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OCA Contact Linda H. Bowman

1) Sponsor Technical Contact:

2) Sponsor Admin/Contractual Matters:
Ms. Brenda McNamara, 171
New Mexico State University
Physical Science Laboratory
Anderson Hall
Box 3548
Las Cruces, NM 88003-3548

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RESTRICTIONS

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Date 10/4/84

Project No. A-3711

~~SEM&L~~ Lab EML

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Project Director(s) Jim Gallagher

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Title Quantitative Analysis and Measurements of Fron 22

Effective Completion Date: 3/1/84

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FINAL TECHNICAL REPORT
GIT Project No. A-3711

**QUANTITATIVE ANALYSIS AND
MEASUREMENTS OF FREON 22**

Prepared by:

**J. J. Gallagher
D. P. Campbell
D. Swank**

Performed for:

**REGENTS OF NEW MEXICO STATE UNIVERSITY
Physical Science Laboratory
P. O. Box 3548
Las Cruces, New Mexico 88003-3548**

Under

Purchase Order No. 32878

August 1984

GEORGIA INSTITUTE OF TECHNOLOGY

**A Unit of the University System of Georgia
Engineering Experiment Station
Atlanta, Georgia 30332**



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I. INTRODUCTION

This program has been performed to measure the absorption coefficient of Freon 22 under various pressure conditions of the gas. The requirements of the contract were -

The absorption coefficient of Freon 22 was to be measured as a function of frequency about 35 GHz (33.5 - 36.5 GHz) and as a function of the concentration of Freon 22 in a buffer gas of nitrogen. The concentration of Freon 22 was to be in the range of 0.1% to 20%. A sufficient number of concentrations were to be used to determine linearity with concentrations. Altitude effects were to be determined by variation of the total pressure between 760 TORR and 600 TORR. The accuracy requirement on measurement of the absorption coefficient was 5% with sufficient frequency resolution for observation of variations across the frequency band of interest.

In order to perform these measurements, a K_a -band spectrometer has been assembled from available microwave components and electronic apparatus. The use of waveguide absorption cells is not appropriate for absolute absorption coefficients, since standing wave effects can give incorrect results. The most accurate and convenient technique is the use of a resonant cavity, which at K_a -band frequencies and higher takes the form of a semi-confocal Fabry-Perot interferometer. These open-structure resonators are low-loss and give the absorption loss of the gas directly as a function of the reduction of resonator Q or the reduction of signal amplitude resulting from introduction of the gas into the resonator.

This report presents the results of the measurement program. The report consists of five sections following this introduction. A brief description is given of techniques for absorption measurements (Section II), the measurements performed are discussed (Section III), the data taken are tabulated and analyzed in Section IV and V, and conclusions and recommendations are presented in Section VI.

II. TECHNIQUES FOR ABSORPTION MEASUREMENTS

In the millimeter wave-length region, absolute absorption measurements are best performed in a resonant cavity. The use of a waveguide structure is inappropriate because of standing waves and reflections within the transmission cell. Inaccuracy of absorption intensity measurement and lack of knowledge of the actual absorption path because of multiple reflections negate the use of the technique. Harrington (Reference 1) has demonstrated a Stark modulation technique for absolute intensity determinations for individual spectral lines. For broadband absorption such as that of interest to this program, the technique is not applicable.

The resonant cavity technique has been employed for many years at lower frequencies (<30 GHz) in the form of conventional microwave cavities. Weidner (Reference 2) used a resonant cavity at 6700 MHz to measure the loss of iodine monochloride with a sensitivity of $6 \times 10^{-8} \text{cm}^{-1}$. At millimeter wavelengths, the low loss cylindrical cavities become too small and, if used in the TE_{01} mode, which is usually employed for maximum Q at lower frequencies, it becomes increasingly difficult to couple into the circular waveguide TE_{01} mode from the rectangular waveguide TE_{10} mode over a large range of frequencies. The absorption measurement method relies upon the reduction of cavity Q as a result of gas loss so that the sensitivity of the instrument is proportional to the Q of the evacuated cavity. The problems with conventional cavities when used at high frequencies can be alleviated by the use of a Fabry-Perot interferometer. This resonant device can take the form of parallel plate, semi-confocal, spherical or confocal resonator. The semi-confocal offers the simplest, most easily aligned configuration with high Q. The first use of a semi-confocal interferometer for millimeter wave spectroscopy (Reference 3) was for observation of weak discrete molecular transitions. The technique was later extended to observations

of water vapor absorption (Reference 4) between absorption lines and to the measurement of extremely weak molecular transitions to determine dipole moments (Reference 5).

The use of spherical mirrors makes mirror alignment less critical and reduces diffraction losses for the dominant TEM₀₀ mode. In addition, it permits the suppression of higher-order modes by the proper choice of mirror radius. The criterion for optimum mirror radius a in terms of confocal mirror spacing ($b = d =$ radius of mirror curvature) and wavelength λ is the Fresnel number,

$$N = \frac{a^2}{b \lambda} \approx 1 \quad (1)$$

Figure 1 shows the confocal and semi-confocal Fabry-Perot interferometer relations. By satisfying the conditions of the Fresnel number, it is ensured that the diffraction losses associated with unwanted higher-order modes are significantly larger than the diffraction losses associated with the TEM₀₀ mode.

The losses of the propagating medium between the resonator mirrors can be determined by measuring the Q of the interferometer with (Q_2) and without (Q_1) the absorbing gas. The absorption coefficient is

$$\alpha = \frac{2\pi}{\lambda} \left(\frac{1}{Q_2} - \frac{1}{Q_1} \right) = \frac{2\pi}{\lambda} \tan \delta \text{ cm}^{-1} \quad (2)$$

A more easily handled form of this equation is given by the expression

$$\alpha = \frac{2\pi}{\lambda Q_1} \left[\left(\frac{A_1}{A_2} \right)^{1/2} - 1 \right] \text{ cm}^{-1} \quad (3)$$

where the A terms are the outputs of a loosely coupled square law detector at the output of the resonator. A_1 refers to no gas in the cell and A_2 , to the cases of gas in the cell. The

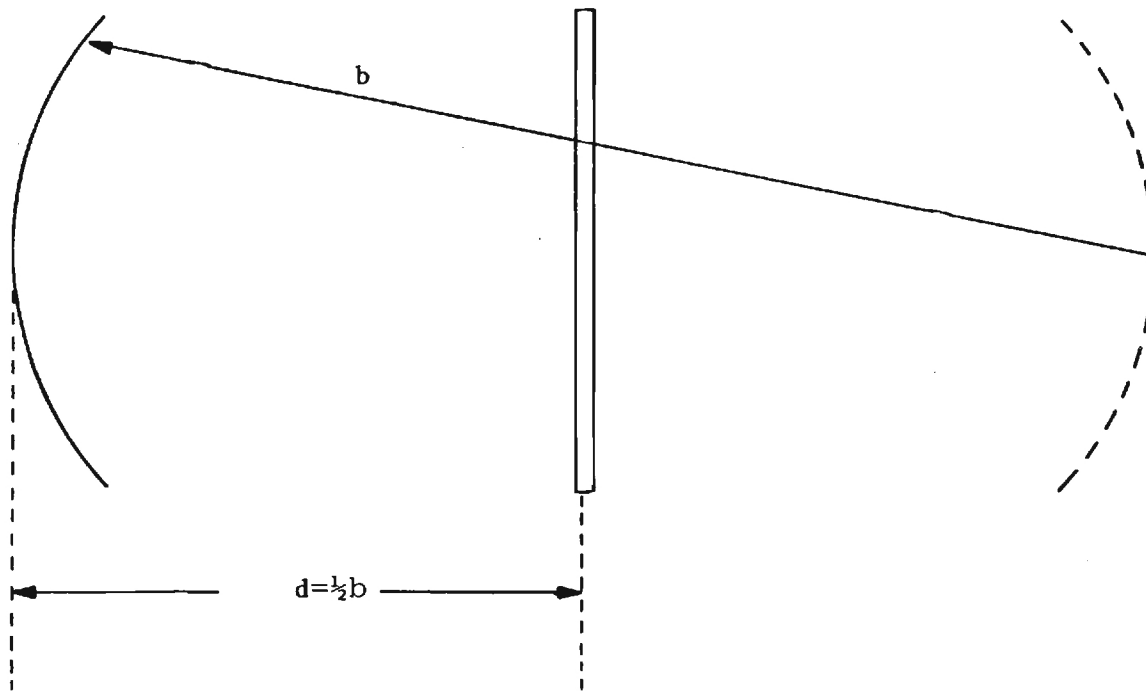


Figure 1. Semiconfocal resonator configuration.
 b = Radius of curvature of curved plate
 d = plate separation = $\frac{1}{2}b$.

effective absorption pathlength is

$$EPL = Q_1 \lambda / 2\pi \quad (4)$$

The higher the resonator Q , the greater is the effective pathlength and, therefore, the sensitivity. Q -values as high as 10^5 - 10^6 have been achieved at high frequencies.

In order to use the semiconfocal resonator as an absorption cell, several techniques can be employed. The use of phase-locked sources can provide an accurate technique but time-consuming operation is necessary. Three techniques are briefly described here. It is possible to obtain quick and accurate results with these methods.

1) Figure 2 shows a technique employing a CW Gunn oscillator as the radiation source operating in the K_a -band (26-40 GHz). In this technique, the signal is applied to the input of a semi-confocal interferometer through an isolator, attenuator and directional coupler. The interferometer absorption cell is a two-port device with input and output on the flat plate. The directional coupler provides a frequency monitoring arm with an EIP diode detector as the sensing element. The EIP Model 578 counter, when used with the appropriate detector, will measure frequency directly up to 110 GHz. The output signal from the cell is detected by a HP mixer which is part of the Hewlett-Packard Model 8569B Spectrum Analyzer. The Spectrum Analyzer will operate to 110 GHz with the mixers and multiplexers that are available. The multiplexer serves to accept a local oscillator (LO) signal from the spectrum analyzer, which is mixed with the signal from the absorption cell. The resulting heterodyned signal that is applied to the spectrum analyzer is at the intermediate frequency of 321.4 MHz. The combined use of the HP spectrum analyzer and EIP counter has the advantage of direct reading and high sensitivity. The absorption cell output is displayed

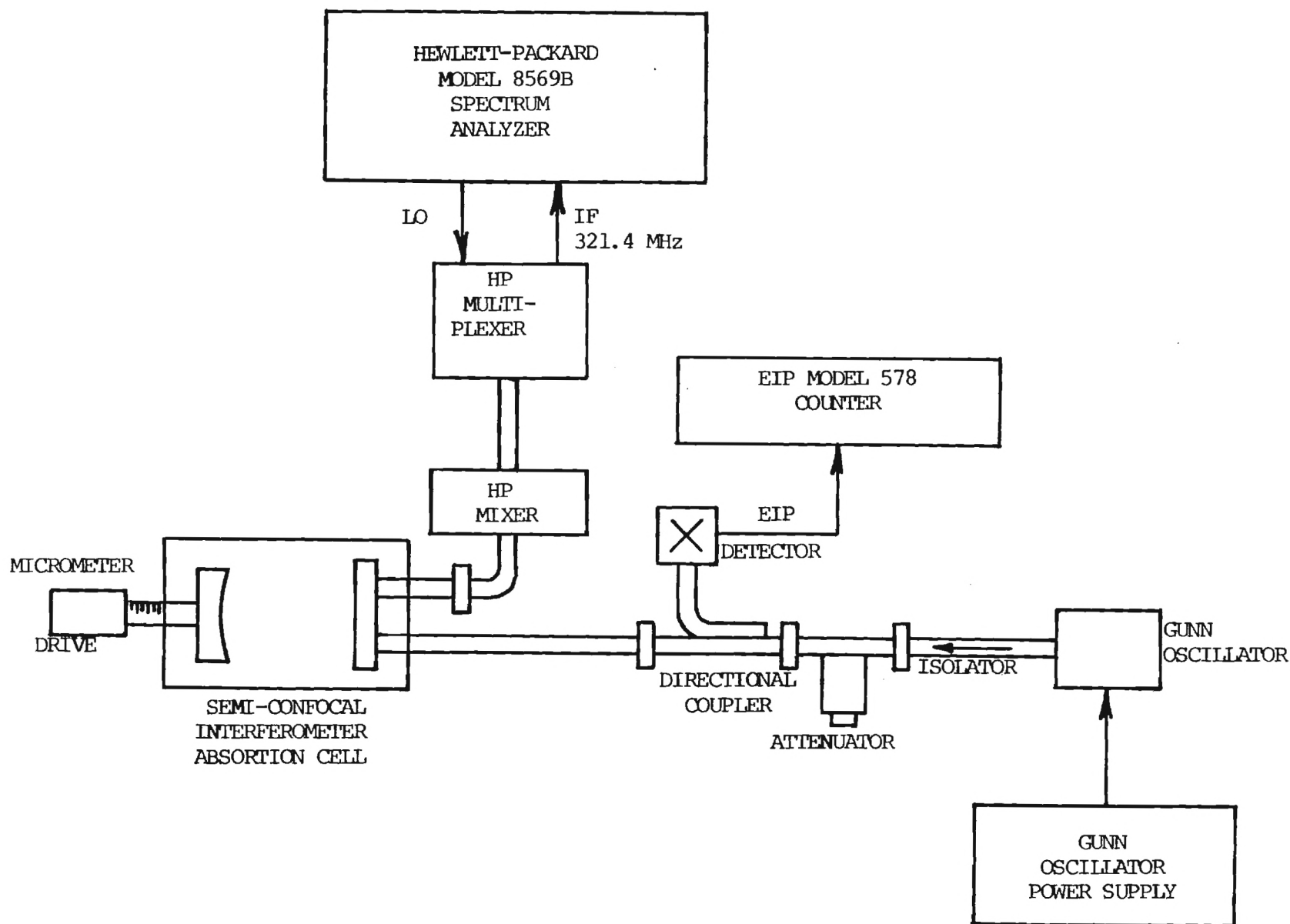


Figure 2. Absorption Measurement Technique Employing a cw Gunn Oscillator as the Radiation Source Operating in the K_a -band (26-40 GHz) region and a Hewlett-Packard spectrum analyzer as detector.

on the spectrum analyzer oscilloscope. The Gunn oscillator output, operating unlocked, is a relatively stable signal allowing accurate determination of resonator center frequency, half-power points and amplitude attenuation due to the presence of vapors in the absorption cell.

To achieve true representation of the signal with the spectrum analyzer, it is necessary to use a slow sweep of the analyzer. This is to assure that the signal fully develops to its maximum value during the sweep. Too rapid a scan will cause the trace to pass the signal in too short a time for the signal to build to its full intensity. As a result, a time sweep/division of 0.5 seconds and a frequency span/division of 100 kHz are employed. The resolution bandwidth is optimized at 10 kHz. The slow scan also results in a more stable presentation of the amplitude, since the fluctuations of a rapid scan system are reduced considerably. For a sweep of 0.5 seconds/division, the total scope scan takes 5 seconds and visual averaging can be done for several sweeps. A digital averager exists in the spectrum analyzer, but testing has indicated that, with the stability of the Gunn oscillator that is available, the visual averaging is quicker and as equally effective as the digital averager.

2) Figure 3 shows a similar scheme for determining absorption in a vapor. Here, a lock-in amplifier with digital millivoltmeter readout is employed in place of the spectrum analyzer. A diode detector senses the output of the resonator. The input signal from the Gunn oscillator is modulated by a mechanical chopper which also provides a reference signal for the lock-in amplifier. This is the conventional technique for absorption measurements and gives results compatible with those of the system shown in Figure 2.

3) Figure 4 shows an interesting technique which has been investigated for determination of absorption. It really offers no advantage over the previous techniques but does provide a

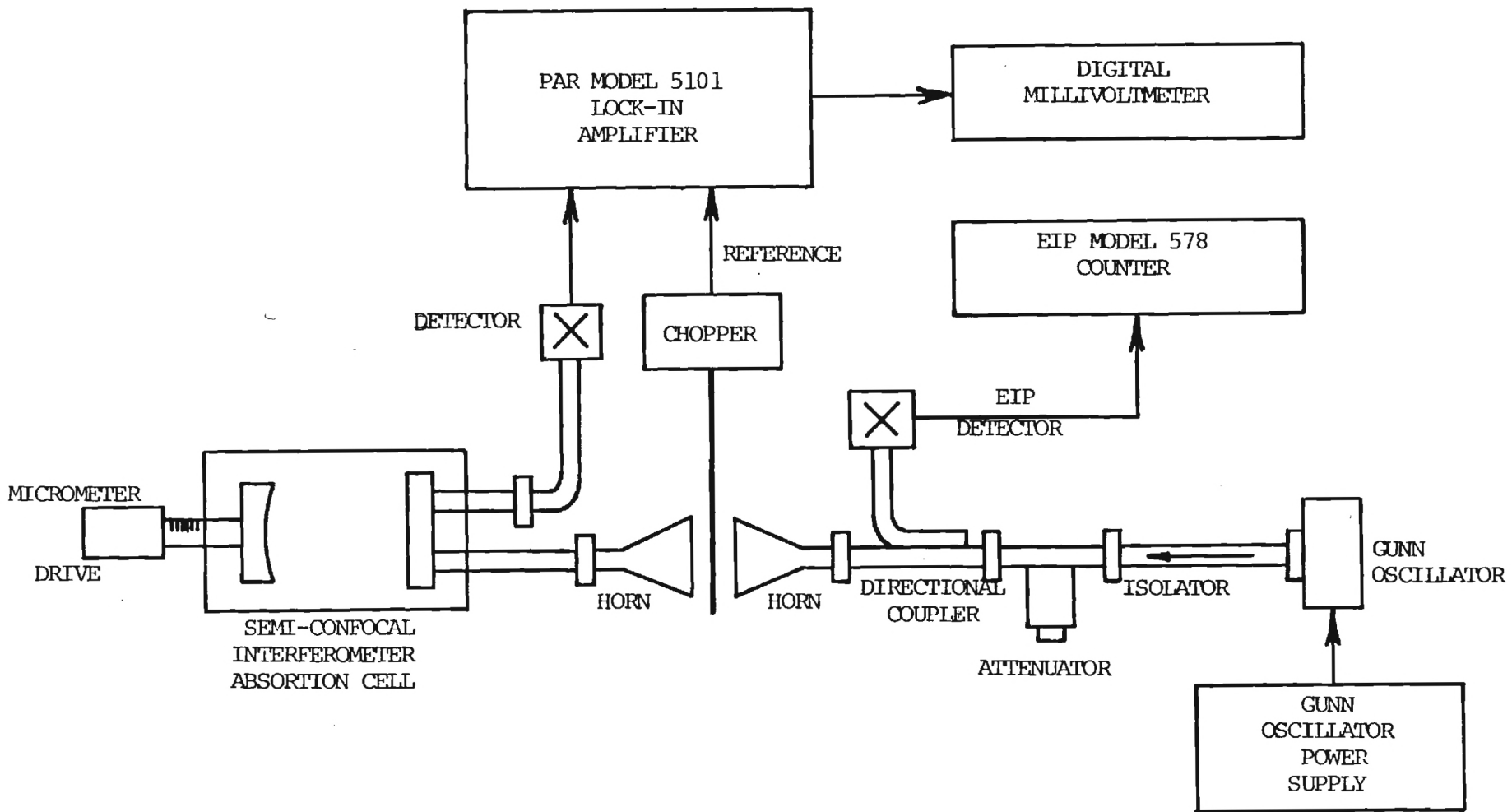


Figure 3. Absorption Measurement Technique Employing a cw Gunn Oscillator and Lock-In Amplifier System.

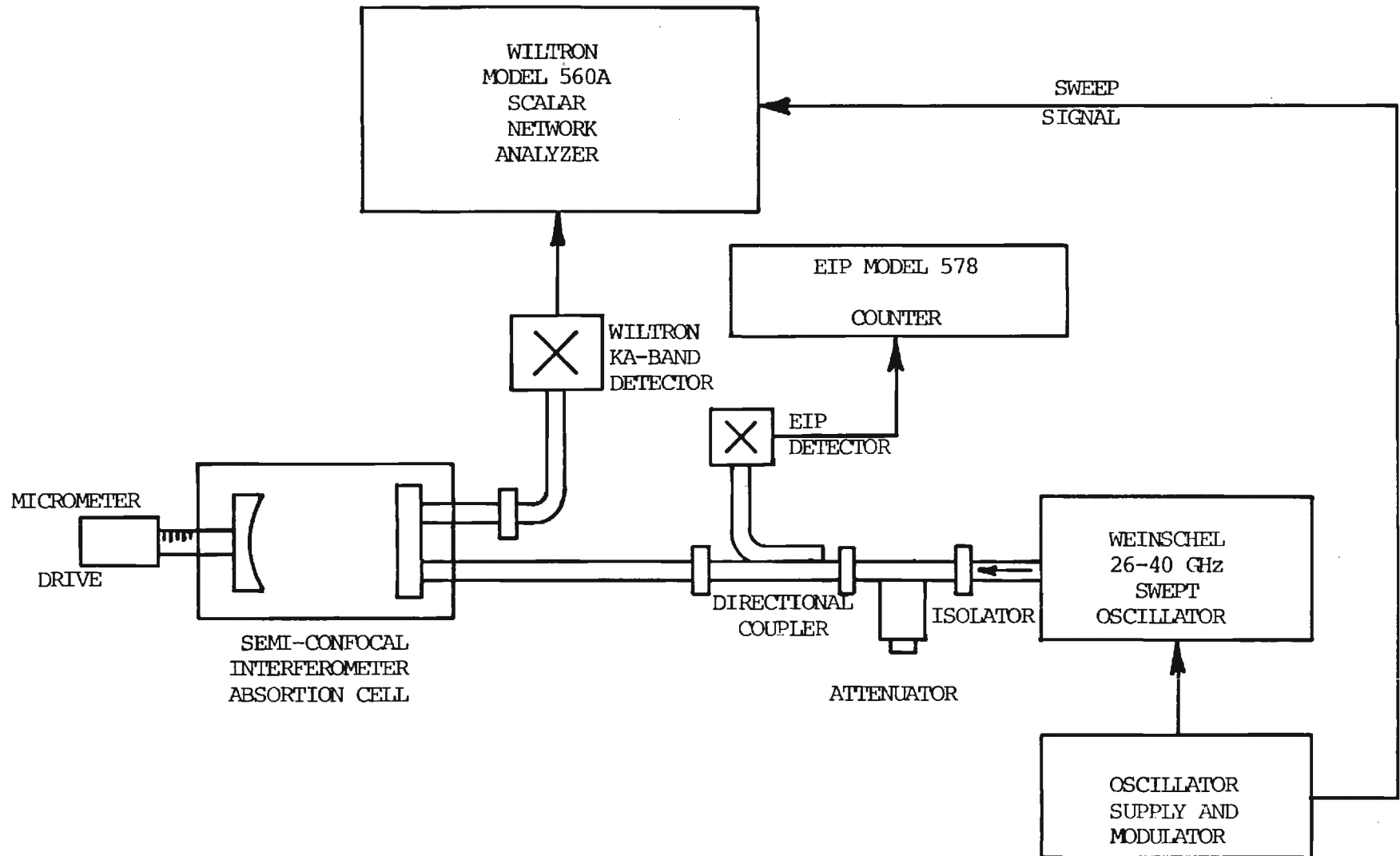


Figure 4. Absorption Measurement Technique Employing a Weinschel Swept Oscillator and a Wiltron Scalar Network Analyzer.

visual presentation of the resonator response which can be used for both Q-measurements and intensity measurements. The technique employs a Weinschel swept oscillator as the source and a Wiltron Scalar Network Analyzer as the detection and display part of the system. The Weinschel swept oscillator can be swept to a minimum of 20 MHz about a frequency unless it is used with a (frequency) start/stop arrangement that does not provide as accurate a frequency determination. The resonator response shape and intensity changes can be determined directly from the scope display of the network analyzer.

The portion of the K_a -band region (namely, 33-36 GHz) of interest to this program can be covered by swept oscillators (Weinschel or HP), Gunn oscillators or klystrons. We chose to use Gunn oscillators for some of the measurements because of their better spectral purity and greater power output (100-300 mW) than available with the other sources. The Gunn oscillators do not have as large a tuning range as the other sources that are available. Because of the simplicity and stability of the Gunn oscillator, we have employed these sources where possible during the program. The Gunn oscillators do not cover all frequencies of interest so the swept oscillators were also used. The HP oscillator had the greatest amplitude stability of all sources whereas the Weinschel could be phase-locked in frequency by the EIP counter. The approximate frequencies and sources used for each measurement are listed as follows:

36.5 GHz	HP SWEPT OSCILLATOR
36.0 GHz	HP SWEPT OSCILLATOR
35.5 GHz	GUNN OSCILLATOR
35.0 GHz	GUNN OSCILLATOR
34.5 GHz	GUNN OSCILLATOR
34.0 GHz	HP SWEPT OSCILLATOR
33.5 GHz	WEINSCHEL SWEPT OSCILLATOR

III. MEASUREMENTS PERFORMED DURING PROGRAM

The absorption measurements performed on Freon 22 during the program were performed in a semi-confocal Fabry-Perot interferometer that was assembled in a glass pipe chamber. The dimensions of this apparatus are shown in Figure 5. The configuration has the waveguide feeds (input and output) on the flat plate. The curved plate is moved by a micrometer vacuum sealed in the back-plate of the chamber. Three adjusting screws provide further alignment of the curved plate for the semiconfocal interferometer. The flat-plate coupling holes are drilled initially very small in size and increased during observation to obtain optimum coupling. The plates are machined from aluminum and are gold plated. The flat plate which was initially employed had signal leakage between waveguides and did not provide as high a Q-value as expected. A second plate was prepared, and this eliminated the signal leakage but did not improve the Q-value, which at different frequencies was measured to be 5000-8000. A value of at least 30,000 should be achievable with the resonator shown in Figure 5. The resulting lower Q corresponds to a lower sensitivity of the system. The lowest concentration of 0.1% that was requested was not achievable with the limited sensitivity. The mirror separation for the semiconfocal configuration is 21.84 cm with plate diameter of 8.89 cm. The separation of coupling holes is 1.78 cm, well within the beam waist at the flat plate. With a plate diameter of 8.89 cm and the confocal distance being 21.84 cm, the Fresnel number for this interferometer at 8 millimeters wavelength is 1.13.

Measurements of absorption losses were made at seven frequencies in the band from 33.5 to 36.5 GHz under pressure conditions corresponding to the concentration range from 1% to 20% of Freon 22 in N₂. Figure 6 shows a sketch of the gas handling manifold for the measurements. The system could be evacuated by a fore-pump/diffusion pump combination with a

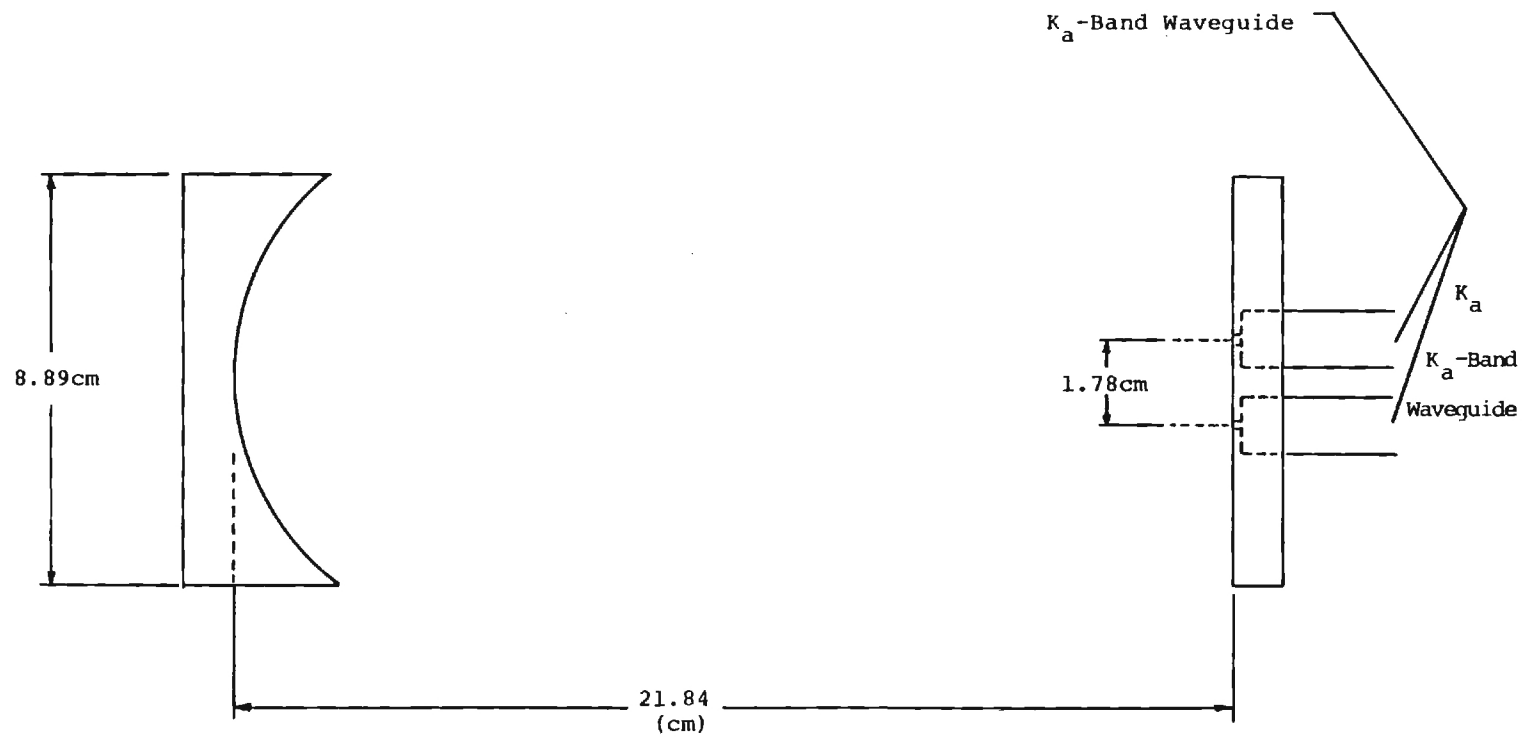


Figure 5. Dimensions of Semi-Confocal Fabry-Perot Interferometer.

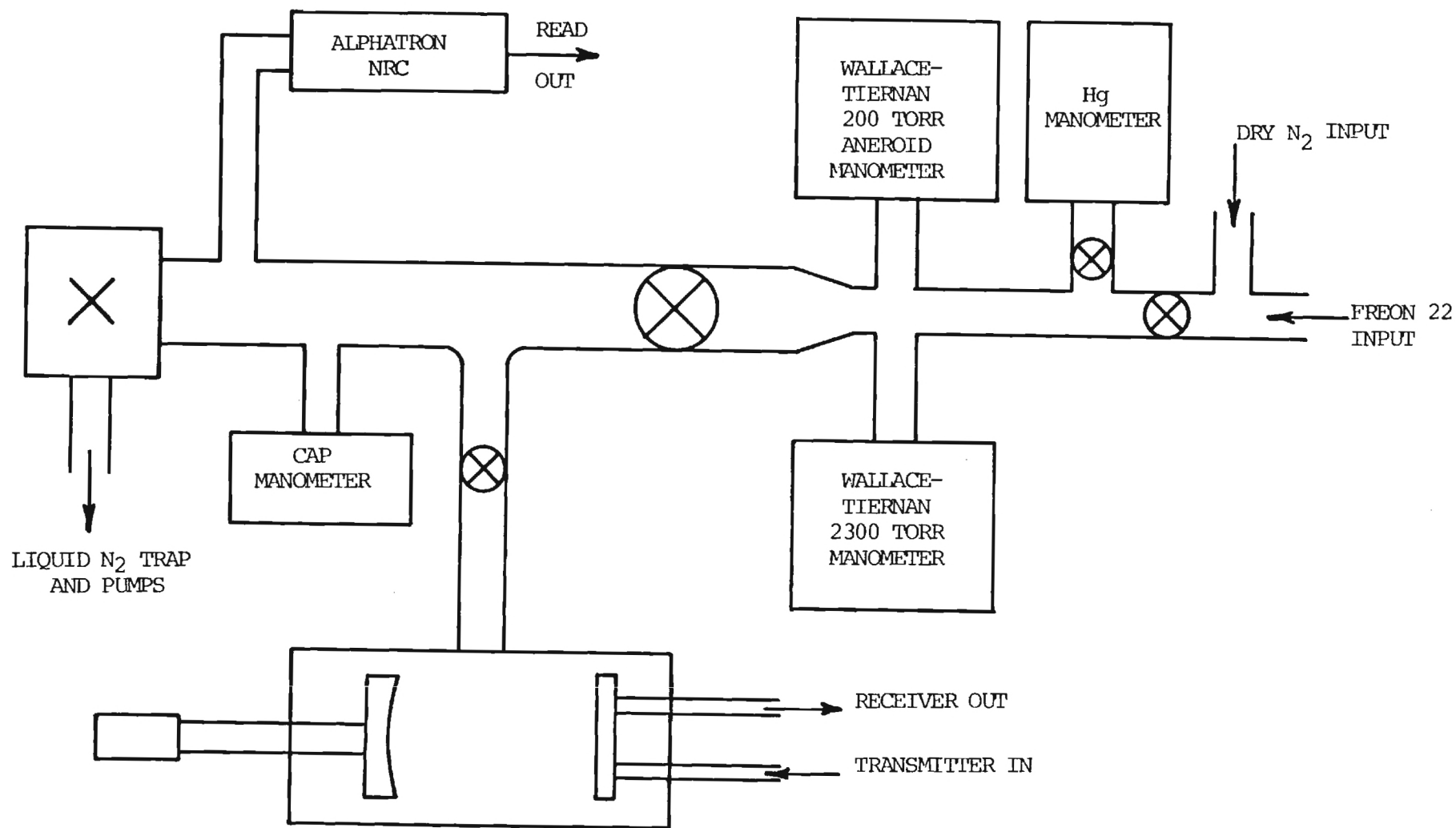


Figure 6 . Gas Handling Manifold for Freon 22 Absorption Measurements

liquid nitrogen trap. Several pressure measuring devices were attached to the manifold for comparison of pressure readings. The mercury manometer can provide accurate pressure data to approximately 240 TORR. Two Wallace-Tiernan Aneroid Manometers (one with maximum pressure range of 200 TORR and the other, a maximum pressure range of 2300 TORR) were employed. Within the range of the Hg manometer, the three gauges agreed well so that, with zeroing corrections, the Wallace-Tiernan gauges could be used for all measurements. At low pressures (<12 TORR), the capacitance manometer was employed as a pressure indicator. The Freon 22 was admitted to the vacuum system from a lecture bottle. The nitrogen, Matheson High Purity 99.99% pure, was further dried by passing through a tube of sodium hydroxide before entering the vacuum chamber.

The measurements were performed by initially evacuating the chamber and manifold to approximately 20-40 millitorr, filling the system to the desired pressure of Freon 22 and completing the fill to 760 TORR with Nitrogen. For the lower pressure readings to 600 TORR, the system was pumped down to this pressure from 760 TORR. Excellent reproduction of results were achieved in all cases.

The admission of Freon 22 to the system resulted in higher evacuated pressures for starting conditions as the Freon was difficult to remove from the apparatus. This resulted in longer time between measurements as the vacuum system would eventually be saturated with Freon.

The measurements were performed with a Gunn oscillator in the region of 34.5, 35.0 and 35.5 GHz and with a Weinschel swept oscillator at 33.5, and a Hewlett-Packard swept oscillator at 34.0, 36.0 and 36.5 GHz. The Gunn oscillator was limited in range and was actually being used outside of its prescribed frequency range. The narrow frequency range which is achieved by mechanical tuning is 34.9 to 35.1 GHz with 220 mW output. The Gunn source has been used outside this range (to

34.5 GHz and to 35.5 GHz) with sufficient output power for performance of measurements. The source output power varies as a function of frequency and this variation had to be accounted for at each frequency in both Q-value measurements and in absorption coefficient measurements.

The experimental apparatus is shown in Figures 7 and 8. Figure 7 shows the over-all apparatus with the gas-handling equipment in the background, the glass pipe containing the resonator at the left and the H-P spectrum analyzer and EIP counter at the right. Figure 8 shows the Gunn oscillator attached to a rotary-vane attenuator.

For each measurement performed at the seven different frequencies, data were taken for 760 TORR, 700 TORR, 650 TORR and 600 TORR total pressures at nine different concentrations of Freon. For each recorded attenuation reading, five to ten measurements were averaged. The nine Freon 22 concentrations (percentage of Freon 22 pressure in total pressure of Freon and nitrogen) were 20%, 17.5%, 15%, 12.5%, 10%, 7.5%, 5%, 2.5% and 1%. In some cases, 0.5% concentration measurements were made.

The average measured attenuations which are tabulated in Section IV are averages of two or more recorded averages taken under different experimental conditions at different times. A calibrated thermometer provided temperature values at the time of attenuation measurements. The temperature for all measurements remained in the range 23.5°C to 26°C.

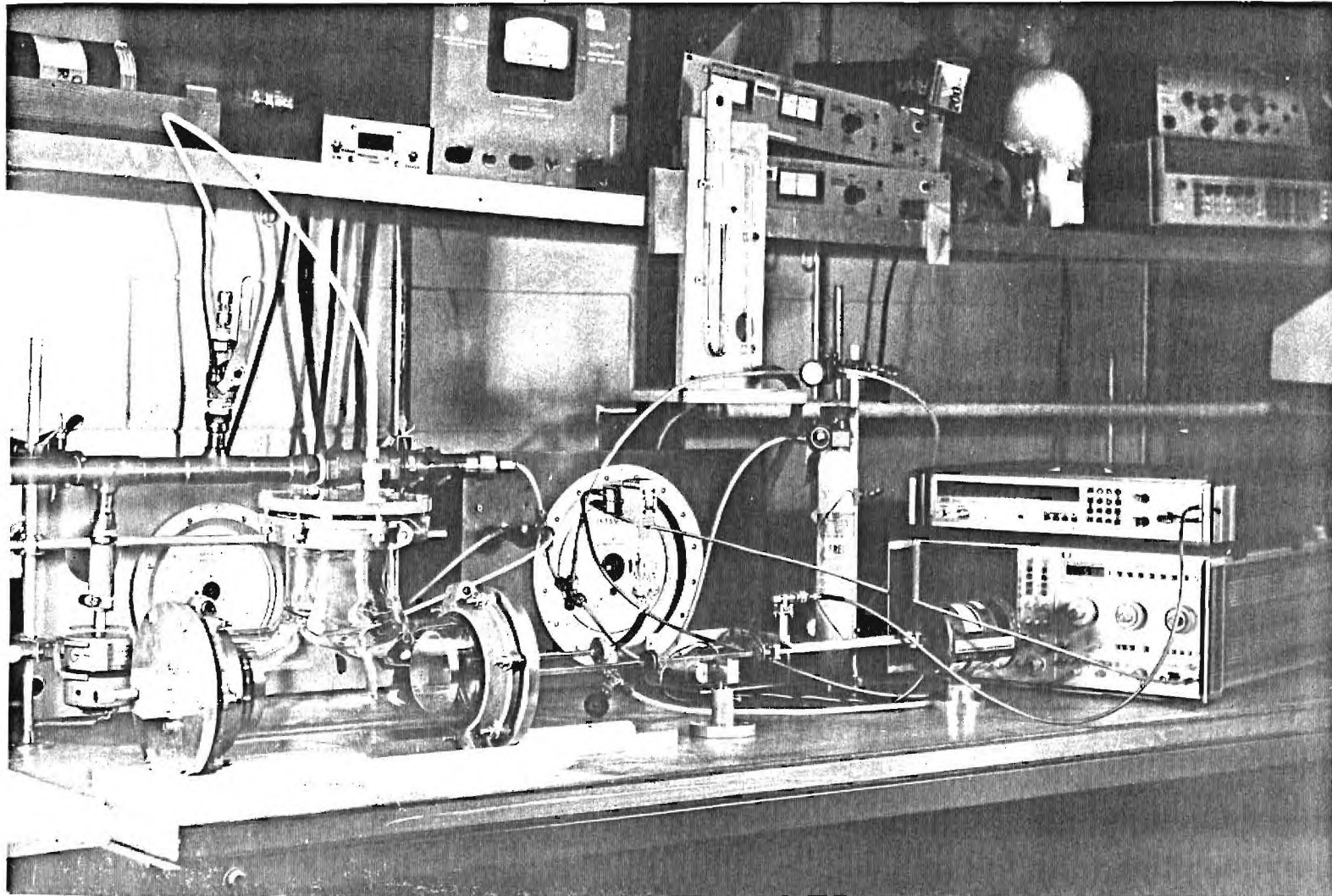


Figure 7. Photograph of the Experimental Apparatus with Resonator at the Left and the Hewlett-Packard Spectrum Analyzer and EIP Counter at the Right.

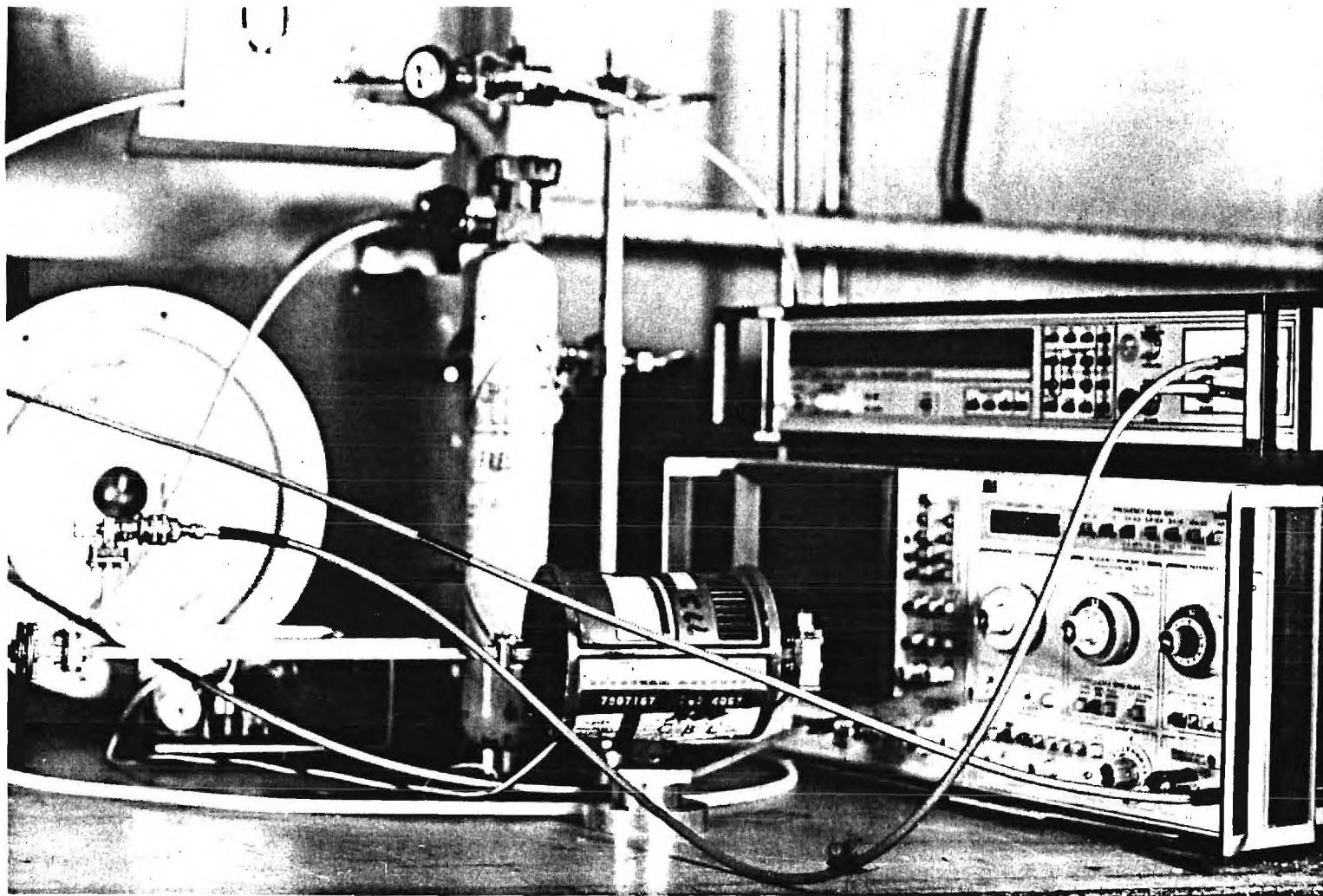


Figure 8. Close-up Photograph of Small Gunn Oscillator Attached to a Rotary Vane Attenuator in Front of H-P Spectrum Analyzer.

IV. DATA TABULATION

The average measured attenuation (dB) for Freon 22 is tabulated in Table 1 for all frequencies except 34 GHz. The average deviation is given for each measured value and is also expressed in percentage deviation. At 35 GHz, for the concentration of 5% at 700 TORR and 650 TORR total pressure, only one set of measured values were employed, so that an average deviation does not exist.

Table 2 lists the measured attenuation in dB for the frequency 34.0 GHz. These are not averages of recorded sets of data, but actually the values for one recorded set. Two sets of data were taken, but the calibration procedure for the second set was incorrect so that only one set of data is employed to calculate the absorption coefficients at 34.0 GHz.

V. DATA ANALYSIS

With the data tabulated in Section IV, the absorption coefficient in cm^{-1} has been calculated for the seven frequencies from 33 GHz to 36.5 GHz. The calculations have been performed for at least seven concentrations from 5% to 20% of Freon 22 in dry nitrogen. Data were taken to 1% concentration and in some cases to 0.5% and 0.1% but sensitivity of the system (because of low resonator Q) limited the accuracy of the calculation of the absorption coefficients. Extrapolation of the absorption coefficient calculated for high concentrations should provide sufficient accuracy for use at lower (<5%) concentrations.

The calculations were performed using Equation 3 of Section II. The resonator Q-value was the average of approximately 10 measured values for each frequency. The Q was obtained by measuring half-power points at each frequency to

TABLE 1
AVERAGE MEASURED ATTENUATION (dB)

FREQUENCY = 33.5 GHz

CONCENTRATION = 20%

760 TORR:	3.87	±	0.048	(1.25%)
700	3.63	±	0.044	(1.20%)
650	3.44	±	0.042	(1.22%)
600	3.12	±	0.079	(2.53%)

CONCENTRATION = 17.5%

760 TORR:	3.52	±	0.090	(2.56%)
700	3.28	±	0.092	(2.81%)
650	3.11	±	0.139	(4.46%)
600	2.83	±	0.085	(3.01%)

CONCENTRATION = 15%

760 TORR:	3.08	±	0.211	(6.8%)
700	2.93	±	0.176	(6.0%)
650	2.74	±	0.204	(7.5%)
600	2.65	±	0.164	(6.2%)

CONCENTRATION = 12.5%

760 TORR:	2.63	±	0.025	(0.95%)
700	2.47	±	0.024	(0.97%)
650	2.37	±	0.022	(0.93%)
600	2.17	±	0.078	(3.59%)

AVERAGE MEASURED ATTENUATION (dB)

FREQUENCY = 33.5 GHz

CONCENTRATION = 10%

760 TORR:	2.28	±	0.075	(3.3 %)
700	2.18	±	0.125	(5.75%)
650	1.91	±	0.098	(5.13%)
600	1.73	±	0.125	(7.25%)

CONCENTRATION = 7.5%

760 TORR:	1.98	±	0.125	(6.33%)
700	1.80	±	0.149	(8.28%)
650	1.68	±	0.075	(4.48%)
600	1.58	±	0.125	(7.94%)

CONCENTRATION = 5.0%

760 TORR:	1.58	±	0.025	(1.59 %)
700	1.40	±	0.001	(0.071%)
650	1.30	±	0.000	(0.00 %)
600	1.20	±	0.050	(4.16 %)

AVERAGE MEASURED ATTENUATION (dB)

FREQUENCY = 34.5 GHz

CONCENTRATION = 20%

760 TORR:	5.09 ± 0.008	(0.16%)
700	4.68 ± 0.044	(0.94%)
650	4.39 ± 0.012	(0.27%)
600	4.06 ± 0.013	(0.32%)

CONCENTRATION = 17.5%

760 TORR:	4.69 ± 0.013	(0.27%)
700	4.37 ± 0.028	(0.64%)
650	3.97 ± 0.007	(0.16%)
600	3.71 ± 0.013	(0.34%)

CONCENTRATION = 15%

760 TORR:	4.10 ± 0.003	(0.07%)
700	3.85 ± 0.046	(1.18%)
650	3.53 ± 0.025	(0.71%)
600	3.14 ± 0.065	(2.07%)

CONCENTRATION = 12.5%

760 TORR:	3.77 ± 0.031	(0.82%)
700	3.55 ± 0.053	(1.49%)
650	3.13 ± 0.032	(1.02%)
600	2.88 ± 0.076	(2.64%)

CONCENTRATION = 10%

760 TORR:	3.07 ± 0.068	(2.21%)
700	2.79 ± 0.003	(0.117%)
650	2.48 ± 0.0019	(0.77%)
600	2.26 ± 0.044	(1.95%)

AVERAGE MEASURED ATTENUATION (dB)

FREQUENCY = 34.5 GHz

CONCENTRATION = 7.5%

760 TORR:	2.26 ± 0.056	(2.48%)
700	2.03 ± 0.033	(1.63%)
650	1.86 ± 0.044	(2.36%)
600	1.61 ± 0.039	(2.42%)

CONCENTRATION = 5%

760 TORR:	1.35 ± 0.050	(3.70%)
700	1.18 ± 0.029	(2.46%)
650	1.05 ± 0.054	(5.14%)
600	0.85	

AVERAGE MEASURED ATTENUATION (dB)

FREQUENCY = 35 GHz

CONCENTRATION = 20%

760 TORR:	5.45 ± 0.042	(0.78%)
700	4.93 ± 0.018	(0.37%)
650	4.48 ± 0.063	(1.41%)
600	3.80 ± 0.084	(2.20%)

CONCENTRATION = 17.5%

760 TORR:	5.31 ± 0.156	(2.94%)
700	4.59 ± 0.097	(2.10%)
650	4.11 ± 0.070	(1.71%)
600	3.65 ± 0.095	(2.62%)

CONCENTRATION = 15%

760 TORR:	4.48 ± 0.140	(3.03%)
700	4.11 ± 0.141	(3.42%)
650	3.79 ± 0.133	(3.50%)
600	3.26 ± 0.089	(2.72%)

CONCENTRATION = 12.5%

760 TORR:	3.70 ± 0.100	(2.7 %)
700	3.37 ± 0.127	(3.8 %)
650	3.05 ± 0.050	(1.64%)
600	2.80 ± 0.025	(0.88%)

AVERAGE MEASURED ATTENUATION (dB)

FREQUENCY = 35 GHz

CONCENTRATION = 10%

760 TORR:	3.03 ± 0.022	(0.71%)
700	2.70 ± 0.098	(3.63%)
650	2.52 ± 0.079	(3.13%)
600	2.30 ± 0.050	(2.17%)

CONCENTRATION = 7.5%

760 TORR:	2.23 ± 0.111	(4.97%)
700	2.00 ± 0.100	(5%)
650	1.85 ± 0.150	(8.1 %)
600	1.70 ± 0.133	(7.8%)

CONCENTRATION = 5%

760 TORR:	1.63 ± 0.025	(1.54%)
700	1.50	
650	1.40	
600	1.28 ± 0.025	(1.96%)

CONCENTRATION = 2.5%

760 TORR:	0.90 ± 0.001	(0.11%)
700	0.70 ± 0.100	(14.3%)
650	0.65 ± 0.15	(23.1%)
600	0.60 ± 0.15	(25%)

AVERAGE MEASURED ATTENUATION (dB)

FREQUENCY = 35.5 GHz

CONCENTRATION = 20%

760 TORR:	5.91 ± 0.113	(1.91%)
700	5.63 ± 0.138	(2.45%)
650	5.26 ± 0.030	(0.57%)
600	4.79 ± 0.012	(0.25%)

CONCENTRATION = 17.5%

760 TORR:	5.21 ± 0.100	(1.92%)
700	4.89 ± 0.085	(1.74%)
650	4.58 ± 0.082	(1.79%)
600	4.29 ± 0.0115	(0.27%)

CONCENTRATION = 15%

760 TORR:	4.70 ± 0.138	(2.94%)
700	4.34 ± 0.094	(2.17%)
650	4.07 ± 0.066	(1.62%)
600	3.84 ± 0.141	(3.67%)

CONCENTRATION = 12.5%

760 TORR:	3.98 ± 0.118	(2.96%)
700	3.63 ± 0.032	(0.88%)
650	3.36 ± 0.044	(1.21%)
600	3.09 ± 0.030	(0.97%)

CONCENTRATION = 10%

760 TORR:	3.46 ± 0.057	(1.65%)
700	3.18 ± 0.030	(0.94%)
650	2.86 ± 0.043	(1.50%)
600	2.61 ± 0.093	(3.56%)

AVERAGE MEASURED ATTENUATION (dB)

FREQUENCY = 35.5 GHz

CONCENTRATION = 7.5%

760 TORR:	2.72 ± 0.019	(0.70%)
700	2.54 ± 0.046	(1.81%)
650	2.29 ± 0.044	(1.92%)
600	2.09 ± 0.005	(0.24%)

CONCENTRATION = 5%

760 TORR:	2.02 ± 0.119	(5.89%)
700	1.82 ± 0.015	(0.82%)
650	1.72 ± 0.031	(1.80%)
600	1.60 ± 0.058	(3.63%)

AVERAGE MEASURED ATTENUATION (dB)

FREQUENCY = 36 GHz

CONCENTRATION = 20%

760 TORR:	3.68	\pm 0.025	(0.68%)
700	3.32	\pm 0.076	(2.29%)
650	3.13	\pm 0.128	(4.08%)
600	2.85	\pm 0.055	(1.93%)

CONCENTRATION = 17.5%

760 TORR:	3.27	\pm 0.023	(0.695%)
700	3.02	\pm 0.019	(0.629%)
650	2.70	\pm 0.002	(0.074%)
600	2.50	\pm 0.048	(1.92 %)

CONCENTRATION = 15%

760 TORR:	2.97	\pm 0.044	(1.49%)
700	2.72	\pm 0.078	(2.86%)
650	2.60	\pm 0.068	(2.60%)
600	2.26	\pm 0.062	(2.73%)

CONCENTRATION = 12.5%

760 TORR:	2.57	\pm 0.023	(0.89%)
700	2.38	\pm 0.025	(1.05%)
650	2.18	\pm 0.019	(0.87%)
600	2.00	\pm 0.0017	(0.085%)

AVERAGE MEASURED ATTENUATION (dB)

FREQUENCY = 36 GHz

CONCENTRATION = 10%

760 TORR:	2.10	\pm	0.00	(0.00%)
700	1.90	\pm	0.00	(0.00%)
650	1.78	\pm	0.028	(1.58%)
600	1.58	\pm	0.025	(1.59%)

CONCENTRATION = 7.5%

760 TORR:	1.55	\pm	0.102	(6.58%)
700	1.43	\pm	0.075	(5.26%)
650	1.35	\pm	0.050	(3.70%)
600	1.25	\pm	0.050	(4.0 %)

CONCENTRATION = 5.0%

760 TORR:	1.10	\pm	0.102	(9.3 %)
700	0.98	\pm	0.025	(2.56%)
650	0.93	\pm	0.025	(2.70%)
600	0.78	\pm	0.025	(3.23%)

AVERAGE MEASURED ATTENUATION (dB)

FREQUENCY = 36.5 GHz
 CONCENTRATION = 10%

760 TORR:	3.34	± 0.038	(1.14%)
700	3.11	± 0.026	(0.83%)
650	2.84	± 0.038	(1.34%)
600	2.64	± 0.013	(0.49%)

CONCENTRATION = 7.5%

760 TORR:	2.79	± 0.088	(3.2 %)
700	2.54	± 0.038	(1.5 %)
650	2.24	± 0.012	(0.54%)
600	2.04	± 0.062	(3.04%)

CONCENTRATION = 5.0%

760 TORR:	1.76	± 0.037	(2.10%)
700	1.61	± 0.012	(0.75%)
650	1.46	± 0.014	(0.96%)
600	1.29	± 0.085	(6.6 %)

AVERAGE MEASURED ATTENUATION (dB)

FREQUENCY = 36.5 GHz
 CONCENTRATION = 20%

760 TORR:	5.15	\pm 0.041	(0.80%)
700	4.88	\pm 0.077	(1.6 %)
650	4.54	\pm 0.058	(1.3 %)
600	4.21	\pm 0.037	(0.88%)

CONCENTRATION = 17.5%

760 TORR:	4.89	\pm 0.088	(1.8 %)
700	4.67	\pm 0.093	(2.0 %)
650	4.34	\pm 0.138	(3.18%)
600	4.06	\pm 0.037	(0.91%)

CONCENTRATION = 15%

760 TORR:	4.29	\pm 0.088	(2.05%)
700	4.00	\pm 0.106	(2.65%)
650	3.80	\pm 0.076	(2.00%)
600	3.49	\pm 0.088	(2.52%)

CONCENTRATION = 12.5%

760 TORR:	3.87	\pm 0.010	(0.26%)
700	3.70	\pm 0.012	(0.32%)
650	3.41	\pm 0.037	(1.08%)
600	3.24	\pm 0.062	(1.91%)

TABLE 2

MEASURED ATTENUATION (dB)

FREQUENCY = 34 GHz

CONCENTRATION = 20%

760 TORR:	2.79
700	2.66
650	2.59
600	2.44

CONCENTRATION = 17.5%

760 TORR:	2.45
700	2.30
650	2.15
600	2.00

CONCENTRATION = 15%

760 TORR:	2.10
700	1.95
650	1.85
600	1.75

TABLE 2

MEASURED ATTENUATION (dB)

FREQUENCY = 34 GHz

CONCENTRATION = 12.5%

760 TORR:	1.90
700	1.80
650	1.65
600	1.55

CONCENTRATION = 10%

760 TORR:	1.75
700	1.65
650	1.60
600	1.45

CONCENTRATION = 7.5%

760 TORR:	1.50
700	1.35
650	1.30
600	1.20

CONCENTRATION = 5.0%

760 TORR:	1.05
700	1.00
650	0.95
600	0.85

calculate $Q = f_0 / \Delta f$, where f_0 is the center frequency of the resonator and Δf is the frequency separation between half-power points. The measured Q-values are listed in Table 3.

Table 4 exhibits the results of the calculation of the absorption coefficient. The coefficient, $\alpha(\text{cm}^{-1})$, is the result of using the data of Table 2, the Q-values of Table 3 and Equations 3 of Section II. The units of the absorption coefficients are reciprocal centimeters, cm^{-1} . The absorption coefficient is calculated from average measured attenuation for each frequency, concentration and pressure. For each concentration, $\alpha(\text{cm}^{-1})$ is further reduced to $\alpha(\text{cm}^{-1})/\text{TORR}$ to produce a coefficient convertible to $\alpha(\text{cm}^{-1})$ for any pressure. Average $\alpha(\text{cm}^{-1})/\text{TORR}$ is calculated and plotted as a function of concentration in Figure 9 through 15. In addition, for each frequency, and average value of $\alpha(\text{cm}^{-1})/\text{TORR}/\%$ is obtained by dividing out the concentration. This value is listed for each concentration in Table 4. In Table 5, the average value for $\alpha(\text{cm}^{-1})/\text{TORR}/\%$ is listed for each frequency. These values are convenient for use in applications of the absorption coefficient at any pressure and concentration percentage. The same utility applies to Figures 9 through 15, which can be used for the same applications. Figure 16 is a plot of $\alpha(\text{cm}^{-1})/\text{TORR}/\%$ as a function of frequency.

TABLE 3
RESONATOR Q-VALUES AS A
FUNCTION OF FREQUENCY

<u>FREQUENCY (GHz)</u>	<u>Q</u>
33.5	5346
34.0	5171
34.5	6157
35.0	7924 (8076)
35.5	6533
36.0	6482
36.5	6411

TABLE 4

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 34 GHz

CONCENTRATION = 15%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	3.77 x 10 ⁻⁴	4.96 x 10 ⁻⁷
700	3.47	4.96
650	3.27	5.03
600	3.08	5.13

AVERAGE α (cm⁻¹)/TORR = 5.01 ± 0.061(1.21%) x 10⁻⁷ α (cm⁻¹)/TORR/% = 3.34 x 10⁻⁸

CONCENTRATION = 12.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	3.37 x 10 ⁻⁴	4.43 x 10 ⁻⁷
700	3.17	4.53
650	2.88	4.44
600	2.69	4.49

AVERAGE α (cm⁻¹)/TORR = 4.47 ± 0.032(0.71%) x 10⁻⁷ α (cm⁻¹)/TORR/% = 3.58 x 10⁻⁸

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 34 GHz

CONCENTRATION = 15%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	3.77×10^{-4}	4.96×10^{-7}
700	3.47	4.96
650	3.27	5.03
600	3.08	5.13

AVERAGE α (cm⁻¹)/TORR = $5.01 \pm 0.061(1.21\%) \times 10^{-7}$

α (cm⁻¹)/TORR/% = 3.34×10^{-8}

CONCENTRATION = 12.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	3.37×10^{-4}	4.43×10^{-7}
700	3.17	4.53
650	2.88	4.44
600	2.69	4.49

AVERAGE α (cm⁻¹)/TORR = $4.47 \pm 0.032(0.71\%) \times 10^{-7}$

α (cm⁻¹)/TORR/% = 3.58×10^{-8}

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 34 GHz

CONCENTRATION = 10%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	3.08×10^{-4}	4.05×10^{-7}
700	2.88	4.12
650	2.79	4.29
600	2.41	4.02

$$\text{AVERAGE } \alpha \text{ (cm}^{-1}\text{) / TORR} = 4.12 \pm 0.086 (2.09\%) \times 10^{-7}$$

$$\alpha \text{ (cm}^{-1}\text{) / TORR / \%} = 4.12 \times 10^{-8}$$

CONCENTRATION = 7.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	2.60×10^{-4}	3.42×10^{-7}
700	2.32	3.31
650	2.23	3.42
600	2.04	3.40

$$\text{AVERAGE } \alpha \text{ (cm}^{-1}\text{) / TORR} = 3.49 \pm 0.050 (1.44\%) \times 10^{-7}$$

$$\alpha \text{ (cm}^{-1}\text{) / TORR / \%} = 4.65 \times 10^{-8}$$

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 34GHz

CONCENTRATION = 5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	1.77 x 10 ⁻⁴	2.33 x 10 ⁻⁷
700	1.68	2.40
650	1.59	2.45
600	1.42	2.36

$$\text{AVERAGE } \alpha \text{ (cm}^{-1}\text{)}/\text{TORR} = 2.39 \pm 0.034(1.40\%) \times 10^{-7}$$

$$\alpha \text{ (cm}^{-1}\text{)}/\text{TORR}/\% = 4.78 \times 10^{-8}$$

CONCENTRATION = 2.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	0.99 x 10 ⁻⁴	1.30 x 10 ⁻⁷
700	0.90	1.29
650	0.82	1.26
600	0.65	1.08

$$\text{AVERAGE } \alpha \text{ (cm}^{-1}\text{)}/\text{TORR} = 1.23 \pm 0.074(6.01\%) \times 10^{-7}$$

$$\alpha \text{ (cm}^{-1}\text{)}/\text{TORR}/\% = 4.92 \times 10^{-8}$$

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 33.5 GHz

CONCENTRATION = 20%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	7.38×10^{-4}	9.71×10^{-7}
700	6.80	9.72
650	6.38	9.81
600	5.67	9.45

AVERAGE α (cm⁻¹)/TORR = 9.67 ± 0.110 (1.13%) $\times 10^{-7}$

α (cm⁻¹)/TORR/% = 4.84×10^{-6}

CONCENTRATION = 17.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	6.57×10^{-4}	8.65×10^{-7}
700	6.02	8.60
650	5.65	8.69
600	5.06	8.44

AVERAGE α (cm⁻¹)/TORR = 8.59 ± 0.078 (0.91%) $\times 10^{-7}$

α (cm⁻¹)/TORR/% = 4.91×10^{-8}

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 33.5 GHz

CONCENTRATION = 15%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	5.60×10^{-4}	7.36×10^{-7}
700	5.26	7.51
650	4.88	7.50
600	4.69	7.82

AVERAGE α (cm⁻¹)/TORR = 7.55 ± 0.135 (1.78%) $\times 10^{-7}$

α (cm⁻¹)/TORR/% = 5.03×10^{-8}

CONCENTRATION = 12.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	4.63×10^{-4}	6.10×10^{-7}
700	4.32	6.17
650	4.12	6.35
600	3.74	6.23

AVERAGE α (cm⁻¹)/TORR = 6.21 ± 0.076 (1.22%) $\times 10^{-7}$

α (cm⁻¹)/TORR/% = 4.97×10^{-8}

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 33.5 GHz

CONCENTRATION = 10%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	3.93 x 10 ⁻⁴	5.17 x 10 ⁻⁷
700	3.74	5.34
650	3.23	4.97
600	2.89	4.81

AVERAGE α (cm⁻¹)/TORR = 5.07 ± 0.184 (3.64%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 5.07 x 10⁻⁸

CONCENTRATION = 7.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	3.35 x 10 ⁻⁴	4.42 x 10 ⁻⁷
700	3.02	4.32
650	2.79	4.30
600	2.61	4.35

AVERAGE α (cm⁻¹)/TORR = 4.35 ± 0.037 (0.86%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 5.79 x 10⁻⁸

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 33.5 GHz

CONCENTRATION = 5.0%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	2.61 x 10 ⁻⁴	3.44 x 10 ⁻⁷
700	2.30	3.28
650	2.12	3.26
600	1.95	3.25

AVERAGE α (cm⁻¹)/TORR = 3.31 ± 0.064 (1.94%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 6.61 x 10⁻⁸

CONCENTRATION =

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760		
700		
650		
600		

AVERAGE α (cm⁻¹)/TORR =

α (cm⁻¹)/TORR/% =

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 34.5 GHz

CONCENTRATION = 20%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	9.36×10^{-4}	12.32×10^{-7}
700	8.39	11.98
650	7.72	11.88
600	7.00	11.68

AVERAGE α (cm⁻¹)/TORR = $11.96 \pm 0.017(1.4\%) \times 10^{-7}$

α (cm⁻¹)/TORR/% = 5.98×10^{-8}

CONCENTRATION = 17.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	8.40×10^{-4}	11.06×10^{-7}
700	7.68	10.98
650	6.80	10.47
600	6.26	10.44

AVERAGE α (cm⁻¹)/TORR = $10.73 \pm 0.028(2.63\%) \times 10^{-7}$

α (cm⁻¹)/TORR/% = 6.13×10^{-8}

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 34.5 GHz

CONCENTRATION = 15%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	7.08×10^{-4}	9.32×10^{-7}
700	6.56	9.37
650	5.88	9.04
600	5.11	8.51

AVERAGE α (cm⁻¹)/TORR = $9.06 \pm 0.283(3.12\%) \times 10^{-7}$

α (cm⁻¹)/TORR/% = 6.04×10^{-8}

CONCENTRATION = 12.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	6.38×10^{-4}	8.40×10^{-7}
700	5.92	8.46
650	5.10	7.84
600	4.62	7.70

AVERAGE α (cm⁻¹)/TORR = $8.10 \pm 0.328(4.05\%) \times 10^{-7}$

α (cm⁻¹)/TORR/% = 6.48×10^{-8}

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 34.5 GHz

CONCENTRATION = 10%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	4.98×10^{-4}	6.55×10^{-7}
700	4.45	6.36
650	3.88	5.97
600	3.48	5.81

AVERAGE α (cm⁻¹)/TORR = $6.17 \pm 0.282(4.57\%) \times 10^{-7}$

α (cm⁻¹)/TORR/% = 6.17×10^{-8}

CONCENTRATION = 7.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	3.48×10^{-4}	4.58×10^{-7}
700	3.09	4.42
650	2.80	4.31
600	2.39	3.99

AVERAGE α (cm⁻¹)/TORR = $4.32 \pm 0.175(4.05\%) \times 10^{-7}$

α (cm⁻¹)/TORR/% = 5.77×10^{-8}

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 34.5GHz

CONCENTRATION = 5.0%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	1.97 x 10 ⁻⁴	2.60 x 10 ⁻⁷
700	1.71	2.44
650	1.52	2.33
600	1.21	2.01

AVERAGE α (cm⁻¹)/TORR = 2.35 ± 0.173(7.38%) x 10⁻⁷

α (cm⁻¹)/TORR/% =

CONCENTRATION =

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760		
700		
650		
600		

AVERAGE α (cm⁻¹)/TORR =

α (cm⁻¹)/TORR/% =

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 35 GHz

CONCENTRATION = 20%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	7.93 x 10 ⁻⁴	10.43 x 10 ⁻⁷
700	6.95	9.92
650	6.13	9.44
600	4.99	8.32

AVERAGE α (cm⁻¹)/TORR = 9.60 ± 0.65 (6.84%) x 10⁻⁷ cm⁻¹

α (cm⁻¹)/TORR/% = 4.76 x 10⁻⁸

CONCENTRATION = 17.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	7.57 x 10 ⁻⁴	9.96 x 10 ⁻⁷
700	6.33	8.00
650	4.95	7.62
600	4.22	7.03

AVERAGE α (cm⁻¹)/TORR = 8.84 ± 0.661 (7.47%) x 10⁻⁷ cm⁻¹

α (cm⁻¹)/TORR/% = 5.05 x 10⁻⁸

CONCENTRATION = 15%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	6.25 x 10 ⁻⁴	8.22 x 10 ⁻⁷
700	5.60	8.00
650	4.95	7.62
600	4.22	7.03

AVERAGE α (cm⁻¹)/TORR = 7.72 ± 0.394 (5.11%) x 10⁻⁷ cm⁻¹

α (cm⁻¹)/TORR/% = 5.14 x 10⁻⁸

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 35 GHz

CONCENTRATION = 12.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	4.91 x 10 ⁻⁴	6.47 x 10 ⁻⁷
700	4.38	6.26
650	3.89	5.99
600	3.51	5.86

AVERAGE α (cm⁻¹)/TORR = 6.14 ± 0.221 (3.59%) x 10⁻⁷ cm⁻¹

α (cm⁻¹)/TORR/% = 4.91 x 10⁻⁸

CONCENTRATION = 10%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	3.87 x 10 ⁻⁴	5.09 x 10 ⁻⁷
700	3.37	4.82
650	3.12	4.80
600	2.81	4.68

AVERAGE α (cm⁻¹)/TORR = 4.85 ± 0.122 (2.52%) x 10⁻⁷ cm⁻¹

α (cm⁻¹)/TORR/% = 4.85 x 10⁻⁸

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 35 GHz

CONCENTRATION = 7.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	2.71×10^{-4}	3.57×10^{-7}
700	2.40	3.42
650	2.20	3.38
600	2.00	3.33

AVERAGE α (cm⁻¹)/TORR = 3.43 ± 0.071 (2.09%) $\times 10^{-7}$

α (cm⁻¹)/TORR/% = 4.57×10^{-8}

CONCENTRATION =

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760		
700		
650		
600		

AVERAGE α (cm⁻¹)/TORR =

α (cm⁻¹)/TORR/% =

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 35 GHz

CONCENTRATION = 5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	1.90 x 10 ⁻⁴	2.51 x 10 ⁻⁷
700	1.74	2.49
650	1.62	2.49
600	1.46	2.44

AVERAGE α (cm⁻¹)/TORR = 2.48 ± 0.021 (0.84%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 4.96 x 10⁻⁸

CONCENTRATION = 2.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	1.01 x 10 ⁻⁴	1.33 x 10 ⁻⁷
700	0.78	1.11
650	0.72	1.11
600	0.66	1.10

AVERAGE α (cm⁻¹)/TORR = 1.16 ± 0.083 (7.17%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 4.65 x 10⁻⁸

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 35.5GHz

CONCENTRATION = 20%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	11.11 x 10 ⁻⁴	14.61 x 10 ⁻⁷
700	10.38	14.83
650	9.41	14.47
600	8.40	14.00

AVERAGE α (cm⁻¹)/TORR = 14.48 ± 0.243(1.68%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 7.24 x 10⁻⁸

CONCENTRATION = 17.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	9.37 x 10 ⁻⁴	12.32 x 10 ⁻⁷
700	8.60	12.28
650	7.91	12.17
600	7.27	12.12

AVERAGE α (cm⁻¹)/TORR = 12.22 ± 0.080(0.65%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 6.98 x 10⁻⁸

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 35.5 GHz

CONCENTRATION = 15%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	8.17 x 10 ⁻⁴	10.75 x 10 ⁻⁷
700	7.39	10.56
650	6.81	10.48
600	6.33	10.56

AVERAGE α (cm⁻¹)/TORR = 10.59 ± 0.084 (0.80%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 7.06 x 10⁻⁸

CONCENTRATION = 12.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	6.62 x 10 ⁻⁴	8.71 x 10 ⁻⁷
700	5.91	8.44
650	5.37	8.26
600	4.86	8.10

AVERAGE α (cm⁻¹)/TORR = 8.38 ± 0.198 (2.36%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 6.70 x 10⁻⁸

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 35.5 GHz

CONCENTRATION = 10%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	5.57 x 10 ⁻⁴	7.32 x 10 ⁻⁷
700	5.03	7.19
650	4.44	6.82
600	3.99	6.64

AVERAGE α (cm⁻¹)/TORR = 7.00 ± 0.26 (3.75%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 7.00 x 10⁻⁸

CONCENTRATION = 7.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	4.19 x 10 ⁻⁴	5.51 x 10 ⁻⁷
700	3.87	5.53
650	3.44	5.30
600	3.10	5.17

AVERAGE α (cm⁻¹)/TORR = 5.38 ± 0.144 (2.68%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 7.168 x 10⁻⁸

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 35.5 GHz

CONCENTRATION = 5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	2.98 x 10 ⁻⁴	3.92 x 10 ⁻⁷
700	2.65	3.78
650	2.49	3.83
600	2.30	3.83

AVERAGE α (cm⁻¹)/TORR = 3.84 ± 0.160 (4.18%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 7.68 x 10⁻⁸

CONCENTRATION =

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760		
700		
650		
600		

AVERAGE α (cm⁻¹)/TORR =

α (cm⁻¹)/TORR/% =

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 36.0GHz

CONCENTRATION = 20%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	6.13 x 10 ⁻⁴	8.0 x 10 ⁻⁷
700	5.41	7.73
650	5.05	7.76
600	4.52	7.53

AVERAGE α (cm⁻¹)/TORR = 7.77 ± 0.147 (1.89%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 3.89 x 10⁻⁸

CONCENTRATION = 17.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	5.32 x 10 ⁻⁴	7.00 x 10 ⁻⁷
700	4.84	6.91
650	4.25	6.54
600	3.89	6.48

AVERAGE α (cm⁻¹)/TORR = 6.73 ± 0.224 (3.33%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 3.85 x 10⁻⁸

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 36GHz

CONCENTRATION = 15%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	4.74×10^{-4}	6.24×10^{-7}
700	4.28	6.11
650	4.06	6.25
600	3.45	5.76

AVERAGE α (cm⁻¹)/TORR = 6.09 ± 0.166 (2.72%) $\times 10^{-7}$

α (cm⁻¹)/TORR/% = 4.06×10^{-8}

CONCENTRATION = 12.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	4.01×10^{-4}	5.28×10^{-7}
700	3.66	5.23
650	3.32	5.11
600	3.02	5.03

AVERAGE α (cm⁻¹)/TORR = 5.16 ± 0.092 (1.79%) $\times 10^{-7}$

α (cm⁻¹)/TORR/% = 4.13×10^{-6}

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 36 GHz

CONCENTRATION = 10%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	3.18×10^{-4}	4.19×10^{-7}
700	2.85	4.07
650	2.64	4.07
600	2.31	3.86

AVERAGE α (cm⁻¹)/TORR = $4.05 \pm 0.094(2.32\%) \times 10^{-7}$

α (cm⁻¹)/TORR/% = 4.05×10^{-8}

CONCENTRATION = 7.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	2.27×10^{-4}	2.99×10^{-7}
700	2.08	2.96
650	1.96	3.01
600	1.80	3.00

AVERAGE α (cm⁻¹)/TORR = $2.99 \pm 0.054(1.80\%) \times 10^{-7}$

α (cm⁻¹)/TORR/% = 3.99×10^{-8}

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 36 GHz

CONCENTRATION = 5.0%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	1.57×10^{-4}	2.07×10^{-7}
700	1.38	1.98
650	1.31	2.01
600	1.09	1.81

AVERAGE α (cm⁻¹)/TORR = 1.97 ± 0.079 (4.0%) $\times 10^{-7}$

α (cm⁻¹)/TORR/% = 3.93×10^{-8}

CONCENTRATION =

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760		
700		
650		
600		

AVERAGE α (cm⁻¹)/TORR =

α (cm⁻¹)/TORR/% =

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 36.5 GHz

CONCENTRATION = 20%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	9.21×10^{-4}	12.12×10^{-7}
700	8.59	12.28
650	7.82	12.03
600	7.11	11.85

AVERAGE α (cm⁻¹)/TORR = 12.07 ± 0.130 (1.07%) $\times 10^{-7}$

α (cm⁻¹)/TORR/% = 6.03×10^{-8}

CONCENTRATION = 17.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	8.60×10^{-4}	11.32×10^{-7}
700	8.11	11.59
650	7.38	11.35
600	6.79	11.32

AVERAGE α (cm⁻¹)/TORR = 11.40 ± 0.098 (0.86%) $\times 10^{-7}$

α (cm⁻¹)/TORR/% = 6.51×10^{-8}

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 36.5GHz

CONCENTRATION = 15%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	7.27 x 10 ⁻⁴	9.56 x 10 ⁻⁷
700	6.66	9.52
650	6.25	9.61
600	5.63	9.38

AVERAGE α (cm⁻¹)/TORR = 9.52 ± 0.070 (0.74%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 6.35 x 10⁻⁸

CONCENTRATION = 12.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	6.38 x 10 ⁻⁴	8.40 x 10 ⁻⁷
700	6.05	8.65
650	5.48	8.43
600	5.14	8.57

AVERAGE α (cm⁻¹)/TORR = 8.51 ± 0.098 (1.15%) x 10⁻⁷

α (cm⁻¹)/TORR/% = 6.81 x 10⁻⁸

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 36.5 GHz

CONCENTRATION = 10%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	5.34×10^{-4}	7.02×10^{-7}
700	4.91	7.01
650	4.40	6.77
600	4.04	6.74

AVERAGE α (cm⁻¹)/TORR = 6.89 ± 0.122 (1.92%) $\times 10^{-7}$

α (cm⁻¹)/TORR/% = 6.89×10^{-8}

CONCENTRATION = 7.5%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	4.31×10^{-4}	5.67×10^{-7}
700	3.86	5.52
650	3.86	5.15
600	3.01	5.02

AVERAGE α (cm⁻¹)/TORR = 5.34 ± 0.256 (4.79%) $\times 10^{-7}$

α (cm⁻¹)/TORR/% = 7.12×10^{-8}

CALCULATED ABSORPTION COEFFICIENTS

FREQUENCY = 36.5 GHz

CONCENTRATION = 5.0%

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760	2.56×10^{-4}	3.37×10^{-7}
700	2.32	3.31
650	2.09	3.22
600	1.82	3.04

AVERAGE α (cm⁻¹)/TORR = 3.23 ± 0.107 (3.31%) $\times 10^{-7}$

α (cm⁻¹)/TORR/% = 6.47×10^{-8}

CONCENTRATION =

	α (cm ⁻¹)	α (cm ⁻¹)/TORR
760		
700		
650		
600		

AVERAGE α (cm⁻¹)/TORR =

α (cm⁻¹)/TORR/% =

TABLE 5

α (cm⁻¹)/TORR/% x 10⁸ AS A
FUNCTION OF FREQUENCY

<u>FREQUENCY (GHZ)</u>	<u>α (cm⁻¹)/TORR/%</u>
33.5	5.17 \pm 0.443 (8.56%)
34.0	4.05 \pm 0.570 (14.0%)
34.5	5.89 \pm 0.380 (6.45%)
35.0	4.84 \pm 0.156 (3.22%)
35.5	7.12 \pm 0.210 (2.95%)
36.0	3.99 \pm 0.082 (2.07%)
36.5	6.60 \pm 0.294 (4.46%)

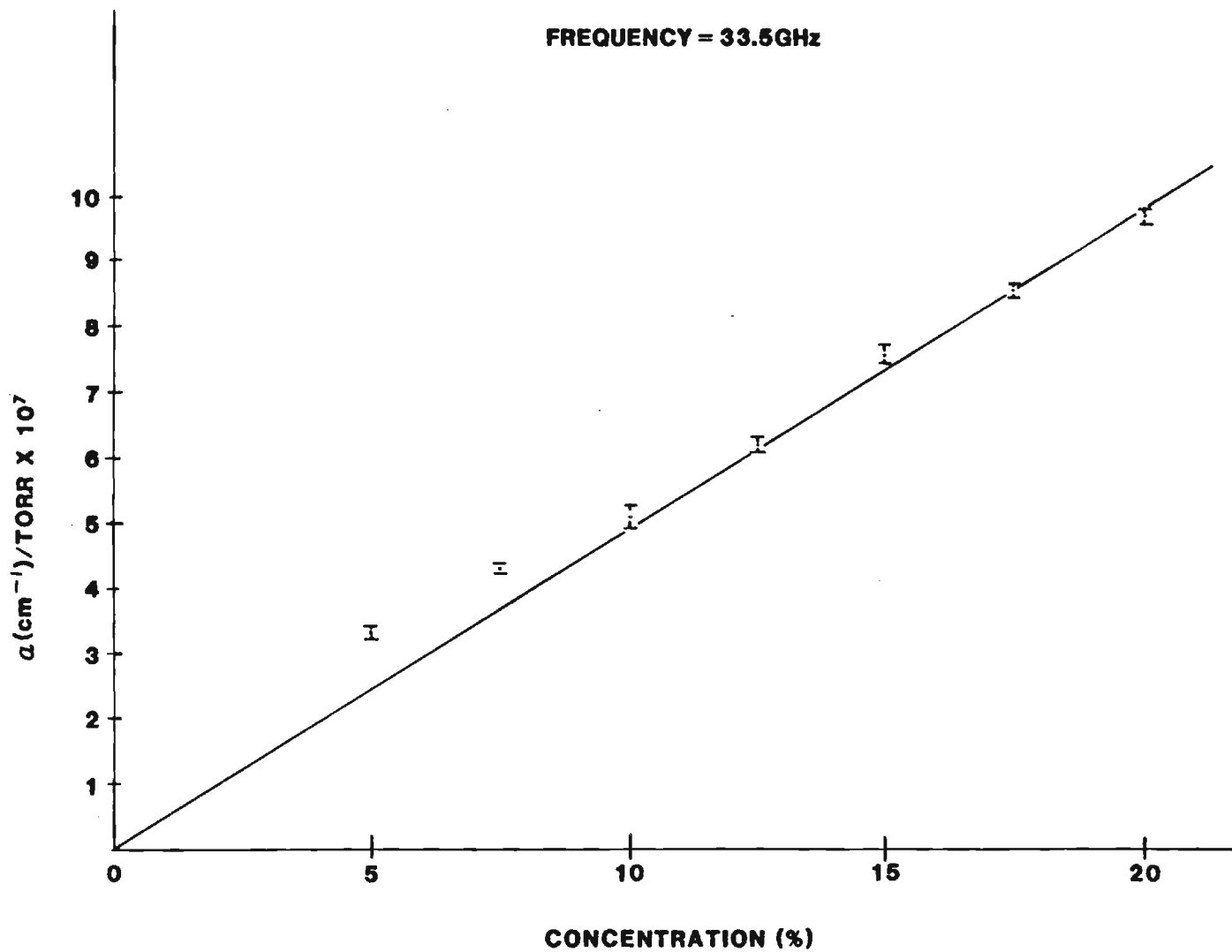


Figure 9. $\alpha (\text{cm}^{-1})/\text{TORR} \times 10^7$ as a Function of Concentration;
 Frequency = 33.5 GHz.

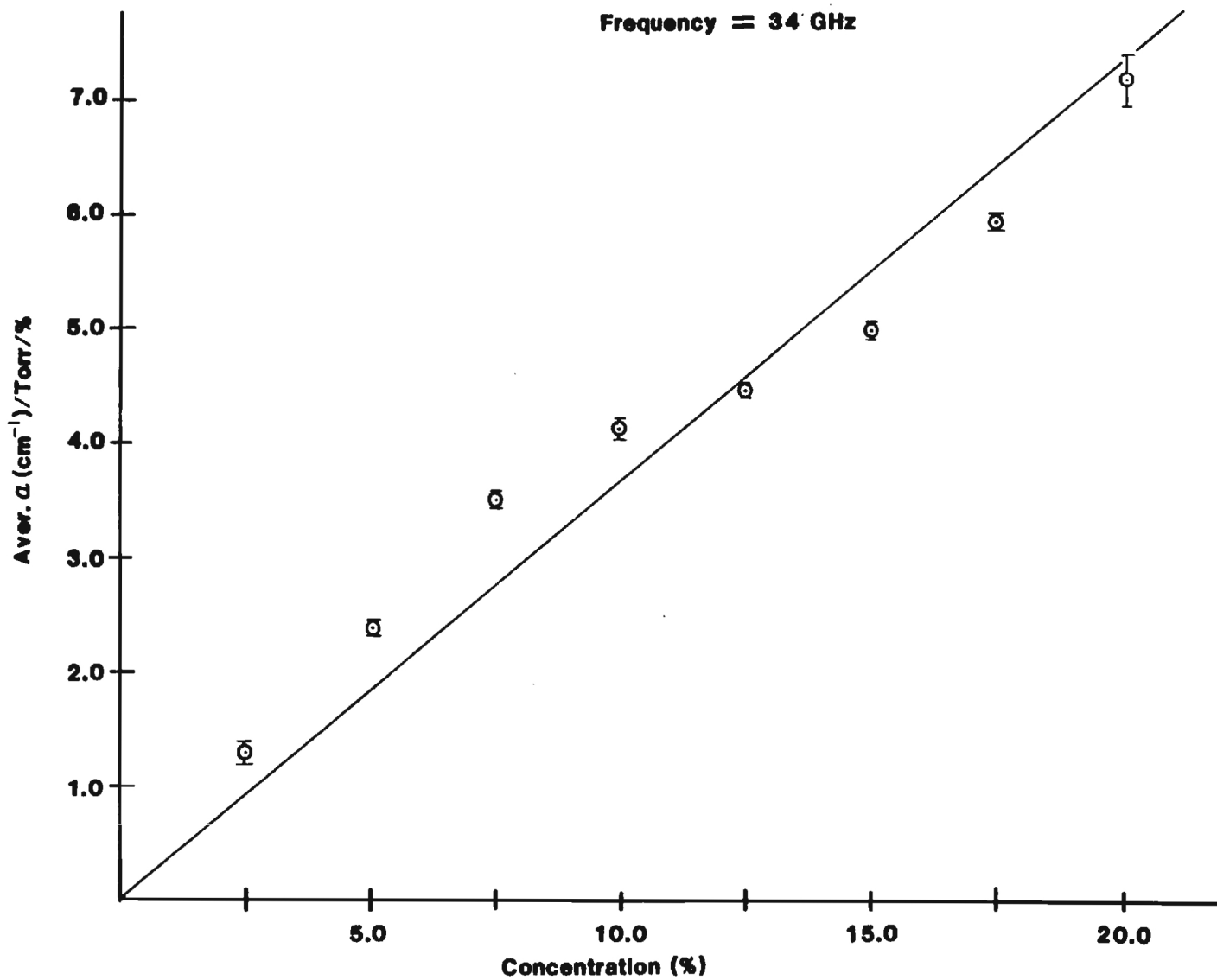


Figure 10. $\alpha(\text{cm}^{-1})/\text{TORR} \times 10^7$ as a Function of Concentration; Frequency = 34.0 GHz.

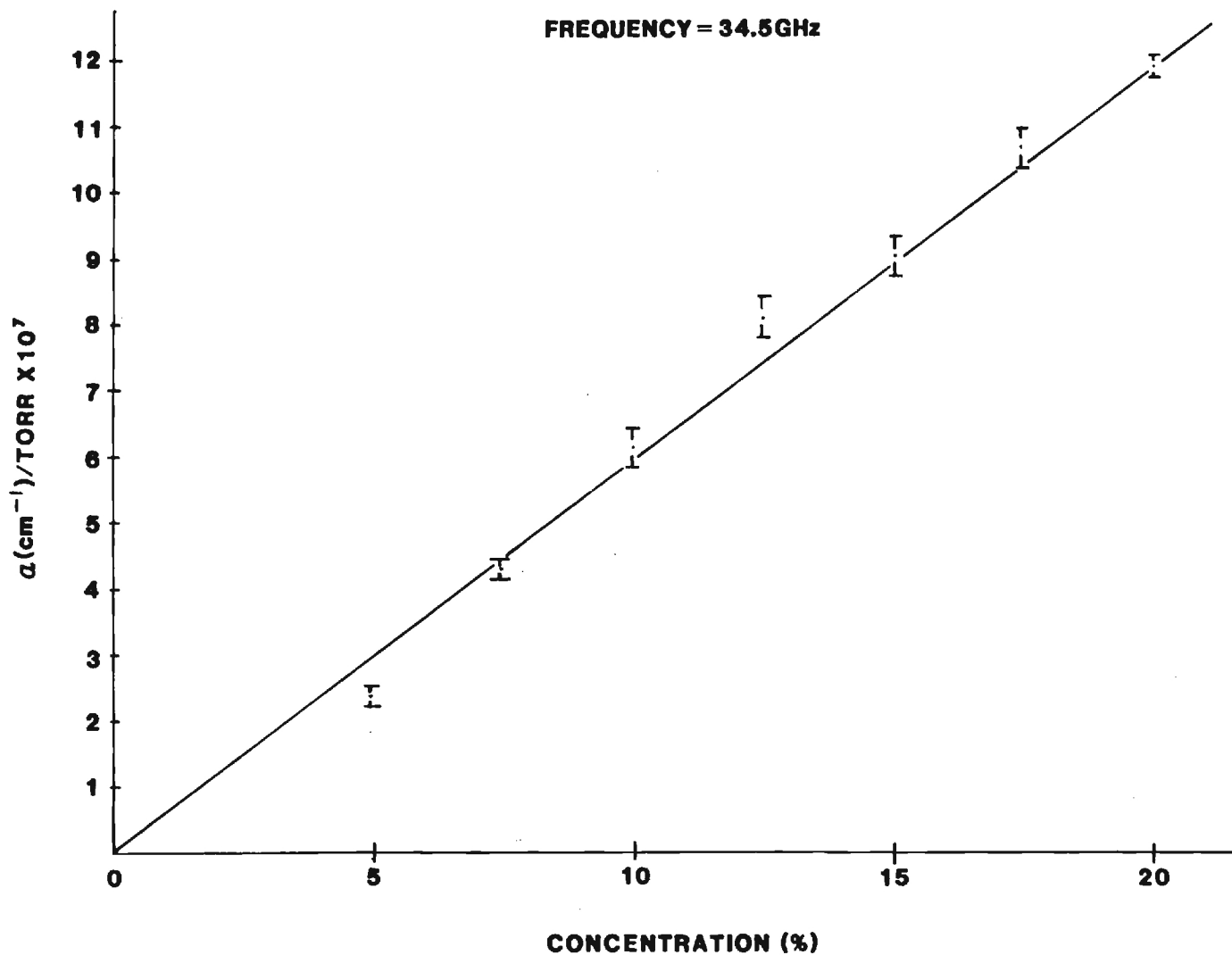


Figure 11. $\alpha(\text{cm}^{-1})/\text{TORR} \times 10^7$ as a Function of Concentration; Frequency = 34.5 GHz.

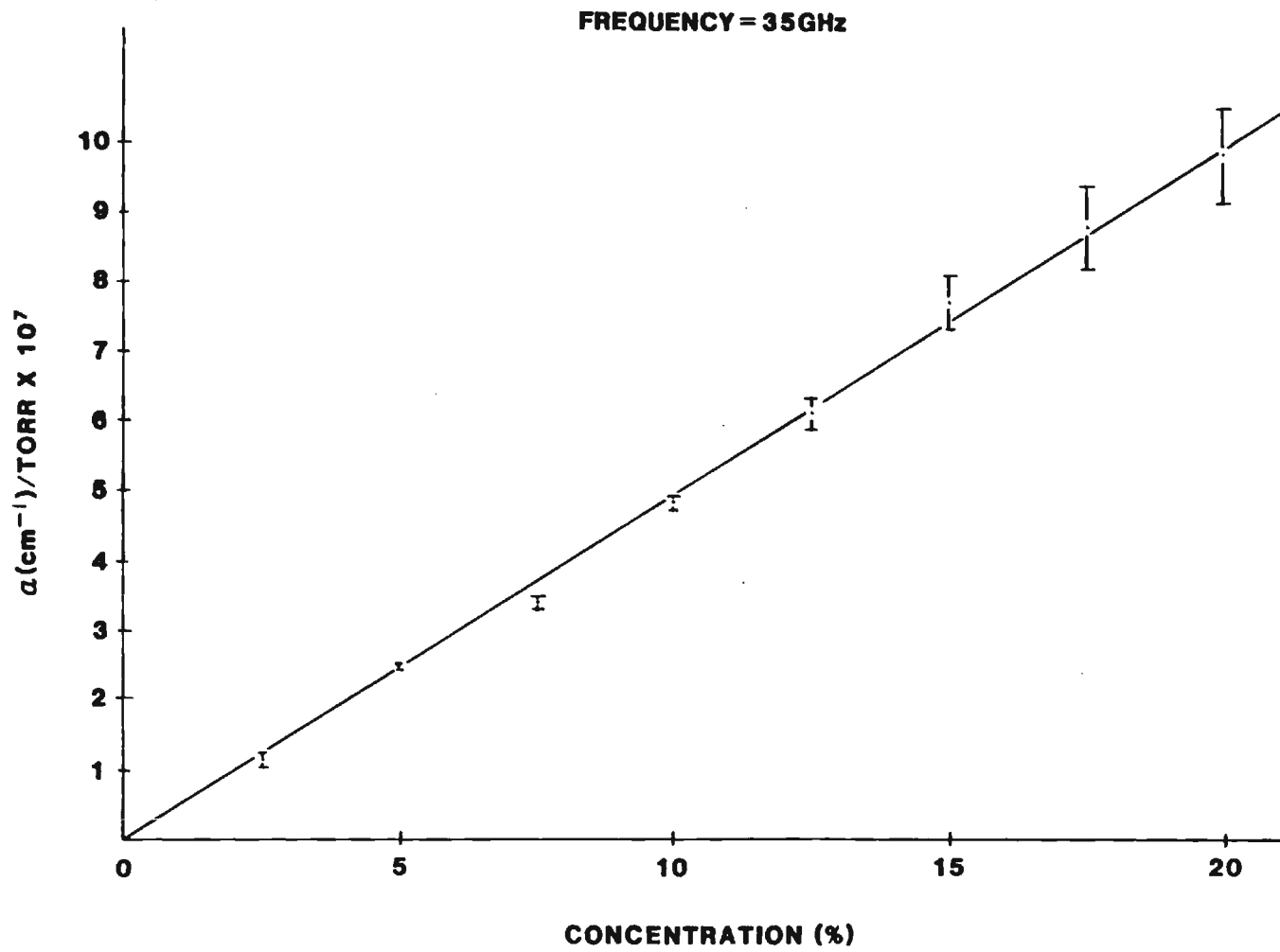


Figure 12. $\alpha(\text{cm}^{-1})/\text{TORR} \times 10^7$ as a Function of Concentration; Frequency = 35.0 GHz.

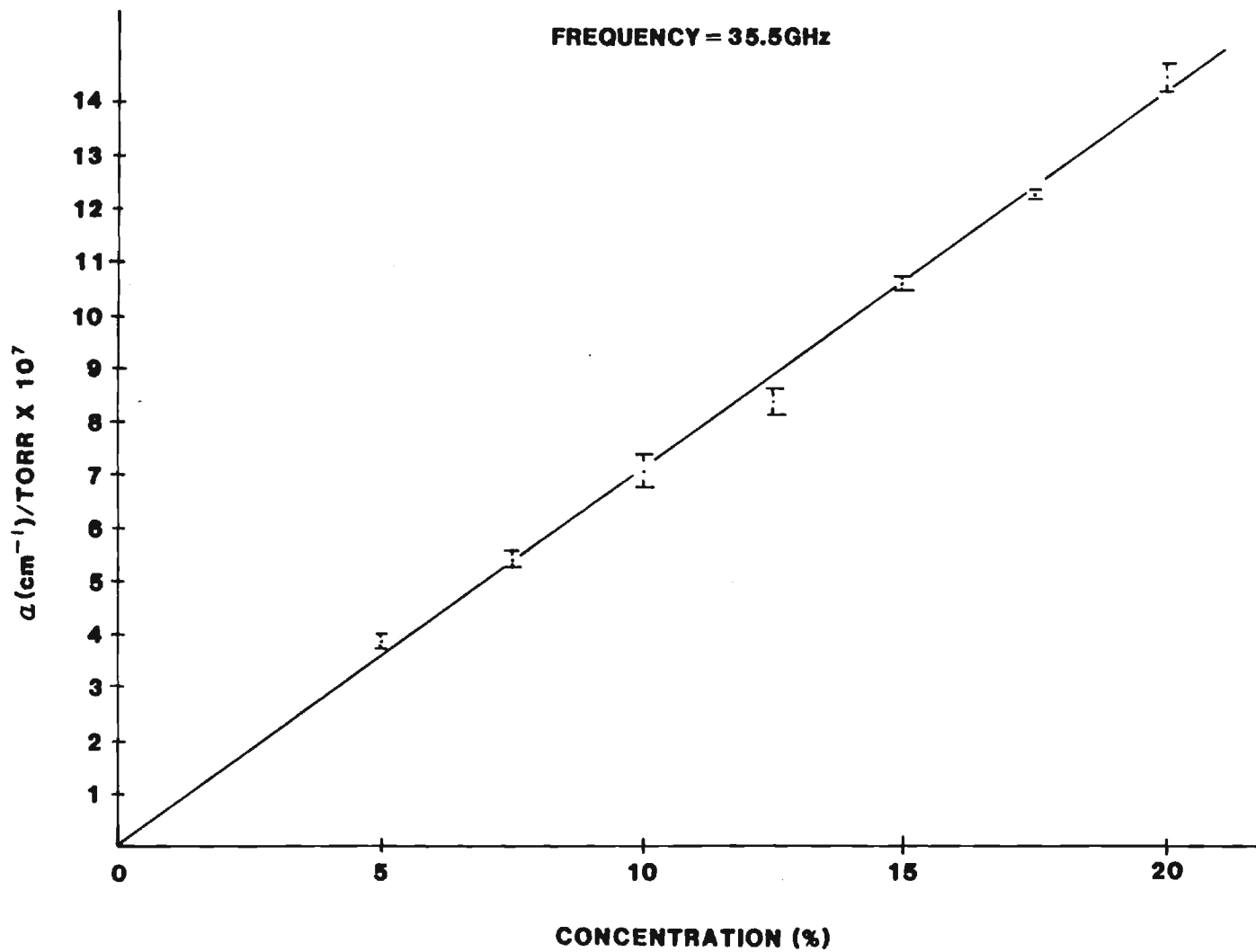


Figure 13. $\alpha(\text{cm}^{-1})/\text{TORR} \times 10^7$ as a Function of Concentration; Frequency = 35.5 GHz.

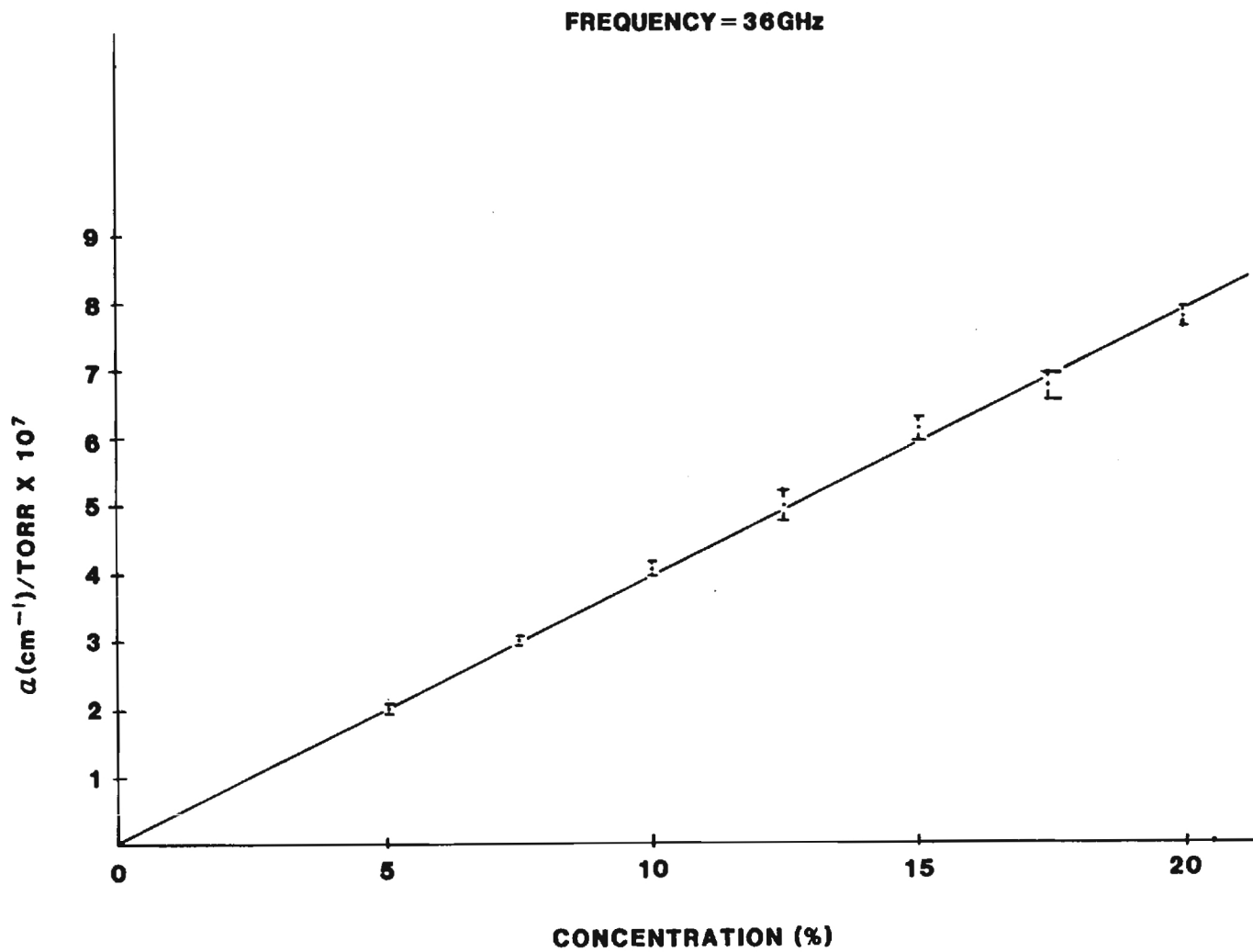


Figure 14. $\alpha(\text{cm}^{-1})/\text{TORR} \times 10^7$ as a Function of Concentration; Frequency = 36.0 GHz.

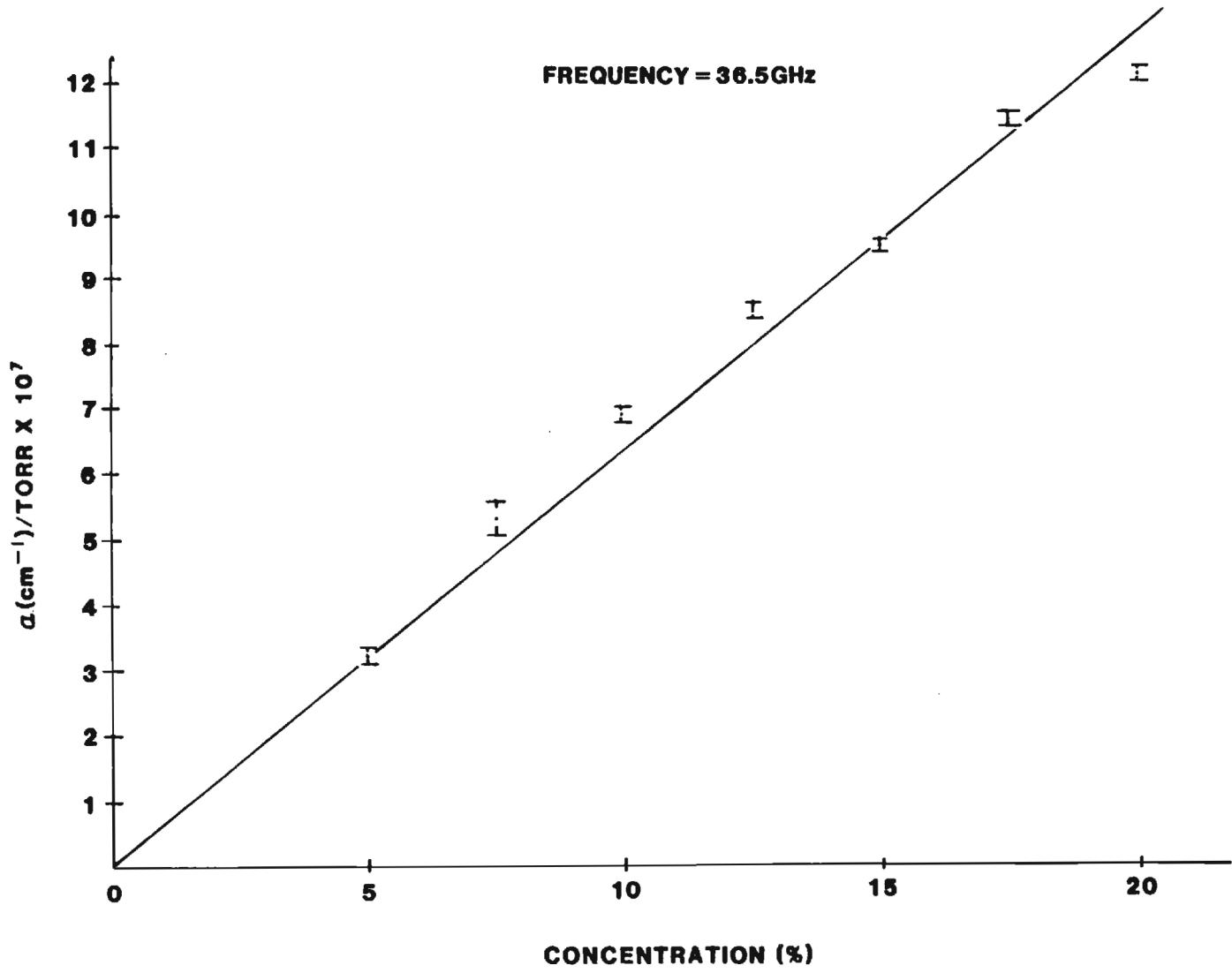


Figure 15. $\alpha(\text{cm}^{-1})/\text{TORR} \times 10^7$ as a Function of Concentration; Frequency = 36.5 GHz.

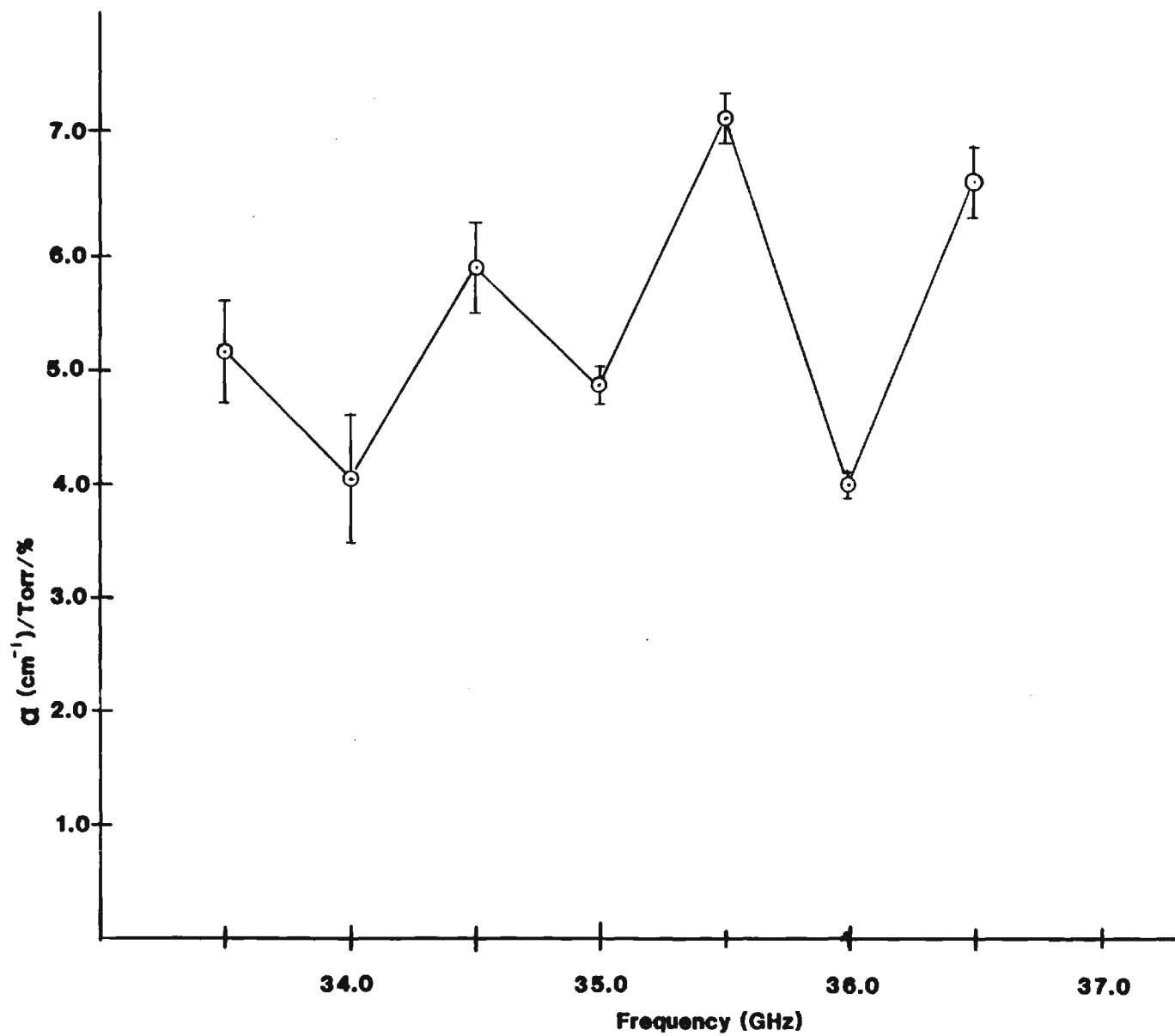


Figure 16. Average α (cm^{-1})/TORR/% as a Function of Frequency.

VI. CONCLUSIONS AND RECOMMENDATIONS

Data on the absorption of Freon 22 have been taken at 7 frequencies in the K_a -band region from 33.5 GHz to 36.5 GHz. The calculated absorption coefficients have been presented in a format allowing their use in applications requiring different concentrations and different total pressures (Freon 22 and dry nitrogen). Table 1 presents the average measured attenuation in dB. The average deviation with the percentage deviation is given for each data points. At least two sets of measurements were made for each frequency, concentration and total pressure, and each measurement within each set was the average of approximately 10 attenuation readings. For the cases where no average deviation is given, only one set of data was used. Table 2 lists data for 34.0 GHz. Whereas two sets of data were taken for this frequency, only one set of data is listed and is employed for the calculations. The calibration for the second set did not provide sufficient accuracy to include the data in the tabulation. The low Q-values of the resonator resulted in a lower sensitivity of the system and, therefore, inaccurate results for the lower concentrations. Data were taken for almost all cases for concentrations as low as 0.5% and in some cases as low as 0.1%. The low concentration data are not tabulated in the report nor are they used in any calculations. Extrapolation from high concentrations will give sufficiently accurate absorption coefficients for use at low concentrations.

The accuracy for the attenuation measurements was in most cases, greater for higher concentrations than for lower concentrations. This was due to the low-Q of the resonators resulting in low system sensitivity. In order to detect accurately an attenuation of 0.1 dB corresponding to an absorption coefficient of 10^{-5} , the resonator Q should exceed at least 10,000, and the system sensitivity should allow detection of attenuations of 0.01 - 0.001 dB for an adequate signal-to-noise ratio.

Future measurements should consider the use of the apparatus shown in Figure 3 in which integration and direct reading in output voltage are possible with the lock-in amplifier scheme. The method that was employed, i.e. use of a spectrum analyzer as a detection system, was quick but needs further development for increased sensitivity. In future experiments, resonator with a higher Q (on the order of 10^5) should be employed. This will take some effort beyond the use of what is available as was done in this program.

The attenuation and calculated absorption coefficients for 34.0 GHz are the least precise of all data because of the use of only one set of measurements in the analysis, but probably provide accuracy within or close to the 5% accuracy requirement. In the table of resonator Q-values, Table 3, two values are listed for the frequency of 35.0 GHz. These correspond to the two Q-values measured before and after the coupling holes were opened up. Data were taken under both conditions.

The data for all frequencies prove to be quite linear with concentrations and do not show any consistent deviations which can be interpreted as nonlinearities. During the measurements, pulling effects were on occasions observed but insertion of attenuation or use of tuning mechanisms could remove or minimize such effects.

With data taken at seven frequencies, Figure 16 shows the variation of absorption between the frequency points. This is not unreasonable because of the possibility of spectral structure for Freon 22 at the concentrations for which measurements were made. Future measurements must include more data points at several frequencies between those for which measurements were made in this program. Because of the inability to set a pulsed IMPATT source exactly to a frequency without injection - or phase-locking and because of the frequency-chirped nature of these sources, using any one set of

determined absorption coefficients will lead to inaccurate results. The frequency-chirp of the IMPATT will have to be removed or at least minimized for use with a photoacoustic cell unless the response is flat across the frequency region of interest. Data taken at more frequencies would, however, contribute to an understanding of the use of these devices in the millimeter wavelength region.

From this discussion, it can be concluded that the results of this investigation provide accurate values for the absorption coefficient of Freon 22 as a function of frequency, total pressure and concentration of Freon 22 in the spectral region of 33.5 GHz to 36.5 GHz. A more extensive investigation should be performed to extend the measurements to a greater resolution (e.g. measurements every 100 MHz within the band). Such a program should include the following:

1. Improvement of the sensitivity based upon higher resonator Q and increased system sensitivity by use of the apparatus in Figure 3.

2. Repeat measurements of this contract with the higher sensitivity apparatus.

3. Provide measurements of absorption coefficient at frequencies throughout the spectral band from 33.5 GHz to 36.5 GHz at frequency intervals no larger than 100 MHz.

4. Perform same measurements on other gases which may provide greater utility as the medium for a spectrophone detection system.

5. Employ phase-locked sources for greater frequency stability with sources having good amplitude stability.

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