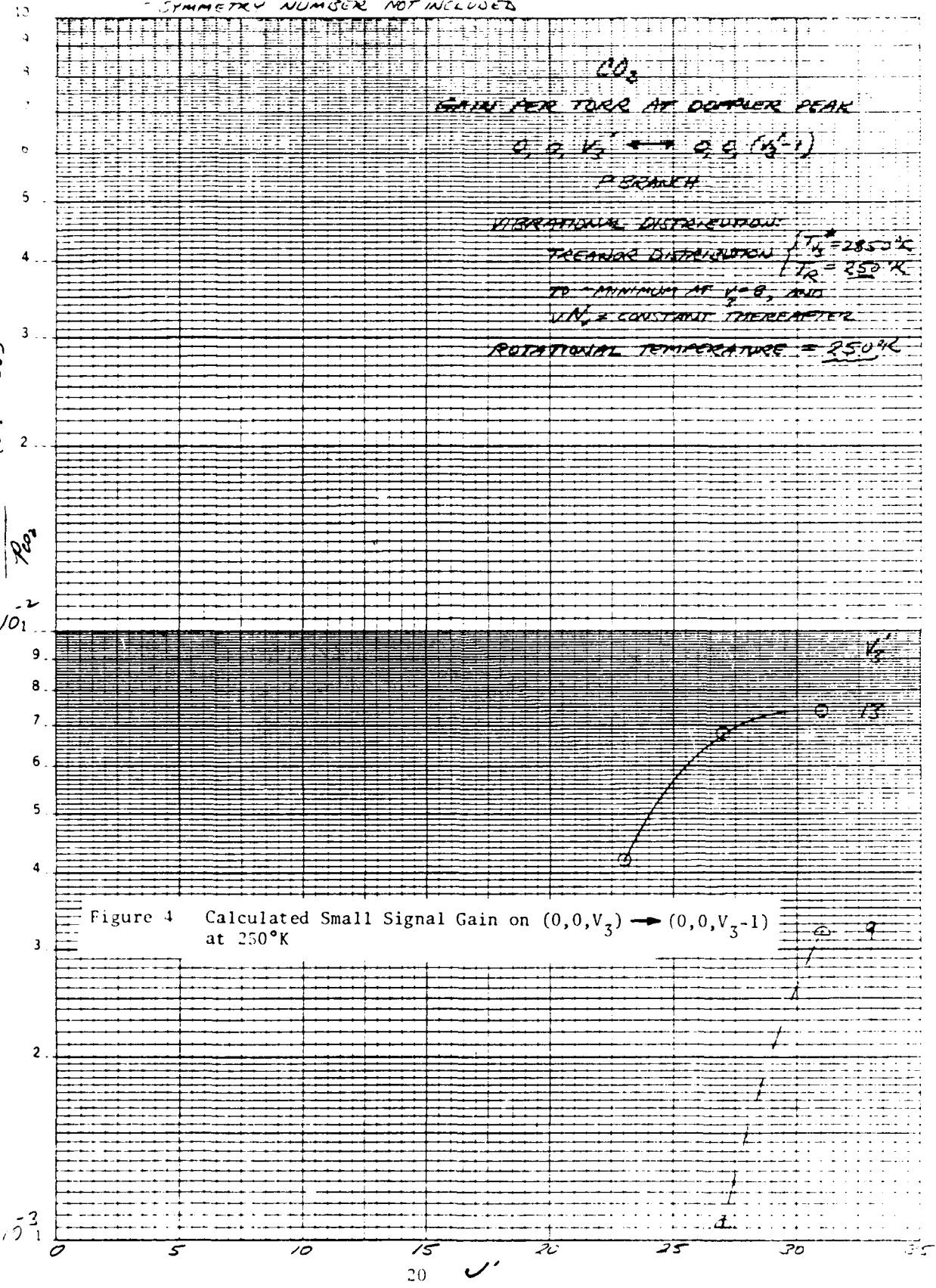
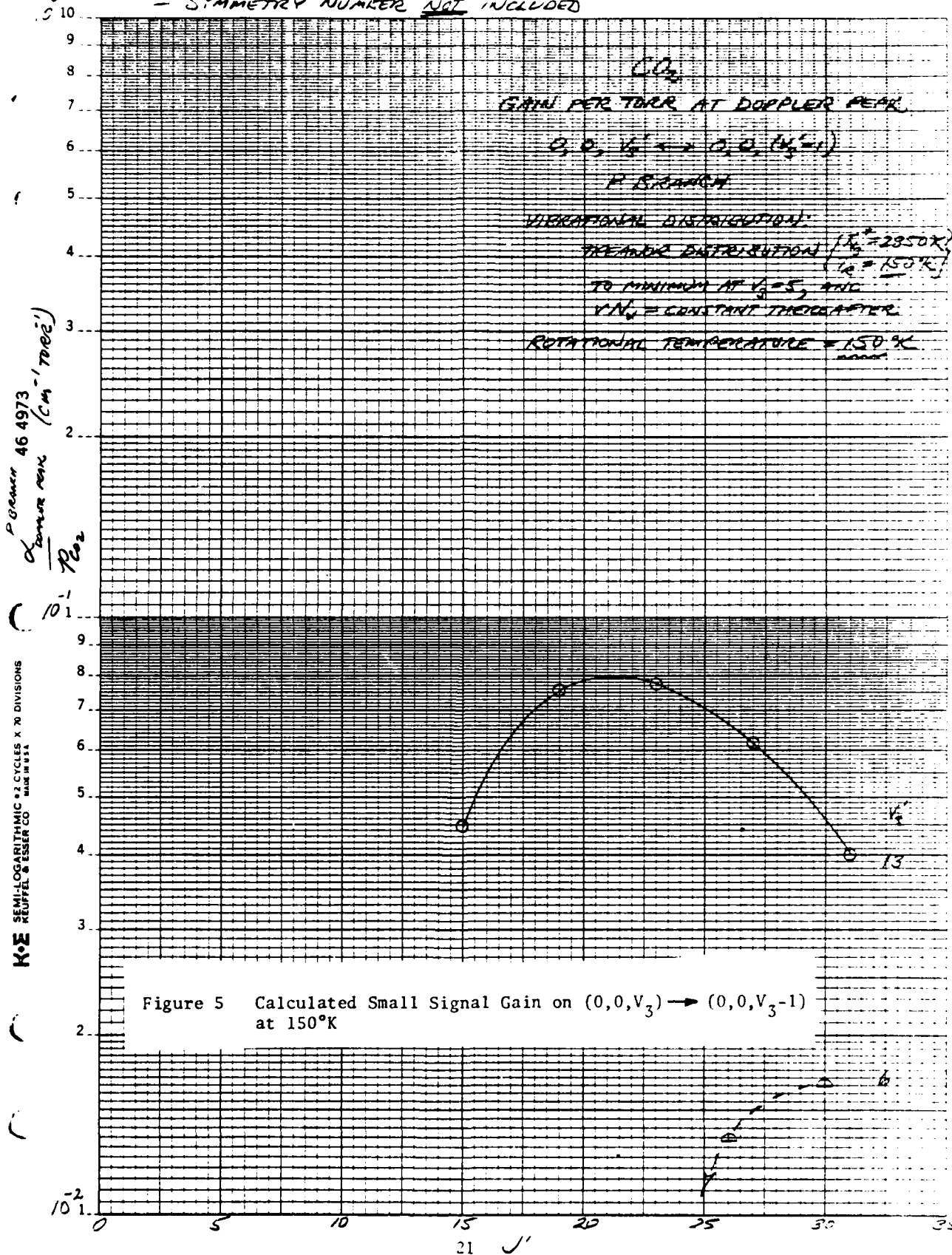


Figure 4 Calculated Small Signal Gain on  $(0,0,v_3) \rightarrow (0,0,v_3-1)$  at  $250^\circ K$

- FOR  $V_3 = \begin{cases} \text{EVEN} \\ 000 \end{cases}$ ,  $J = \begin{cases} \text{EVEN} \\ \text{ODD} \end{cases}$   
 - SYMMETRY NUMBER NOT INCLUDED



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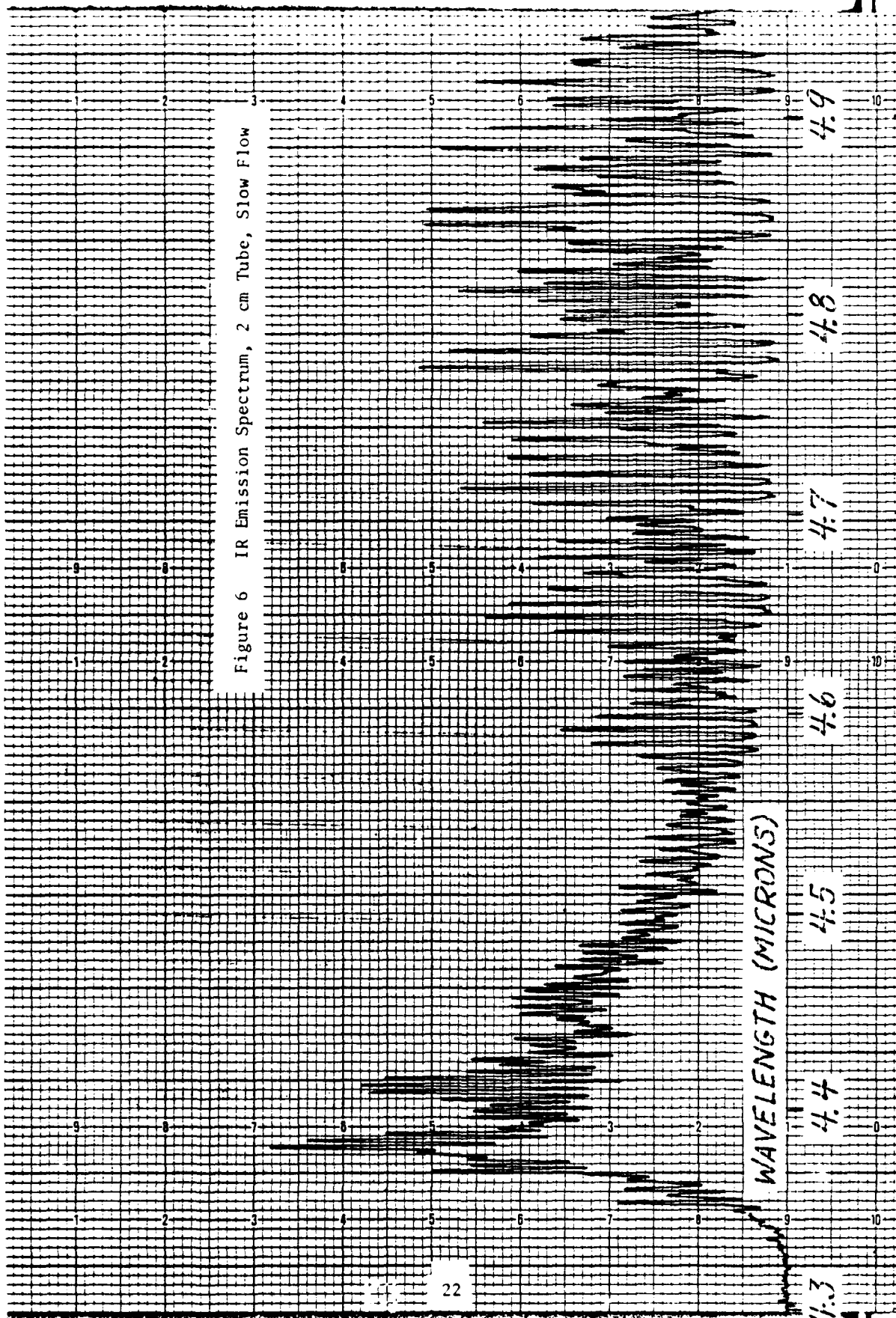
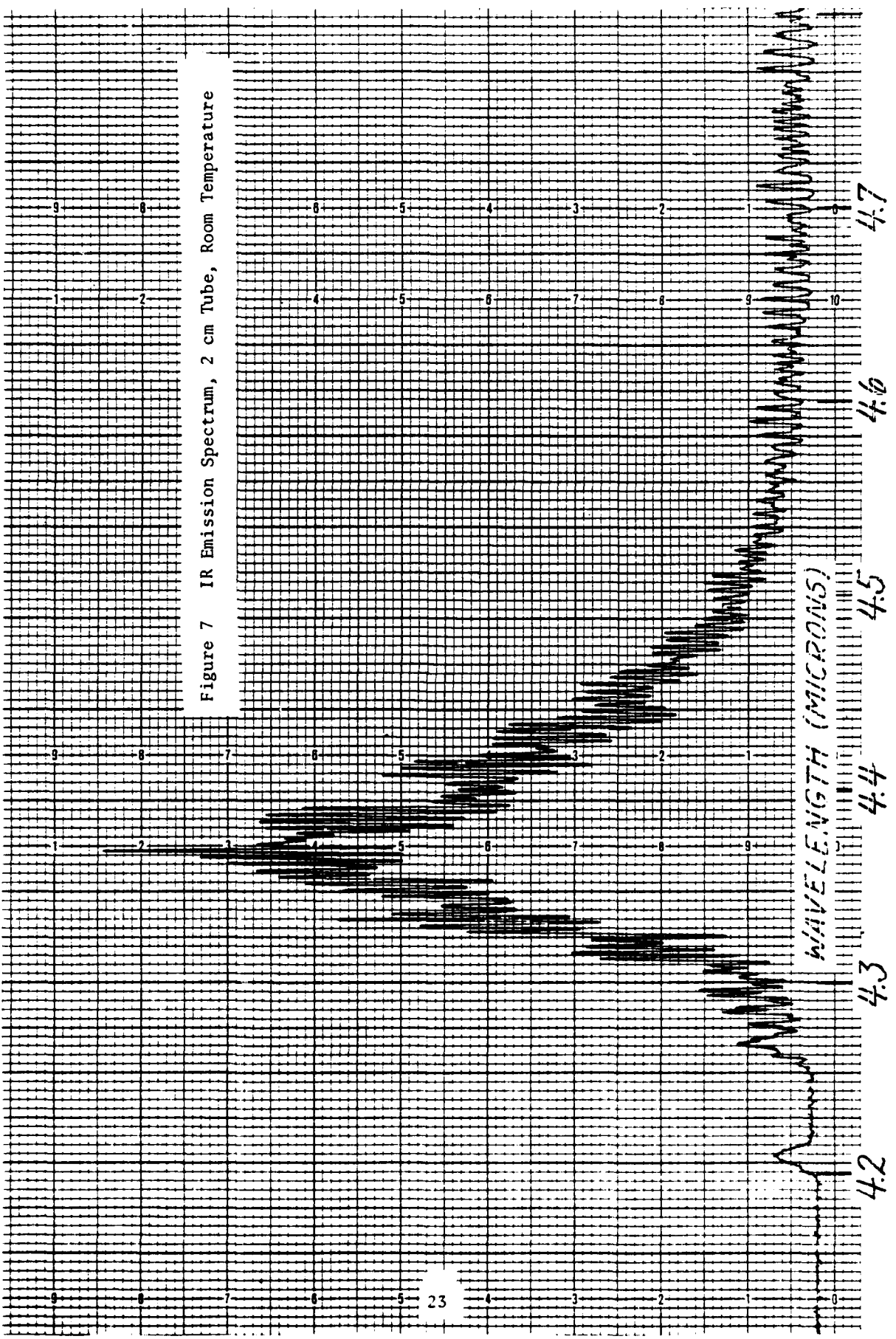


Figure 6 IR Emission Spectrum, 2 cm Tube, Slow Flow

WAVELENGTH (MICRONS)

Figure 7 IR Emission Spectrum, 2 cm Tube, Room Temperature



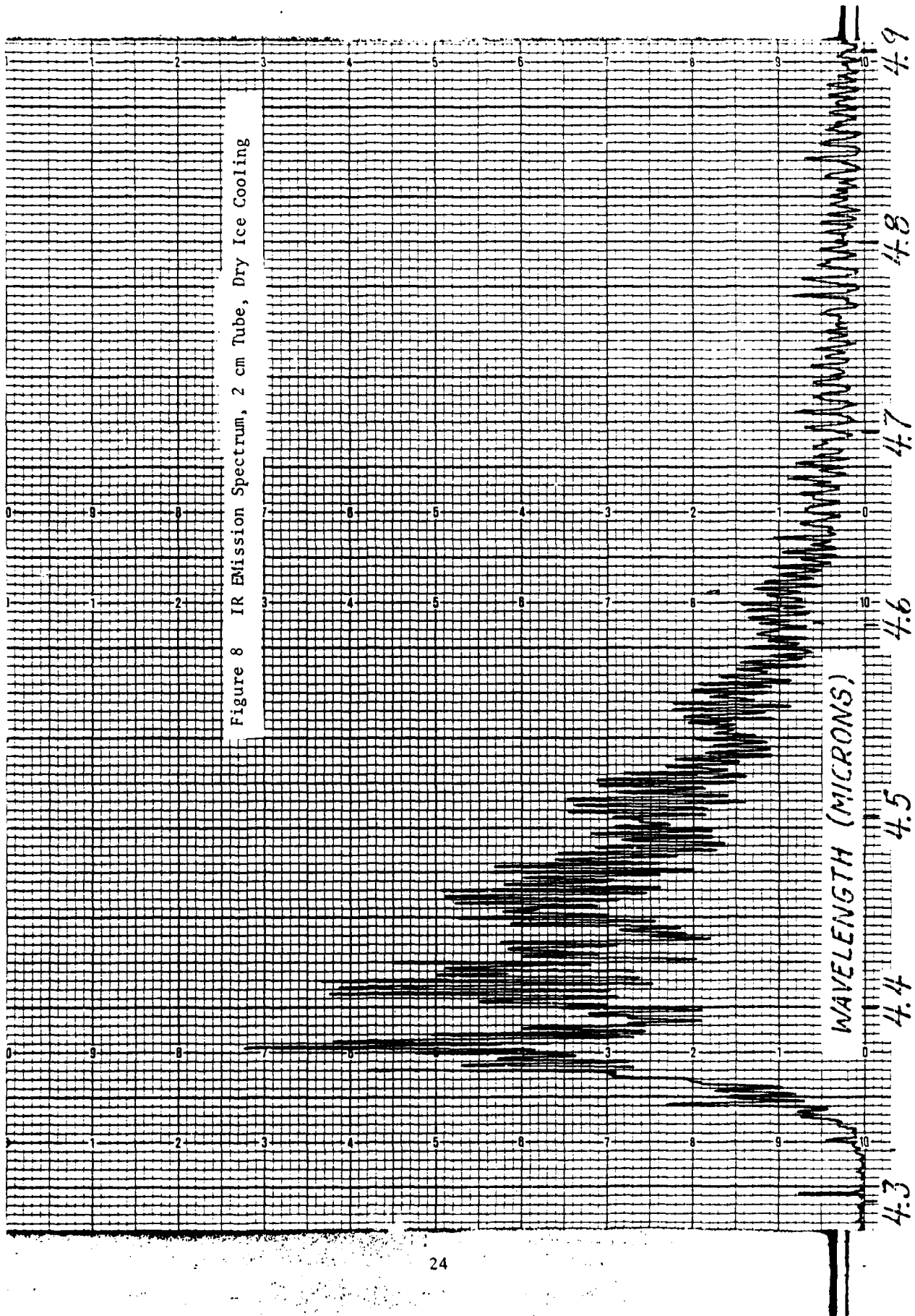


Figure 8 IR Emission Spectrum, 2 cm Tube, Dry Ice Cooling



Figure 9 IR Emission Spectrum, 2 cm Tube, Liquid Nitrogen Cooling

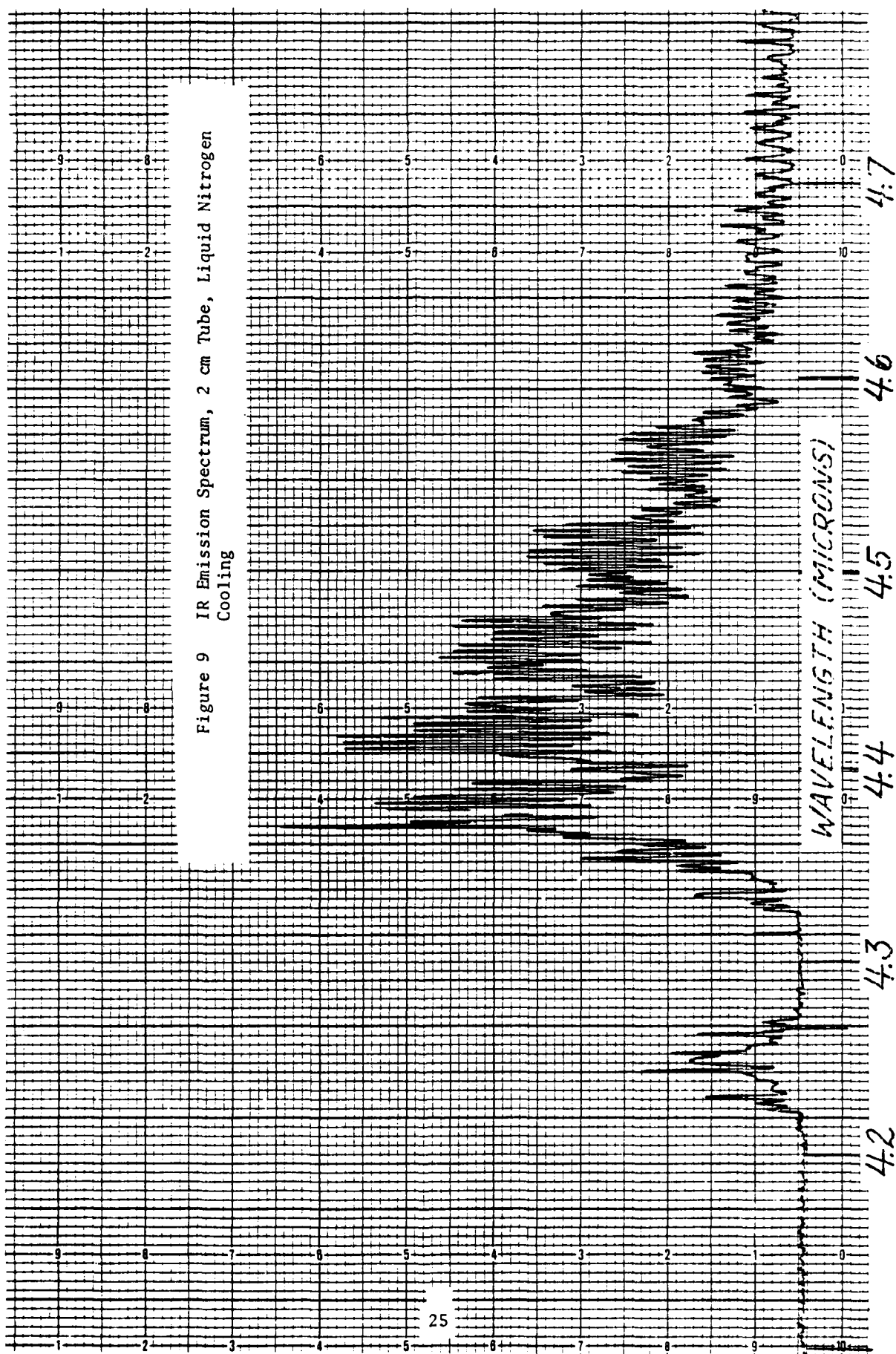


Figure 10 Synthetic CO<sub>2</sub> (V<sub>3</sub>) IR Spectrum for 150°K

$T_{TRANS} = T_{ROT} = 150^{\circ}K$

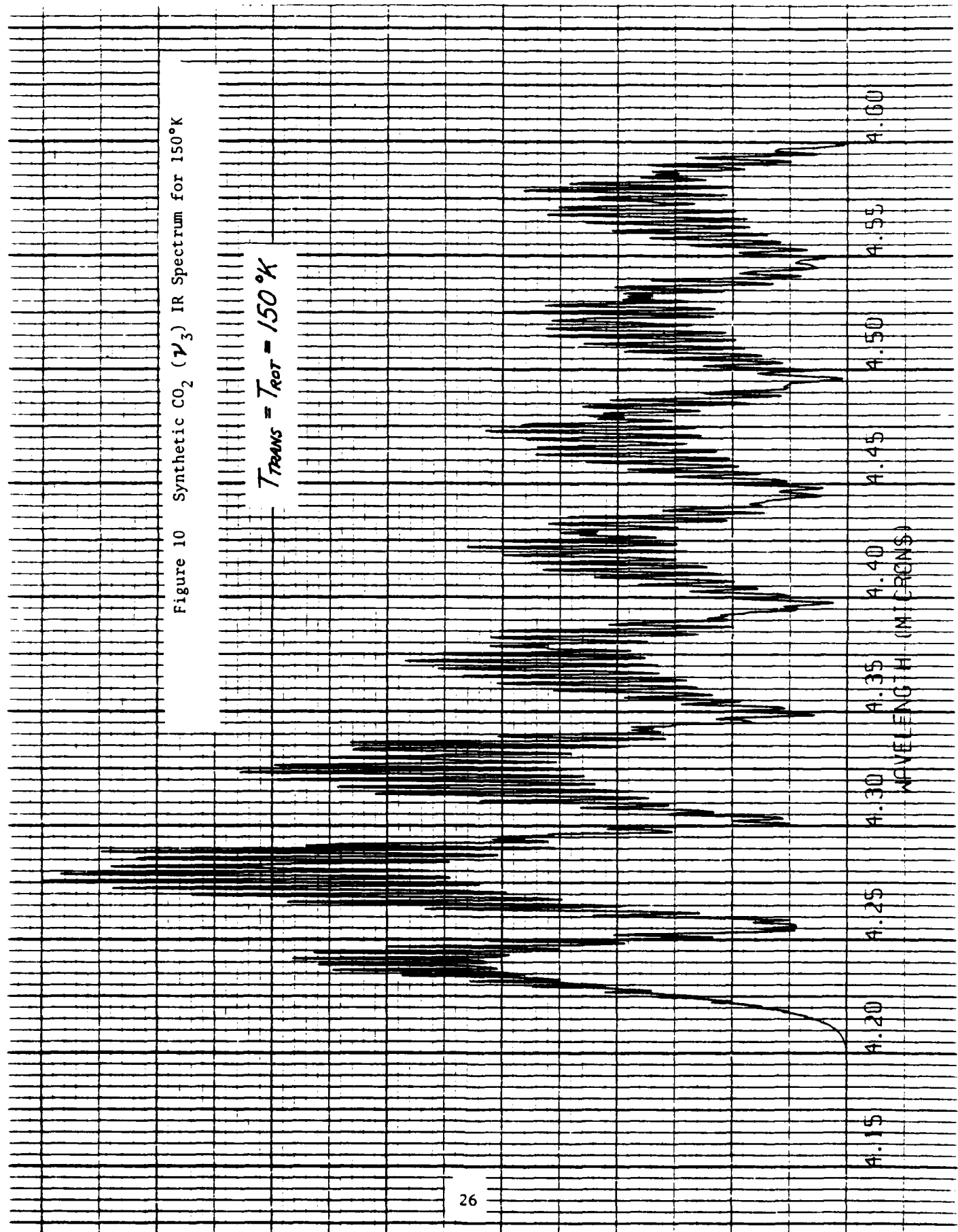


Figure 11 Synthetic CO<sub>2</sub> ( $\nu_3$ ) IR Spectrum for 250°K

$T_{trans} = T_{rot} = 250^{\circ}K$

4.15 4.20 4.25 4.30 4.35 4.40 4.45 4.50 4.55 4.60  
WAVELENGTH (MICRONS)

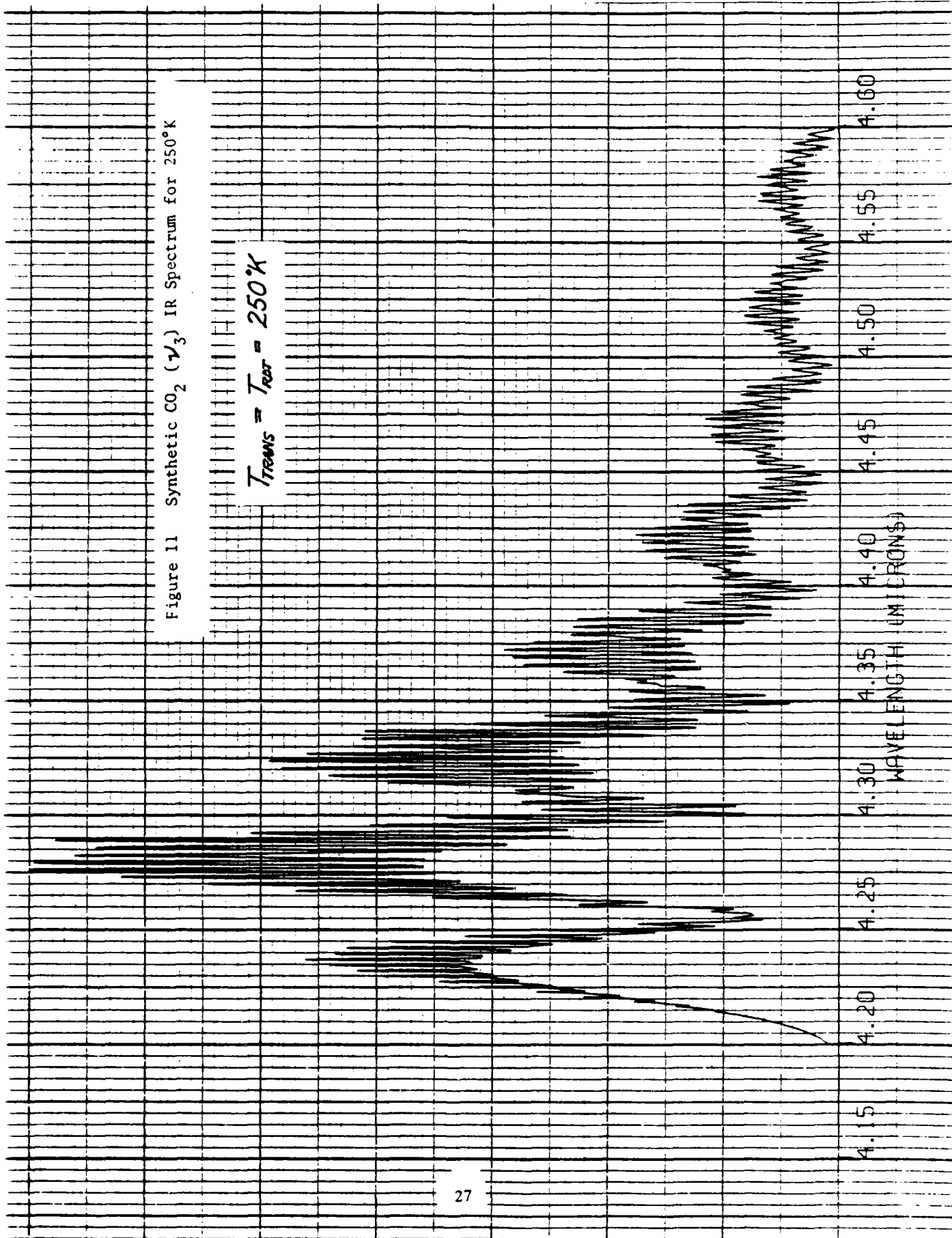
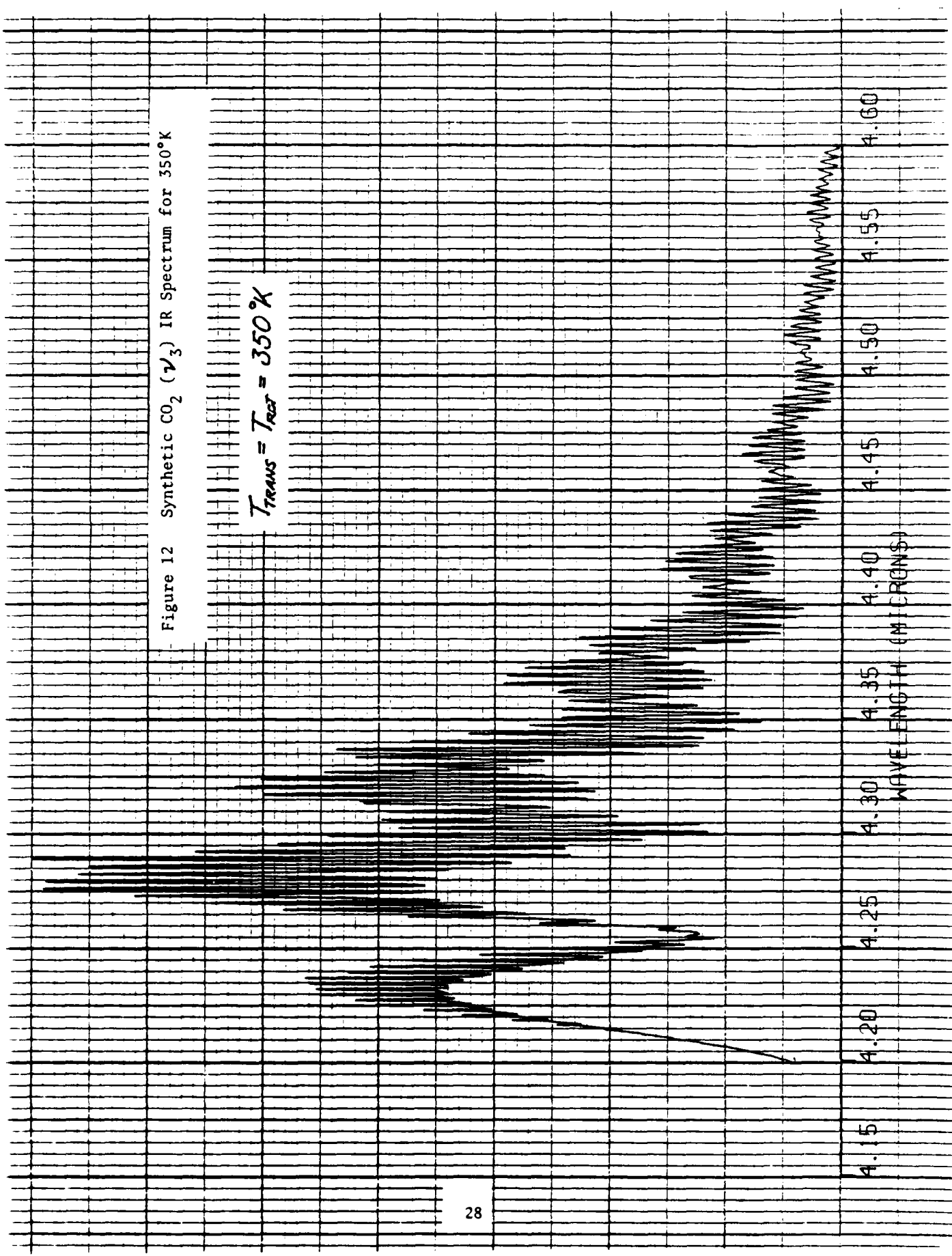


Figure 12 Synthetic CO<sub>2</sub> ( $\nu_3$ ) IR Spectrum for 350°K

$$T_{\text{TRANS}} = T_{\text{REF}} = 350^\circ\text{K}$$



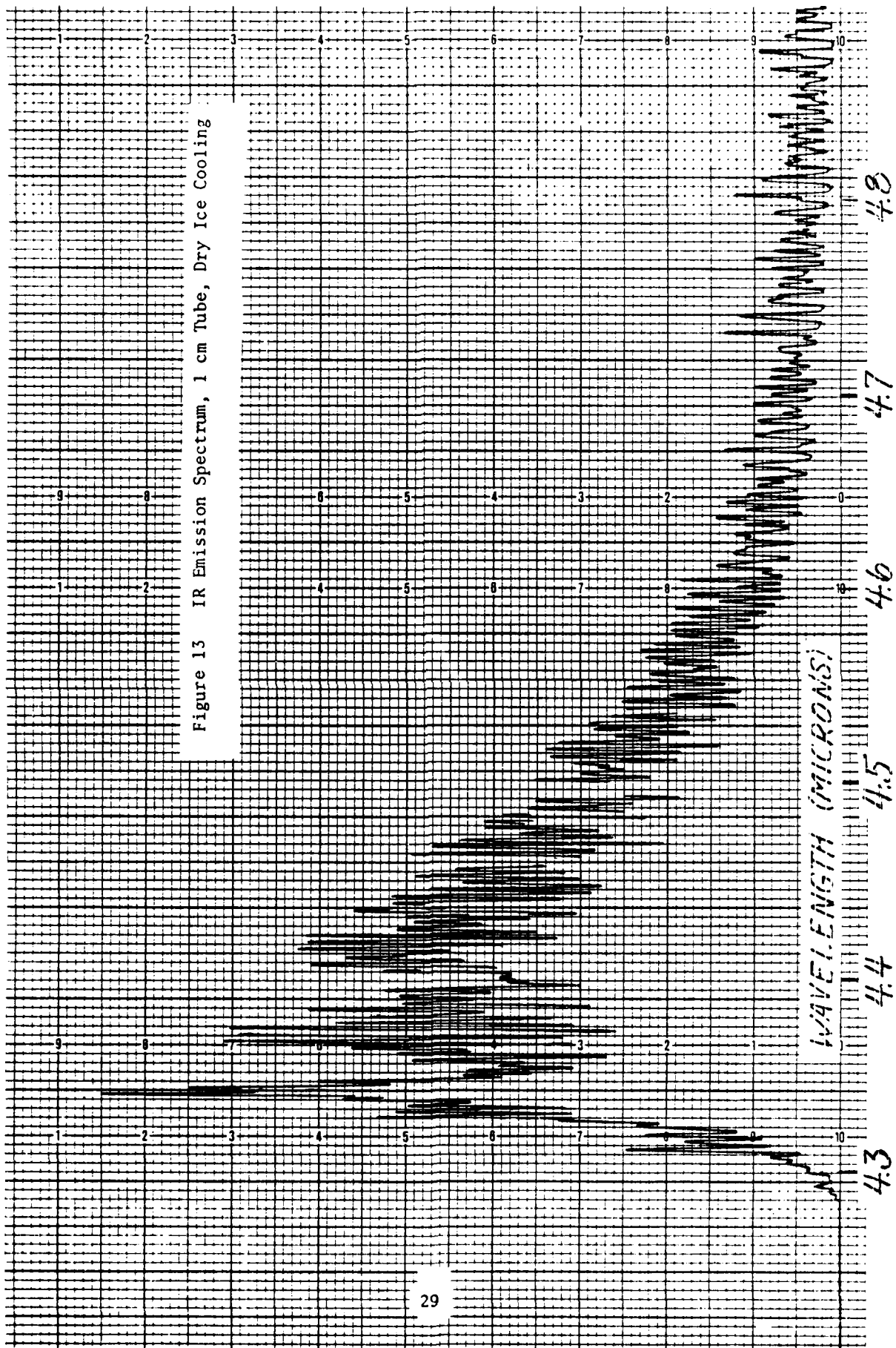
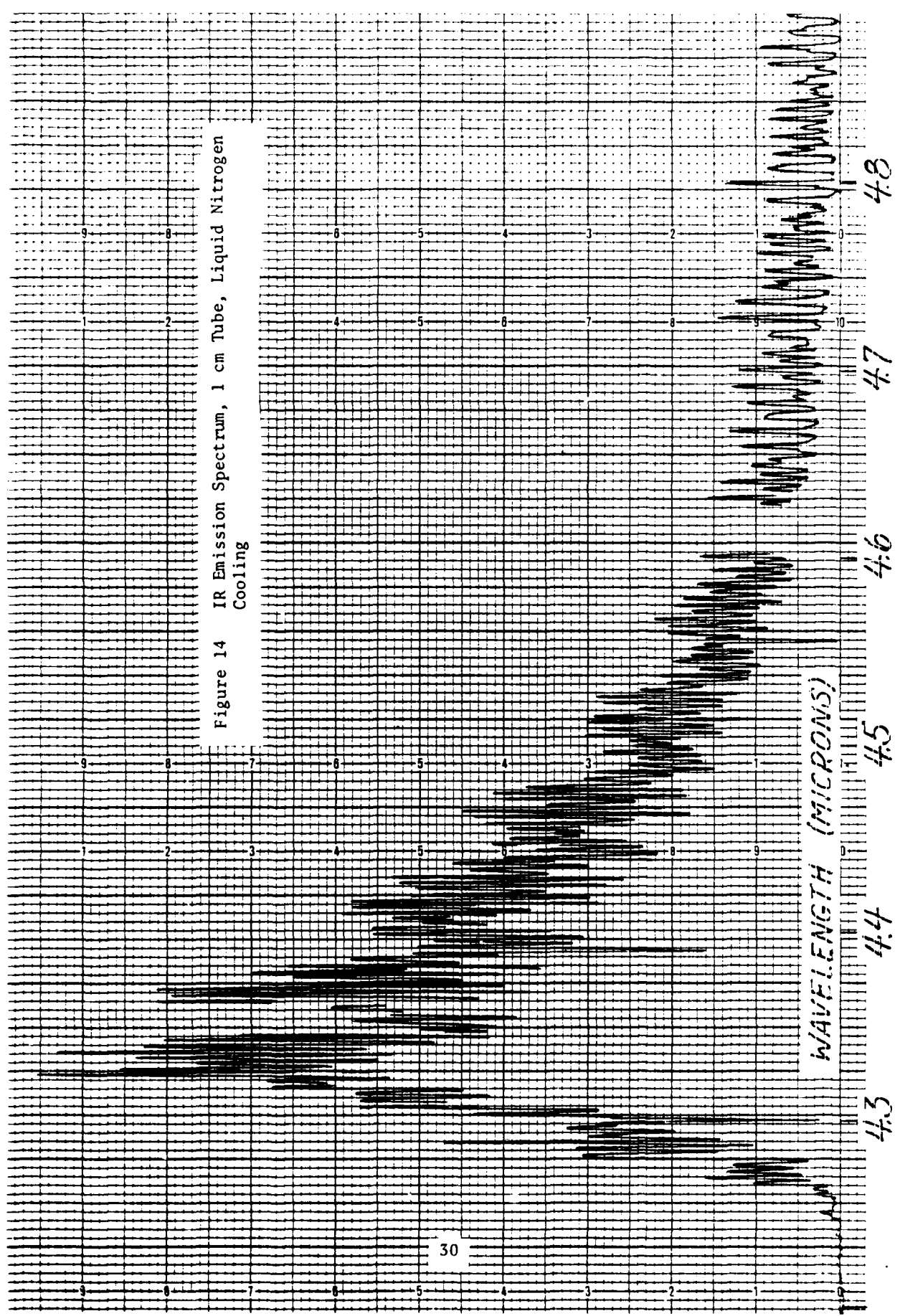


Figure 13 IR Emission Spectrum, 1 cm Tube, Dry Ice Cooling

Figure 14 IR Emission Spectrum, 1 cm Tube, Liquid Nitrogen Cooling



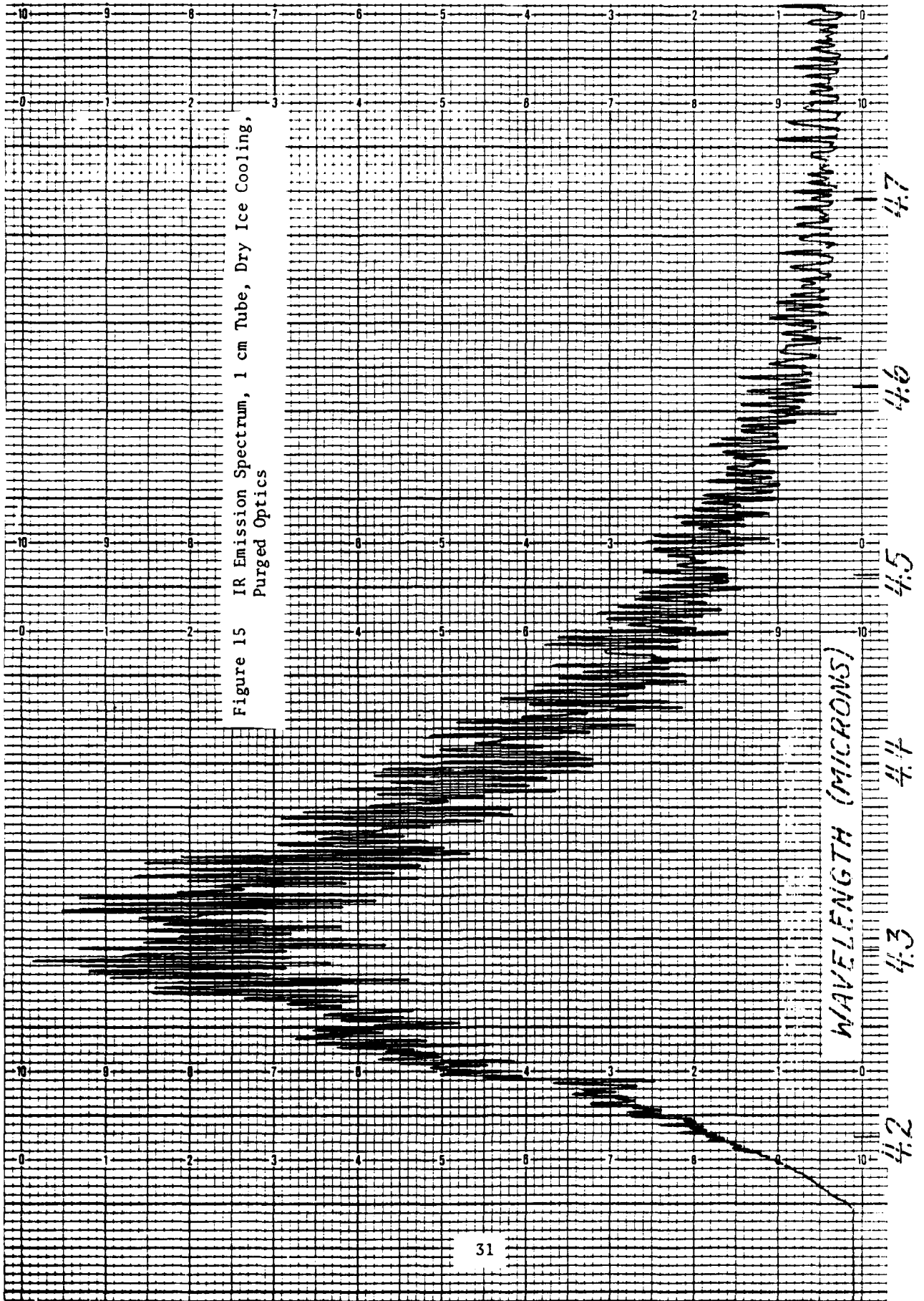


Figure 15 IR Emission Spectrum, 1 cm Tube, Dry Ice Cooling,  
Purged Optics

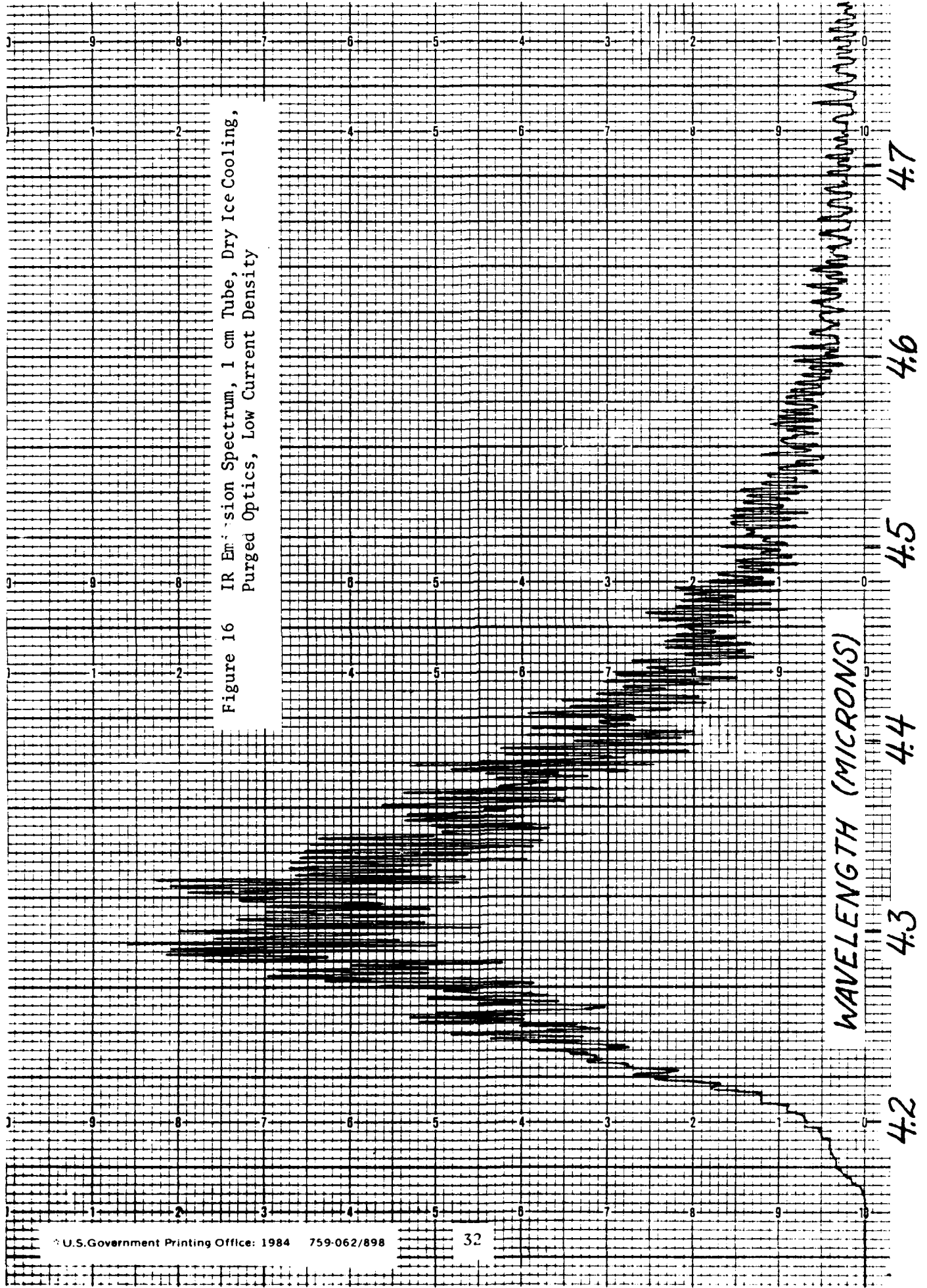


Figure 16 IR Emission Spectrum, 1 cm Tube, Dry Ice Cooling,  
Purged Optics, Low Current Density



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