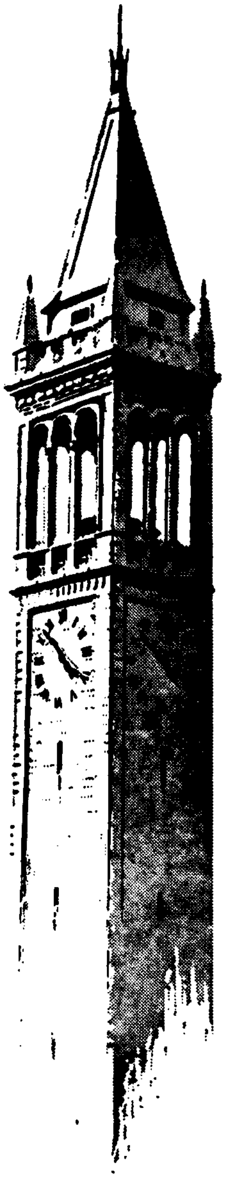

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by

M. M. Abu-Romia

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SUMMARY

The dependence of the infrared absorption spectrum of carbon monoxide on the geometric path length, pressure and temperature was investigated experimentally. The gas samples were heated in a high-temperature furnace which consists of a graphite resistance heater with an inner ceramic tube for containment of the testing gas. Ceramic and stainless steel holders with sapphire windows at the inner ends were used to confine the path length.

Spectral absorption measurements for the 4.67 micron fundamental band were performed for path lengths of 1, 5, 10 and 20 cm at temperatures of 300, 600, 900, 1200 and 1500° K in the pressure range 1/4 to 3 atm. For the first overtone band, measurements were limited for the 20 cm path length and at pressures 1, 2 and 3 atm for the same temperature range as the fundamental.

For the fundamental band, the spectral absorption data for the 10 and 20 cm path lengths were correlated successfully by the Elsasser strong line approximation for all temperatures. These correlations can be used to calculate the spectral absorption either for pure carbon monoxide or for a mixture of carbon monoxide and an inert gas which has the same broadening effect as carbon monoxide. The integrated absorption for both the fundamental and first overtone bands is given in tabular form as a function of temperature, pressure and path length. A method of correlating the integrated band absorption is indicated and the results for 900° K is shown. An example of using the integrated band absorption results in calculating the emissivity of carbon monoxide is demonstrated.

Author

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INTRODUCTION

Infrared absorption or emission of hot gases plays an important role in many thermal systems. Of particular interest is the infrared radiative flux emitted from rocket exhaust plumes which causes surface heating of the base region of multi-engine vehicles.

Theoretical determination of the infrared spectra of gases has been carried out by many investigators [1-3]. However, due to the increasing complexity of the excited states of gases at high temperatures, the approximations involved in these calculations require experimental confirmation. Consequently, many experimental systems have been developed recently for infrared measurements of gases at high temperatures. These can be classified into three groups: 1) combustion systems [4,5], 2) shock tubes [6,7], 3) furnaces [8-11]. With furnace systems, absorption measurements of a variety of gases can be made and a more flexible control of thermodynamic and optical conditions is possible than those using combustion systems or shock tubes [11].

The present report presents spectral absorption measurements for carbon monoxide fundamental and first overtone bands up to a temperature of about 1500° K. In addition to being a fundamental interest, these results are of practical importance for problems related to the energy exchange of carbon monoxide with solids and other gases. The apparatus used in the present study has been described in detail in Reference 11. Therefore, only a brief description is given here.

The infrared spectrum of carbon monoxide has been under investigation for a long time [12-15]. Early studies were concerned with the identification of the characteristic frequencies necessary for an understanding of molecular structure. Relatively few experiments have been conducted to determine quantitative spectral characteristics, and these have been at room temperature. Based on the recent development of the theoretical models, infrared experimental work on carbon monoxide is classified according to the optical region involved in the study. In short, these are the optically weak and strong regions (for details, see the section on correlation of data). When the gas is optically weak, the spectral absorption at any temperature depends only on the product of the partial pressure of the absorbing gas times the geometric path length. Spectral measurements in this region have been limited to room temperature [16,17]. Recently total band measurements in the weak region were reported at high temperatures [18]. These results are of interest for comparison with those obtained by considering the quantum and statistical aspects of emitting-absorbing molecules. However, due to their association with small path lengths and large pressures, their range of applicability in calculating the radiative flux is quite limited. On the other hand, for medium and large path lengths, spectral data most often lie in the strong region. The spectral absorption in this region at any temperature is a function of a single parameter: square root of the product of the effective gas pressure times the optical depth of the gas (i.e., partial pressure of the absorbing gas times the geometric path length). Experimental data covering this range have been limited to room temperature [16,19,20]. In the transition between the weak and the strong regions, Davis [21] obtained few spectral data for the fundamental band at high temperatures. The present report is devoted to the study of the infrared spectrum of carbon monoxide in a wide range of pressures and path lengths in the temperature range 300 to 1500° K.

To study the functional dependence of the spectral and band absorption on pressure and path length at different temperatures, measurements were performed for path lengths 1, 5, 10 and 20 cm at temperatures of 300, 600, 900, 1200 and 1500° K in the pressure range 1/4 to 3 atm. The 10 and 20 cm data were correlated in terms of a function of the effective pressure times the optical depth of the gas. Good correlation of the data was achieved with the Elsasser strong line approximation at each temperature. Using these band absorption values the emissivity of the gas can be calculated. As an example, the emissivity at an optical depth of 10 cm-atm and at a total pressure of one atmosphere is calculated as a function of temperature. Comparison is made with reported data of other investigators [2,22-24].

INFRARED SPECTRAL ABSORPTION SYSTEM

The apparatus for infrared spectral absorption studies is shown schematically in Fig. 1. It consists of: 1) a globar source with a chopper blade for alternating the input to the energy sensing element, 2) a high-temperature furnace which incorporates a graphite resistance heating element surrounding an inner ceramic tube for containment of high-temperature gases, 3) a monochromator, and 4) an amplifier and automatic recorder. Details of construction and gas supply and exhaust circuits are given in Reference 11.

The test optical path is limited to the central zone of the furnace by the use of window holders at each end. Hot-pressed zinc selenide windows were originally employed because this material is transparent in the 1-20μ wavelength region and inert to H_2O, CO_2 and CO up to a temperature of 540° F. In order to keep these windows below this limit, it was necessary to water-cool the holders in which they were mounted.

Data for the fundamental band of CO at temperatures of 300° K and 1800° K and at pressures from 0.25 to 3 atmospheres obtained with this system were reported in Reference 11. Although agreement with existing results was within 15 per cent, the substantial temperature variation along the test optical path caused by the water-cooling of the windows made the comparison open to question. To eliminate this temperature variation, high-temperature window holders were fabricated and mounted in the furnace as shown in Fig. 2. Each holder was made from a high-purity alumina tube with a sapphire window brazed in one end by using a high-temperature glass frit. The deviation from the maximum center temperature is reduced to within 80° K when the center temperature is 1200° K. Data for a given gas temperature refer to the geometric mean temperature along the test section.

At temperature above 1200° K, the glass frit used to braze the sapphire windows in the alumina tubes weakened and permitted gas leakage to occur. Nitrogen-cooled stainless steel window holders were therefore designed. Sapphire windows were held in these by means of inside threads and a ring-shaped nut. Sealing of the windows in the holders was accomplished with a platinum O-ring. To minimize any leakage through the O-ring, provisions were made to balance the pressures on both sides of the sapphire windows. This was accomplished by installing a second window (NaCl) at the other end of the stainless steel holders. During operation a continuous flow of nitrogen at a pressure equal to or a little less than the carbon monoxide pressure is provided between the NaCl windows and the sapphire windows.

Spectral measurements were obtained with these holders for the 5, 10 and 20 cm path lengths at the 1500° K temperature. Upon completion of the testing at 1500° K the temperature was raised to 1800° K. This was about 50° K higher than the stainless steel window holders could tolerate, the end nuts began to melt. However, it is believed that slight redesign of the inner ends of these holders (possibly incorporating shielding) will make them operate up to 1800° K.

EXPERIMENTAL RESULTS

The infrared absorption of pure carbon monoxide is a function of the geometrical path length, gas pressure and temperature. The path lengths chosen for this investigation are 1, 5, 10 and 20 cm. At higher temperatures the 1 cm path length was excluded since little absorption was observed. Data were obtained at temperatures 300, 600, 900, 1200 and 1500° K and over the pressure range of 1/4 to 3 atm.

The data were obtained by setting the path length, heating the gas sample to the required temperature and then recording an absorption spectrum for each pressure. The spectral absorptivity A_ω was calculated (as described in Reference 11) for a series of wave numbers. The resulting spectral absorption profiles, as function of wave number, for the CO fundamental band are shown in Figs. 3 to 20.

The integrated band absorptivity defined by

$$A = \int_{\Delta\omega} A_\omega \, d\omega \qquad d\omega \qquad (1)$$

was determined by measuring the area under the absorption curve. The integrated band absorptivities of the CO fundamental band as a function of pressure and path length for each temperature are summarized in Tables 1-5.

According to analytical studies, the most effective absorption band for CO is the fundamental (4.67μ), which corresponds to a vibrational quantum number transition from 0 to 1. The only other important one is from 0 to 2 (first overtone) which correspond to a wavelength of 2.35μ. There was a noticable absorption effect in the 2.35μ region for the 20 cm centimeter path length runs at pressures of 1, 2 and 3 atm. Spectral band absorptivities for this path length and at temperatures 300, 600, 900, 1200, 1500° K are shown in Figs. 21-25. The integrated band absorptivity defined by Eqn. (1) for the first overtone is summarized in Table 6 as a function of pressure and temperature for the 20 cm path length.

CORRELATION OF DATA

A. Correlation of Spectral Data

Infrared radiation from gases results primarily from transitions in the vibration-rotation energy levels of the molecules which possess an electric moment (e.g., CO, CO_2, and H_2O). Separations of the rotational energy levels due to the interaction of vibration and rotation are so much smaller than those of the vibrational energy levels that the rotational lines in each vibrational band can only be distinguished by a high-resolution spectrometer.

For radiative transfer studies such detailed observations are not practical and less sensitive spectrometers can be employed. However, interpretation of the measurements requires the application of an appropriate model to simulate the "fine structure" of the spectra, i.e., vibrational bands consisting of closely spaced rotational lines broadened primarily by molecular collisions. These models specify the band structure - intensity distribution, line-spacing distribution, and line-width distribution - and yield relations between absorptivity and band parameters, i.e., integrated band intensity, average line-spacing, and average line-width (see Reference 2).

Two models have received general recognition -- the Elsasser and the statistical [25-28]. In the Elsasser model the spectral lines are assumed to be identical and uniformly spaced. However, the statistical model is composed of randomly spaced spectral lines with arbitrary intensity distribution. The two models yield the same functional form for the spectral absorption when the absorbing gas is optically thin or there is complete overlapping of the spectral lines. This is the special case of the weak line approximation. In general, by comparing the experimental data with the theoretical values predicted by these band models, one can select the model which gives the best fit for the data.

In the weak line approximation the spectral absorption is given by

$$A_{\omega} = 1 - \exp\left(\frac{S_{\omega}}{d} P_{\ell} \right) \qquad (2)$$

where S_{ω} is the mean line intensity, d the mean line-spacing, P the partial pressure of the absorbing gas and ℓ the geometric path length of the gas. Plass [27,28] has shown that the condition for the weak line approximation to apply is

$$\frac{S_{\omega} P_{\ell}}{2\pi \alpha_{\omega}^{o} P_{e}} < 0.2 \qquad (3)$$

where the effective pressure P_e is given by [19,29]:

$$P_e = DP + \sum_i F_i P_i$$

Here α_{ω}^{o} is the line half-width, P_i the partial paressure of the ith foreign gas, D the self-broadening constant and F_i the broadening constant due to the ith foreign gas.

For pure carbon monoxide, $P_i = 0$ and $D = 1.02$ (D for CO gas at all temperatures is assumed to have the same value as that at room temperature). At room temperature the maximum line intensity [30] for the carbon monoxide fundamental band is 9.17 cm^{-2} atm^{-1}. The half-width of rotational lines at room temperature [31] is 0.061 cm^{-1}/atm^{-1} (self-broadened fundamental).

At temperatures higher than room temperature, the maximum line intensity decreases mainly due to density change and the half-line width varies inversely with the square root of temperature. Then, correcting the values of the line strength and half-width to the temperatures used in the present experiment, then Eqn. (3) indicates that, at temperatures in the range 300 to 1500° K and total pressure in the range 1/4 to 3 atm, for all lines within the band system to be optically weak the path length ℓ should be less than 0.1 mm.* This is well below the minimum distance which could be provided by the present equipment. As anticipated, it was found that the spectral absorption data for the minimum path length of 1 cm. could not be correlated by the weak line approximation.

For spectral absorption to be described by the strong line approximation, the following condition should hold [27,28]:

$$\frac{S_{\omega} P_{\ell}}{2\pi \alpha_{\omega}^{o} P_{e}} > 1.63 \qquad (4)$$

where S_{ω}, P, ℓ, α_{ω} and P_e are defined above. Since the intensity of spectral lines in the band wings decreases asymptotically to zero, then Eqn. (4) is not satisfied for each line in the band however large ℓ is. However, in

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*It should be mentioned here that this condition is probably much too stringent when applied to the whole band since it is possible for several lines within the band to become optically strong while the band as a whole is weak.

the temperature range used in the present study, it is customary to confine the band to those spectral lines whose intensity is large enough to contribute significantly to the band absorption. Therefore, it is expected that spectral absorption for longer path lengths would be governed by Eqn. (4) and therefore could be correlated by the strong line approximation for most of the spectral lines in the band.

Attempts to correlate the spectral data by the strong line in the statistical model were not successful. This could be due to the assumption of random distribution of the spectral lines for carbon monoxide bands. This led to the consideration of the strong line approximation in the Elsasser band model which yields [27]:

$$A_\omega = \mathrm{erf}\left[\left(\frac{1}{2}\; B_\omega^{\,2}\; X_\omega\right)^{1/2}\right] \qquad (5)$$

where

$$B_\omega = \frac{2\pi\,\alpha_\omega}{d}\;,\quad X_\omega = \frac{S_\omega\,P_\ell}{2\,\alpha_\omega}$$

$$\alpha_\omega = \alpha_\omega^{o}\;P_e$$

α_ω is the half-line width

For pure carbon monoxide gas, Eqn. (5) takes the form

$$A_\omega = \mathrm{erf}\left[\left(\pi\,\frac{S_\omega}{d}\cdot\frac{\alpha_\omega}{d}\right)^{1/2}(P_e \times P\ell)^{1/2}\right] \qquad (6)$$

For each of the spectral curves of the 10 and 20 cm path length data, $P_e \times P\ell$ was determined, then $\left(\pi \frac{S_\omega}{d} \cdot \frac{\alpha_\omega}{d} \right)^{1/2}$ was calculated by using Eqn. (6). The results were plotted as functions of wave number for each temperature. Figures 26-30 shows the calculated data of the strong line parameter $\left(\pi \frac{S_\omega}{d} \cdot \frac{\alpha_\omega}{d} \right)^{1/2}$ against wave number for temperatures 300, 600, 900, 1200 and 1500° K. As can be seen, good correlation for the data with a mean line is obtained.

B. Correlation of Band Absorption Data

In general, the correlation of band absorption depends on the spectral correlation of the constitutent lines. However, the condition required on the strength of each line in the band can be relaxed if we consider the strength of the whole band. The reason for this is because few lines in the band can be weak and still the band can be correlated by the strong line approximation and vice versa. An example of such a case is provided by the present experimental data. Based on the previous estimates which are confirmed experimentally for the validity of the strong line approximation, spectral absorption for the 1 cm data cannot be correlated by the strong line approximation in an appreciable region of the carbon monoxide fundamental band. However, by plotting the integrated absorption for the 1, 5, 10 and 20 cm path lengths against the strong line optical variable $(P_e \times P\ell)^{1/2}$, good correlation was obtained for all path lengths. Figure 31 shows band absorption as function of $(P_e \times P\ell)^{1/2}$ for carbon monoxide fundamental band at temperature 900° K.

C. Carbon Monoxide Emissivity Calculation

The total emissivity of a gas in thermodynamic equilibrium at a temperature T_g, having an optical depth $X = P\ell$ and an effective pressure P_e is given by:

$$E_T(T_g, X, P_e) = \frac{1}{\sigma T_g^4} \int_0^\infty B_\omega (T_g) A_\omega (T_g, X, P_e) d\omega \tag{7}$$

where B_ω is the monochromatic blackbody radiancy and A_ω the spectral absorption. Under the conditions used in the present experiment, carbon monoxide has significant emission only within narrow regions of the radiant energy spectrum so that the variation of B_ω is small along each band. Hence, an average blackbody radiancy $\bar{B}_\omega$, evaluated at each band center can be used for the entire band, and Eqn. (7) can be written as:

$$\begin{aligned} E_T(T_g, X, P_e) &= \sum_i \frac{\bar{B}_{\omega_i}}{\sigma T_g^4} \int_{\Delta\omega_i} A_\omega (T_g, X, P_e) d\omega \\ &= \sum_i \frac{\bar{B}_{\omega_i}}{\sigma T_g^4} A_i \end{aligned} \tag{8}$$

where the summation is extended to all bands of the gas which make significant contribution to the total radiation. A_i is the integrated band absorptivity defined in Eqn. (1).

Eqn. (8) can be used to calculate the emissivity of carbon monoxide gas from band absorption data given in Tables 1-6. A representative plot of the emissivity of carbon monoxide fundamental band, for an optical depth 10 cm-atm and total pressure 1 atm as function of temperature is shown in Fig. 32. The first overtone contribution to the emissivity is neglected due to the relatively small effective pressure and optical depth considered.

DISCUSSION AND CONCLUSION

The good correlation obtained for the 10 and 20 cm data by using the Elsasser strong line confirms the validity of this model for correlating data of carbon monoxide in the temperature range used in the present study. A comparison between the correlation of the present data and the experimental data obtained at room temperature by Burch [16] and correlated by Oppenheim [29] shows general agreement (see Fig. 26). Using these correlations, the spectral absorption in the strong region can be determined for any effective pressure and optical depth from Eqn. (5). Also, once the spectral intensity is known from theoretical or experimental study, the rotational half-width α^o can be determined as a function of temperature from Figs. 26-30. This makes it possible to estimate the spectral absorption at reasonably higher temperatures than those used in the present study.

The correlation of the integrated band absorption as a function of the optical strong parameter $(P_e \times P\ell)^{1/2}$ (shown in Fig. 31) serves two purposes. Firstly, a variation of the integrated absorption with respect to the optical strong parameter can be obtained by averaging over experimental data at various conditions. Therefore, in using this mean integrated absorption other than the tabulated values, the error which may be involved in measuring temperature, pressure and path length in each individual value is minimized. It also indicates the integrated band absorption for any path length and pressure other than those used in the present study.

With reference to Fig. 32, the emissivity values calculated from the present experimental data are in good agreement with those calculated from Oppenheim's total absorption measurements [22]. General agreement is also obtained with Lee's data [24] and Penner's theoretical results [2], while Ullrich's data [23] are considerably higher. For final judgment, comparison of emissivities should be made in a wider range of pressures and optical depths.

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Table 1: Integrated Band Absorptivities in cm^{-1} of CO Fundamental at 300° K

Pressure in atm	Path length = 1 cm	Path length = 5 cm	Path length = 10 cm	Path length = 20 cm
3	127.2	193.5	205.0	226.0
2	90.0	159.2	184.0	210.0
1	48.5	112.0	148.0	169.0
1/2	22.0	58.5	89.0	122.0
1/4	-	30.2	45.0	66.0

Table 2. Integrated Band Absorption in cm^{-1} of CO Fundamental at 600° K

Pressure in atm	Path length = 1 cm	Path length = 5 cm	Path length = 10 cm	Path length = 20 cm
3	120.6	206.0	232.0	262.0
2	84.4	160.0	184.0	224.8
1	44.0	82.8	115.2	151.6
1/2	27.4	36.4	56.2	90.0
1/4	-	-	28.0	44.4

Table 3. Integrated Band Absorption in cm^{-1} of CO Fundamental at 900° K

Pressure in atm	Path length = 1 cm	Path length = 5 cm	Path length = 10 cm	Path length = 20 cm
3	90.5	191.0	234.0	273.0
2	57.6	134.3	176.0	226.0
1	27.7	82.0	106.2	134.0
1/2	-	38.0	55.0	66.0
1/4	-	-	26.3	37.8

Table 4. Integrated Band Absorption in cm^{-1} of CO Fundamental at 1200^{o} K

Pressure in atm	Path length = 5 cm	Path length = 10 cm	Path length = 20 cm
3	187.2	255.0	294.0
2	119.4	150.0	233.2
1	46.6	77.8	127.4
1/2	-	-	49.0

Table 5. Integrated Band Absorption in cm^{-1} of CO Fundamental at 1500° K

Pressure in atm	Path length = 5 cm	Path length = 10 cm	Path length = 20 cm
3	190.0	232.0	190.0
2	117.0	141.0	117.0
1	40.4	58.6	40.4

Table 6. Integrated Band Absorption in cm^{-1} of CO First-Overtone for Path Length 20 cm at Different Temperatures

Pressure in atm	300° K	600° K	900° K	1200° K	1500° K
3	50.0	33.9	31.4	29.0	24.0
2	33.5	20.6	19.36	14.8	15.1
1	18.8	10.2	9.48	7.07	-

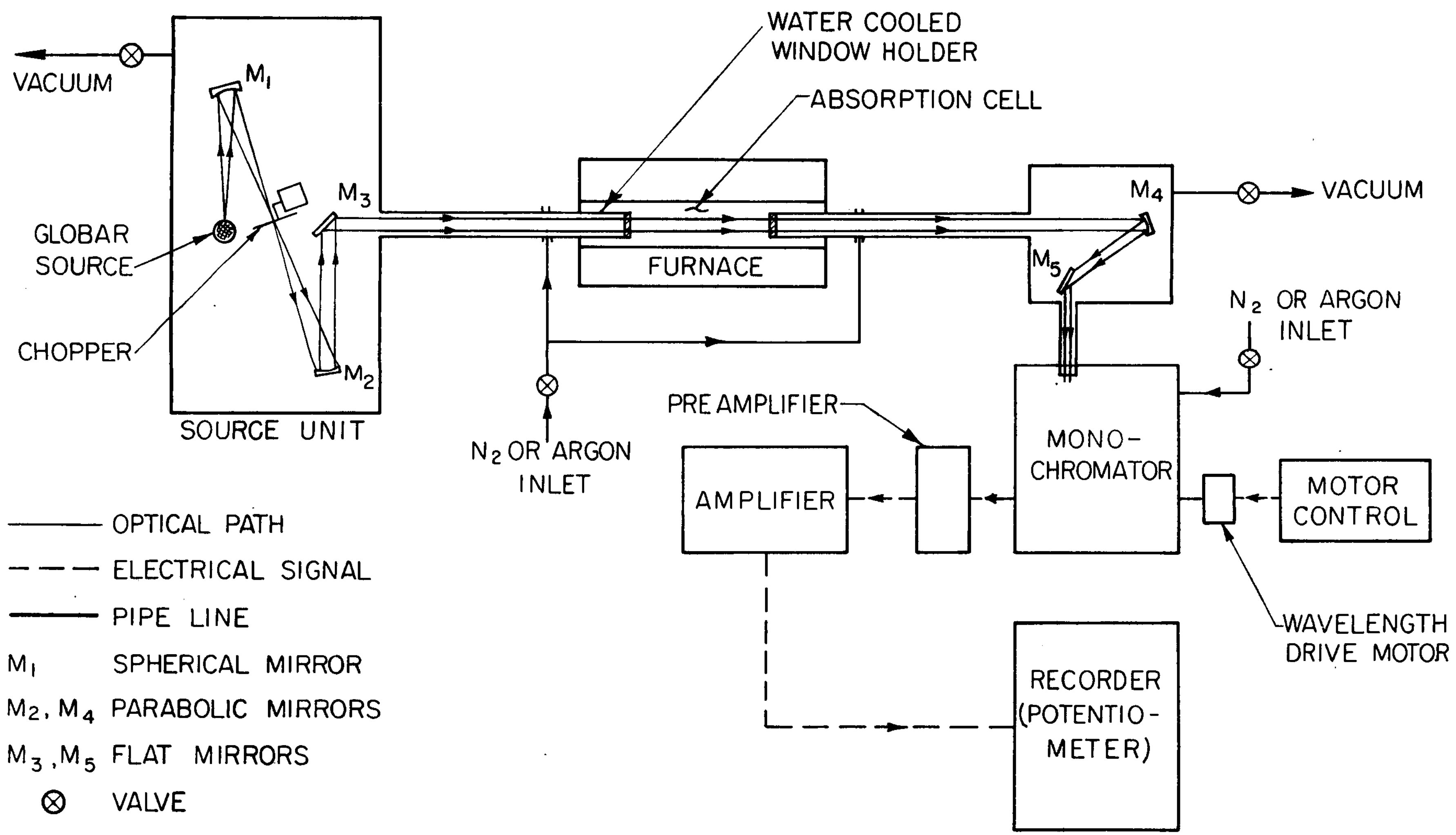

FIG. 1 HIGH TEMPERATURE INFRARED ABSORPTION SYSTEM

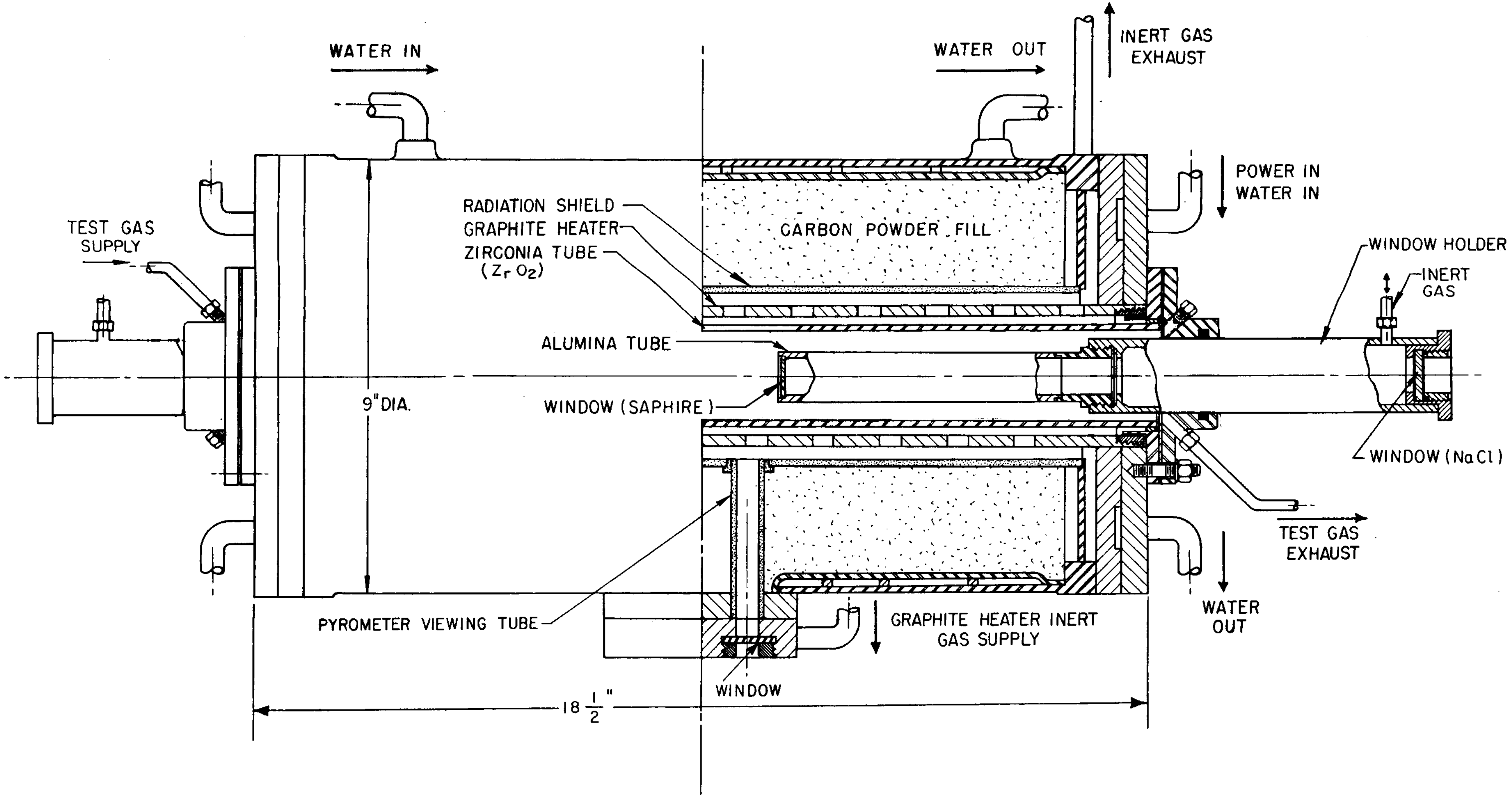

FIG. 2 HIGH TEMPERATURE FURNACE

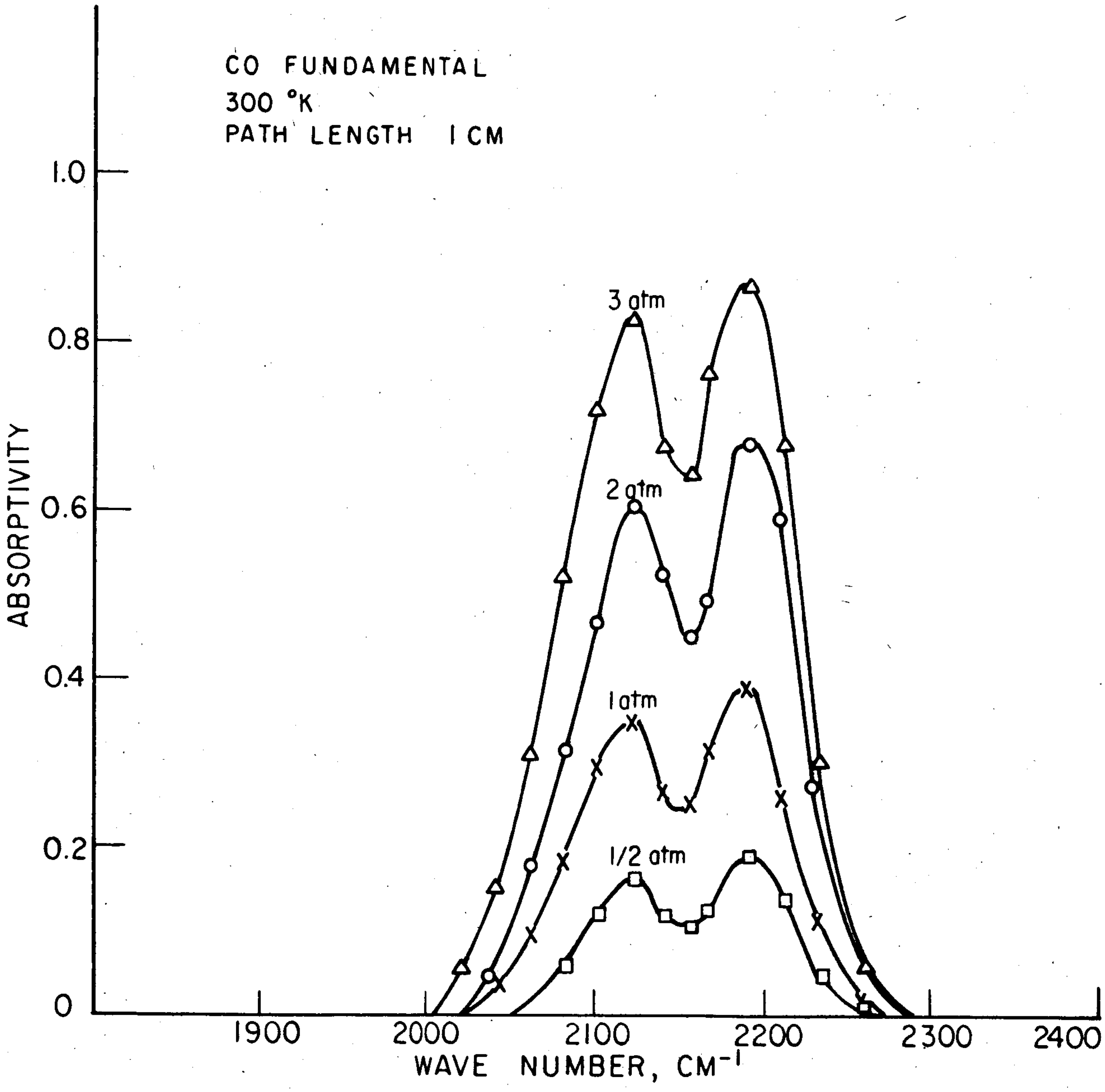

FIG. 3 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 300 °K AND AT PATH LENGTH 1 CM.

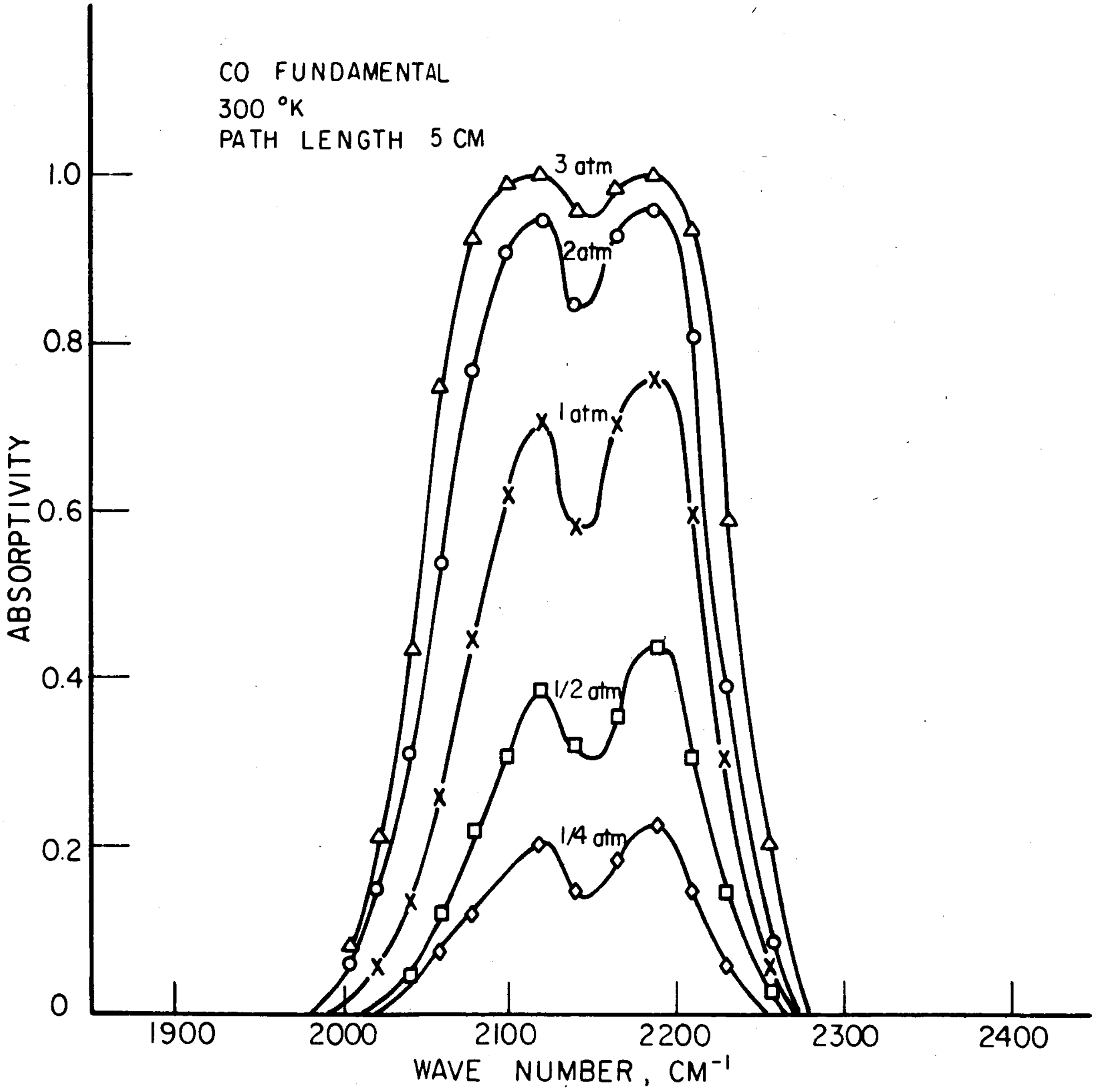

FIG. 4 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 300 °K AND AT PATH LENGTH 5 CM.

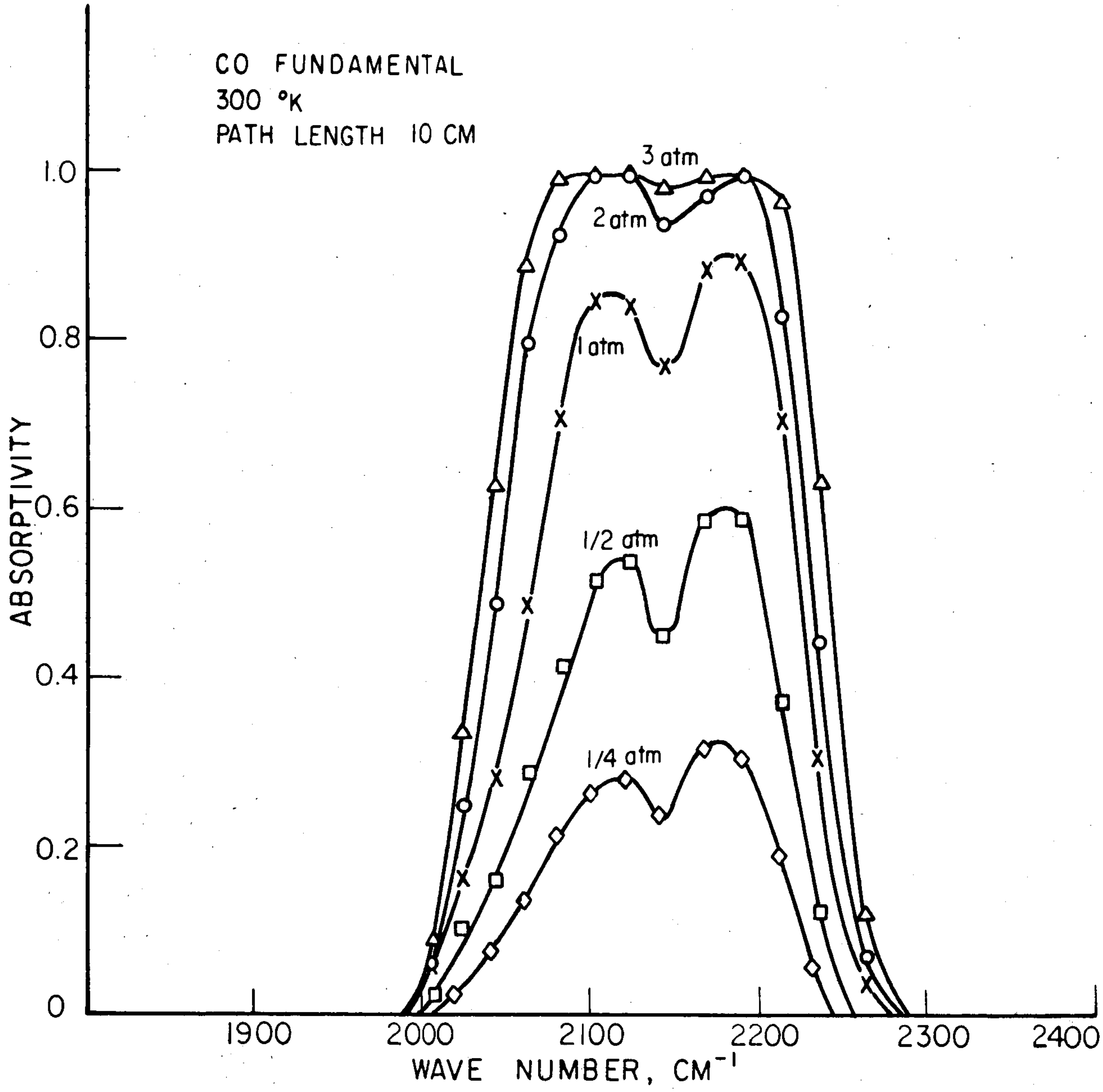

FIG. 5 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 300°K AND AT PATH LENGTH 10 CM.

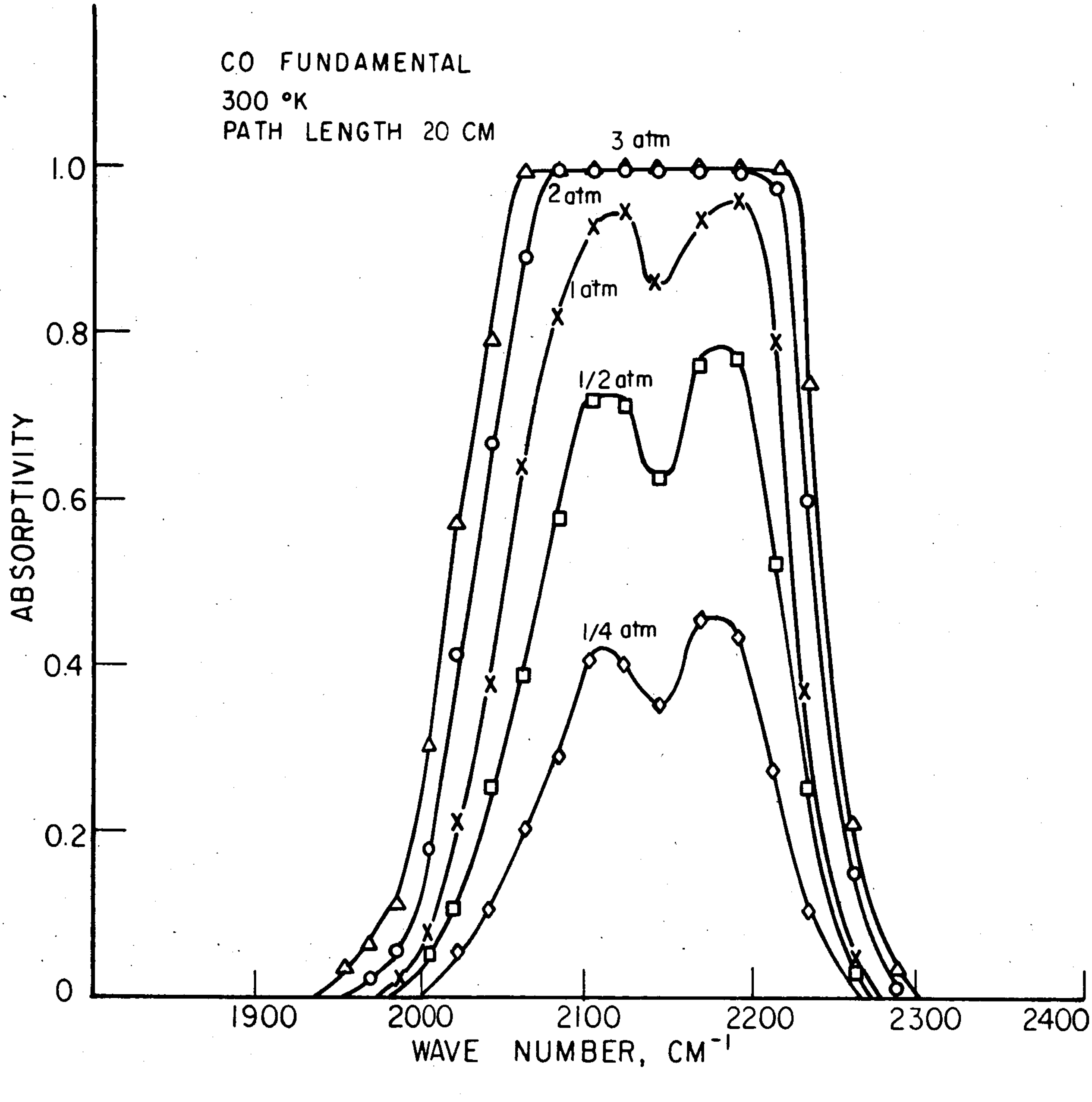

FIG. 6 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 300 °K AND AT PATH LENGTH 20 CM.

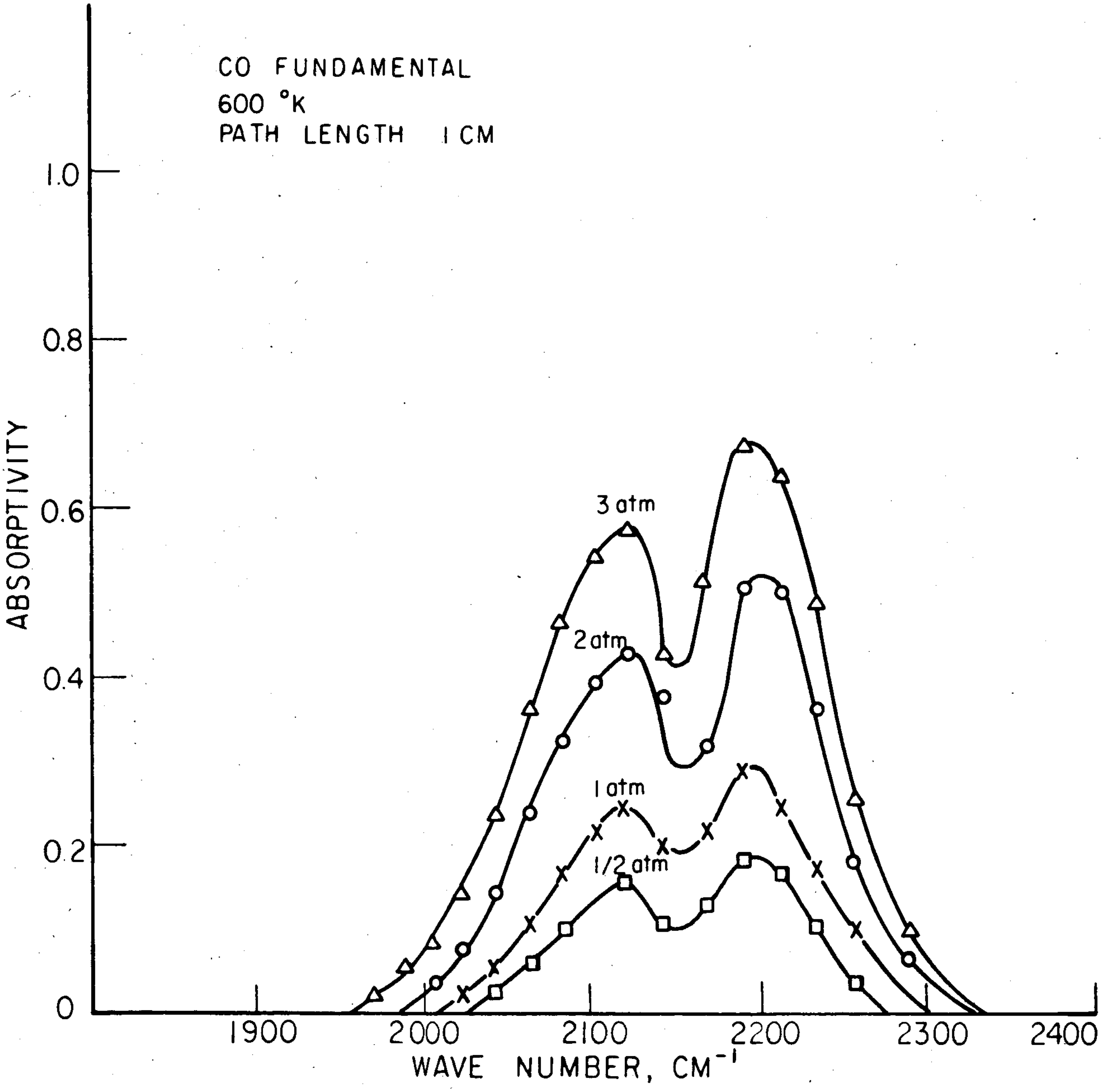

FIG. 7 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 600 °K AND AT PATH LENGTH 1 CM.

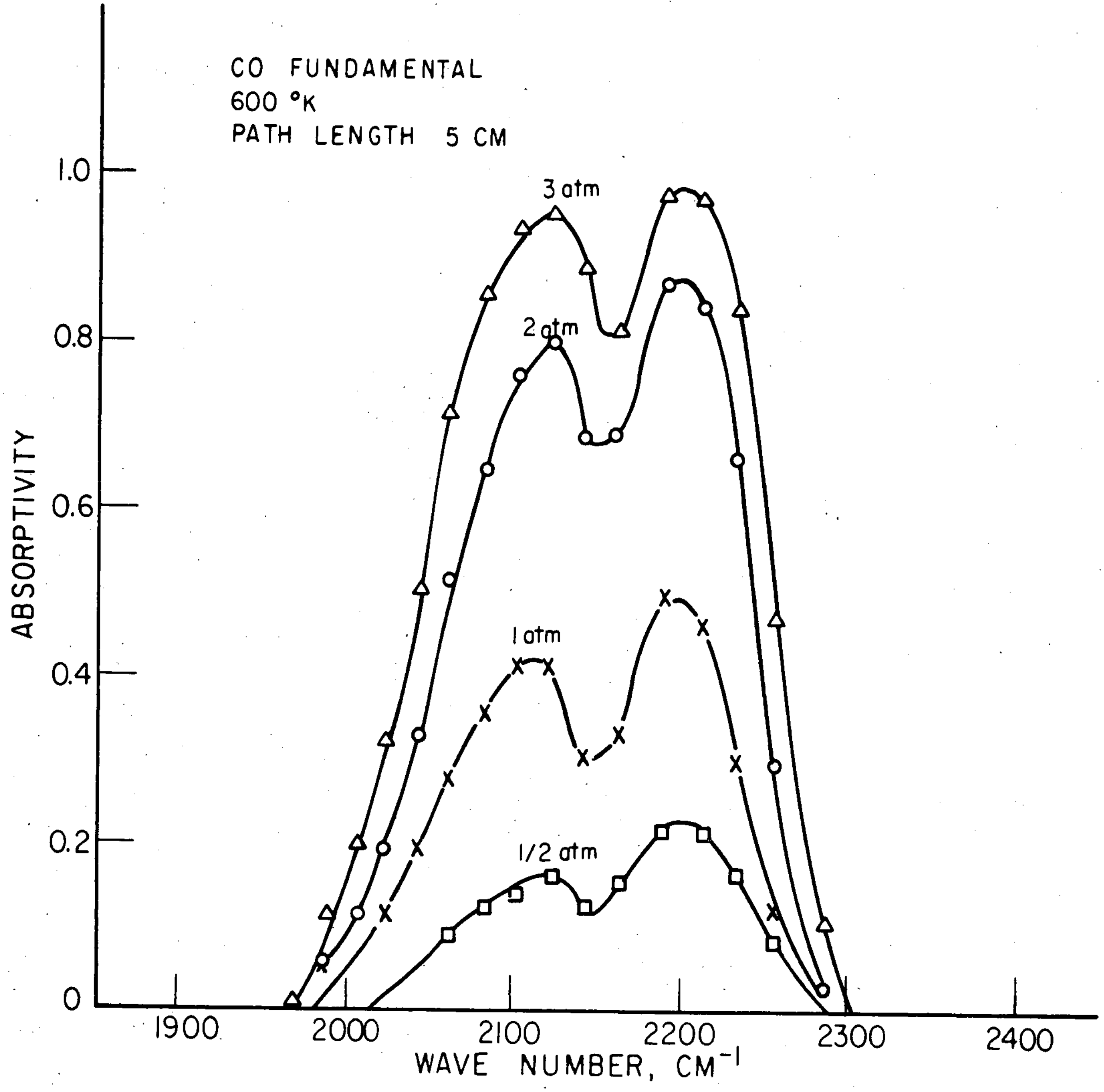

FIG. 8 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 600 °K AND AT PATH LENGTH 5 CM

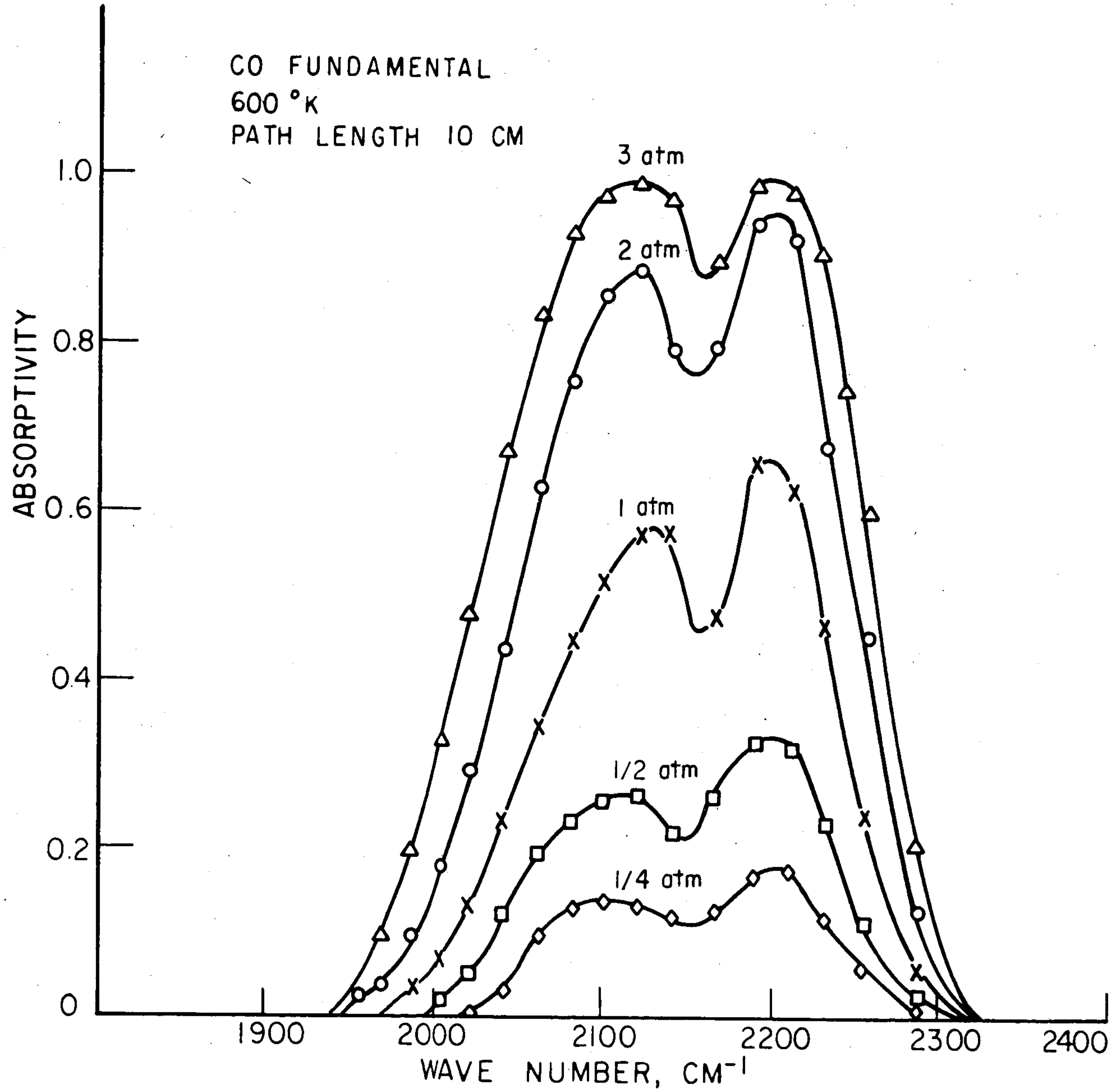

FIG. 9 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 600 °K AND AT PATH LENGTH 10 CM

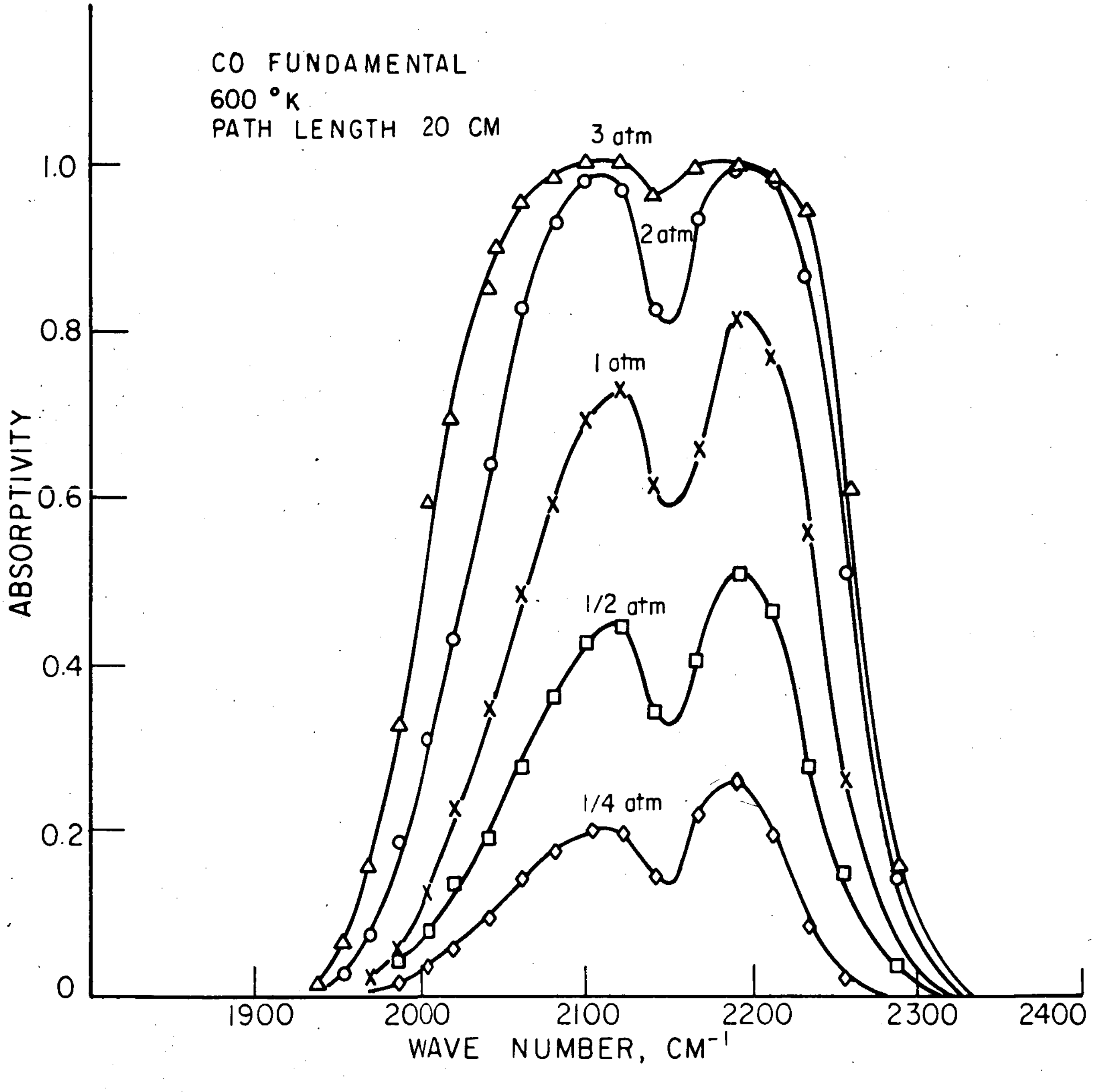

FIG. 10 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 600 °K AND PATH LENGTH 20 CM.

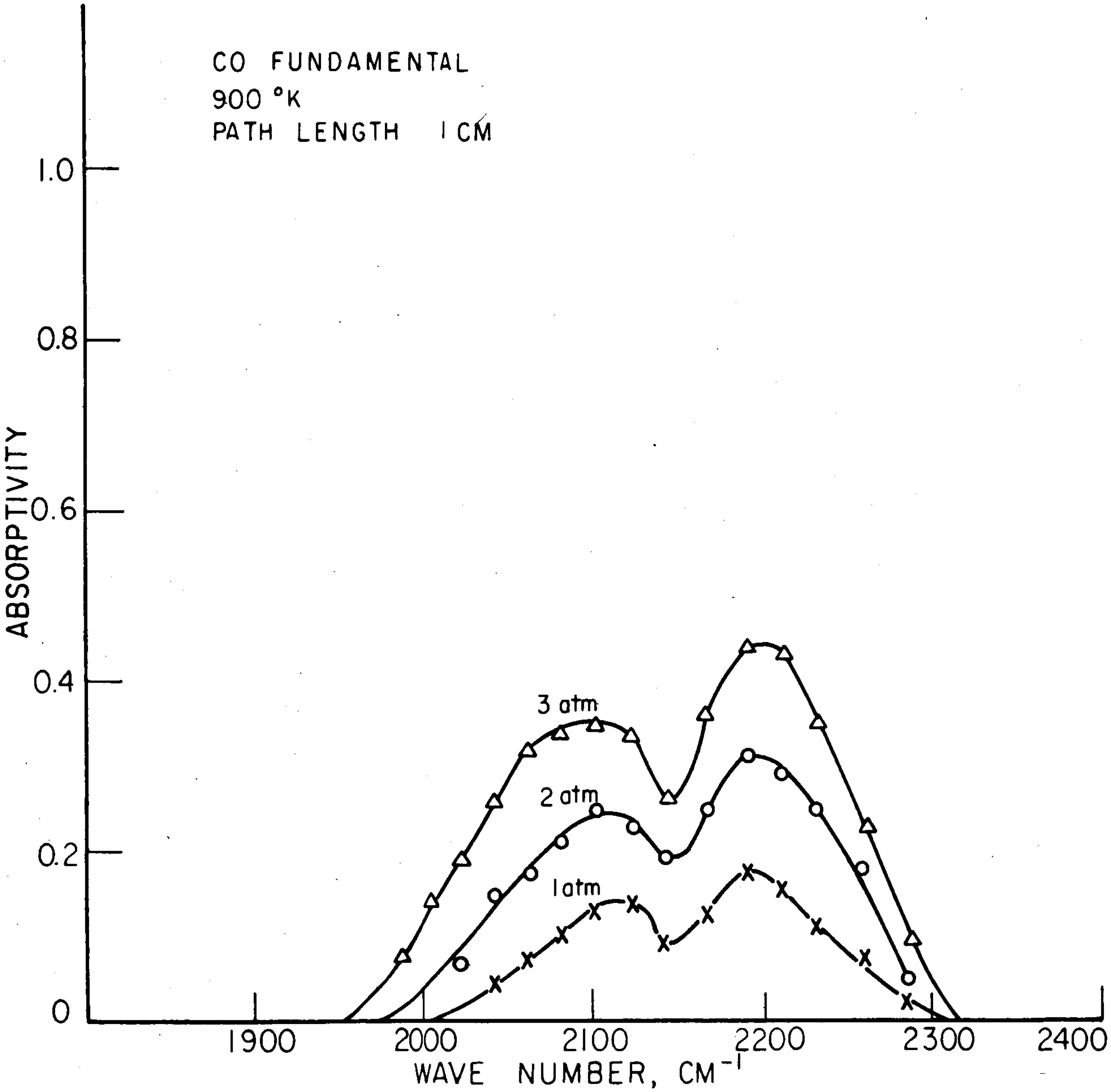

FIG. 11 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 900 °K AND AT PATH LENGTH 1 CM.

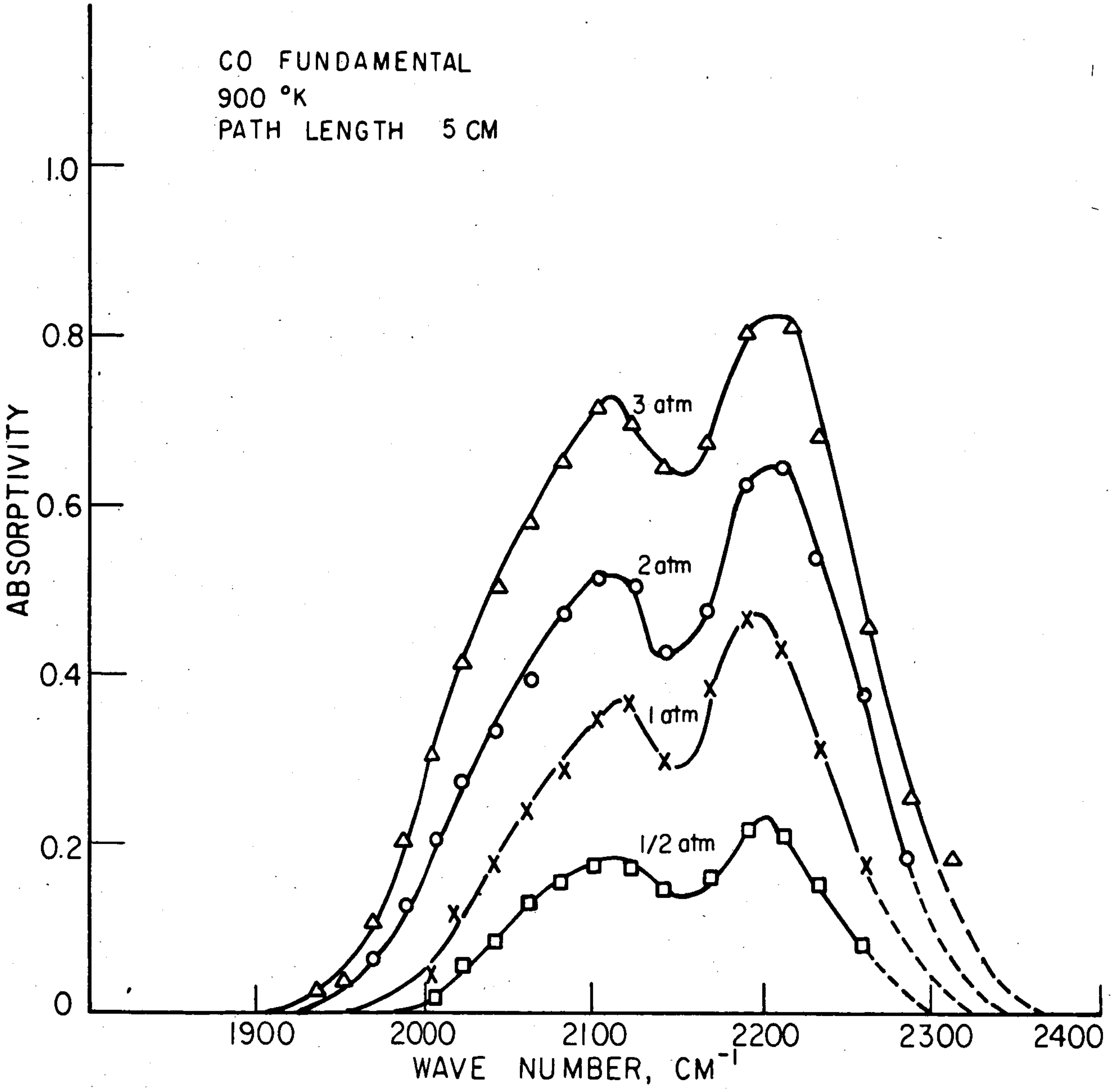

FIG. 12 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 900 °K AND AT PATH LENGTH 5 CM.

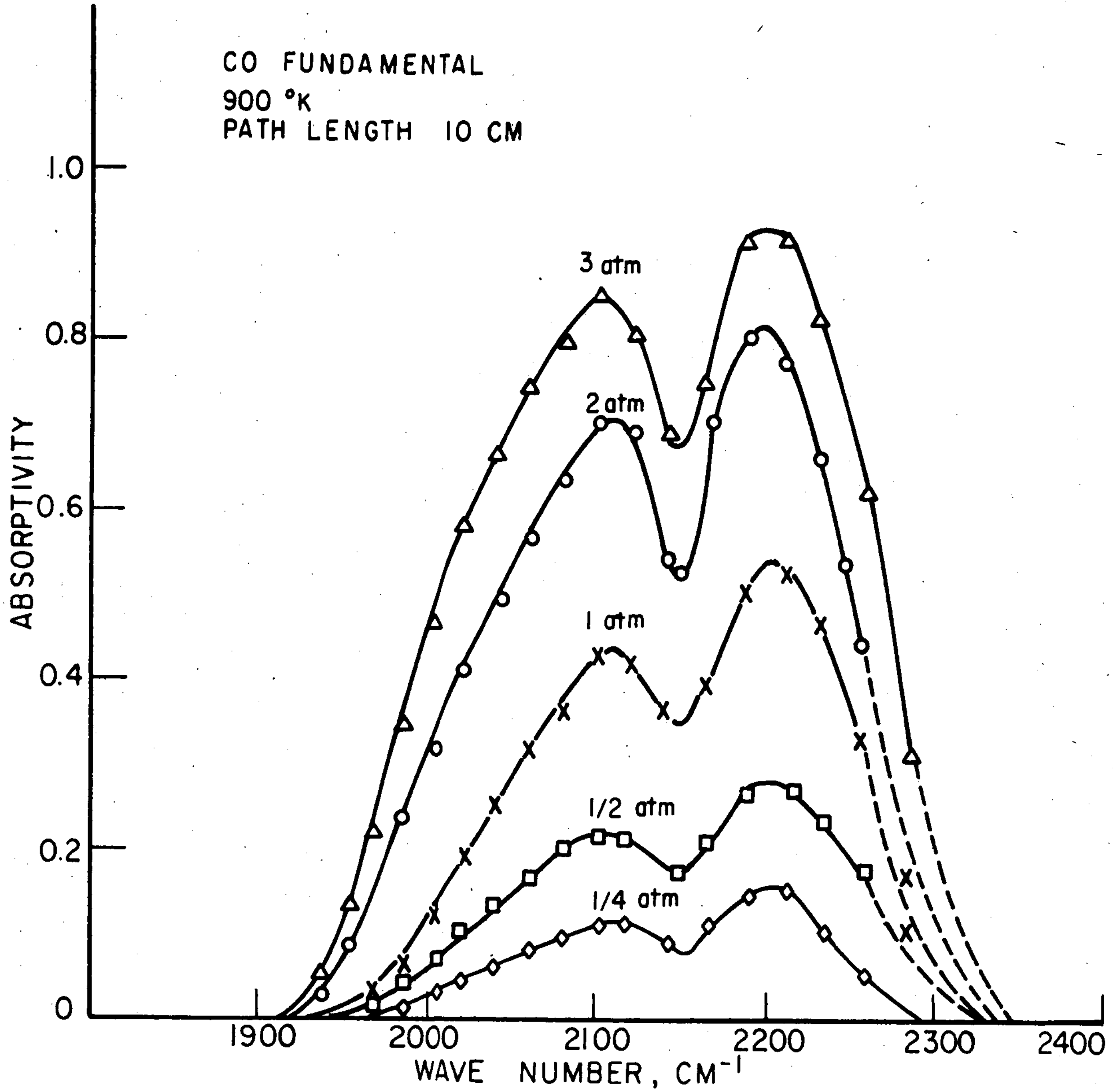

FIG. 13 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 900 °K AND AT PATH LENGTH 10 CM.

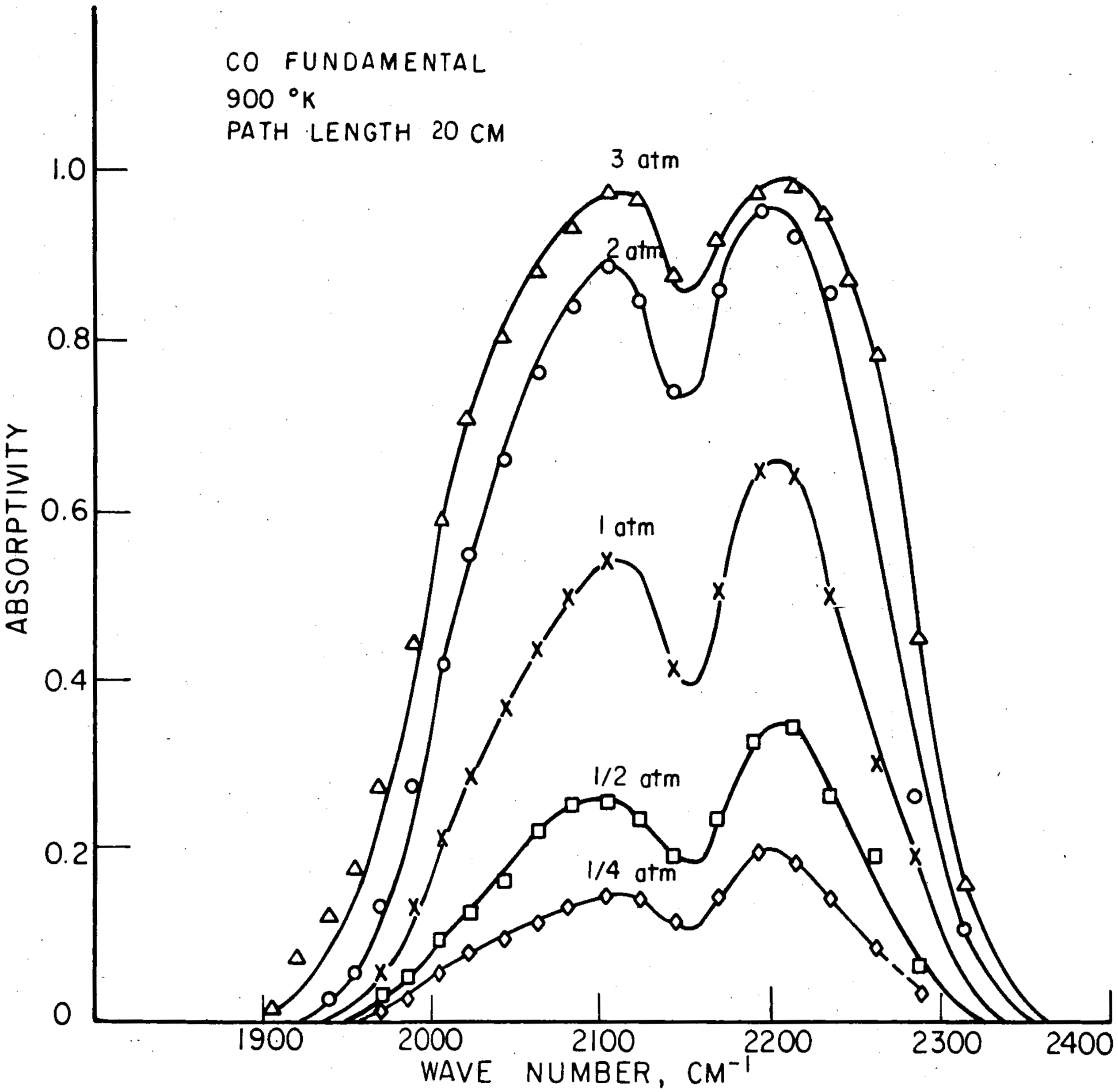

FIG. 14 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 900 °K AND AT PATH LENGTH 20 CM.

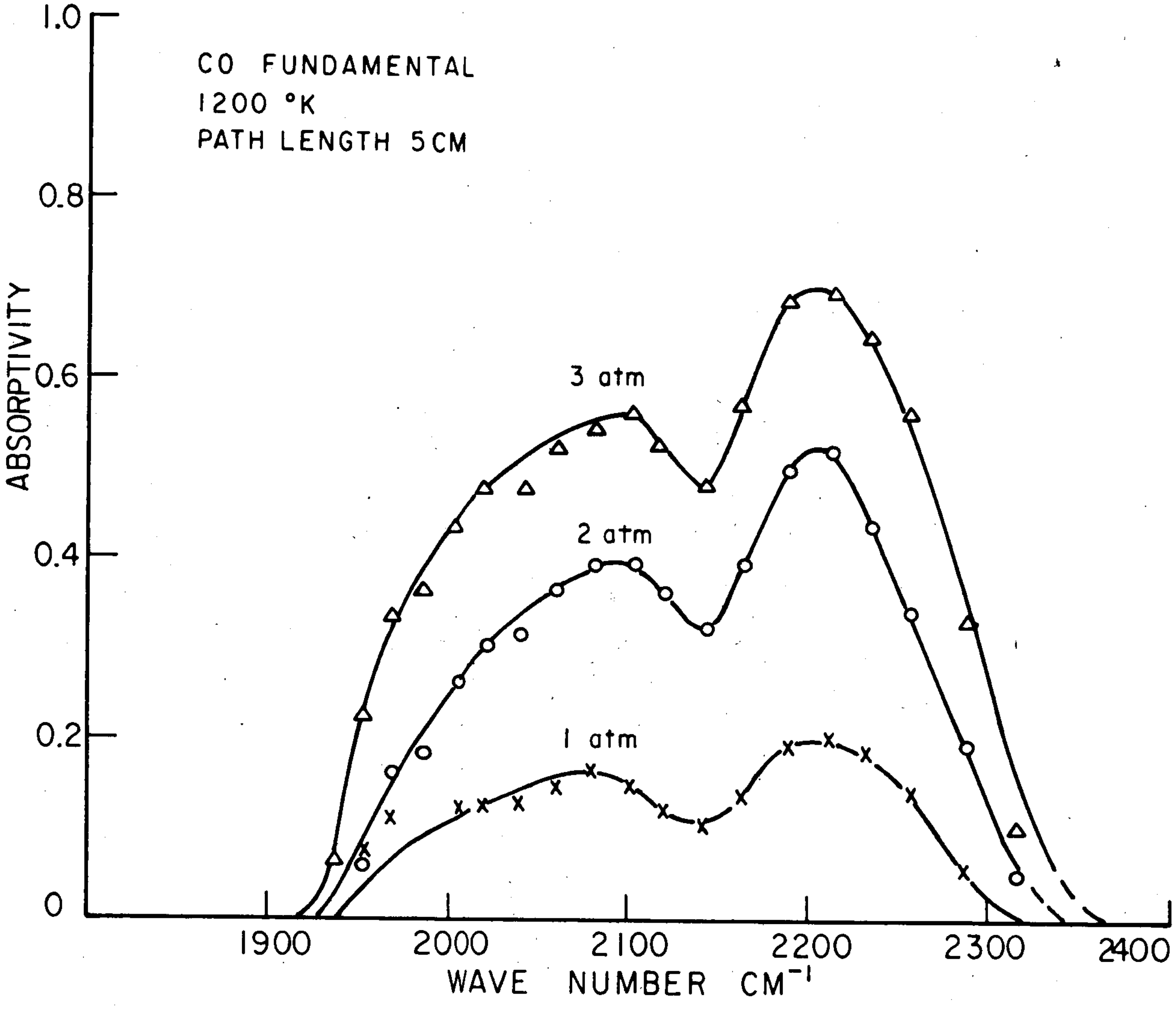

FIG. 15 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 1200 °K AND AT PATH LENGTH 5 CM.

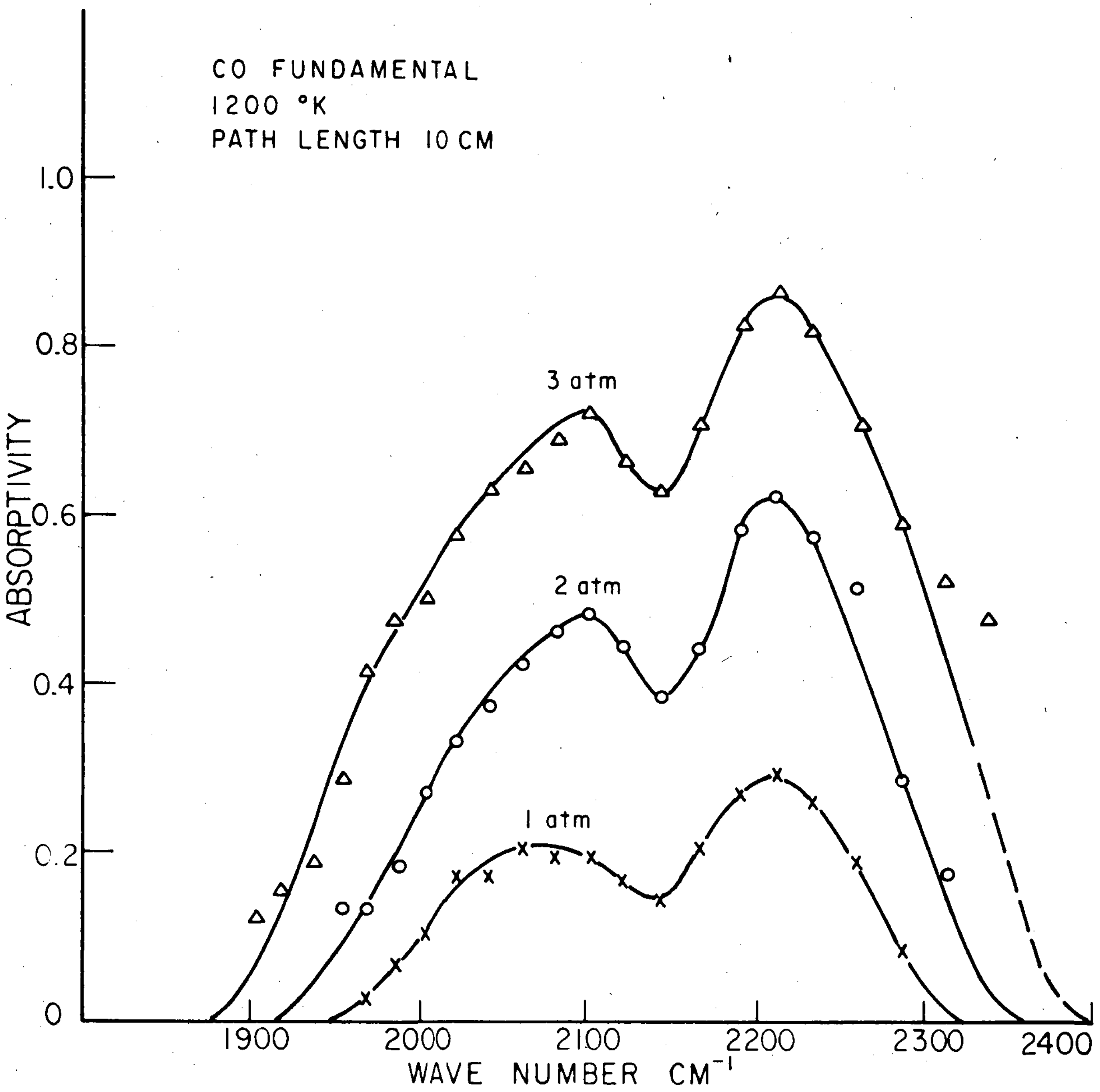

FIG. 16 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 1200 °K AND AT PATH LENGTH 10 CM

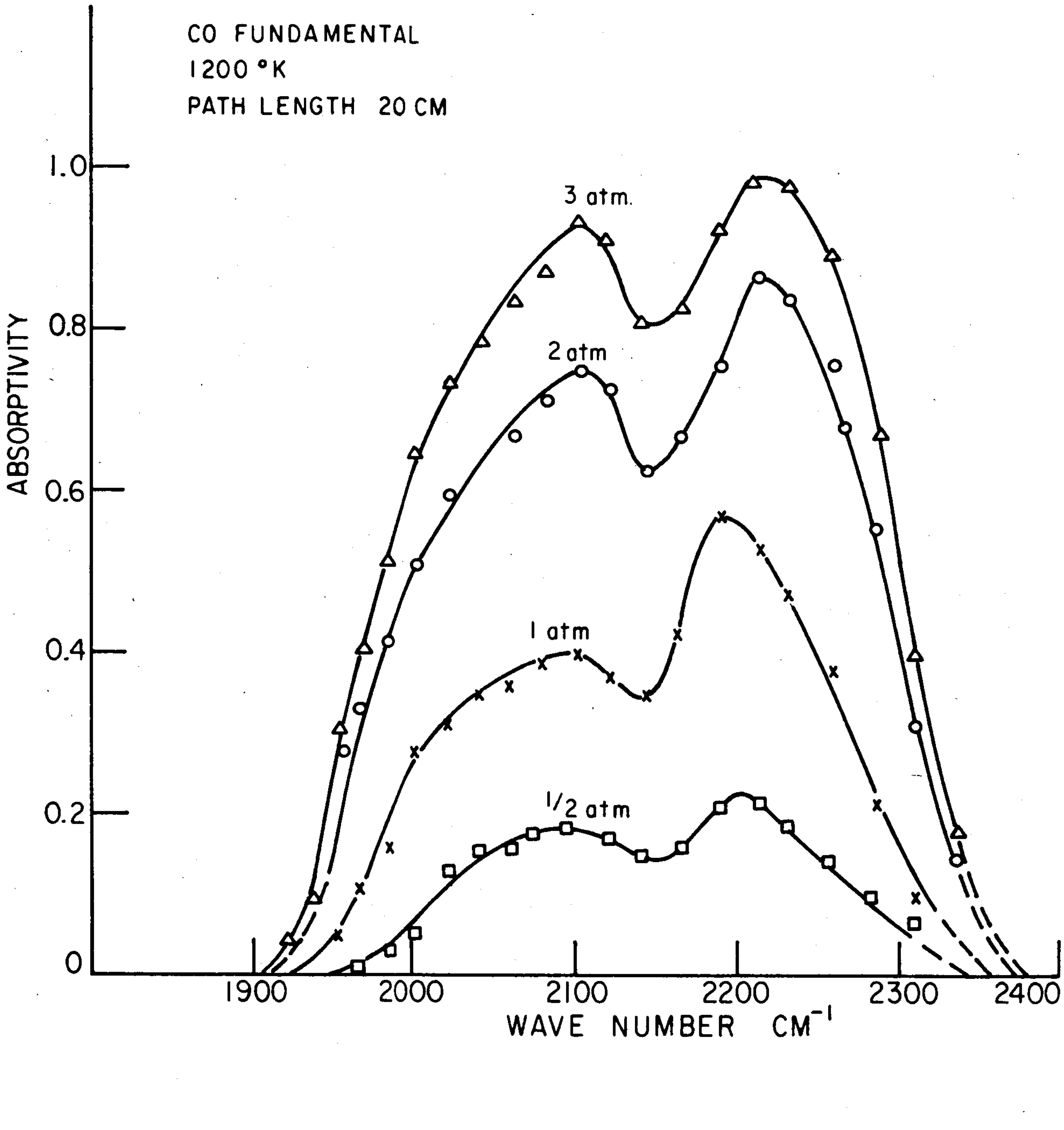

FIG. 17 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 1200 °K AND AT PATH LENGTH 20 CM

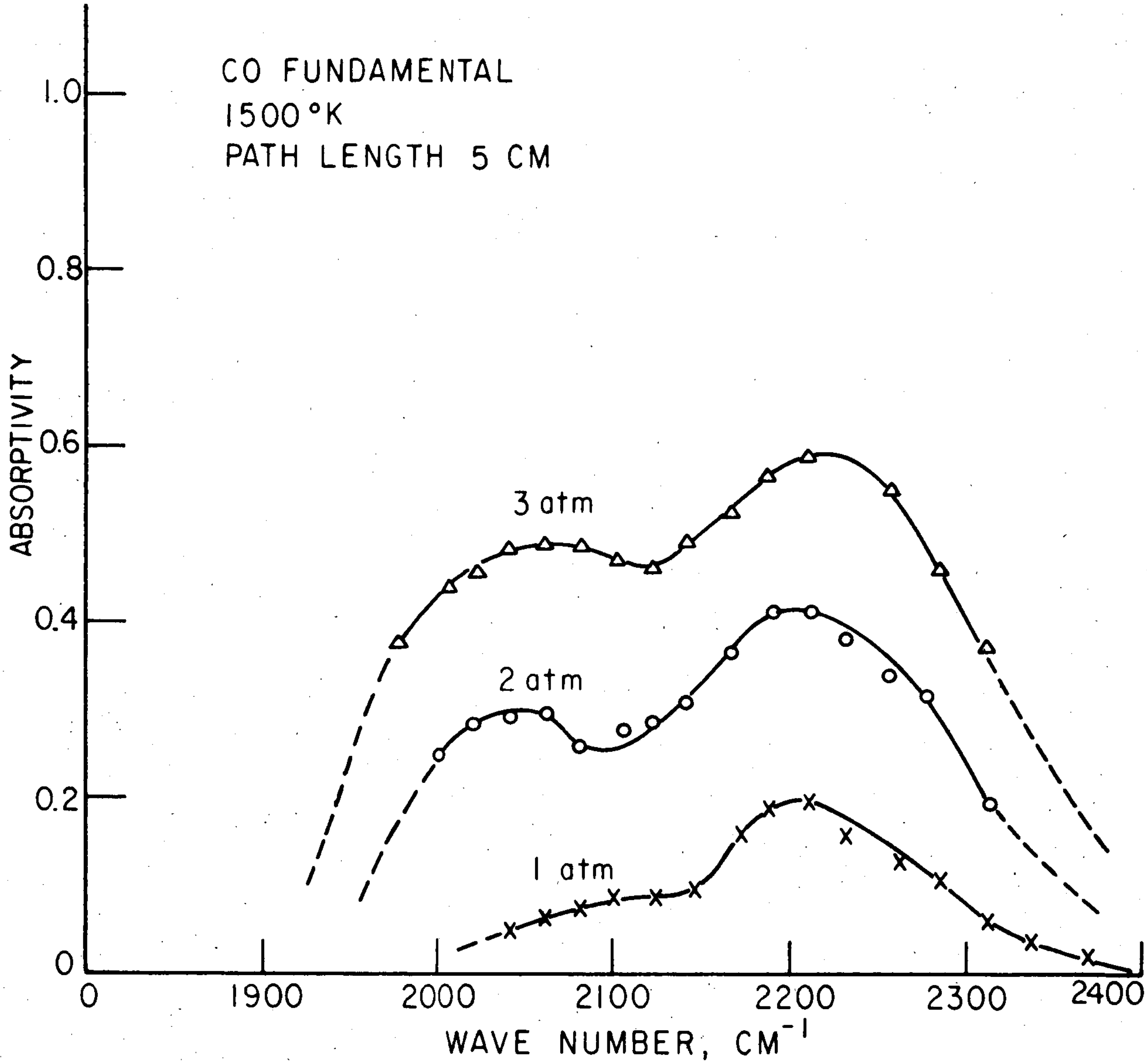

FIG. 18 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 1500 °K AND AT PATH LENGTH 5 CM

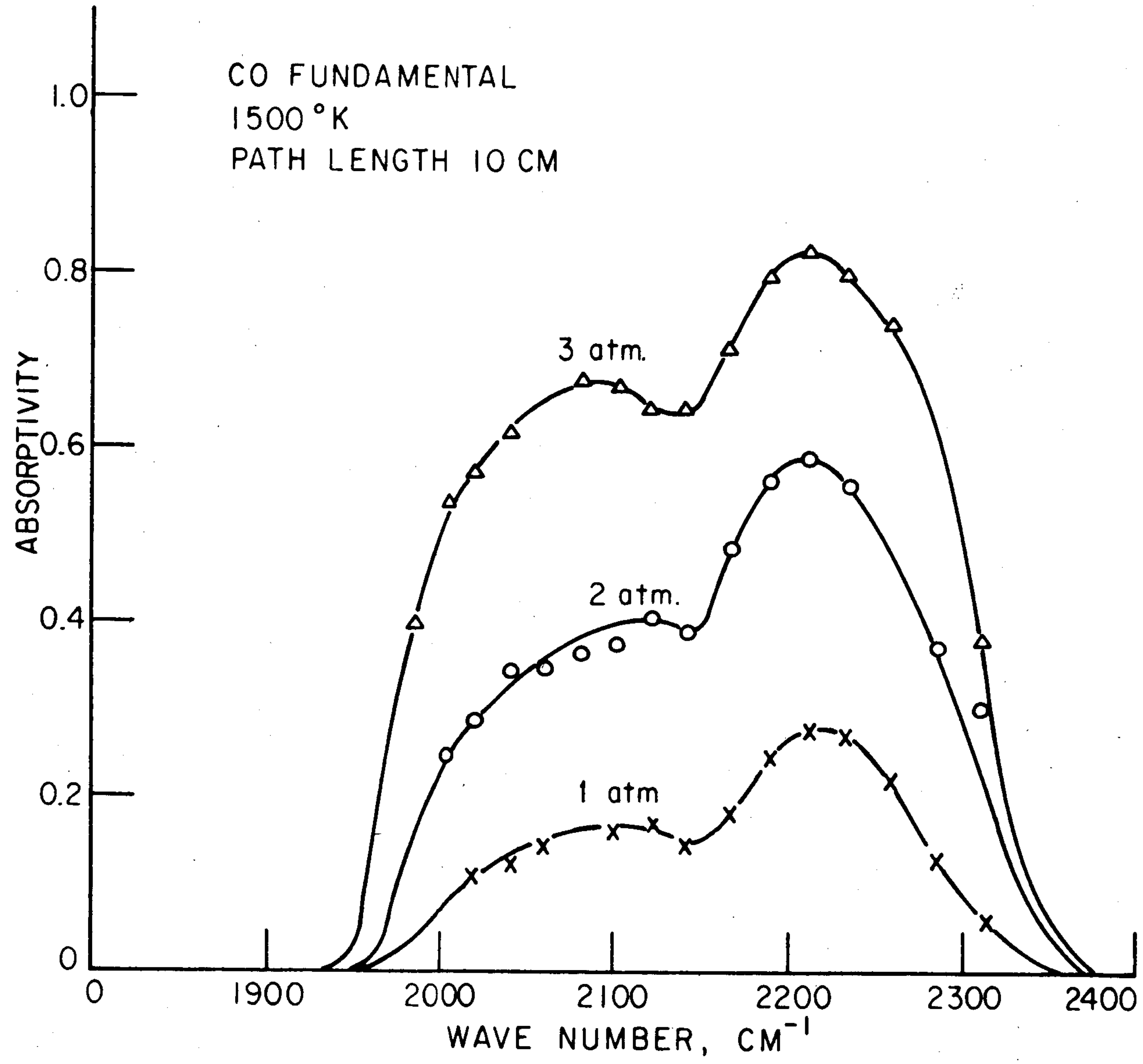

FIG. 19 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 1500 °K AND AT PATH LENGTH 10 CM

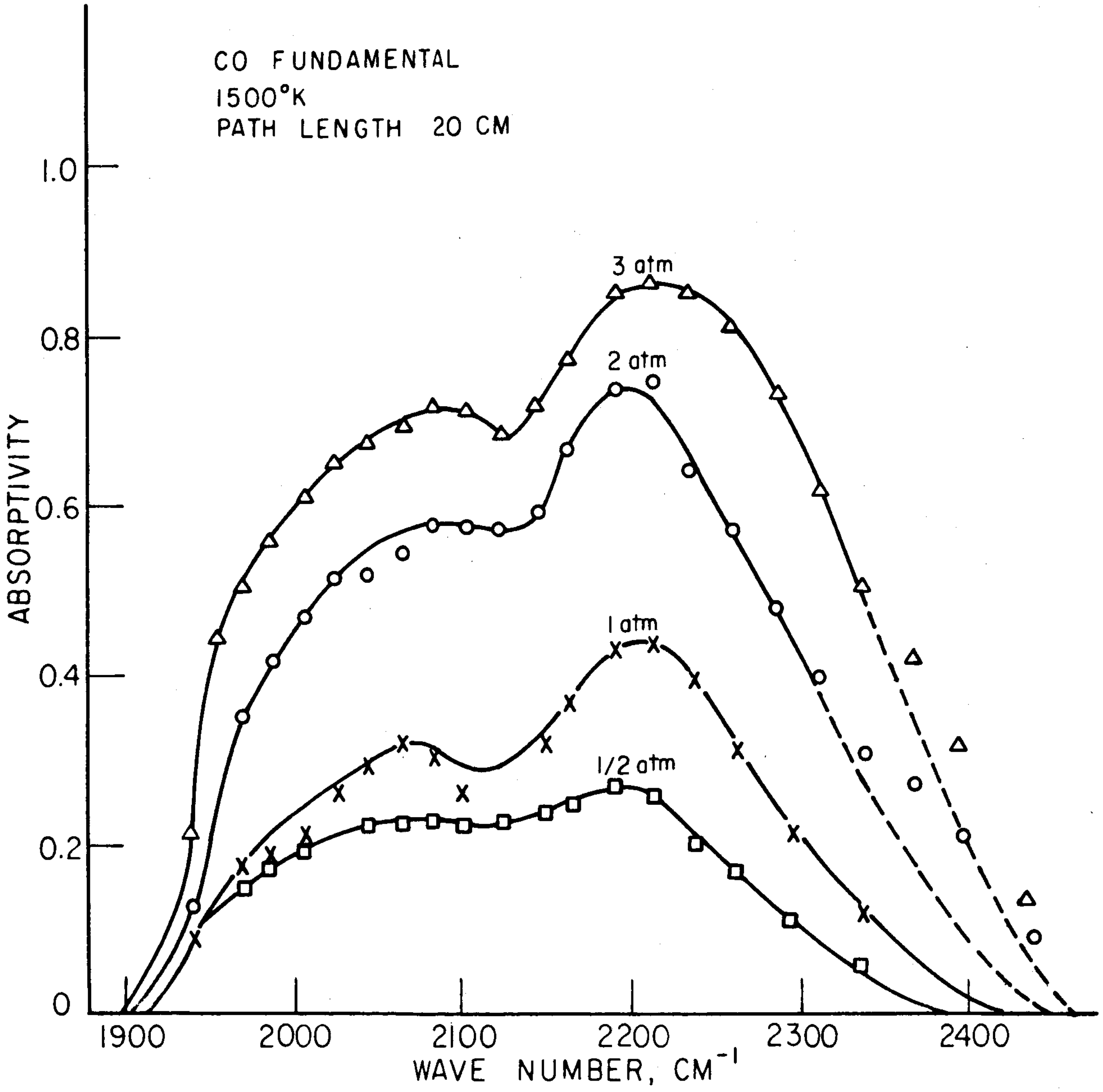

FIG. 20 SPECTRAL ABSORPTIVITY OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 1500 °K AND AT PATH LENGTH 20 CM.

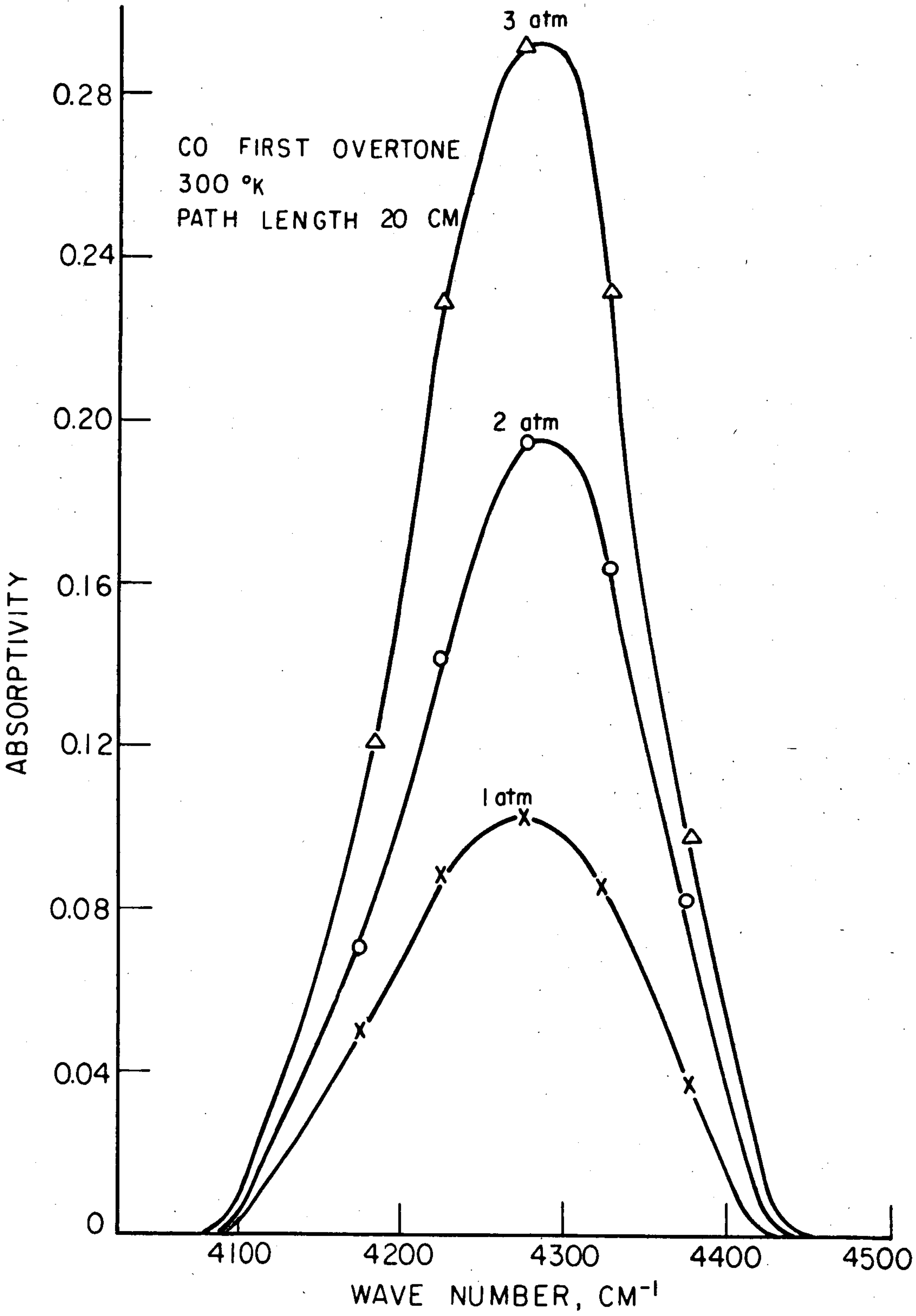

FIG. 21 SPECTRAL ABSORPTIVITY OF FIRST OVERTONE BAND OF CO GAS AT TEMPERATURE 300 °K AND AT PATH LENGTH 20 CM.

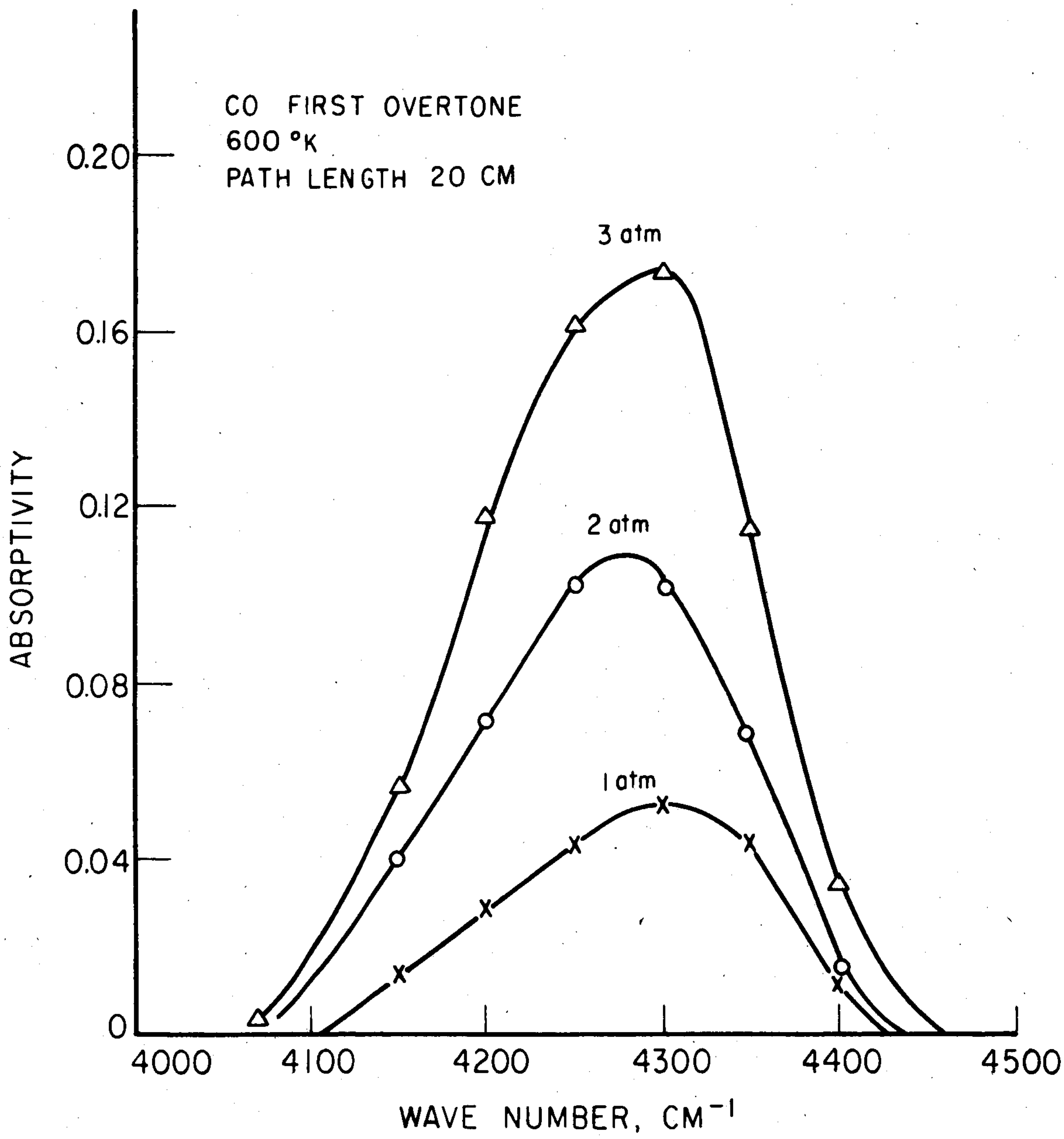

FIG. 22 SPECTRAL ABSORPTIVITY OF FIRST OVERTONE BAND OF CO GAS AT TEMPERATURE 600 °K AND AT PATH LENGTH 20 CM.

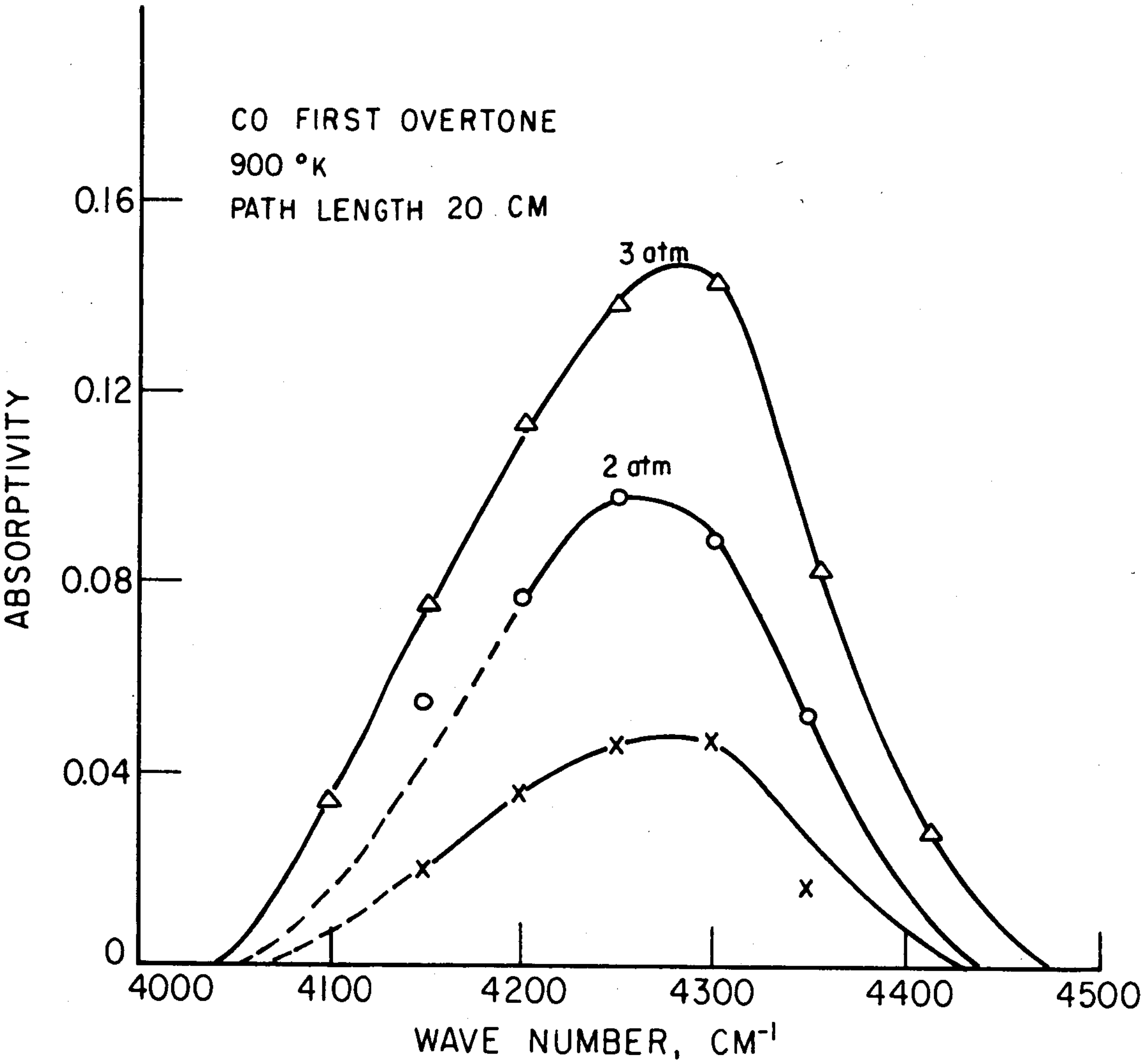

FIG. 23 SPECTRAL ABSORPTIVITY OF FIRST OVERTONE BAND OF CO GAS AT TEMPERATURE 900 °K AND AT PATH LENGTH 20 CM.

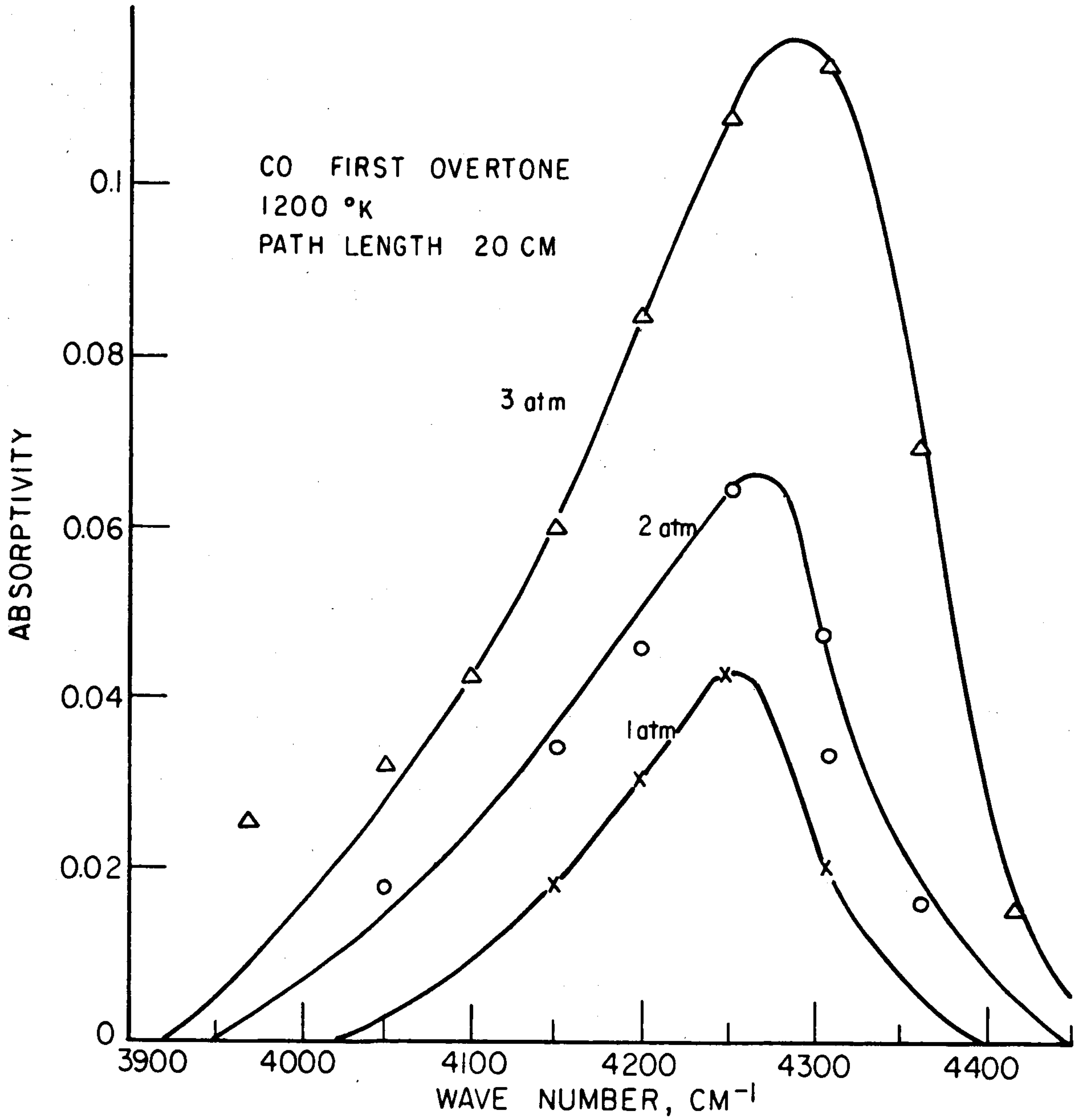

FIG. 24 SPECTRAL ABSORPTIVITY OF FIRST OVERTONE BAND OF CO GAS AT TEMPERATURE 1200°K AND AT PATH LENGTH 20 CM.

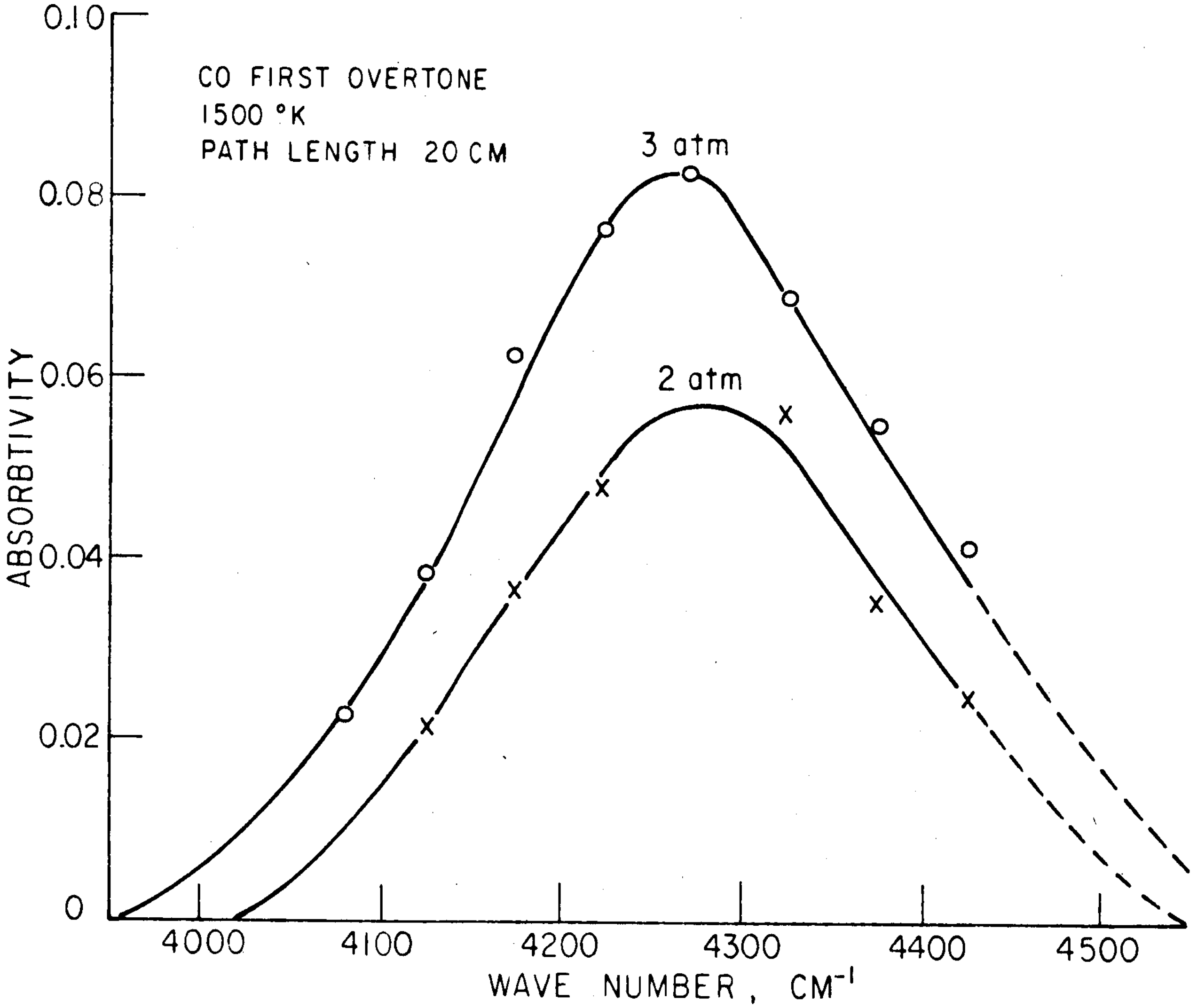

FIG. 25 SPECTRAL ABSORPTIVITY OF FIRST OVERTONE BAND OF CO GAS AT TEMPERATURE 1500 °K AND AT PATH LENGTH 20 CM.

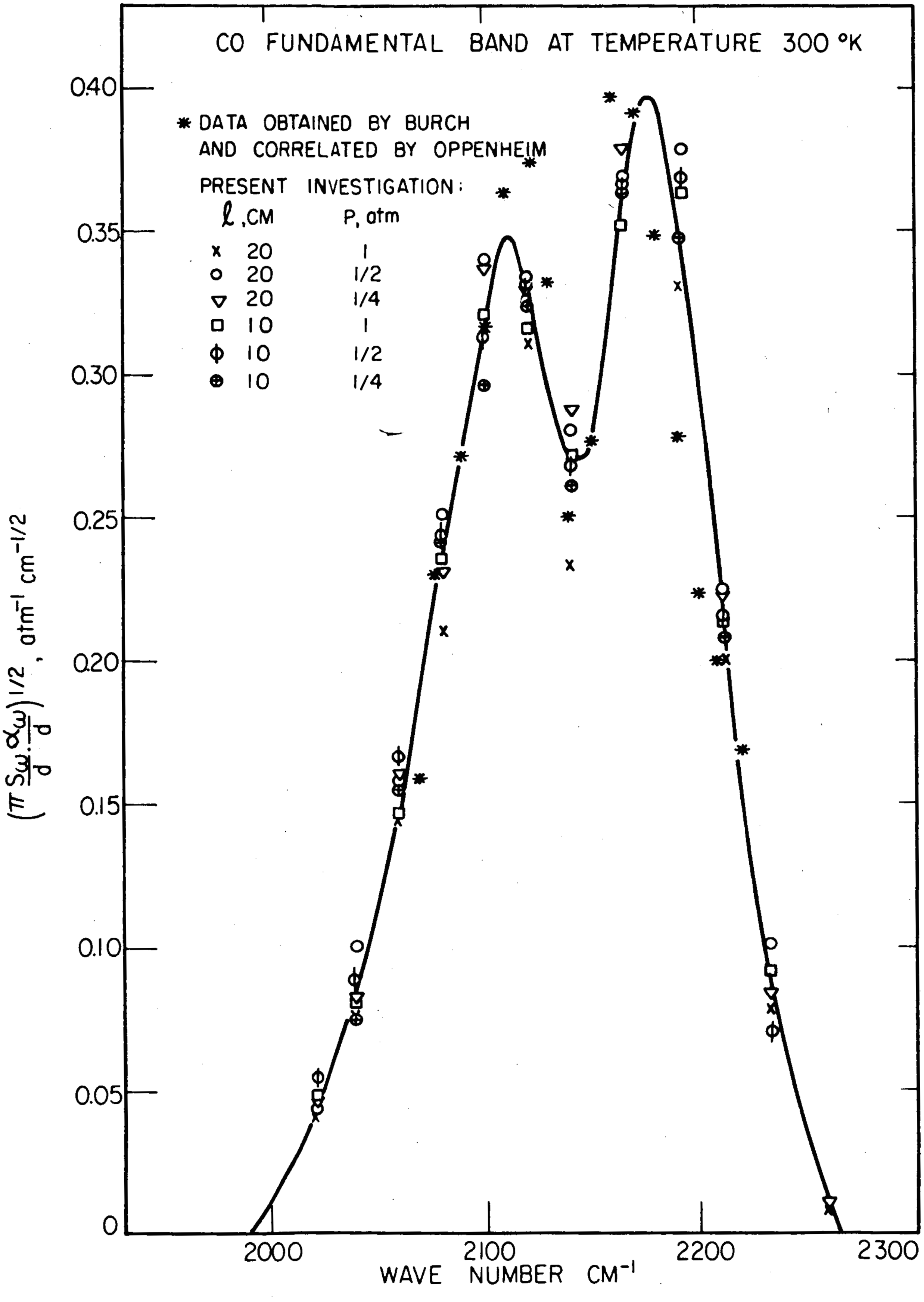

FIG. 26 STRONG LINE PARAMETER $\left(\pi \frac{S_\omega}{d} \cdot \frac{\alpha_\omega}{d}\right)^{1/2}$ FOR FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 300 °K

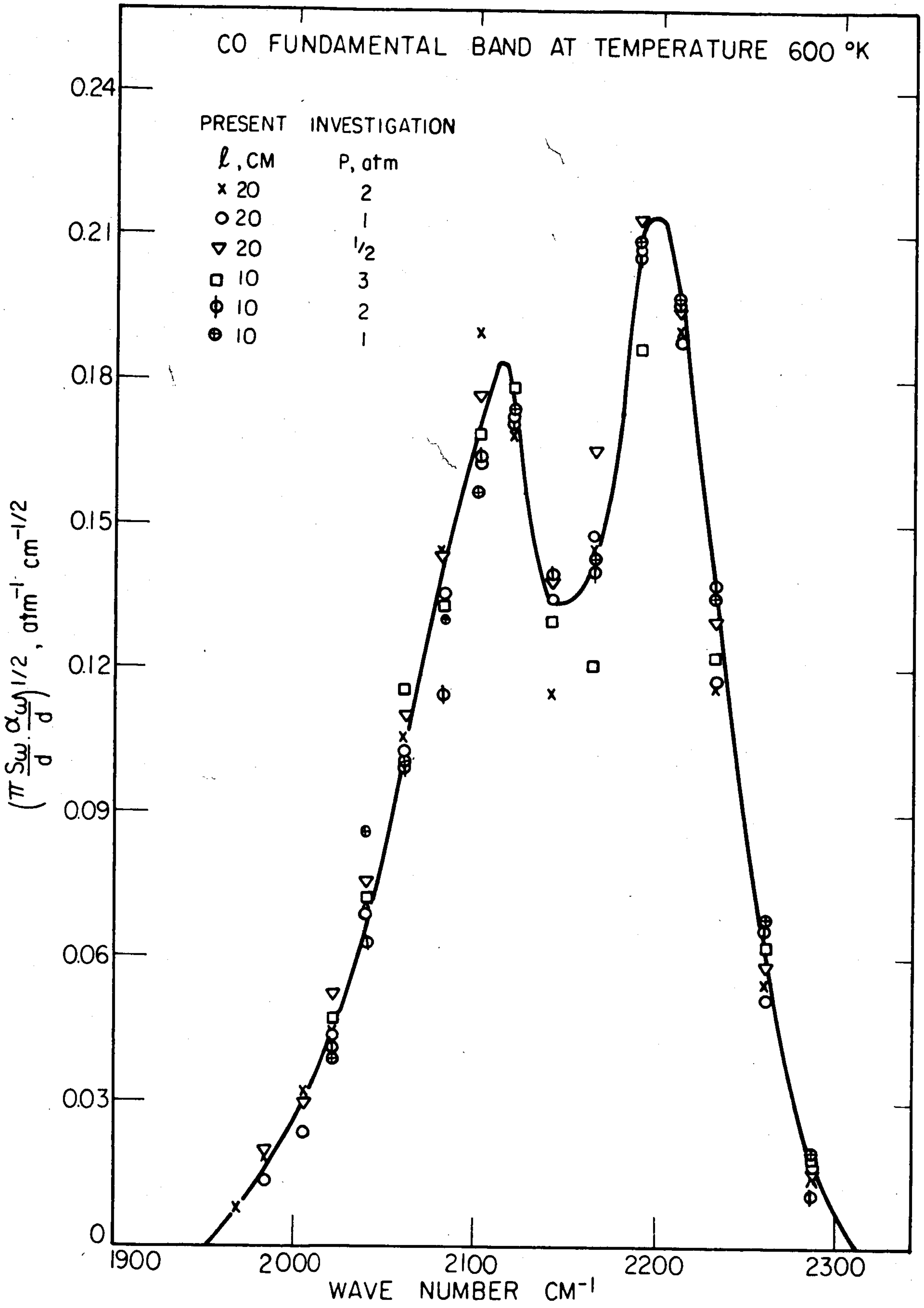

FIG. 27 STRONG LINE PARAMETER $\left(\pi \frac{S_\omega}{d} \cdot \frac{\alpha_\omega}{d}\right)^{1/2}$ FOR FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 600 °K

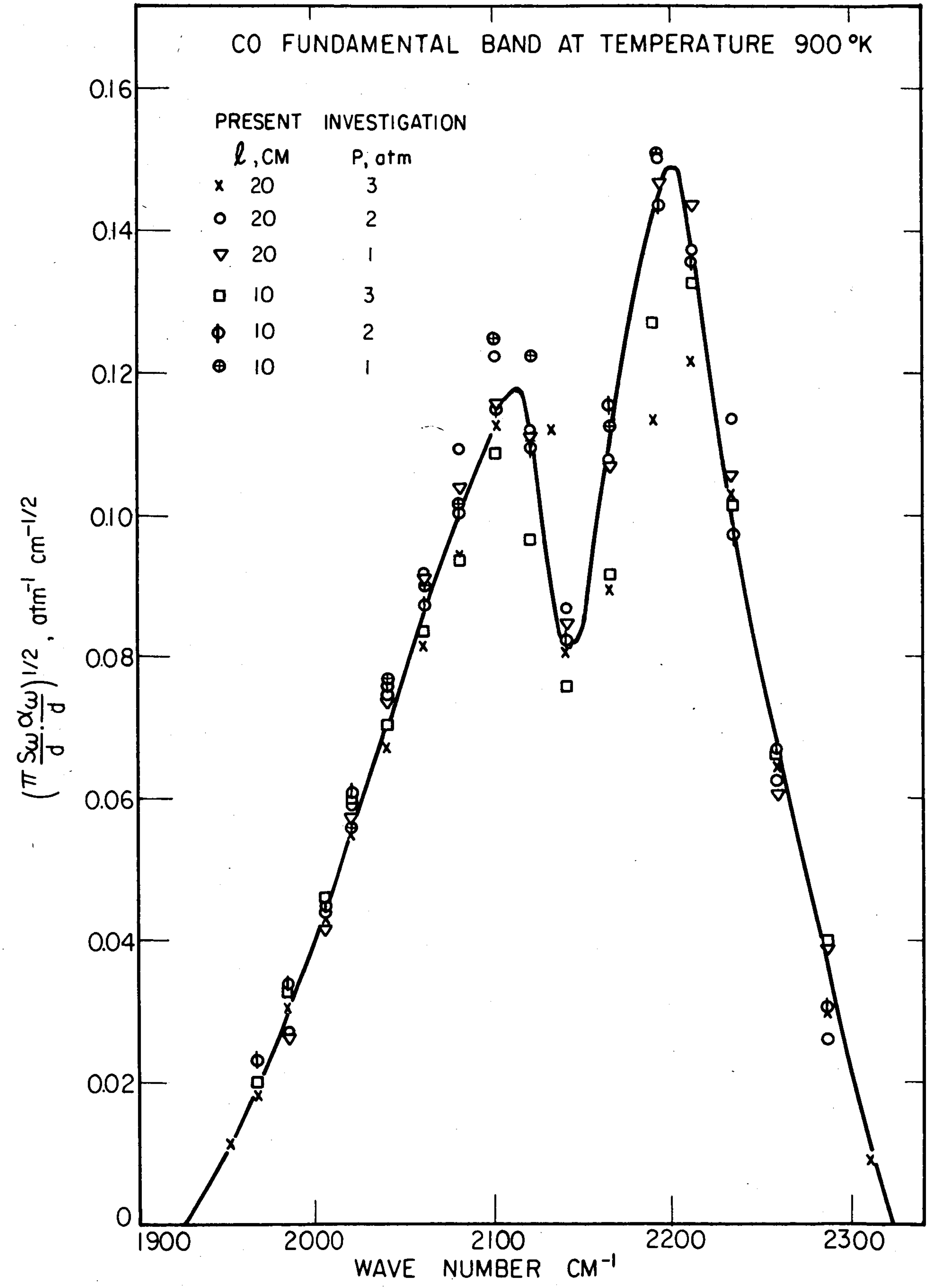

FIG. 28 STRONG LINE PARAMETER $\left(\pi \frac{S_\omega}{d} \cdot \frac{\alpha_\omega}{d}\right)^{1/2}$ FOR FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 900 °K

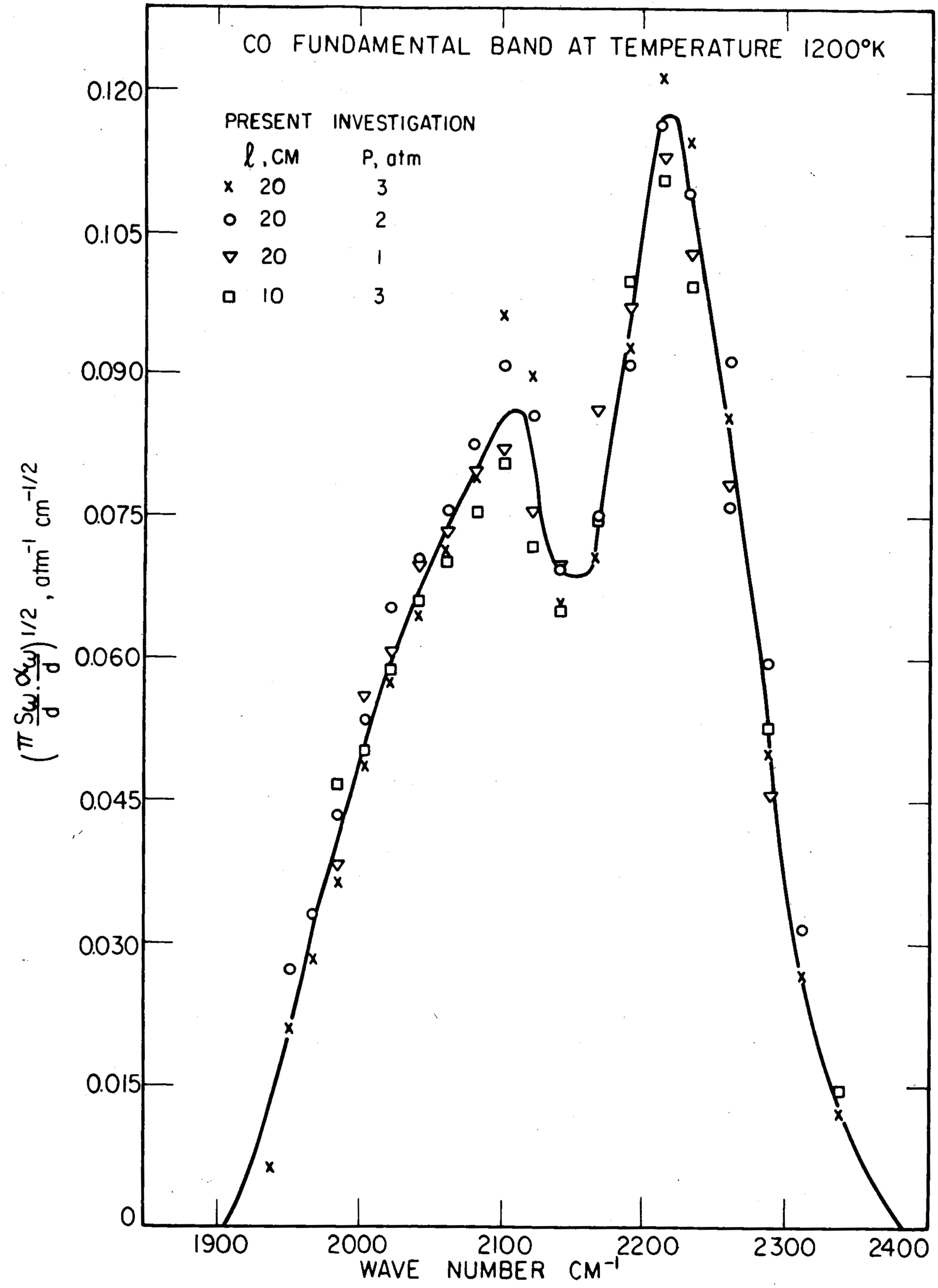

FIG. 29 STRONG LINE PARAMETER $\left(\pi \frac{S_\omega}{d} \cdot \frac{\alpha_\omega}{d}\right)^{1/2}$ FOR FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 1200°K

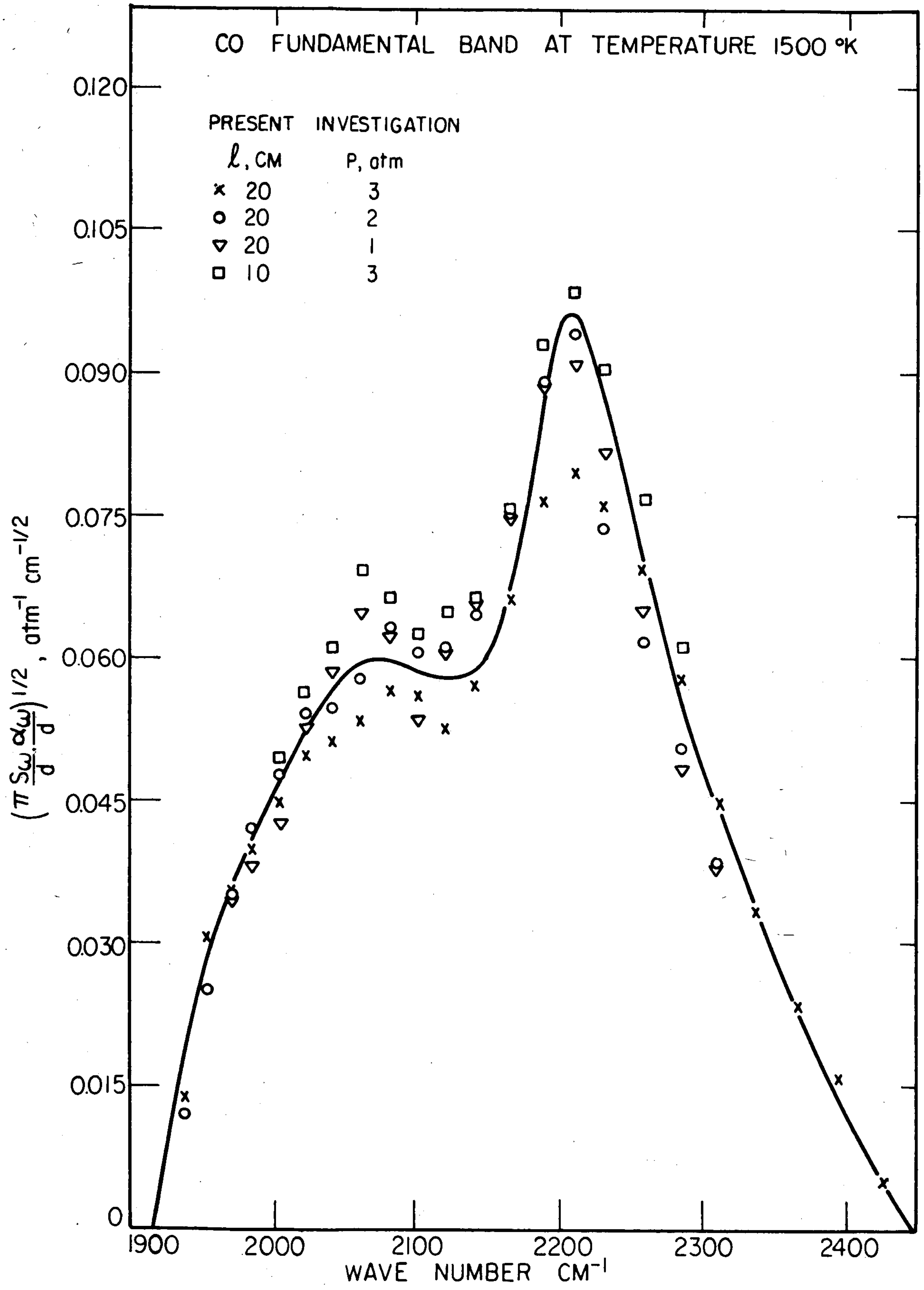

FIG. 30 STRONG LINE PARAMETER $\left(\pi \frac{S_\omega}{d} \cdot \frac{\alpha_\omega}{d}\right)^{1/2}$ FOR FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 1500°K

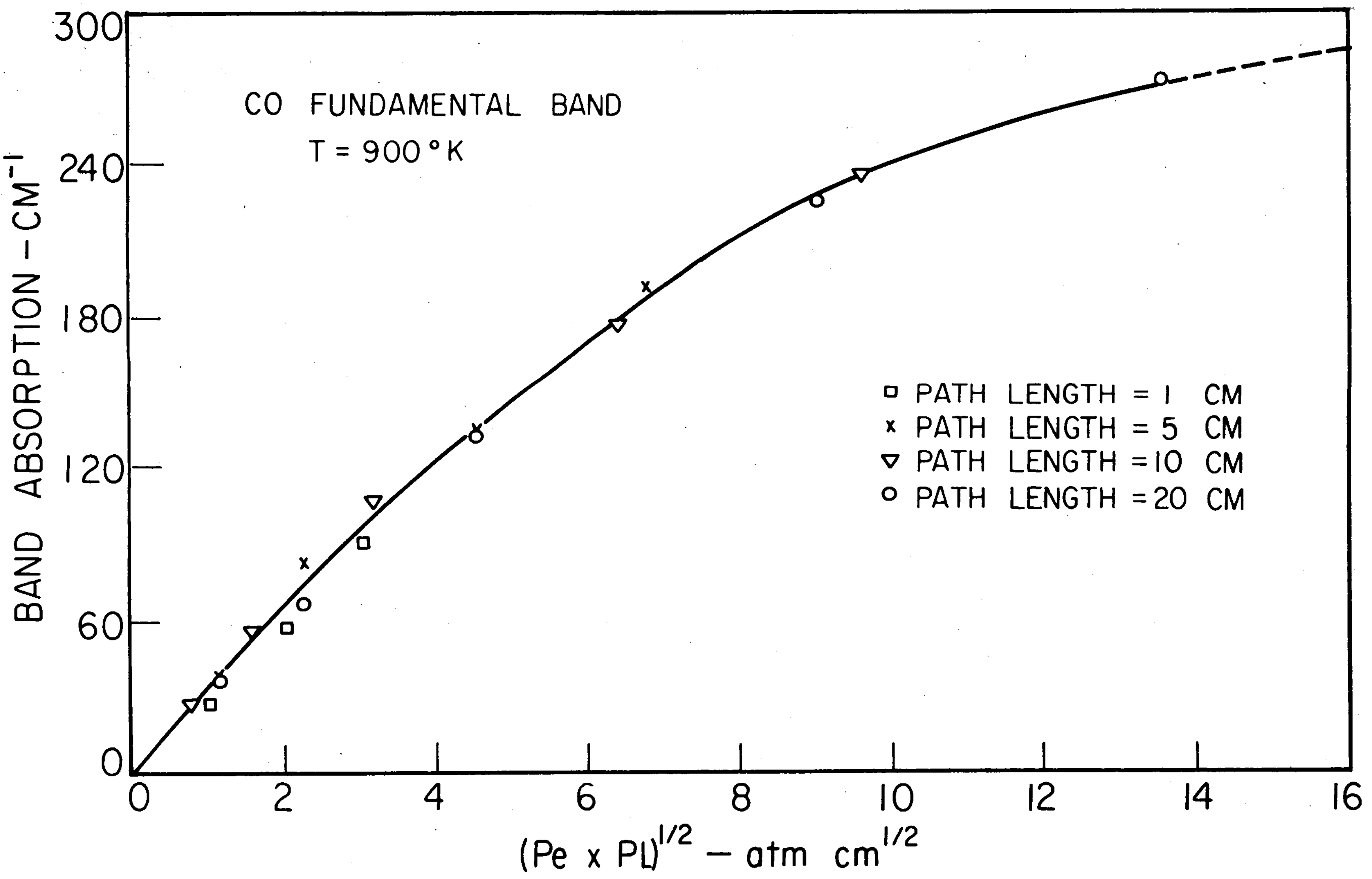

FIG. 31 INTEGRATED BAND ABSORPTION OF FUNDAMENTAL BAND OF CO GAS AT TEMPERATURE 900 °K AND AT PATH LENGTHS 1, 5, 10 AND 20 CMS.

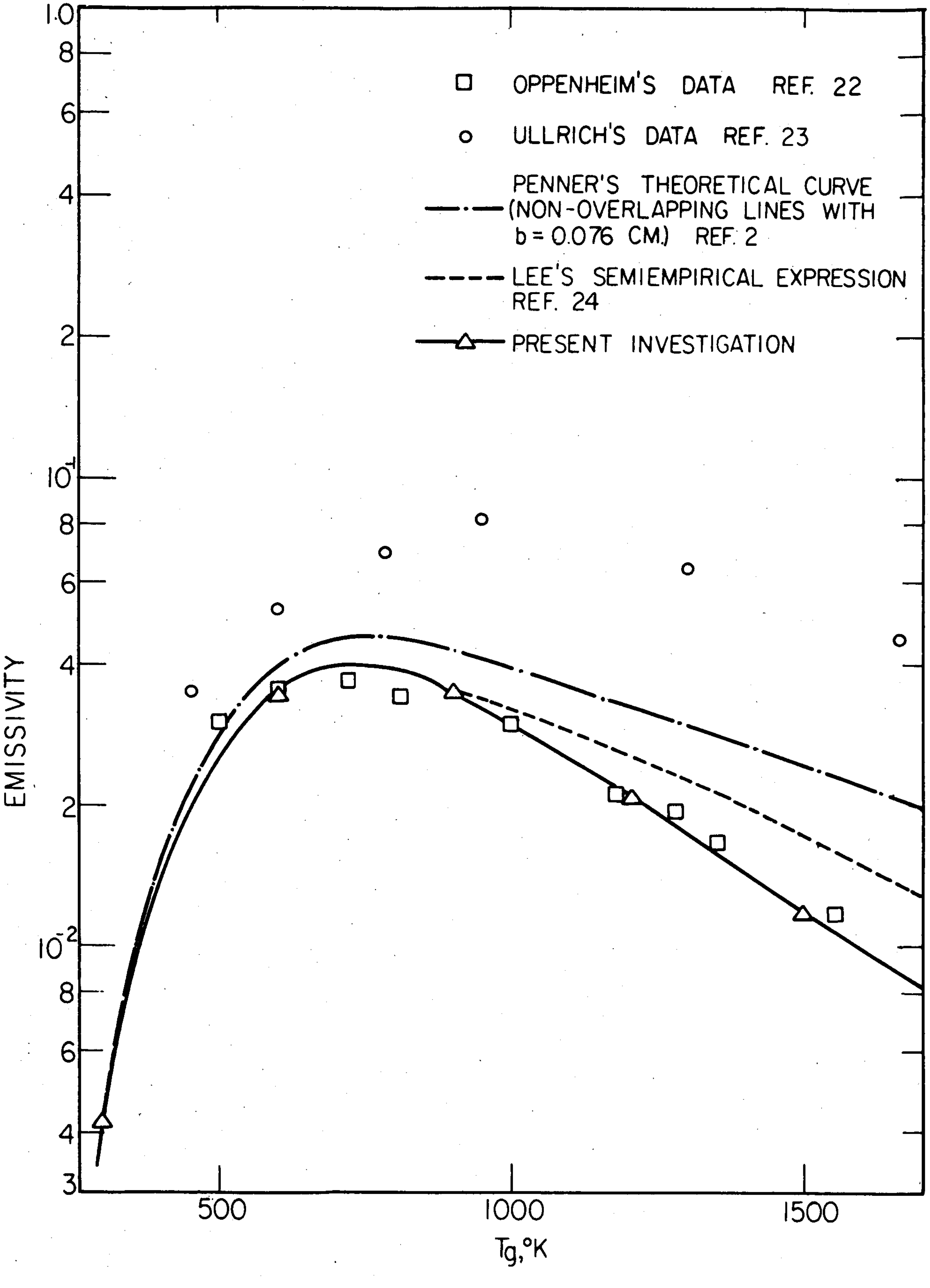

FIG. 32 EMISSIVITY OF CARBON MONOXIDE AT OPTICAL DEPTH 10 CM-ATM. AND TOTAL PRESSURE 1 ATM.