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DEVELOPMENT
OF AN
INFRARED HYGROMETER
OCTOBER 1969

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DEVELOPMENT
OF AN
INFRARED HYGROMETER

By

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F. R. Reich

ABSTRACT

Infrared techniques and instrumentation show promise for measuring gas coolant impurities within high temperature nuclear reactors. An experimental hygrometer using an infrared absorption null instrumentation technique responded smoothly over water vapor contents at STP from 20 to 10,000 ppm. An instrument accuracy greater than 80% was obtained from calibration data obtained with a helium gas carrier and a water content controlled with a variable pressure saturator. A digital computer analog of the infrared hygrometer helped in gaining insight of the absorption null instrumentation and in optimizing sensitivity. The response and sensitivity of various infrared filter components could be examined before the tedious and expensive fabrication process was initiated. The computer analog also indicated instrument response for the infrared detection of other impurity gases and liquids for absorption null instrumentation.

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INTRODUCTION

Safe and efficient operation of modern gas-cooled reactors depends in part upon fast, accurate measurement of coolant impurities. Impurity levels indicate the presence of coolant system leaks and may assist in evaluating reactor core corrosion rate and in up-dating the projected reactor core parameters. The inadvertent introduction of coolant impurities into the severe reactor environment must be promptly detected and corrected by appropriate measures.⁽¹⁾ Many conventional instruments approach or exceed their design limits in modern gas-cooled reactor environments.

New instruments utilizing infrared absorption have been proposed and described.⁽²⁾ Water vapor is one of the important coolant impurities which may be detected with infrared techniques. An examination of the infrared spectrum of water vapor indicates absorption at wavelengths of 1.38, 1.87, and 2.6 μ .⁽³⁾ The 2.6 μ absorption is the strongest, making this spectral region the most desirable for instrumentation. Instrumentation at longer wavelengths is limited by availability of suitable electro-optical components.

This report describes the development of an infrared hygrometer utilizing the 2.6 μ absorption of water vapor for a continuous gas flow. The technique is not unique and may be applied in the detection of other reactor coolant impurities, including CO₂.⁽⁴⁾

SUMMARY

An experimental infrared absorption hygrometer was developed to measure water vapor content in a flowing gas. The response in a standard temperature and pressure (STP) environment extended smoothly over water vapor content of 20 ppm by volume to 10,000 ppm. Instrument accuracy over this range was greater than 80%. Data for calibration and testing was obtained by using helium gas and a variable pressure saturator to inject water vapor into the flowing gas.

Operation of the hygrometer in severe reactor environments can be predicted with the gas law equation. At 600 °F and 300 psia, the sensitive range of the hygrometer extends from 2 to 1000 ppm with an 80% confidence level. Since the hygrometer uses a null detection principle, impurity particles carried by the flowing gas and deposited on the optical components of the infrared hygrometer will not appreciably affect the response or sensitivity.

The hygrometer development effort included a digital computer program developed to simulate operation of the infrared hygrometer. Digital analogs of the hygrometer filters and functional forms of the spectral response of varying water vapor concentrations were stored in the computer. The response and sensitivity of the infrared hygrometer for various combinations of optical filters could be examined before the tedious and expensive fabrication of the filters was initiated. The computer analog also helped in gaining insight of the hygrometer null principle and in maximizing sensitivity with the design of optical filter parameters. The computer analog was also instrumental in determining hygrometer sensitivity for other gases. CO₂ has an absorption at 2.7 μ overlapping a portion of the water vapor absorption at 2.6 μ . The selection of filter parameters minimizing CO₂ sensitivity and maximizing water vapor sensitivity was aided by the computer analog.

The hygrometer principle is not unique to the detection of water vapor and CO_2 . The technique may be applied to the detection of other flowing gases and liquids by selecting the proper spectral region of instrumentation. The required optical components are readily designed and fabricated with the application of the present art of thin film deposition and the development of new infrared optical materials.

HYGROMETER OPERATION

The infrared transmission spectrum of water vapor has been obtained from both experimental and theoretical data.⁽³⁻⁵⁾ Calculations using high speed computers have been correlated with experimental data to obtain accurate theoretical models attributing infrared absorption in the 1.0 to 3.0 μ region to transitions between various vibration-rotation energy levels. A portion of the infrared spectrum in Figure 1 indicates strong absorption peaks at 1.38, 1.87, and 2.6 μ . Absorption is strongest at 2.6 μ , making this energy range the most desirable for instrumentation. The intensity of absorption at 2.6 μ is dependent on water vapor concentration as indicated in Figure 2. The units correlation between precipital-centimeters (prec-cm) and volume ppm is presented in Appendix A.

The operating principle of the infrared hygrometer can be understood by referring to Figure 3. The defining and comparing of two narrow band-passes of energy, one at 2.6 μ and one at 2.3 μ , will yield a measure of the water vapor content in an optical sighting path. The energy of the 2.6 μ band-pass is dependent on the water vapor content in the sighting path, while the 2.3 μ band-pass is unaffected by water vapor. The presence of other gases in the optical sighting path will also affect the hygrometer if the defined optical band-pass intercepts an energy region where optical transmission is dependent on the gas concentration. CO_2 , also present in reactor coolant gases, absorbs energy as indicated in Figure 3.⁽⁶⁾ However, by

FIGURE 1. Water Vapor Near Infrared Transmission

FIGURE 2. Water Vapor 2.6 μ Transmission Variation with Water Vapor Content

FIGURE 3. Instrumentation of 2.6 μ Water Vapor Absorption

designing the absorption band-pass filter to include only the short wavelength region of the 2.6μ absorption, sensitivity to CO_2 may be reduced. Water vapor sensitivity, however, will also decrease since the most active region of absorption lies above 2.6μ .

The components of the developmental infrared hygrometer are shown in Figure 4. The source of infrared energy is a tungsten filament lamp. The optical energy is chopped at 60 Hz with a rotating band-pass filter. Alternate quadrants of the filter wheel contain reference and absorption band-pass filters as shown in Figure 5. The chopped energy passes into the absorption chamber and is collected by the detector cell. The combination of curved and plane mirrors minimize energy divergence and lengthen the optical sighting path. The lamp filament is focused in front of the detector cell to decrease the energy density and reduce vibrational noise. The detected signal is amplified and applied to the control field of the servo motor. By energizing the servo motor reference with a signal in phase with the synchronous motor driving the filter wheel, the detector signal is phase detected. The energy of the two band-pass filters is balanced by the wedge filter whose spectral characteristics are indicated in Figure 6. The optical cutoff of the high-pass edge varies with the physical dimensions of the wedge filter. The servo motor positions the wedge filter until a zero ac signal from the wedge filter indicates a band-pass energy balance. The position of the wedge filter indicates the concentration of water vapor sighting path.

1. ABSORPTION CHAMBER	9. SERVO MOTOR
2. PLANE MIRROR	10. 4:1 MECHANICAL COUPLING
3. CURVED MIRRORS	11. INDICATOR POTENTIOMETER
4. FOCAL POINT	12. SERVO AMPLIFIER
5. LAMP	13. LEAD SULPHIDE CELL
6. SYNCHRONOUS MOTOR	14. THERMOELECTRIC COOLER
AND PREAMPLIFIER
7. FILTER WHEEL	15. MOTOR CHAMBER
8. CIRCULAR WEDGE FILTER	

FIGURE 4. Mark II Infrared Hygrometer Operation Diagram

FILTER WHEEL

WEDGE FILTER

REFERENCE
BAND-PASS

ABSORPTION
BAND-PASS

FIGURE 5. *Infrared Hygrometer Optical Filters*

FIGURE 6. Hygrometer Wedge Filter Spectral Response

DEVELOPMENTAL HYGROMETER

The components of the developmental hygrometer are shown in Figure 7a. The motor chamber, absorption chamber, and detector housing were air tight. Quartz windows and gaskets provided leak-proof optical coupling between the hygrometer chambers and the detector cell. Reflecting the infrared energy with the front surface, Al coated mirrors provided approximately 108 cm of optical sighting path in the absorption chamber. The detector assembly (Figure 7b and 7c) shows the lead sulphide detector with biasing cell and preamplifier. The temperature of the lead sulphide cell and bias cell was stabilized with a thermoelectric cooler and thermistor temperature sensor. The sensor, the lead sulphide cell, and bias cell were mounted on a copper block thermally coupled to the detector Al housing with the thermoelectric cooler. Valves on the detector housing allowed the introduction of dry gas to stabilize the lead sulphide cell. Regulated voltages were supplied for the lamp and bridge readout as shown by the electrical circuit diagram on Figure 8. The indicator potentiometer mechanically coupled to the wedge filter formed one branch of the bridge readout circuit. Imbalance of the bridge was indicated by the ammeter. The ambient temperature of the lead sulphide cell was adjusted by the bias control of the thermoelectric cooler circuit. Latching relays provided the proper phase relation signal to the servo motor, since the mechanical phase of the synchronous motor can energize at a 0 or 180° relationship to the 60 Hz power.

FIGURE 7a. Mark II Infrared Hygrometer

FIGURE 7b. Lead Sulphide Detector Cell

FIGURE 7c. Detector Preamplifier

OPTICAL FILTERS

Since the hygrometer operation is dependent on an energy comparison of two optical band-passes, proper fabrication of the optical filters is highly essential to performance of the infrared hygrometer. The multilayer optical filters are fabricated by vacuum deposition of layers of germanium and silicon monoxide on glass substrates. The spectral response of the glass (Figure 9) indicates a high optical transmission in the 2.6μ spectral region. The wedge filter was designed and fabricated with a multilayer stack of HLHLH, where H and L are quarter-wave optical thicknesses of germanium and silicon monoxide. The spectral response of a typical wedge at two physical positions is shown in Figure 10. The total response is similar to that shown in Figure 5.

FIGURE 9. *Filter Substrate Spectral Transmission*

FIGURE 10. *Infrared Hygrometer Wedge Filter*

A double half-wave band-pass filter of the form HLHHLHLHHLH, H, and L, referring to quarter-wave optical thicknesses of germanium and silicon, was designed for the purpose of reducing CO₂ sensitivity. The filter has a very sharp cut-off and high transmission peak. Should the center wavelength of the filter lie between 2.52 and 2.55 μ, only a small portion of the CO₂ absorption would be included in the band-pass. However, the ±2% accuracy of the deposition thickness monitor would not allow the individual half-wave (HLHHLH) band-pass peaks to be accurately matched. Single half-wave filters were then fabricated after many unsuccessful attempts to fabricate the double half-wave filter. Deposition accuracy was also improved by replacing the silicon monoxide with cryolite (Na₃AlF₆). A typical half-wave band-pass spectrum is shown in

Figure 11. Transmission below 2.0 μ is also limited by the wedge, while the glass substrate attenuates energy above 3.0 μ . Absorption and reference band-pass filters were fabricated by using the same multilayer stack design and materials.

FIGURE 11. Infrared Hygrometer Band-Pass Filter Spectrum

HYGROMETER CALIBRATION

Gases of known and controllable water vapor content are needed to calibrate the infrared hygrometer. One method of providing a varying mixture of water vapor and a carrier gas using the adiabatic saturation process is shown in Figure 12. Dry gas is introduced through a pressure regulating valve to a constant temperature water bath. The dry gas acquires moisture in the bath to produce a gas mixture with a dew point dependent on the temperature and pressure of the water bath. Variation in the humidity ratio H with the meter pressure P_m is given by

$$H = \frac{M_H P_H}{M_g (P_m - P_H)} \frac{\text{gm H}_2\text{O}}{\text{gm gas}} .$$

1. PRESSURE REGULATING VALVE	5. HEATER
2. PRESSURE GAUGE	6. TEMPERATURE MONITOR
3. SATURATION CHAMBER	7. FLOWMETER
4. CONSTANT TEMPERATURE BATH	8. FLOW CONTROL VALVE

FIGURE 12. Variable Pressure Saturator Diagram

Moisture content of the gas was established with an Alnor dew pointer. Conversion of dewpoint units to volume parts per million for the hygrometer absorption chamber is described in Appendix A.

Grade 4 helium gas was used in all calibrations and tests with the hygrometer. An impurity analysis indicated an average impurity content as shown in Table I.⁽⁷⁾

TABLE I. Grade 4 Helium Impurity Analysis

<u>Impurity</u>	<u>Volume, ppm</u>
Water Vapor	15.0
Hydrogen	0.2
Neon	10.0
Nitrogen	5.0
Oxygen	0.8
Carbon Dioxide	0.4
Argon	<0.05

The calibration apparatus and gas flow diagram are shown in Figures 13 and 14. The maximum pressure limit of the variable pressure saturator limited the water vapor concentration of gas directly from the saturator to a minimum of approximately 5000 ppm at room temperature. Mixtures of helium and water vapor with less than 5000 ppm water vapor were obtained with a closed loop flow. Dry helium and "wet" helium were simultaneously introduced into the closed loop. Any water vapor content below 5000 ppm was obtained by adjusting the flow ratio of dry and "wet" helium. Pressure differentials in the closed loop were compensated by the expansion balloon to facilitate measurement of dew point with the Alnor dew pointer instrument.

The response of the hygrometer extended smoothly over a range of water vapor concentrations of 10 to 10,000 ppm as shown in Figure 15. The data points were obtained with absorption and reference band-pass filters centered at 2.52 and 2.4 μ . The reproducibility of each data point was less than $\pm 20\%$ with essentially no long term drift. Sources of error included mechanical and electrical drift of the wedge components and absorption from water vapor in the motor and detector chambers. The calibration curves included data when the motor chamber was filled with dry CO_2 . Although the

CARBON
DIOXIDE

HELIUM

VARIABLE
PRESSURE
SATURATOR

ALNOR
DEW-POINTER

INFRARED
HYGROMETER

FIGURE 13. *Infrared Hygrometer Calibration Apparatus*

FIGURE 14. Calibration Gas Flow Diagram

FIGURE 15. Hygrometer Response with 2.4 to 2.53 μ Band-Pass Filters

sensitivity remained essentially constant, the calibration curve was no longer valid. The amount of calibration shift was equated to the moisture content of the room atmosphere. Insensitivity of the 2.52μ absorption band-pass to CO_2 was verified when equivalent hygrometer readings were obtained for dry helium and dry CO_2 in the absorption chamber.

DIGITAL COMPUTER ANALOG

The fabrication of multilayer band-pass filters for specific wavelengths is costly and slow. Therefore, a digital computer program was written to simulate the infrared hygrometer. A complete listing of the program is included in Appendix B. Operation of the computer analog is summarized by the following equations:

$$V_{(R,A)}(I) = \int_{\lambda_1}^{\lambda_2} L(\lambda)E(\lambda)H_2O(\lambda)CO_2(\lambda)P(\lambda) F_{(R,A)}(\lambda)W(\lambda + I)d\lambda \quad (1)$$

$$V_{(A)}(I) - V_{(R)}(I) = 0 \quad (2)$$

where λ_1 and λ_2 define the spectral range of energy detected by the hygrometer lead sulphide cell; $L(\lambda)$, the spectral response of the infrared energy source (Figure 16); $E(\lambda)$, the lens and window constriction and absorption loss (Figure 17); $\text{CO}_2(\lambda)$ and $\text{H}_2\text{O}(\lambda)$, the spectral transmission of carbon dioxide and water vapor in the hygrometer sighting path (Figure 3); $P(\lambda)$, the spectral response of the lead sulphide detector cell (Figure 18); $F(\lambda)$, the spectral response of the absorption (A) or reference (R) band-pass filters; and $W(\lambda + I)$, the spectral response of the wedge filter with and index I for simulation of spectral changes from physical movement as indicated in Figure 5. In Equation (1), $V_{(R,A)}(I)$ is the response of the detector for either the absorption (A) or reference (R) band-passes. For each water vapor and CO_2

FIGURE 16. Hygrometer Lens, Window, and Aperture Optical Loss

FIGURE 17. Infrared Hygrometer Lamp Emission

FIGURE 18. Lead Sulphide Cell Response - KODAK EKTRON

concentration, introduced into Equation 1 by $H_2O(\lambda)$ and $CO_2(\lambda)$, $V_{(R \text{ or } A)}(I)$ is calculated as a function of index I and tested to determine whether Equation (2) is satisfied. The index I is then advanced to change the spectral response of the wedge $W(\lambda + I)$. The calculations and indexing are repeated until a solution of Equation (2) is obtained. The value of I is read out and the calculations repeated for a new CO_2 and H_2O concentration. In this manner, a complete response of the computer analog may be obtained.

The spectral response of each optical filter is stored in the computer in table form. The hygrometer response of any combination of band-pass and wedge filter are easily obtained by replacing the appropriate filter table with a new table. The filter response is specified at 0.02 μ intervals. However, smaller wedge increments are obtained satisfying the balancing Equation (2) by interpolation. The magnitudes of $V_R(I)$, $V_A(I)$ and index I are noted where Equation (2) changes sign. These magnitudes are used to interpolate I between the 0.02 μ intervals.

A typical computer wedge and band-pass filter response is shown in Figure 19. The spectral shape was obtained from spectrophotometer data of existing multilayer stack filters. The computer analog response of these filters is shown in Figure 20. The somewhat arbitrary wedge position scale was adjusted to fit experimental data.

FIGURE 19. Computer Analog Filters

FIGURE 20. Computer Analog Response

COMPUTER AND EXPERIMENTAL RESULTS

Calibration data for various combinations of reference and absorption band-pass filters were obtained for both the experimental and computer analog hygrometers. The data in Figure 21 were obtained with two filter combinations; a $2.33\ \mu$ (2.34 for the computer analog) reference with a $2.5\ \mu$ (2.53 for the computer analog) and $2.64\ \mu$ (2.64 also for the computer analog) absorption band-pass. The computer analog data were adjusted for the best fit with experimental data by using an arbitrary scale for wedge position. The computer response deviates significantly for large concentrations of water vapor. Of real importance in the comparison of the computer analog and experimental hygrometer data is the sensitivity increase when the $2.5\ \mu$ ($2.53\ \mu$) band-pass filter is replaced by the $2.64\ \mu$ band-pass filter for both the computer analog and experimental hygrometer. Sensitivity is defined by the inverse slope of the data curve.

A variety of band-pass filter combinations was applied to the computer analog. The purpose was to gain an insight of the infrared hygrometer principle and to maximize sensitivity of the infrared hygrometer. Figure 22 shows the response of the computer analog for five band-pass filter combinations. The wedge filter spectral response was obtained from a spectrophotometer analysis of an existing wedge filter. An increase in sensitivity when the separation of the reference and absorption band-pass filters is decreased is evidenced by a comparison of the 2.34 to $2.53\ \mu$ data with the 2.50 to $2.53\ \mu$ data. Sensitivity also increases when the absorption band-pass includes more of the "active" spectral region of the $2.6\ \mu$ (see Figure 2) water vapor absorption, as shown by a comparison of the 2.34 to $2.53\ \mu$ and 2.34 to $2.64\ \mu$ band-pass filter combination. The most sensitive response is obtained with the 2.50 to $2.53\ \mu$ band-pass filter combination.

FIGURE 21. Comparison of Computer Analog
and Infrared Hygrometer Response

FIGURE 22. Response of Computer Analog
for Band-Pass Filter Combinations

Band-pass filters with center wavelengths similar to the computer filters were fabricated for the experimental hygrometer. The response data are shown in Figure 23. Increases in sensitivity by moving the reference and absorption band-passes closer together and including more of the active 2.6μ water vapor absorption were verified by the experimental data. A spectrum analysis of the wedge filter at various physical points indicated both reference and absorption band-passes to lie on the cutoff edge of the wedge filter. The net result was positive feedback requiring a larger wedge movement to accomplish an energy balance between the reference and absorption band-passes.

FIGURE 23. *Response of Infrared Hygrometer for Band-Pass Filter Combinations*

The search for increased hygrometer sensitivity resulted in the filter responses shown in Figure 24. Narrowing the reference band-pass and reducing the spectral slope of the wedge filter increases the positive feedback interaction between the wedge and absorption band-pass filters. Since the area included in an optical band-pass is proportional to energy, a larger wedge movement is now required to balance absorption by water vapor in the absorption band-pass. The ultimate sensitivity limit is a reference band-pass with an impulse function shape. However, such a band-pass is a physical impossibility and the spectral shape in Figure 24 was selected. A comparison of the computer analog response for a regular and narrow band-pass filter in combination is shown in Figure 25. Both data curves were obtained with reference band-passes centered at 2.3 to 2.34 μ and the wedge and absorption band-pass indicated in Figure 24.

FIGURE 24. Computer Analog Narrow Band-Pass Filter and Low Spectral Slope Wedge Spectra

FIGURE 25. *Computer Analog Response with Regular and Narrow Band-Pass Reference Filters*

Various combinations of narrow reference with the regular absorption band-pass were applied to the computer analog. The response data is shown in Figure 26. A maximum sensitivity is observed for the 2.4 to 2.65 band-pass filters where the active portion of 2.6 μ water vapor absorption is intercepted by the absorption band-pass and positive feedback occurs between the absorption band-pass and wedge filters. The positive feedback is observed to have an optimum as indicated by the sensitivity decrease of the 2.46 to 2.65 filter combination.

Verification of the sensitivity increase with the experimental hygrometer was not completed. Development effort was terminated before the narrow band-pass filters were fabricated.

FIGURE 26. *Computer Analog Response with the Narrow Band-Pass Reference Filter*

PROJECTED HYGROMETER OPERATION

Operation of the infrared hygrometer in the severe environment of a gas-cooled reactor will require a special high temperature and pressure absorption chamber. Coolant gases flowing directly from the reactor may exceed a temperature and pressure of 350 °C and 450 psia. The absorption chamber will require a high temperature and pressure window for infrared transmission. An indication of the complexity of the design problem can be seen in Figure 27. The absorption of quartz is observed to increase as the thickness increases nonlinearly with wavelength. A total quartz window thickness of 2 in. would transmit less than 10% of the incident energy. The design of the window is also complex since materials with

a wide range of characteristics, especially thermal expansion, are to be noted. Before the infrared hygrometer can be tested in a reactor environment, a material search must be completed and an absorption chamber design thoroughly safety tested for 100% safe operation.⁽⁸⁾

FIGURE 27. Optical Transmission of Fused Quartz for a Varying Optical Pathlength

The extended temperature and pressure will enhance sensitivity as indicated in Figure 28. The data were obtained from the gas law equation and thus ignores any affects of absorption broadening. Operation at standard temperature and pressure (STP) is used as the reference. A sensitivity of 1.0 ppm by volume at STP is equivalent to approximately 20 ppm by volume at 400 psia and 350 °C with identical sighting paths. The infrared hygrometer is especially suitable for gases containing suspended contaminants such as graphite dust. Optical dispersion and absorption affect both reference and absorption band-pass energy, and the induced optical variations are nulled out. This result was verified when chalk

dust introduced in the gas flowing to the hygrometer, and glass plates 1.5 in. thick inserted in the optical path, produced no change of hygrometer reading.

FIGURE 28. Hygrometer Sensitivity Variation with Temperature and Pressure

CONCLUSION

An infrared hygrometer using the 2.6μ water vapor absorption has been developed and tested in an STP environment. The hygrometer response extended smoothly over a range of water vapor content exceeding 20 to 10,000 ppm. Instrument error in this range was less than $\pm 20\%$. Since the hygrometer uses a null detection, impurity particles suspended in the monitored gas do not affect sensitivity or hygrometer calibration. The operation of the infrared hygrometer principle was studied with a digital computer analog. The digital computer model

response easily provided an indication of hygrometer operation with various optical filters. Sensitivity was maximized by designing optical filters to include the most active regions of the 2.6μ absorption and utilizing a positive feedback produced by an interaction of the optical filters.

Operation of the infrared hygrometer in the environment of gas-cooled reactors will require an extensive materials search and high temperature and pressure chamber and infrared window design. The severe environment, however, will enhance the hygrometer sensitivity. The STP sensitivity of 20 to 10,000 ppm equates to approximately 2 to 1000 ppm at 600 °F and 300 psia.

The infrared hygrometer technique is not unique to water vapor but could be applied to the detection of other gases including CO_2 and N_2O . The required multilayer optical filters are readily designed and fabricated by applying the present art of thin film deposition techniques.

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APPENDIX A

DEW POINT CONVERSION TO ppm

APPENDIX A

DEW POINT CONVERSION TO ppm

The Alnor dew pointer measures moisture content in dew point temperature units of the Fahrenheit scale. The gas law equation

$$\frac{n}{V} = \frac{p}{RT} \quad (1)$$

can be used to convert the dew point units to a mole per unit volume unit, with n/V the desired mole/unit volume ratio; p , gas pressure; R , the universal gas content [0.08208 (liter $\times$ atm)/(mole $^{\circ}$ K)]; and T , gas temperature. For each dew point reading, the gas temperature and vapor pressure of water is noted. Then the molar density of the water vapor at the dew point reading will be

$$\left(\frac{n}{V}\right)_{H_2O} = \frac{V_p/760}{RT} \quad (2)$$

with V_p the vapor pressure of water at the specific dew point temperature, T becomes the normal gas temperature. An approximation is now made. The contribution of water vapor to the total volume and pressure of the gas in the absorption chamber is assumed negligible. Then the molar density of the total gas in the absorption chamber can be attributed to the helium carrier gas as

$$\left(\frac{n}{V}\right)_{He} = \frac{p}{RT} \quad (3)$$

Dividing Equation (2) by (3) gives a volume ratio

$$\frac{\left(\frac{n}{V}\right)_{H_2O}}{\left(\frac{n}{V}\right)_{He}} = \frac{\frac{V_p/760}{RT}}{\frac{p}{RT}} = \frac{V_p}{p} \frac{1}{7.60 \times 10^{-4}} \text{ ppm.}$$

Figure 29 shows the relationship between ppm and dew point units for a helium gas carrier at STP. The method of calculating water vapor content from dew point data was verified with the data presented in Reference 1.

FIGURE 29. Dew Point to ppm by Volume Conversion for Helium Gas

PRECIPITAL-CENTIMETERS AND ATMOSPHERE-CENTIMETERS TO ppm

The units of water vapor and CO_2 concentration are generally given in precipital-centimeters and atmosphere-centimeters.^(3,6) Precipital-centimeters are defined as the depth in cm of the water that would be obtained if all the water vapor in a column were condensed out. The diagram of the hygrometer absorption chamber in Figure 30 shows a column of cross-section area A and an optical path of 185.4 cm with a prec-cm water vapor content C. C is shown as the depth of

water obtainable by condensing out all water vapor in the 185.4 cm column. The number of moles of water in the absorption chamber is then given by

$$\text{moles of H}_2\text{O} = \frac{CA}{18.02} \rho \quad (4)$$

where CA is the condensed water volume; ρ , the density of water vapor; and 18.02, the weight of one mole of water vapor. Since $\rho = 1 \text{ gm/cm}^3$ Equation (4) becomes

$$\text{moles of H}_2\text{O} = \frac{CA}{18.02} \text{ moles.} \quad (5)$$

FIGURE 30. Hygrometer Optical Sighting Path

The volume and pressure contributed by the water vapor to the total gas pressure and volume in the absorption chamber can now be assumed to be neglected. Then the mole/volume ratio can be written as

$$\left(\frac{n}{V}\right)_{\text{H}_2\text{O}} = \frac{CA}{18.02} \frac{1}{V} = \frac{C}{(18.02)(185.4)} \frac{\text{moles}}{\text{cm}^3} \quad (6)$$

since volume = area $\times$ length. From the ideal gas law we have

$$\left(\frac{n}{V}\right)_{\text{He}} = \frac{P}{RT} = \frac{P}{82.08T} \frac{\text{mole}}{\text{cm}^3} \quad (7)$$

Dividing Equation (6) by (7) gives the ratio

$$\frac{\left(\frac{n}{V}\right)_{\text{H}_2\text{O}}}{\left(\frac{n}{V}\right)_{\text{He}}} = \frac{\frac{C}{(18.02)(185.4)}}{\frac{P}{82.08T}} \quad (8)$$

At STP, Equation 8 gives the conversion equations of

$$\text{ppm} = 7.32 \times 10^6 \text{ prec-cm} \quad (9)$$

$$\text{prec-cm} = 1.366 \times 10^{-7} \text{ ppm} \quad (10)$$

Figure 31 shows the relation of ppm and prec-cm for gas at STP conditions.

FIGURE 31. *Conversion of Precipital-Centimeters to ppm by Volume Units for 108-cm Optical Sighting Path*

Atmosphere-centimeters are defined as the absorber path length in cm times the absorber partial pressure in atmospheres corrected to standard temperature. For the absorption chamber in Figure 30

$$\text{atm-cm} = V_p(185.4 \text{ cm}). \quad (11)$$

We assume that the pressure and volume of the gas mixture is attributed entirely to the carrier gas. Using the ideal gas law equation, we can find the mole ratio of CO₂ gas in a helium carrier as

$$\frac{n_{\text{CO}_2}}{n_{\text{He}}} = \frac{\frac{n_{\text{CO}_2}}{V}}{\frac{n_{\text{He}}}{V}} = \frac{\frac{p_{\text{CO}_2}}{RT}}{\frac{PT}{RT}} \quad (12)$$

Combining Equations (11) and (12) gives

$$\frac{\left(\frac{n}{V}\right)_{\text{CO}_2}}{\left(\frac{n}{V}\right)_{\text{He}}} = \frac{\text{atm-cm}}{185.4 PT} = 5.39 \times 10^3 \text{ atm-cm}$$

In the total gas pressure is 1 atmosphere, we have

$$\text{atm-cm} = 1.854 \times 10^{-4} \text{ ppm} \quad (13)$$

and

$$\text{ppm} = 5.39 \times 10^3 \text{ atm-cm} \quad (14)$$

The relationship between ppm and atm-cm units is shown in Figure 32.

FIGURE 32. Conversion of Atmosphere-Centimeters to ppm by Volume Units for a 108-cm Optical Sighting Path

APPENDIX B

PROGRAM LISTING FOR THE DIGITAL COMPUTER ANALOG

```

TEL BNW      JOB B0522 NO TAPES
RUN 8B0522,CUB091,5,100
T  FRN HOHTRA,HOHTRA
      F REICH, PSB, EXT. 2173
30 FORMAT (20H RUN 8/1/68 -C
    DIMENSION EMIS(56), PBS(52), QTZ(52), HOH(60), COO(60), FWA(55), F
    1WR(55), WEDG(198), CHOH(16), CCOO(16), HOW(55), COW(55), FTWA(55),
    2 FTWR(55), PL(55), FTOA(55), FTOR(55), PPMH(16) ATMC(16)
    1 FORMAT (8E10.3)
    2 FORMAT (13F6.4)
    3 FORMAT (13F6.2)
    4 FORMAT (10F8.4)
    5 FORMAT (10F8.5)
    6 FORMAT (3I5,F5.3,3F5.2)
    7 FORMAT (11F7.4)
    8 FORMAT (8F10.1)
    9 FORMAT (50H
10 FORMAT (96H LAMDA ABS B.P. REF B.P. WEDGE EMIS PB
    25 QUARTZ HOH COEF COO COEF )
11 FORMAT (37H WEDGE INDEX FOR READOUT SHIFTED FROM F5.2, 16H TO 2.0
    20 MICRONS//)
12 FORMAT (1X, 26H WATER VAPOR CONTENT = F10.1,5H PPM )
13 FORMAT (26H CARBON DIOXIDE CONTENT = F10.1,5H PPM )
14 FORMAT (45H LAMDA HOH TRAN COO TRAN FW ABS. FW REF.//)
15 FORMAT (1H F4.2,2E10.4,2H F6.4,4H F6.4)
16 FORMAT (34H ABSORPTION PASS BAND PBS OUTPUT = E15.8,6H VOLTS )
17 FORMAT (34H REFERENCE PASS BAND PBS OUTPUT = E15.8, 6H VOLTS//)
18 FORMAT (30H PBS CELL OUTPUT DIFFERENCE = E15.8, 6H VOLTS//)
19 FORMAT (45H PBS CELL OUTPUT WITH A MOVEABLE WEDGE FILTER//)
20 FORMAT (51H WEDGE ABSORPTION REFERENCE DIFFERENCE )
21 FORMAT (33H INDEX QUADRANT QUADRANT//)
22 FORMAT (1H F5.2, 2E15.8, F10.6 )
23 FORMAT (49H WAVELENGTH REFERENCED TO INITIAL WEDGE READ-IN F5.2,8
    2H MICRONS//)
24 FORMAT (1H F5.2,3H F7.4,3H F7.4,3H F7.4,3H E10.3,3H F6.4
    2,3H F6.2,3H E10.3,3H E10.3)
25 FORMAT (40H WEDGE INDEX AT THE BALANCING POINT IS F10.5 )
50 READ (5,1) EMIS
51 READ (5,2) PBS
52 READ (5,3) QTZ
53 READ (5,4) HOH
54 READ (5,5) COO
55 READ (5,7) FWA
56 READ (5,7) FWR
57 READ (5,7) WEDG
58 READ (5,6) NPBS
59 READ (5,8) PPMH
60 READ (5,8) ATMC
61 DO 62 I=1, 198

```

```

62 WEDG(I) = WEDG(I)*PWE
   WRITE (6,30)
63 WRITE (6,9)
64 WRITE (6,11) RW
65 WRITE (6,10)
   IR = (2.0 - SW) / 0.02 - RW / 0.02 - 1.0
66 DO 68 J=1,51
67 PL(J) = 2.0 + 0.02 *(J-1)
68 WRITE (6,24) PL(J), FWA(J), FWR(J), WEDG(J+IR), EMIS(J), PBS(J), Q
   2TZ(J), HOH(J), COO(J)
69 DO 111 I=1, NHOH
   CHOH(I) = 1.36587E-07 * PPMH(I)
70 DO 71 J=1, 51
71 HOW(J) = EXP(-(HOH(J)*(CHOH(I)**0.71)))
72 DO 111 K=1, NCOO
   CCOO(K) = 1.854E-04 * ATMC(K)
73 DO 74 J=1, 51
74 COW(J) = EXP(-(COO(J)*(CCOO(K)**0.71)))
75 DO 77 J=1, 51
76 FTWA(J) = EMIS(J)*PBS(J)*QTZ(J)*NPBS*FWA(J)*HOW(J)*COW(J)
77 FTWR(J) = EMIS(J)*PBS(J)*QTZ(J)*NPBS*FWR(J)*HOW(J)*COW(J)
83 SUMA = 0.0
84 SUMR = 0.0
85 DO 87 J=2, 50
86 SUMA = SUMA + FTWA(J)
87 SUMR = SUMR + FTWR(J)
88 AREA = 0.01*(FTWA(1) + 2.0*SUMA + FTWA(51))
89 ARER = 0.01*(FTWR(1) + 2.0*SUMR + FTWR(51))
90 VOLT = AREA - ARER
   WRITE (6,30)
91 WRITE (6,16) AREA
92 WRITE (6,17) ARER
93 WRITE (6,18) VOLT
94 WRITE (6,19)
   WRITE (6,23) SW
   WRITE (6,12) PPMH(I)
   WRITE (6,13) ATMC(K)
95 WRITE (6,20)
96 WRITE (6,21)
   LH = (2.0 - SW) / 0.02 - CW / 0.02
   VOLA = 0.000
97 DO 111 M=1, 101
98 LW = LH - M
99 DO 101 L=1, 51
100 FTOA(L) = FTWA(L)*WEDG(L + LW)
101 FTOR(L) = FTWR(L)*WEDG(L+LW)
102 SUMA = 0.0
103 SUMR = 0.0

```

```

104 DO 106 J=2, 50
105 SUMA = SUMA + FTOA(J)
106 SUMR = SUMR + FTOR(J)
107 AREA = 0.01*(FTOA(1) + 2.0*SUMA + FTOA(51))
108 ARER = 0.01*(FTOR(1) + 2.0*SUMR + FTOR(51))
109 VOLT = AREA - ARER
110 RL = CW + (M-1) * 0.02
    VOLT = AREA - ARER
    DIFF = VOLT - VOLA
    AVOA = ABS(VOLA)
    AVOB = ABS(VOLT)
    DIFA = ABS(DIFF)
    IF (AVOA - AVOB) 200, 210, 210
200 IF (DIFA - AVOB) 320, 320, 300
210 IF (DIFA - AVOA) 320, 320, 300
300 SUMD = (AVOB * 0.02) / (AVOB + AVOA)
301 AL = RL - SUMD
302 WRITE (6,25) AL
303 WRITE (6,12) PPMH(I)
304 WRITE (6,13) ATMC(K)
320 WRITE (6,22) RL, AREA, ARER, VOLT
    VOLA = VOLT
111 CONTINUE
    END
    XQT HOHTRA

LAMP EMISSION
0.235E-01 0.231E-01 0.227E-01 0.223E-01 0.219E-01 0.215E-01 0.212E-01 0.209E-01
0.206E-01 0.203E-01 0.200E-01 0.197E-01 0.195E-01 0.192E-01 0.189E-01 0.186E-01
0.183E-01 0.181E-01 0.178E-01 0.175E-01 0.172E-01 0.170E-01 0.167E-01 0.164E-01
0.161E-01 0.157E-01 0.155E-01 0.152E-01 0.149E-01 0.147E-01 0.144E-01 0.141E-01
0.138E-01 0.135E-01 0.132E-01 0.129E-01 0.126E-01 0.124E-01 0.121E-01 0.118E-01
0.112E-01 0.109E-01 0.105E-01 0.101E-01 0.097E-01 0.093E-01 0.089E-01 0.085E-01
0.081E-01 0.077E-01 0.000E-00 0.000E-00 0.000E-00 0.000E-00 0.000E-00 0.000E-00

LEAD SULPHIDE CELL RESPONSE
.9999 .9966 .9932 .9898 .9864 .9830 .9692 .9554 .9416 .9278 .9140 .8950 .8760
.8570 .8380 .8190 .7966 .7742 .7518 .7294 .7070 .6828 .6586 .6344 .6102 .5860
.5516 .5172 .4828 .4484 .4140 .3726 .3312 .2898 .2484 .2070 .1547 .1444 .1341
.1238 .1030 .0918 .0805 .0692 .0579 .0466 .0415 .0363 .0311 .0259 .0207 .0000

QUARTZ LENS AND APETURE COEFFICIENT
00.68 00.68 00.68 00.68 00.68 00.68 00.68 00.68 00.68 00.68 00.68 00.68 00.68
00.68 00.68 00.68 00.68 00.68 00.68 00.68 00.68 00.68 00.68 00.68 00.68 00.68
00.67 00.66 00.66 00.65 00.65 00.65 00.64 00.64 00.64 00.64 00.62 00.60 00.58 00.57 00.57

```

00.56 00.55 00.54 00.53 00.52 00.51 00.52 00.52 00.52 00.53 00.53 00.54 00.00

WATER VAPOR ABSORPTION RESPONSE

00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000
 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000
 00.0000 00.0000 00.1350 00.4053 01.3557 04.2480 09.7825 17.8588 30.1012 34.9072
 35.4324 34.2101 35.2571 55.0334 58.5267 58.3187 46.2007 30.1012 15.7199 02.4503
 01.6285 01.3558 00.9476 00.8118 00.6762 00.5407 00.4053 00.2701 00.1350 00.1350
 00.0674 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000

CARBON DIOXIDE ABSORPTION RESPONSE

0.01256 0.00487 0.00241 0.00210 0.00180 0.0012 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
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 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000

FILTER WHEEL ABSORPTION QUADRANT

0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020
 0.0050 0.0050 0.0060 0.0075 0.0080 0.0100 0.0100 0.0100 0.0100 0.0100 0.0100 0.0100 0.0130
 0.0160 0.0200 0.0250 0.0325 0.0450 0.0650 0.0900 0.1500 0.2500 0.4250 0.6000
 0.6100 0.4100 0.2300 0.1500 0.0950 0.0650 0.0540 0.0400 0.0350 0.0250 0.0210
 0.0190 0.0150 0.0130 0.0100 0.0100 0.0080 0.0075 0.0000 0.0000 0.0000 0.0000

FILTER WHEEL REFERENCE QUADRANT

0.0100 0.0120 0.0140 0.0160 0.0180 0.0200 0.0250 0.0350 0.0450 0.0600 0.0900
 0.1200 0.2500 0.4100 0.5800 0.6200 0.4050 0.2300 0.1500 0.1000 0.0700 0.0550
 0.0400 0.0350 0.0250 0.0200 0.0190 0.0150 0.0120 0.0110 0.0100 0.0090 0.0080
 0.0070 0.0060 0.0050 0.0040 0.0030 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020
 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020

WEDGE FILTER RESPONSE

0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005
 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005
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 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005
 0.0140 0.0150 0.0170 0.0200 0.0250 0.0370 0.0450 0.0600 0.0700 0.0900 0.1100
 0.1300 0.1600 0.2000 0.2500 0.3000 0.3750 0.4400 0.5200 0.5900 0.6700 0.7450
 0.7900 0.8350 0.8650 0.8950 0.9000 0.9000 0.9000 0.8990 0.8990 0.8950 0.8900
 0.8890 0.8850 0.8825 0.8800 0.8800 0.8750 0.8700 0.8650 0.8600 0.8500 0.8400
 0.8300 0.8250 0.8200 0.8150 0.8100 0.8050 0.8000 0.7950 0.7900 0.7850 0.7800
 0.7750 0.7700 0.7650 0.7600 0.7550 0.7500 0.7450 0.7400 0.7350 0.7300 0.7250
 0.7200 0.7150 0.7100 0.7050 0.7000 0.6950 0.6900 0.6850 0.6800 0.6750 0.6700

[illegible]

NPBS	NHOH	NCOO	PWE	RW	CW	SW
600	16	2	0.999	0.30	-1.50	+1.00

WATER VAPOR CONCENTRATIONS			
0.0	1.0	5.0	10.0
1000000.0	200.0	500.0	101.0
			110.0
			150.0
			1000.0
			10000.0
			250.0
			300.0

CARBON DIOXIDE CONCENTRATIONS					
0.0	100.0	0.0			
0.0	0.0	0.0			
' FIN					
				X	
		0.0	0.0	0.0	0.0
		0.0	0.0	0.0	0.0

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