

A STUDY OF METHODS OF MEASUREMENT OF HUMIDITY

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Ernest Timmons Hungerford

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TABLE OF CONTENTS

| | PAGE |
|---|------|
| Acknowledgements | iii |
| Summary. | 1 |
| Introduction; | |
| Statement of the Problem | 2 |
| Discussion of the Problem | 2 |
| Desirable Characteristics of an Instrument for Humidity Measurement. | 3 |
| Definition of Terms | 4 |
| Historical Review of Principal Methods of Humidity Measurement | |
| Classification of Humidity Instruments According to Type | 8 |
| Discussion of the Various Types | 8 |
| Theoretical Study of Possible Fundamental Methods for Determination of the Absolute Humidity | |
| Resonant Cavity Methods | 19 |
| Infra-Red Methods | 26 |
| Experimental Study of the Infra-Red Methods | |
| Use of Diffraction Grating | 36 |
| Use of Prisms | 42 |
| Interpretation of Data and Graphs | 44 |
| Conclusions. | 56 |
| BIBLIOGRAPHY | 58 |

LIST OF GRAPHS

| | PAGE |
|---|------|
| Graph I Energy Distribution of Infra-Red Spectrometer Source. . | 46 |
| Graph II Experimental Absolute Humidity Curves | 47 |
| Graph III Experimental Absolute Humidity Curves | 50 |
| Graph IV Experimental Curves of Absolute Humidity Versus Natural Logarithm of Galvanometer Deflection | 54 |

LIST OF FIGURES

| | PAGE |
|--|------|
| Figure 1 Block Diagram of Precision Frequency Measurement of Resonant Cavities | 22 |
| Figure 2 Oscilloscope Figures of Frequency Measurement | 23 |
| Figure 3 Schematic Diagram of Refractive Index Method of Separation of Wave Lengths of the Far Infra-Red | 30 |
| Figure 4 Schematic Diagram of an Infra-Red Gas Detector and Gas Analyzer. | 32 |
| Figure 5 Schematic Diagram of the Diffraction Grating Experimental Apparatus | 37 |

A STUDY OF METHODS OF MEASUREMENT OF HUMIDITY

SUMMARY

The problem of atmospheric humidity measurement is discussed, and the more important applications are described. A historical review is given of the principal methods of humidity measurement in use today. Particular instruments classified under the various methods are also described. A theoretical survey is made of several possibly better methods of absolute humidity measurement: (1) resonant cavity methods, and (2) infra-red methods. Finally, an experimental study of the infra-red methods is presented. Positive results are obtained which indicate that by use of an absorption band of water vapor in the infra-red, absolute humidities and absolute humidity changes can be detected accurately and quickly.

INTRODUCTION

Statement of the Problem

The purpose of this thesis is to study existing methods of humidity measurement, to make a theoretical investigation into several fundamental and possibly better methods for humidity measurement, and to develop one of these fundamental methods experimentally.

Discussion of the Problem

The problem of humidity measurement is an old one, and there are today a great variety of humidity measuring instruments. Many of these instruments give satisfactory results for their particular applications, enabling humidity determination within several per cent. Where greater accuracy is required, some instruments are applicable but response is generally slow, and appreciable deterioration is present in some of the instrument types. Under laboratory controlled conditions some instruments give accuracies to tenths of a per cent, but the undesirable limitations in application of the instruments are still present. In fact, to the writer's knowledge, there exists no instrument today which might be called ideal; that is, there is no instrument capable of field use which permits very accurate and very rapid determinations of the humidity.

Furthermore, the need for such an improved instrument is acute. Possible applications are many, and more important, the applications are very desirable as aids in the solution of many fundamental problems.

Water vapor is one of the major factors affecting propagation of

electromagnetic waves in the lower atmosphere.¹ For microwave frequencies in particular, the refractive index of the air is highly dependent upon the quantity of water vapor present. Therefore, in determining changes in the refractive index and resultant effects on propagation, it is important to know accurately the water vapor density variations in height above the earth and horizontally over the surface of the earth. Fundamental studies in this field are greatly handicapped by lack of proper equipment for accurate and rapid determination of absolute humidities and humidity variations.

Water vapor also plays an important part in the absorption of centimeter electromagnetic waves, infra-red radiation, and ultrasonic waves.² Therefore, signal intensities of radar and communication and signalling devices may be greatly affected by the amount and distribution of water vapor in the atmosphere.

Desirable Characteristics of an Instrument for Humidity Measurement

Reference has been made above to the desirable characteristics of an ideal instrument for measuring humidity. The following characteristics appear highly desirable for measurements under variable conditions, such as those existing in the lower atmosphere.

¹Office of Scientific Research and Development, Tropospheric Propagation and Radio-Meteorology, Report WPG-5, September, 1944, pp.2.

²C.E. Drumheller, W.L. Nyborg, H.P. Thorpe, "On Micrometeorology," American Journal of Physics, Vol. 14, No. 6, November, December, 1946, p. 353.

1. Quick response. This characteristic is necessary in the study of the rapid and abrupt changes of atmospheric humidity.
2. High sensitivity. Small changes in absolute humidity often have an important effect on wave propagation, so it is important that they be detected.
3. Accuracy. In fundamental studies of electromagnetic radiation through the atmosphere, accurate knowledge of the humidity is very necessary.
4. Humidity dimension relation of simple form. The instrument must have a humidity dimension relation of such form that it can be expressed mathematically over the entire useful range so that a reliable scale may be incorporated.
5. Negligible variance with time and use. Permanent calibration is necessary at least for a reasonable time under field use. If fatigue or deterioration cannot be eliminated, then it is desirable that effect on instrument readings be eliminated.
6. Insensitivity to other atmospheric variables. The instrument readings should be independent of variations in temperature and pressure or easily corrected for changes in these quantities.

Definition of Terms

Before going into a more detailed study of the humidity instrument, several explanations and definitions of terms are needed.

Dew point. The dew point of the air is defined to be that temperature at which the air with its particular amount of water vapor becomes saturated. It is called the "dew point" since at that temperature the

water vapor in the air commences to condense to the visible liquid form.

Relative humidity. Relative humidity is defined to be the ratio of the density of the vapor present in the air at a given temperature to the density of vapor if the air were saturated at that temperature.

Absolute humidity. Absolute humidity is defined as the actual mass of water vapor present in the air per unit volume.

Dry bulb temperature. Dry bulb temperatures are actual temperatures measured with a suitably shielded and dry thermometer bulb.

Wet bulb temperature. Wet bulb temperatures are temperature readings obtained when the thermometer element has been wet with pure water (by some suitable means) and circulated through the air. The evaporation of the water from the wet bulb causes a drop in temperature, which depends upon the amount of water vapor present in the air. Ideally, this new temperature reading should equal the dew point temperature.

Relative humidity is related to the dew point in the following manner. If the dew point has been determined, tables may be used to find what the existing water vapor pressure must be to give saturation at the dew point temperature. By use of the room temperature or dry bulb temperature, tables may again be used to find what the existing vapor pressure must be to produce saturation at this dry bulb temperature. The relative humidity may then be calculated from the ratio of the existing vapor pressure (determined from the dew point temperature) to the vapor pressure that would exist if the air were saturated (determined from the dry bulb temperature).

Here it may be noted that the relative humidity has been deter-

mined from vapor pressures instead of from vapor densities, as it was defined. The reason is that it is more convenient to determine the dew point at constant pressure than at constant volume. That is, if densities of the water vapor are used, it would be necessary to determine the dew point by cooling the air to the dew point at a constant volume in order that the density to be determined is not changed by the cooling process used to make the determination. This is a relatively difficult procedure. Therefore, since the relative humidity is approximately equal to the ratios of the vapor pressures, as stated above, the latter method of vapor pressures is usually used.

In actual determination of humidity the procedure is much more simple, since corrected humidity charts are available giving the relative humidity directly from the dry bulb temperature and the wet bulb temperature. The term "corrected humidity charts" was used because these charts, as they exist today, are actually corrected for certain inherent errors as will be mentioned below under psychrometric instruments.

Finally, the refractive index of air, n , for microwave frequencies, may be calculated from the following formula,³

$$(n-1) 10^6 = \frac{79}{T} (P \text{ total} + \frac{4800 e}{T}) \quad (1)$$

where T is the existing temperature in degrees Kelvin, P is the total

³P.J. Rubenstein, "Note on the Index of Refraction of Air," RL - Report No. 551, February 26, 1945, Part IV.

barometric pressure in millibars, and e is the existing water vapor pressure in millibars. Thus, it is seen that the highly important refractive index of air is dependent on water vapor pressure in the air as well as on total atmospheric pressure and temperature.

HISTORICAL REVIEW OF PRINCIPAL METHODS OF HUMIDITY MEASUREMENT

Classification of Humidity Instruments According to Type

Instrument makers have been devising humidity measuring devices since 1653 when a dew point apparatus was described at the Florence Academy.⁴ Even in this country Americans have been designing and constructing various types of humidity measuring instruments for more than a century. Thus today, there exists an extremely large number of varied types of these instruments.

In general, the various instruments may be divided or classified under seven principles or methods as follows.

1. Psychrometry
 - (a) true-psychrometry
 - (b) semi-psychrometry
2. Hygroscopy
3. Dew point determination
4. Electrical methods
5. Thermal conductivity
6. Evaporimetry
7. Absorption and other chemical methods

Discussion of the Various Types1. (a) True Psychrometric Instruments

⁴M.F. Behar, Handbook of Industrial Temperature and Humidity Measurement and Control, (Instruments Publishing Company, 1932), p. 337.

As noted above, psychrometry is subdivided into true psychrometry and semi-psychrometry.

The true psychrometric instruments determine wet bulb temperatures directly by motion of air around the wet bulb element. The semi-psychrometric instruments include all other instruments based on wet bulb methods. In this latter case the wet bulb element is usually fixed or has no motion with respect to the air.

Ideally, a true psychrometric instrument would determine the true dry bulb temperature and the true wet bulb temperature. Determination of the dry bulb temperature presents no special problem since the art of thermometry has developed enough to allow reasonable accuracy providing the type of thermometer used suits the conditions. For example, under rather rapid temperature changes, a thermometer of low thermal capacity must be used.

In the case of extreme accuracy, radiation protection shields may be needed to shield the dry bulb thermometer from particular radiations which might affect its accuracy.

The problem is then mainly reduced to one of wet bulb temperature determination. Here several difficulties appear. The lengthy paper by Carrier and Lindsay⁵ presented in 1924 to the American Society of Mechanical Engineers, represented over four years of research into these difficulties. Rather large errors were reported in the assumed correct methods of wet bulb temperature determinations. The radiation error can also be present in the wet bulb readings. Proper shielding is probably the simplest solution.

⁵Ibid., p. 341.

According to Carrier and Lindsay,⁶ the velocity error in wet bulb determination is much more serious. For the wet bulb reading to approach the true theoretical wet bulb (dew point) temperature, the wet bulb must be circulated at a lively rate through the air. Carrier and Lindsay observed that actually the errors in wet bulb readings might cause errors as high as twenty per cent of the relative humidity, depending on the velocity with which the air is circulated over the bulb (or the bulb through the air as the case might be). Furthermore, they found that wet bulb error also depends on the existing air temperatures and on the relative humidity itself. In saturated air (relative humidity 100 per cent) all accurate psychrometric instruments will give identical wet and dry bulb readings (excluding radiation errors). However, as the temperature increases or as the relative humidity decreases, wet bulb errors increase. According to Carrier and Lindsay,⁷ these errors are proportional to the depression of the wet bulb readings regardless of the temperature at which it occurs. Most of these inherent errors, however, have been calculated and are incorporated in the psychrometric charts in use today. Calculations are made on a basis of 76 centimeters of mercury barometric pressure, and further corrections to the charts are necessary for accurate work if the existing barometric pressure differs appreciably from this standard value.

Another such true psychrometer is the aspiration type. The instru-

⁶Ibid., p. 341.

⁷Ibid., p. 343.

ment usually consists of two tubes containing matched precision thermometers (mercurial thermometers are almost exclusively used). Sample air is drawn through the tubes at a high uniform velocity. One thermometer is the dry bulb, the other the wet bulb, but again humidity readings are not rapid. It might be noted that in precision instruments of this type, even the purity of the water used for moistening the wet bulb is a source of error necessitating use of distilled water for this purpose.

The sling psychrometer is of the true psychrometric type also. It is a highly popular humidity instrument perhaps because of its relatively good accuracy and simplicity. The instrument does not give instantaneous readings and is not capable of following rapid fluctuations in humidity. Accuracy is usually of the order of several per cent.

The sling psychrometer usually consists of two matched thermometers which are mounted with a rotating handle so that they may be slung around through the air. The dry bulb reading is taken first; the wet bulb is then moistened and the instrument slung around to obtain the wet bulb reading. For greatest accuracy, the lowest of several readings should be taken since psychrometer error is always in the positive direction.⁸ Humidity may be determined by reference to proper tables. One basic formula for determination of water vapor pressure is called the U. S. Psychrometric Formula,⁹

⁸Ibid., p. 345.

⁹Smithsonian Meteorological Tables, Fifth Revised Edition, First Reprint, Smithsonian Institute, 1939, Table 84, pp. LXXI.

$$e = e' - 0.000660 B (T - T') (1 + 0.00115 T') \quad (2)$$

where e is the actual water vapor pressure present in millimeters of mercury, e' is the water vapor pressure when in equilibrium with water at the wet bulb temperature, T is the dry bulb temperature in degrees Centigrade, T' is the wet bulb temperature, and B is the barometric pressure in millimeters of mercury. It may be noted that the formula takes into account the above-mentioned errors as brought forth by Carrier and Lindsay and approximates the actual existing vapor pressure.

(b) Semi-Psychrometric Instruments

Semi-psychrometric instruments are in general similar to the true psychrometric instruments except that the former are usually fixed or stationary. That is, the wet bulbs are not circulated through the air (nor the air around the wet bulb), and wet bulb depressions occur only from normal air motion. Errors in the wet bulb reading, therefore, can run rather high as proved by Carrier and Lindsay.¹⁰ Relative accuracies are low. The instruments do not give instantaneous readings, nor will they follow rapid fluctuations in humidity.

The Kata thermometer is also worthy of consideration, particularly since different principles are involved. The modern Kata thermometer may consist of two matched, short range spirit thermometers, having very large bulbs accurately calibrated over some short range such as 95 to 100 degrees Fahrenheit. The bulbs, one wet and one dry, are heated to above 100 degrees, and the rate of fall of both thermometers is observed by

¹⁰Behar, op. cit., p. 337.

some method such as a stop watch. Since the rate of fall of the dry bulb depends on radiation and convection, and the rate of fall of the wet bulb depends on radiation, convection and evaporation, a comparison enables determination of the humidity with the use of proper charts. The applications of such an instrument are limited, and for best results laboratory conditions are necessary.

2. Hygroscopic Instruments

Under this second class there are actually thousands of various organic materials which respond to atmospheric humidity. Measurements are made possible through changes in linear dimensions, shapes, or weights of the materials. Many of these materials are excellent in the respect that they offer an inexpensive, often simple, means of detection. However, instruments designed on this principle have strong limitations. The particularly desirable properties of rapid response, a reliable mathematical scale for reading, and wide temperature range are in general missing. Furthermore, the moisture content of these materials at a given relative humidity is affected by changes in temperature. Often too, the materials take on (or "absorb") dust and foreign matter from the atmosphere. Thus, deterioration is a prominent factor. Under controlled conditions, errors can run as low as several per cent. Accuracy may be better, in some cases within five tenths of a per cent of the true humidity value, but such accuracy is usually realizable only for an indefinite and usually rather short period after calibration.

However, despite these limitations the hair-element hygrometer is a well known and popular humidity instrument, particularly for use in meteorological observations. The simplest form of the instrument consists

of several strands of matched human hairs attached between some fixed point and some mechanically variable point, such as a very small light tension spring. To the movable end of the spring a pointer may be attached with suitable lever arm to magnify the small linear variations of the hairs with humidity changes. The pointer may be directly observed to read humidity at any particular time or may be connected to a recorder of the ink-pen type. Frequent calibration checks of such instruments are necessary, and the minimum error is approximately five per cent.

The gravimetric type hygroscopic instruments vary of course as to design but are similar in principle. This principle usually involves a precision balance or spring-scale for actual weighing of a given hygroscopic substance. Thus, the higher the humidity the greater is the weight of the material. Because of the necessarily controlled conditions, the instrument has so far been confined to the laboratory.

3. Dew-Point Instruments

This class of instruments is actually one of the original fundamental methods first developed. In principle, the instrument determines the true dew point or condensation temperature of the air. In its simplest form, the instrument consists of a container of ice water, a highly polished or reflecting metal cup, and a sensitive thermometer.

The metal cup is half filled with water at approximately room temperature; ice water is slowly added as the mixture is stirred. The temperature of the water at which moisture appears on the cup is observed. No more ice water is added, and as the cup becomes warmer the temperature at which the moisture disappears is observed. A mean of the two readings gives a fairly accurate measure of the true dew point. Accuracy of the

method is limited, however, depending on the observer, the thermometer accuracy, and radiation errors. Surrounding conditions must also be controlled, and the instrument is in general limited to laboratory use.

4. Electrical Instruments

This class of electrical instruments for humidity measurement is relatively new, some of the instruments having been developed during World War II. The underlying principle of such instruments is accurate measurement of the electrical resistance of some substance, this measured resistance being some function of the humidity. The method is suitable for most applications, but readings are not instantaneous. In some types of instruments, the time lag is appreciable, and errors are again of the order of several per cent.

The recently developed "humidity strip" is becoming rather popular as a means for humidity measurement. The humidity strip is actually a strip of some hygroscopic material, coated on the edges for good electrical contact. As the humidity changes, because of the hygroscopic properties of the "strip," its electrical resistance changes. Humidity determination then consists of measurement of the resistance by some suitable means and reference to a humidity versus resistance calibration chart to obtain the value of the humidity.

There are several important limitations to this method. The humidity strip has a high rate of deterioration, becoming useless approximately four hours after being removed from its moisture proof container. The circuit for measuring strip resistance must be of particular design. Best results are obtained with an A.C. impedance bridge circuit, since the strip will polarize (and become useless) if D.C. currents are used.

Another electrical method is based on the same physical principle as the wet-dry bulb psychrometer, except that resistance elements are used instead of mercury thermometers. One resistance element is kept dry; the other is kept wet with air circulating over it. The resistance elements are made of semi-conducting ceramic materials with a high negative temperature coefficient of resistance. At any given temperature the resistance element, called a thermistor, is an ohmic conductor. If the temperature changes, the thermistor resistance changes. The resistance temperature function is approximated by the following,¹¹

$$R = R_0 e^{B\left(\frac{1}{T} - \frac{1}{T_0}\right)} \quad (3)$$

where R is the actual resistance in ohms at any absolute temperature T, and R₀ is the resistance at some reference absolute temperature T₀, and B is approximately a constant whose value depends on the ceramic resistor.

The same inherent errors are present in this instrument as are present in psychrometric instruments where wet bulb determinations are made. Furthermore, the instrument has appreciable lag or thermal time constant and does not give rapid readings.

5. Thermal Conductivity Instruments

The class of thermal conductivity instruments is also relatively new. To the writer's knowledge the only practical instrument in this field is a Leeds and Northrup circuit.¹²

¹¹Western Electric Company, Radio Division, Thermistor Information Pamphlet, 1947, p.6.

¹²Behar, op. cit., p. 360.

Although the Leeds and Northrup instrument has certain limitations it has also certain great advantages. Humidity measurement comes from interpretation of the instrument Wheatstone bridge readings, the difference occurring because of varying amounts of thermal conductivity of the air due to varying amounts of humidity.

The instrument is very accurate for low humidities (detecting a change of two hundredths of a per cent at 25°C.), but the accuracy decreases as higher humidities are reached. The instrument is temperature conscious in that corrections have to be made for the existing temperature, and the range of humidities which the instrument will read is not continuously variable; that is, it varies in steps. One great advantage is the fact that the instrument can be used at temperatures below the freezing point and above the boiling point of water.

6. Evaporimetric Instruments

This class of instruments is one which so far has not found appreciable engineering use. The principle consists of measurement of the amount of water evaporated from a known area of some surface (usually linen, or paper) when exposed to the existing atmospheric conditions. The method is approximate, and accuracy is low. Indeed, suitable standard measuring scales have never been decided on, since the scale involves the measurement of the evaporative power of air.

7. Chemical Instruments

With the exception of the thermal conductivity methods mentioned above, most of the chemical class of instruments are laboratory devices. Included under them might be the already mentioned gravimetric method and a vapor pressure method.

The vapor pressure method depends on the hygroscopic characteristics of sulphuric acid. A known amount of sulphuric acid is admitted into a chamber which was open to the air, but which is automatically closed off from the air upon entrance of the sulphuric acid. The chamber is also connected to a manometer, and by reading the fall in the manometer, the humidity can be calculated. Use of the instrument has been confined to the laboratory. The biggest disadvantage is one of time lag.

THEORETICAL STUDY OF POSSIBLE FUNDAMENTAL METHODS
FOR DETERMINATION OF THE ABSOLUTE HUMIDITY

The general present day methods for humidity measurement have been reviewed above. Particular instruments under some of the types have been discussed along with their limitations and general per cent errors. It is again noted that none of the above types of instruments fulfill all of the desirable properties of the ideal humidity instrument.

With the idea of developing an improved instrument based on some fundamental principle, the writer has made a theoretical survey of several possibly better methods of approach.

One view point has been kept in the discussion of the following possible methods: the possibilities of use of the method to develop an improved instrument, insensitive to temperature and pressure variations, yet possessing all of the desirable properties mentioned above for humidity instruments.

Resonant Cavity Methods

The understanding and application of cavity resonators has advanced greatly in the past several years. The resonant frequency of a cavity open to the air is dependent upon a number of variables. Naturally, the size and shape of the cavity primarily determine its resonant frequency. Other factors determining cavity resonant frequency are the effective capacitance, inductance and resistance of the cavity. In general, the resistance does not itself affect the resonant frequency, that is, as far as shifting this resonant frequency is concerned, except in second order effects.

The phase velocity of electromagnetic waves in a medium of dielectric constant, K , and permeability, μ , is given by an expression of the form:

$$v = \frac{1}{\sqrt{K\mu}} \quad (4)$$

where V is the phase velocity, K is the dielectric constant, and μ is the permeability.

For a cavity of fixed dimensions, the wave length for resonant waves is also fixed. Then since the frequency, f , is given by

$$f = \frac{v}{\lambda} \quad (5)$$

$$f = \frac{1}{\lambda} \frac{1}{\sqrt{K\mu}}$$

and

$$f^2 = \frac{C'}{K\mu}$$

where C' is a constant for a given cavity. Now if the medium in the cavity is air and the permeability does not vary,¹³ we have:

$$K = \frac{C}{f^2} \quad (6)$$

where K is the dielectric constant of the medium within the cavity, f is the resonant frequency of the cavity, and C is a constant of proportionality. If the dielectric constant increases a small amount dK ,

$$dK = \frac{-2Cdf}{f^3}$$

and

$$\frac{dK}{K} = \frac{-2df}{f} \quad (7)$$

¹³J.C. Slater, Microwave Transmission, (McGraw-Hill Book Company, 1942), p. 95.

Since the index of refraction, n , of the medium is given by

$$n^2 = K \quad (8)$$

it follows that

$$\frac{dn}{n} = -\frac{df}{f} \quad (9)$$

If the medium in the cavity is air, a change in absolute humidity will change the dielectric constant (or refractive index) of the air. Therefore, if it is possible to accurately measure very small relative changes in the resonant frequency of the cavity, due to the small changes in the dielectric constant (or refractive index) of air, a possible direct and accurate method is available for measurement of the dielectric constant (or refractive index) of air and its changes with humidity. Since the dielectric constant or refractive index may be expressed as a function of pressure, temperature and water vapor pressure, this method may be used to determine the value of the vapor pressure or the absolute humidity.

Satisfactory methods have been described in the literature¹⁴ which permit very high precision measurement of very small frequency differences of cavity resonators in the centimeter wave length region. The theory of the equipment is briefly described below along with possible modifications for application to measurement of absolute humidity.

A block diagram of the equipment might be as shown in Figure 1.

¹⁴R.L. Sproull and E. G. Linder, "Resonant Cavity Measurements," Proceedings of the I.R.E., May 1946, p. 305.

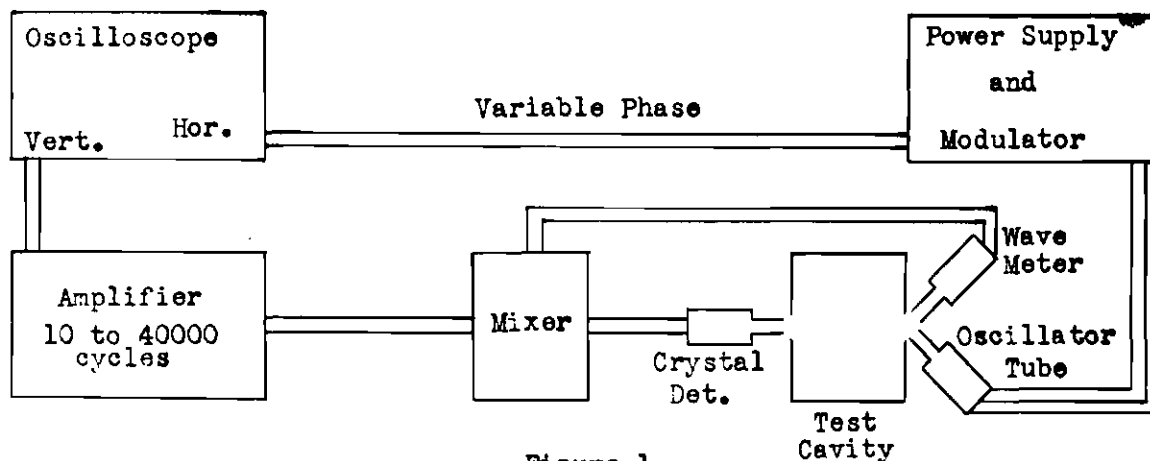


Figure 1

Block Diagram of Precision Frequency Measurement of Resonant Cavities

The frequency of the oscillator tube is modulated at a 60 cycle rate, causing frequency modulation. Care must be exercised to eliminate any amplitude modulation. A short tunable transmission line ending in a probe connects the oscillator to the test cavity. Thus microwave energy of a small range of frequencies is sprayed into the test cavity. A similar probe, very loosely coupled to the test cavity, extracts a small amount of power from the test cavity and feeds it through another short tunable transmission line to a crystal detector. Actual coupling of the probe to the test cavity must be loose enough so that the power extracted will be of the order of five tenths of a per cent or less of the maximum power obtainable when the probe is arranged for maximum power transfer. In addition to the test cavity, another standard cavity, or wave meter, is arranged as shown in the diagram so that it also extracts a small amount of the oscillator's power at whatever frequency it (the wave meter) is tuned. The wave meters used have a crystal detector mounted on them, which is similarly coupled very loosely to the wave meter. The two crystal currents are then fed to a mixer; the resultant currents are fed to an

audio amplifier. The output of the amplifier is connected to the vertical plates of an oscilloscope. The horizontal plates are connected to the same 60 cycle voltage which modulated the oscillator. Thus, circuit connections allow the simultaneous appearance on the screen of the resonance curves of the test cavity and the standard cavity (wave meter), since the oscilloscope picture is a plot of frequency versus amplitude.

When these two cavities are oscillating at very nearly the same frequencies, the oscilloscope deflection is the algebraic sum of the signals from the two detectors. For maximum sensitivity in reading frequency differences, the two detector currents are fed to the mixer with opposite polarity, so that the deflections on the oscilloscope will be opposite; one is above the reference (or zero) line, and one is below the reference line. A series of typical scope pictures¹⁵ are shown in Figure 2, where f_c is the test cavity resonant frequency, and f_w is the standard cavity resonant frequency.

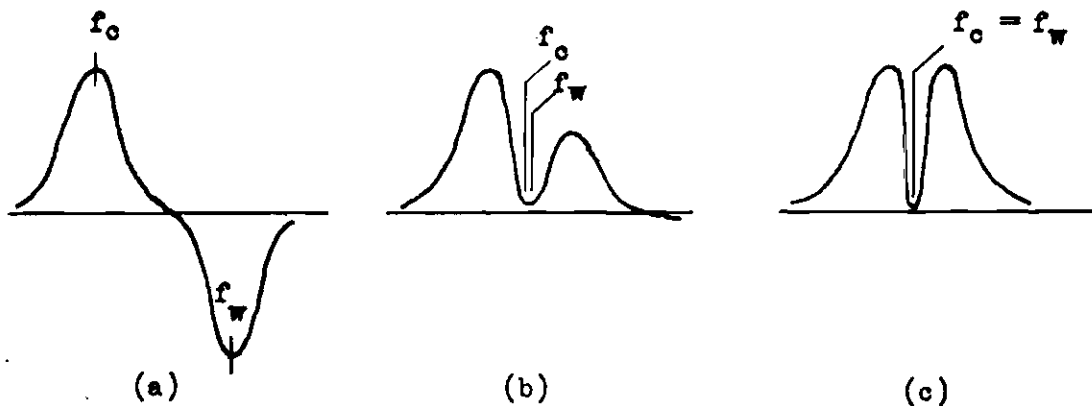


Figure 2

Oscilloscope Figures of Frequency Measurement

¹⁵Ibid, p. 14.

As shown, (a) might resemble the starting conditions where f_c and f_w are separated by a small frequency difference. As the standard cavity is tuned, its frequency moves closer to the test cavity frequency. Although the frequency difference in (b) is only one millionth of the resonant frequency, f_c , the frequency difference between f_c and f_w is very apparent.¹⁶

If such results are to be obtained, certain requirements on the equipment are evident. The coupling in and out of the test cavity must be very loose as mentioned above to prevent frequency "pulling." In the most precise work, wave guide systems can be used instead of probe coupling, but such systems are not too versatile. The crystals must be of the "square law" detector type. The band width of the coupling systems must be greater than that of the cavity. The amplifier and oscilloscope amplifiers must not distort the signals applied to them. The oscillator must have negligible amplitude modulation over a frequency region of several times the band width of the cavity, and the frequency modulation must be linear. That is, the oscillator frequencies must be a linear function of the modulating voltage. All of these conditions can be met approximately if the two cavities are of relatively high Q .¹⁷

One type of wave meter which can be used is a rectangular resonant cavity, the length of which can be varied by means of a micrometer driven piston. The wave length range of the wave meter is therefore rather limited. Another wave meter of the same type, but with higher dispersion, uses the end of the micrometer screw, itself, as a probe inserted into the cavity. This arrangement secures maximum linearity of resonant wave

¹⁶Ibid., p. 305.

¹⁷Ibid., p. 305.

length as a function of the depth of insertion of the pin (and hence the micrometer scale reading). It is noted that high dispersion as used above means that a small change in the micrometer screw setting produces a relatively small change in resonant frequency of the wave meter.

The precision frequency comparison method has been briefly explained. It now remains to carry the principle over to possible application for use as an absolute humidity measuring device.

To eliminate as far as practicable the variations of resonant frequencies of the two cavities with respect to temperature changes, it will be required to construct the two cavities approximately similar. That is, they must be made of a single metal, which is the same for both cavities, and of the same size and shape to a close degree of approximation. Then small changes in frequency due to temperature changes should be the same in both cavities.

It is next required that the standard cavity be humidity tight, (possessing no water vapor) while the test cavity will remain open to the atmosphere (possibly having the atmosphere circulated through it).

The resonant frequency of the test cavity will vary as the atmospheric conditions change. Thus the difference between the test cavity resonant frequency and the wave meter resonant frequency will be a function of the dielectric constant or refractive index of air.

The resonant cavity method, therefore, theoretically offers a precision solution to the problem of determining the dielectric constant or refractive index of air. Further, absolute humidity may be determined if existing temperatures and pressures are known. Response of the

instrument will be very rapid. However, time is required to tune the wave meter and observe the frequency changes. This small time lag might be eliminated by continuously photographing the oscilloscope picture, and refractive indices or absolute humidities determined at a later time.

Infra-Red Methods

Water and its vapors possess many vibration and rotation absorption bands in the infra-red spectrum. The theory of the magnitudes and locations of these absorption bands can be found in any detailed treatise on infra-red spectra.¹⁸

Several marked absorption bands occur in the near infra-red with centers located at approximately 1.3 microns, 1.9 microns, 2.6 microns, and 6.3 microns.¹⁹ The 6.3 micron band is a pure band due entirely to water vapor and is very intense. (The band is believed to be due directly to one of the fundamental vibrational frequencies of the water molecule.)²⁰ The 2.6 micron band is less intense (probably due to a harmonic of one of the vibrational frequencies), and it overlaps one of the absorption bands for carbon dioxide. The 1.9 and 1.3 micron bands are pure water vapor bands but are even less intense.

If no water vapor is present in the path of a beam of infra-red

¹⁸G. Herzberg, Infra-Red and Raman Spectra of Polyatomic Molecules, (New York: D. Van Nostrand Company, Inc., 1945), pp. 61-288.

¹⁹H.H. Nielsen, "Near Infra-Red Spectrum of Water Vapor," Physical Review, Vol. 59, No. 7, April 1, 1941, pp. 565-575.

²⁰Herzberg, op. cit., p. 487.

light of wave lengths say from 6 to 7 microns, then no absorption of the infra-red light will be observed in that band of wave lengths. Also, if a small amount of water vapor is present, some absorption will be observed. Similarly, if a greater amount of water vapor is present, greater absorption will be observed. Thus it appears that the amount of absorption might be some mathematical function of the absolute amount of water vapor present. The absorption of monochromatic infra-red radiation by ideal gases obeys Beer's law,²¹

$$\frac{I}{I_0} = e^{-K cx} \quad (10)$$

where I_0 is the incident intensity of radiation at a particular wave length, I is the transmitted intensity at the same particular wave length, K is the mass absorption coefficient of the material (or medium) at the particular wave length, c is the concentration of the given material in the sample being studied, and x is the length of optical path or the thickness of the absorption layer of the material. The value of K is fairly insensitive to pressure and practically independent of temperature.

Furthermore the absorption of infra-red radiation by a gas such as water vapor will follow this experimental law approximately, depending on the magnitude of the inter-molecular reactions of the molecules.

It appears, therefore, that if an infra-red beam containing only the wave lengths of the absorption band around 6.3 microns could be isolated, and if a suitable means for measurement of the variations in transmitted intensity were available, another method of humidity measurement would be possible.

²¹F.E. Fowle, Smithsonian Physical Tables, Eighth Revised Edition, 1933, p. 392.

The region of 6.3 microns was mentioned in the above drawn conclusions, because it is a pure and very intense water vapor absorption band. Thus for the amount of infra-red energy present in the band, large changes in this energy due to absorption might be expected. The region of 1.9 or 1.3 microns might also be used since the two are also pure water vapor absorption bands, but the changes in the infra-red energy due to absorption could not be expected to be as great as in the 6.3 micron region, since the absorption is not as strong.

The problem of isolating the proper wave lengths can be difficult. The principal reason that isolated wave length bands are necessary is to limit the band of wave lengths to a spectral region of high sensitivity to absorption by water vapor. Furthermore, when water vapor absorption bands are selected, care must be exercised in excluding the carbon dioxide absorption band, since carbon dioxide is also a variable of the atmospheric constituents.

The use of filters for isolating various wave lengths might be considered first. Glass filters are sometimes satisfactory in the very near infra-red region where a rather wide band of wave lengths is acceptable, but the practical transmission limit of glass is 2.2 microns.²² Suitable infra-red filters can be obtained which filter out approximately all light except the band from approximately 1 micron to two or three microns. To the writer's knowledge, there exist no practical glass filters of extreme selectivity such as would pass only the same band of wave lengths desired in some absorption region. Indeed such extreme selectivity

²²J. Strong, Procedures in Experimental Physics, (New York: Prentice-Hall, Inc., 1941), p. 365.

for filters might only be possible by use of "powder filters,"²³ which, for such selectivity, would be very tedious and critical in construction.

For the 6.3 micron region, selective filtering might be accomplished by multiple reflections from calcite crystals.²⁴ These crystals have the characteristic of absorbing certain per cents of the infra-red wave length except at the 6.6 micron region. Thus, by multiple reflections, energy intensities of wave lengths other than the 6.6 micron region might be reduced and therefore allow practical use of an infra-red beam of a 6.6 micron region. This method is rather critical in adjustment and expensive since several highly polished calcite crystals are needed.

Another method used in separating or isolating infra-red wave lengths is due to R.W. Wood.²⁵ The method depends on the differences in the indices of refraction for quartz for the different wave lengths. Quartz lenses are used in combination with very small circular apertures. A simple diagram might be as shown in Figure 3.

²³A.H. Pfund, "Transparent and Opaque Screens for the Near Infra-Red," Journal of the Optical Society of America, Vol. 29, No. 2, February, 1939, pp. 56-58.

²⁴Strong, op. cit., p. 382.

²⁵Strong, op. cit., p. 380.

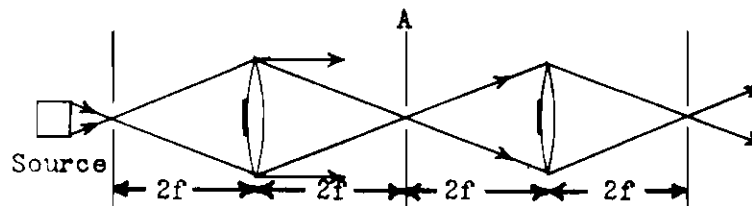


Figure 3

Schematic Diagram of Refractive Index Method of Separation
of Wave Lengths of the Far Infra-Red

The focal length for the particular wave length desired, is adjusted to bring that wave length into focus at the small aperture (A) in Figure 3. Because of different indices of refraction, other wave lengths will not be brought into focus at (A). Energies of these other wave lengths are therefore diminished on the right of (A) in the diagram. The black center area on the lenses indicates a circular black absorber on the center of the lens to prevent transmission of direct rays. Several sets of lenses may be used until the desired purity of wave length is obtained. This method is readily applicable at longer wave lengths²⁶ (the far infra-red). However, the difference in the indices of refraction for the different wave lengths from visible light into the near infra-red do not vary enough for the method to be suitable in this region. This fact was verified by experimental laboratory checks using fused quartz lenses. Indeed, in the region of 6.3 microns the transmission of infra-red through quartz is limited in the same manner as it was for the glass

²⁶Strong, op. cit., pp. 380

filters, since the practical transmission limit of quartz is approximately 3.5 microns.²⁷

The possibility of the source itself producing the selective wave bands is doubtful. There is, however, the possibility of using a source of heated water vapor, but the method has not been investigated.

If the problem is approached from another viewpoint, much better results seem possible. Reflection gratings possess the property of spreading the incident light into different orders of spectra. Therefore, if the spectra were observed at the proper angle to the grating face, the desired wave length might be obtained. (Filters would be necessary to filter out the higher orders of the visible spectra in this method.) The use of reflection gratings will be described in detail in the experimental section.

Prisms also possess the property of dispersing the incident light into spectra. Desired frequency bands can then be isolated by use of slits at some particular angle to the prism face. The use of prisms will also be described in more detail in the experimental section.

The problem of suitable detectors of the infra-red energy is fortunately rather easily solved. The art of detection in this region of wave lengths is advanced so that several suitable detectors are available: the radiometer, the bolometer, and the thermopile. The principles of each will not be given, but they can be found in any technical book covering radiation detectors.²⁸ The thermopile detector has been used by the

²⁷Strong, op. cit., p. 365.

²⁸J.K. Robertson, Physical Optics, (New York: D. Van Nostrand Company, Inc., 1941), p. 178.

writer with satisfactory results, and the thermopile was also used in the Pfund method, and the infra-red spectrometer described below.

An interesting and possibly suitable instrument with proper modifications might be found in an "Infra-Red Gas Detector and Gas Analyzer."²⁹ The instrument was developed under government research during World War II by A. H. Pfund. In principle, the instrument involves the detection of the changes in energy of an infra-red beam due to gas absorption.

A simple diagram of the instrument is shown in Figure 4.

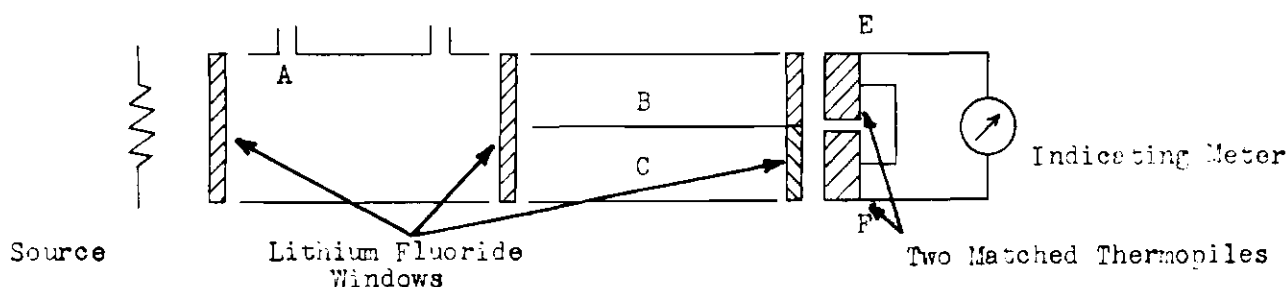


Figure 4

Schematic Diagram of an Infra-red Gas Detector and Gas Analyzer

The source used is an electrically heated nichrome wire. (A) is a chamber which may be evacuated or opened to the air or to the gas to be analyzed; (B) is an evacuated chamber. (C) is a chamber which contains only the gas to be detected. That is, if a gas were to be analyzed for carbon dioxide content then the gas would be admitted to chamber (A), and chamber (C) would contain only pure carbon dioxide. (E) and (F) are two thermopiles connected in opposition (with opposite polarity) so that the meter reads the difference in output between the thermopiles. Lithium fluoride

²⁹Office of Scientific Research and Development, "Summary Report of an Infra-Red Gas Detector and Gas Analyzer," OSRD No. 1642, Div. 17, January 1, 1944.

windows are used since they will transmit all of the near infra-red frequencies.

When the instrument is calibrated, say for carbon dioxide, chamber (A) is evacuated, (B) is always evacuated, and (C) is filled with pure carbon dioxide. With the source radiating at some optimum value the meter is adjusted to read zero. Now, all of the energy in all of the wave lengths from the source are reaching the thermopile (E), while only energy in those wave lengths not absorbed by the carbon dioxide reach thermopile (F). Complete absorption is realized at the particular absorption wave lengths for carbon dioxide in the beam path to thermopile (F) so that further addition of carbon dioxide in this path does not appreciably affect the reading of (F). Thus when a gas is admitted to chamber (A), if any carbon dioxide is present in this gas, the output of thermopile (E) will change, and if the meter is calibrated accordingly, direct readings of the amount of carbon dioxide gas present may be made.

Several conclusions may be drawn. The instrument still depends on a limited band of infra-red wave lengths since errors will be introduced if any two of the gases present have absorption bands in the band emitted by the source. On the other hand, if this handicap is removed, many advantages are evident. The instrument response is practically instantaneous. Extreme accuracy is also possible; determination of particular gas contents as low as one part in one million have been made. The instrument is insensitive to temperature changes and pressure changes since all chambers and both thermopiles experience the same changes. (It is assumed that both thermopile outputs change by approximately the same amount with the

same change in temperature.) Another distinct advantage is that the instrument is not sensitive to reasonable deterioration of the source since a comparison method is used and both thermopiles will be affected in the same manner.

For possible use as an absolute humidity detector, the method must be modified. The filter problem is immediately evident because of the strong absorption band of carbon dioxide at 2.7 microns. However, a similar source might be used, and the necessary filters might be eliminated by adding to the left of chamber (A) another transparent chamber containing pure carbon dioxide which intercepted both infra-red paths. Then, further addition of carbon dioxide into chamber (A), which would occur in humidity measurements when (A) is open to the air, would not affect either of the thermopile readings. This is true since approximately complete absorption of the carbon dioxide wave lengths would take place in the added chamber. Normally there are no other atmospheric gases with appreciable absorption bands in the source region of the near infra-red.

If the same principle of the instrument is to be kept, then for humidity measurement, chamber (C) must be filled with water vapor of high density. (This is to eliminate any detection of thermopile (F) when atmospheric water vapor is admitted to chamber (A).) This is not possible because the windows of the chamber are soluble in water. Furthermore, a high relative density of water vapor could not be maintained under varying temperature conditions, since water vapor density is itself a function of temperature. The problem might be solved by using a very thin coating of some material on the lithium fluoride windows which is not soluble

in water. Parafin might be satisfactory. Although parafin is not in general transparent to all of the near infra-red wave lengths³⁰ a layer thickness of five tenths of a millimeter would cause very little attenuation of wave lengths and would protect the windows. Also instead of water vapor, a thin cell of pure water might be added in place of the larger chamber (C). The absorption characteristics for infra-red at the wave lengths used are very similar for water in the liquid and vapor states.³¹ Thus it might be possible with these modifications, to operate the instrument successfully as an absolute humidity instrument. The temperature range of such an instrument, however, would be limited to the boiling point and freezing point of water due to the thin cell of water used.

³⁰Strong, op. cit., p. 366.

³¹L.G. Bonner, "Water Vibration Bands," The Physical Review, Vol. 46, 1934, pp. 458-464.

EXPERIMENTAL STUDY OF THE INFRA-RED METHODS

Use of Diffraction Grating

Several of the possible methods of absolute humidity measurement have been theoretically investigated. Under the existing conditions of limited time for experimental work and the limited availability of equipment, it was decided that infra-red methods involving the use of gratings or prisms seemed more feasible and practical for an experimental research of the problem.

As has been stated, the problem of isolation of particular bands of the infra-red is difficult. In the first series of experiments a concave reflection grating was used. The principle involved is fundamentally due to Rowland.³² If the grating and the source are both situated on a circle, the diameter of which is equal to the radius of curvature of the grating, the spectra observed will be in focus along the circumference of the same circle.

The basic formula used with diffraction gratings is as follows:³³

$$n\lambda = d(\sin\Theta + \sin\phi) \quad (11)$$

The plus sign is used since in the experimental apparatus the angles Θ and ϕ were both on the same side of the grating normal.³⁴ In the formula, n is the order of the spectrum observed ($n = 1$ for this experimental work

³² R.W. Wood, Physical Optics, (New York: The MacMillan Company, 1934), p. 260.

³³Ibid., p. 249.

³⁴Ibid., p. 249.

and will be omitted hereafter); λ is the particular wave length desired; d is the grating constant which is equal to the distance between any two grating lines; Θ is the angle to the grating normal at which the desired wave length appears; ϕ is the angle between the grating normal and the direction of the incident light.

Therefore, if a particular wave length is desired, according to the principle of Rowland's mentioned above, a slit is placed on the circumference of the circle at the calculated angle for the desired wave length. The slit width depends on the desired broadness of the wave length band selected. A thermopile detector is placed behind the slit. A filter must also be used to filter out the higher orders of shorter wave lengths which may be superimposed on the desired portion of the infra-red spectrum.

The actual experimental setup is diagrammatically represented in Figure 5.

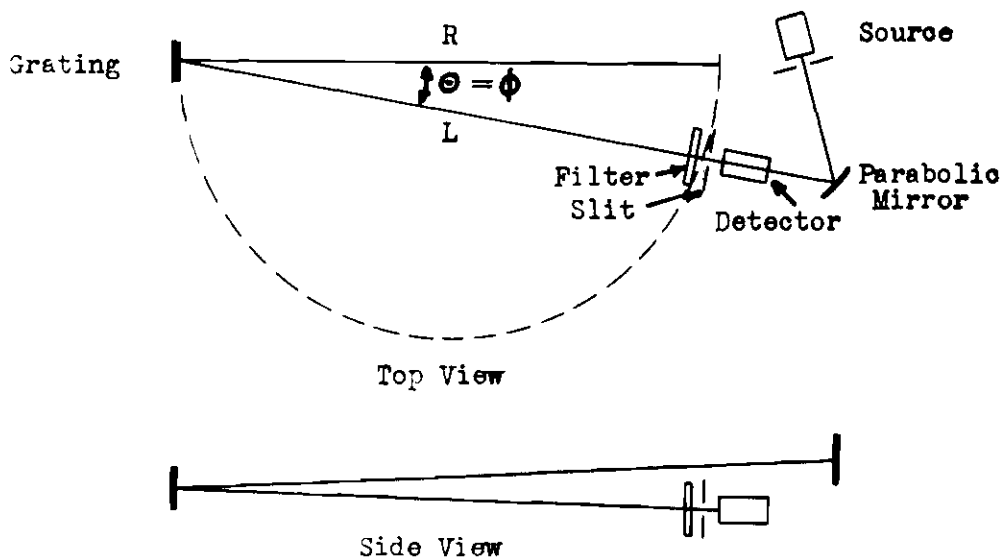


Figure 5

Schematic Diagram of the Diffraction Grating Experimental Apparatus

The grating used was a concave diffraction grating of the reflection type ruled to 14,540 lines per inch; the grating constant was 1.746 microns; the radius of curvature R was 84.8 centimeters.

The source consisted of a single plane, triple filament 200 watt General Electric bulb housed within a suitable glass lens focusing chamber. A variable circular aperture was also used in front of the source. The bulb filament was of tungsten and operated at approximately 3000 degrees Kelvin. The energy radiated by the source in the wave length regions used was approximately 60 per cent of the maximum on the energy versus wave length distribution curve. (A better infra-red source such as a carborundum globar, having maximum energy intensity at 2.5 microns, would have been desirable but was not immediately available.)

A black cardboard slit of 0.50 centimeters width was used, and a Corning glass filter, No. 254, which passed wave lengths from approximately one micron to three microns, was used to filter out the second order visible spectrum occurring at the angle Θ .

It may be noted that the angle Θ has been set equal to the angle ϕ in the experimental setup. This was done as a matter of convenience in adjusting and aligning the system.

Calculation of the correct diffraction angle can be made as follows:

$$\lambda = d(\sin\Theta + \sin\phi)$$

$$\frac{\lambda}{d} = 2 \sin \Theta$$

$$\Theta = 23.3^\circ$$

The value of Θ was obtained from the values; $\lambda = 1.38$ microns, and $d = 1.746$ microns.

The center band wave length of 1.38 microns was used in this experimental setup for several reasons. The wave length, λ , is theoretically limited to approximately 3.5 microns when the angles Θ and ϕ are both equal to 90° . Therefore, because of the limitation of λ , a strong absorption band of water vapor was searched for in the region from 0.9 microns to 3.5 microns. According to W.W. Sleator and E.R. Phelps,³⁵ who have done a great deal of experimental work on absorption bands of water vapor in the near infra-red, one of the strongest absorption bands in this region is centered at 1.38 microns.

There is a strong absorption band at 2.6 microns, but this is rather close to the carbon dioxide absorption band at 2.7 microns.

Furthermore, it was noted that as the longer wave lengths were approached, the energies decreased rather rapidly, so that there was not sufficient energy for suitable measurement.

It may be noted that "Echelette" gratings do not have these limitations. The theory of Echelette gratings can be found in any detailed book on physical optics³⁶ and will not be described. However, it is noted that because of a different form of ruling, the Echelette grating can con-

³⁵W.W. Sleator and E.R. Phelps, "The Fine Structure of the Near Infra-Red Absorption Bands of Water Vapor," Astrophysical Journal, Vol. 62, October 25, 1925, pp. 28-48.

³⁶Wood, op. cit., p. 284.

concentrate maximum energies at any desired small wave length band in the infra-red, depending on the ruling of the grating. Such a grating was highly desirable for the experimental work undertaken but was not available in the limited time of experimentation.

A Leeds and Northrup radiation pyrometer, which was a thermopile consisting of eight thermocouples, was used to detect the infra-red energy. The pyrometer was connected to a wall galvanometer whose sensitivity was 0.003 microamperes per millimeter deflection at 100 centimeters. Galvanometer resistance was 135 ohms, and the period was 9 seconds.

In the experimental apparatus, light from the source was directed on to a parabolic mirror. The mirror focused the source on the circumference of the circle, according to Rowland's principle described above, and thence to the concave grating. The desired wave length along with the second order visible was diffracted at the calculated angle Θ . The infra-red filter removed approximately all of the visible light in the beam, and the slit of 0.50 centimeters limited the wave length band of the infra-red entering the thermopile. The total length of the light path was approximately 200 centimeters. The actual wave length band passed by the slit can be calculated as follows, providing that the source is approximately a point source or a narrow slit:

$$\text{From the grating formula} \quad \lambda = 2d \sin \Theta$$

$$d\lambda = 2d \cos \Theta d\Theta$$

$$\frac{d\lambda}{d\Theta} = 2d \cos \Theta$$

substitution of the known values gives

$$\frac{d\lambda}{d\Theta} = 2 \times 1.746 \times 10^{-4} \times \cos 23.3^\circ \text{ microns/radian}$$

$$\frac{d\lambda}{d\Theta} = 3.429 \times 10^{-4} = 3.429 \text{ microns/radian}$$

The angle subtended by the slit width, D, at a distance, L, from the grating is

$$\Theta \text{ (in radians)} = D/L$$

$$D = 0.50 \text{ centimeters}$$

$$L = R \cos \Theta$$

Substituting the known values

$$\Theta = \frac{0.50}{84.8 \cos 23.3^\circ}$$

$$\Theta = .0060 \text{ radians}$$

Then the band of wave lengths received by the thermopile detector is

$$\Delta\lambda = 3.429 \times 10^{-4} \times 0.0060$$

$$\Delta\lambda = .021 \times 10^{-4} \text{ cm.} = .021 \text{ microns}$$

This wave band is centered around 1.38 microns, and it is evident that the method allows a rather selective wave band to be presented for detection. In the experimental apparatus, a small "point source" was not used, and the wave length band presented was appreciably wider.

A maximum galvanometer deflection of 10 centimeters was obtained with the experimental apparatus just described. It is noted that this is

the total deflection due to the energy contained in the 1.38 micron wave band and the small amount of energy of the second order visible which passed through the filter. It is not the deflection observed for any humidity change.

Experimental data were taken over the period of a week, minor adjustments being made. Humidity changes were present by virtue of the atmospheric humidity changes throughout the day and night and from day to day. Changes of relative humidity from approximately 30 to 60 per cent were thus obtained as determined by the use of a sling psychrometer. Corresponding absolute water vapor pressure changes were from approximately 0.7 centimeters to 1.27 centimeters of mercury.

Positive indications of galvanometer deflections were observed due to the humidity changes. However, no conclusive data could be taken, since changes of deflection were very small. It was further observed that if water vapor from a heated vessel of water at approximately 70 or 80 degrees Centigrade was allowed to pass through the light beam, galvanometer deflection changes of at least two centimeters were easily obtainable. Because no conclusive data were obtained with this experimental apparatus, no data have been included.

Use of Prisms

Since the experimental apparatus discussed above did not provide conclusive data (due to the limitations of the particular components of the equipment and not to the method) a better apparatus was needed. It was found that the Physics Department of Emory University had available immediately an infra-red spectrometer of the prism type. The theory of

the infra-red spectrometer will not be described here, since a detailed discussion of the theory and operation of the instrument may be found in the literature.³⁷

The infra-red spectrometer was operated over the wave length band from approximately 5.9 microns to 6.7 microns. The vacuum thermopile detector in the instrument was connected to a wall galvanometer (the same galvanometer used in the above grating experiment), and the deflections were noted as the wave length was changed. Humidity variations were again secured by virtue of the atmospheric humidity changes from day to day. Some of the higher humidities were obtained by admitting small amounts of steam into the closed room containing the spectrometer. (Precautions were taken to ensure the presence of water was in the form of vapor and not of suspended water particles.) Absolute water vapor pressures from approximately 0.5 centimeters to 1.8 centimeters of mercury were thus obtained as determined by use of the sling psychrometer. Positive indications and positive data were obtained and are included in the data section.

³⁷R. B. Barnes, and others, "Small Prism Infra-Red Spectrometry", Journal of Applied Physics, Vol. 16, No. 2, February, 1945, pp. 77-86.

INTERPRETATION OF DATA AND GRAPHS

Graph I is a plot of the infra-red spectrometer source energy distribution from approximately 1.2 microns to 9 microns. Galvanometer deflections were observed as the spectrometer wave length scale was varied over the region specified. Several of the atmospheric absorption bands are evident and are marked on the graph.

For the experimental work, the 6.3 micron absorption band was used. Galvanometer deflections for the region around 6.3 microns were expanded by increasing the spectrometer slit width, allowing more energy to reach the vacuum thermopile. An approximately optimum slit width of 0.500 millimeters was used. As the slit width increased, the resolution of the spectrometer decreased, and the optimum slit width for maximum deflection with no harmful loss of resolution was chosen. The experimental data for the curves of Graph II are recorded in Tables I, II, and III. The graphical plot shows galvanometer deflection versus wave length. The changes in deflection for changes in absolute humidity (water vapor pressure in centimeters of mercury) are evident in the differences of the curves. Maximum differences of the curves occur in the 6.0 micron region. The curves are in agreement with the theory, since for less absolute humidity the actual absorption of the beam is less, and the apparent absorption curve will approach the source energy curve as a limit for zero humidity. The true energy curve of the source will be approximately as shown. The curve is approximate since absolute zero humidities could not be reached with the experimental apparatus.

A varying difference between the curves may also be noted. For

changes in the absolute humidity (at higher values of the absolute humidity) the changes in deflection are less than those for similar changes in the absolute humidity (at lower values of the absolute humidity). This is also in agreement with theory, since the absorption of infra-red frequencies by water vapor approximates an exponential function, as stated in the section on experimental work.

The experimental data for the curves of Graph III are tabulated in Tables IV, V, VI, VII, and VIII. Similar conditions apply to Graph III as were applied to Graph II above. The relative difference in magnitudes of the curves of Graph II and Graph III may be accounted for by a change in the output of the globar source.

Possible errors of the galvanometer deflection readings are estimated at ± 0.30 millimeter. Estimated possible errors of the sling psychrometer readings are $\pm 0.5^{\circ}$ Fahrenheit for the dry bulb and $\pm 1.0^{\circ}$ Fahrenheit for the wet bulb. Therefore, possible errors in the calculated water vapor pressures in centimeters of mercury, for the range of temperatures and humidities covered, will be approximately ± 0.12 centimeters of mercury.

Graph IV is an experimental curve of absolute humidity (water vapor pressure in centimeters of mercury) versus the logarithm of galvanometer deflection. It is seen that, with the possible error in absolute water vapor pressure determination, the curve is approximately a straight line, demonstrating only approximate agreement with Beer's law.

Graph I

Energy Distribution of Infra-Red Spectrometer Source

Spectrometer Slit Width = 0.180 mm.

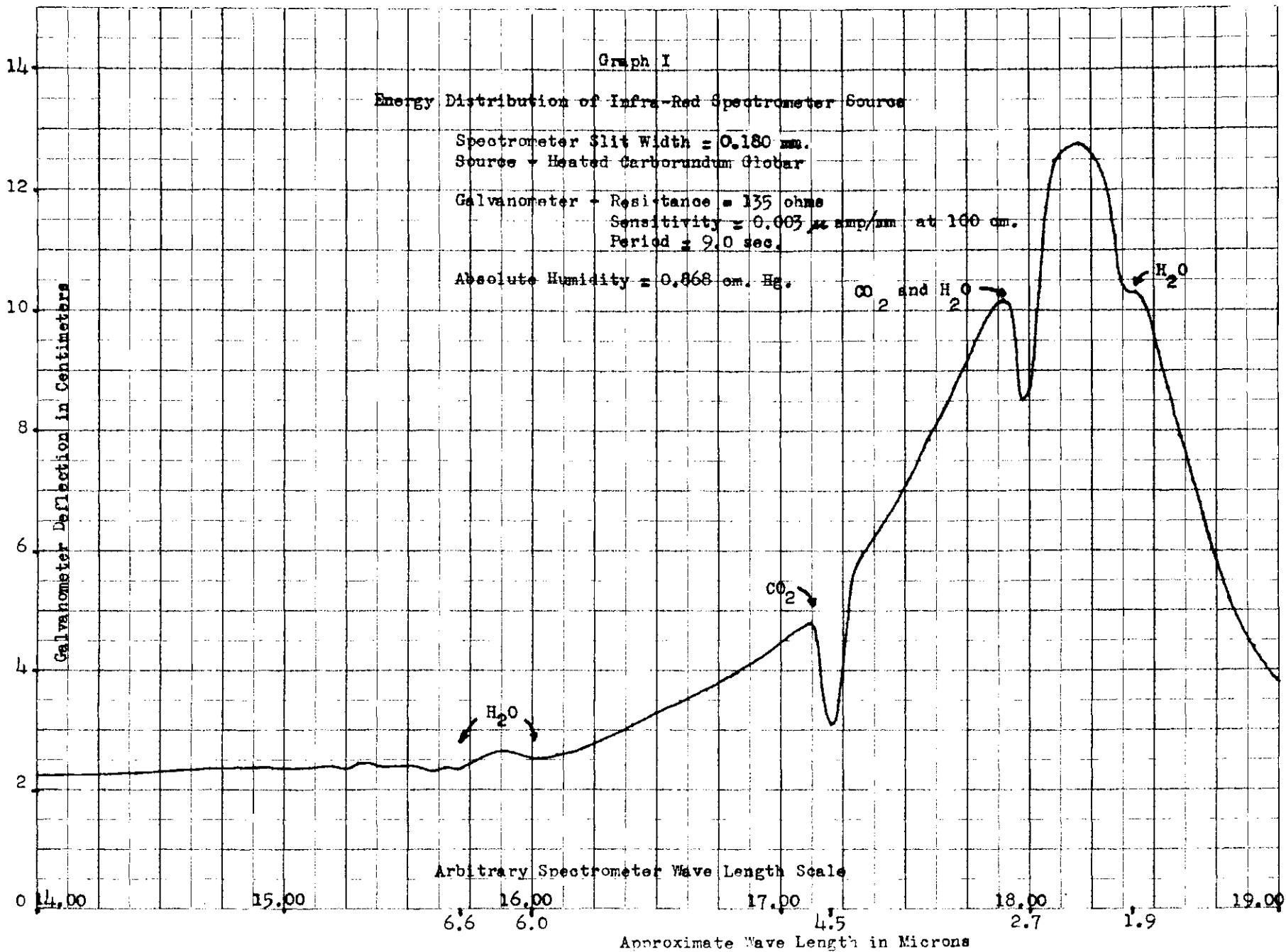
Source - Heated Carborundum Globar

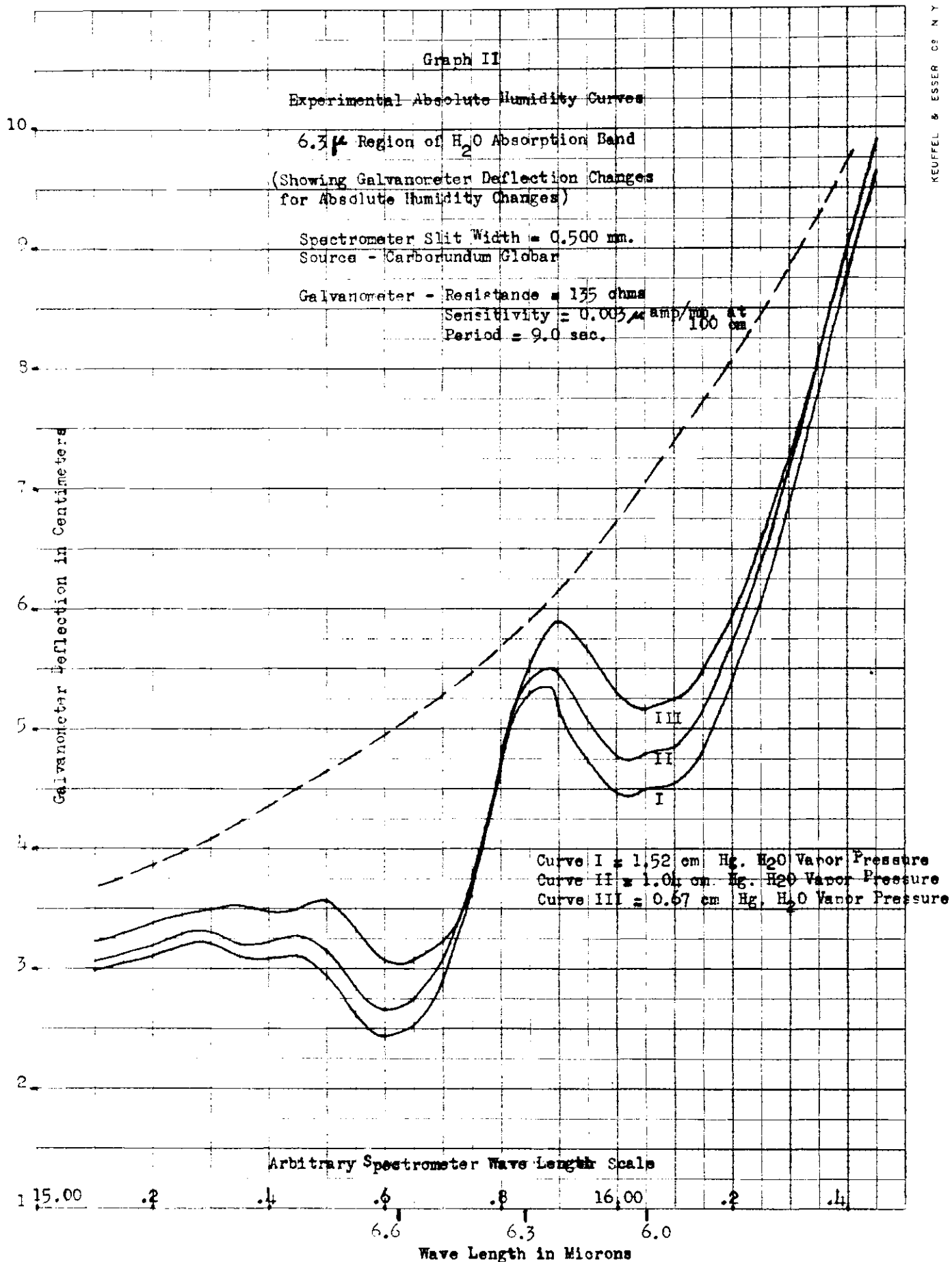
Galvanometer - Resistance = 135 ohms

Sensitivity = 0.003 μ amp/mm at 100 cm.

Period = 9.0 sec.

Absolute Humidity = 0.868 cm. Hg.





DATA FOR GRAPH II

Infra-Red Spectrometer Slit Width = 0.500 Millimeters

Table I

Psychrometer:
 Dry Bulb = 73°
 Wet Bulb = 67°
 Relative Humidity = 73%
 Absolute Humidity = 1.52 cm. Hg.
 Water Vapor Pressure

Table II

Psychrometer:
 Dry Bulb = 71.5°
 Wet Bulb = 60.5°
 Relative Humidity = 53%
 Absolute Humidity = 1.04 cm. Hg.
 Water Vapor Pressure

| Spectrometer Wave Length Scale Arbitrary Units | Galvanometer Def- lection in cm. |
|---|-------------------------------------|
| 15.10 | 2.99 |
| .15 | 3.05 |
| .20 | 3.10 |
| .25 | 3.19 |
| .30 | 3.21 |
| .35 | 3.10 |
| .40 | 3.09 |
| .45 | 3.11 |
| .50 | 2.93 |
| .55 | 2.61 |
| .60 | 2.43 |
| .65 | 2.53 |
| .70 | 2.89 |
| .75 | 3.61 |
| .80 | 4.65 |
| .85 | 5.30 |
| .90 | 5.20 |
| .95 | 4.76 |
| 16.00 | 4.48 |
| .02 | 4.44 |
| .05 | 4.50 |
| .10 | 4.54 |
| .15 | 4.81 |
| .20 | 5.40 |
| .25 | 6.03 |
| .30 | 6.88 |
| .35 | 7.81 |
| .40 | 8.80 |
| .45 | 9.63 |

| Spectrometer Wave Length Scale Arbitrary Units | Galvanometer Def- lection in cm. |
|---|-------------------------------------|
| 15.10 | 3.06 |
| .15 | 3.13 |
| .20 | 3.18 |
| .25 | 3.28 |
| .30 | 3.30 |
| .35 | 3.20 |
| .40 | 3.22 |
| .45 | 3.27 |
| .50 | 3.14 |
| .55 | 2.84 |
| .60 | 2.67 |
| .65 | 2.75 |
| .70 | 3.07 |
| .75 | 3.71 |
| .80 | 4.73 |
| .85 | 3.40 |
| .88 | 5.50 |
| .90 | 5.46 |
| .85 | 5.07 |
| 16.00 | 4.78 |
| .02 | 4.74 |
| .05 | 4.80 |
| .10 | 4.85 |
| .15 | 5.15 |
| .20 | 5.68 |
| .25 | 6.36 |
| .30 | 7.14 |
| .35 | 8.08 |
| .40 | 9.01 |
| .45 | 9.90 |

DATA FOR GRAPH II (cont'd)

Infra-Red Spectrometer Slit Width = 0.500 Millimeters

Table III

Psychrometer:

Dry Bulb = 66°

Wet Bulb = 53°

Relative Humidity = 41%

Absolute Humidity = 0.67 cm. Hg.

Water Vapor Pressure

| Spectrometer Wave Length Scale Arbitrary Units | Galvanometer Def- lection in cm. |
|---|-------------------------------------|
| 15.10 | 3.23 |
| .15 | 3.29 |
| .20 | 3.38 |
| .25 | 3.45 |
| .30 | 3.50 |
| .35 | 3.53 |
| .40 | 3.47 |
| .45 | 3.50 |
| .50 | 3.57 |
| .55 | 3.34 |
| .60 | 3.08 |
| .65 | 3.07 |
| .70 | 3.22 |
| .75 | 3.69 |
| .80 | 4.55 |
| .85 | 5.48 |
| .90 | 5.90 |
| .95 | 5.68 |
| 16.00 | 5.31 |
| .05 | 5.17 |
| .10 | 5.25 |
| .15 | 5.47 |
| .20 | 5.89 |
| .25 | 6.57 |
| .30 | 7.25 |
| .35 | 8.10 |
| .40 | 9.04 |
| .45 | 9.90 |

Graph III

Experimental Absolute Humidity Curves

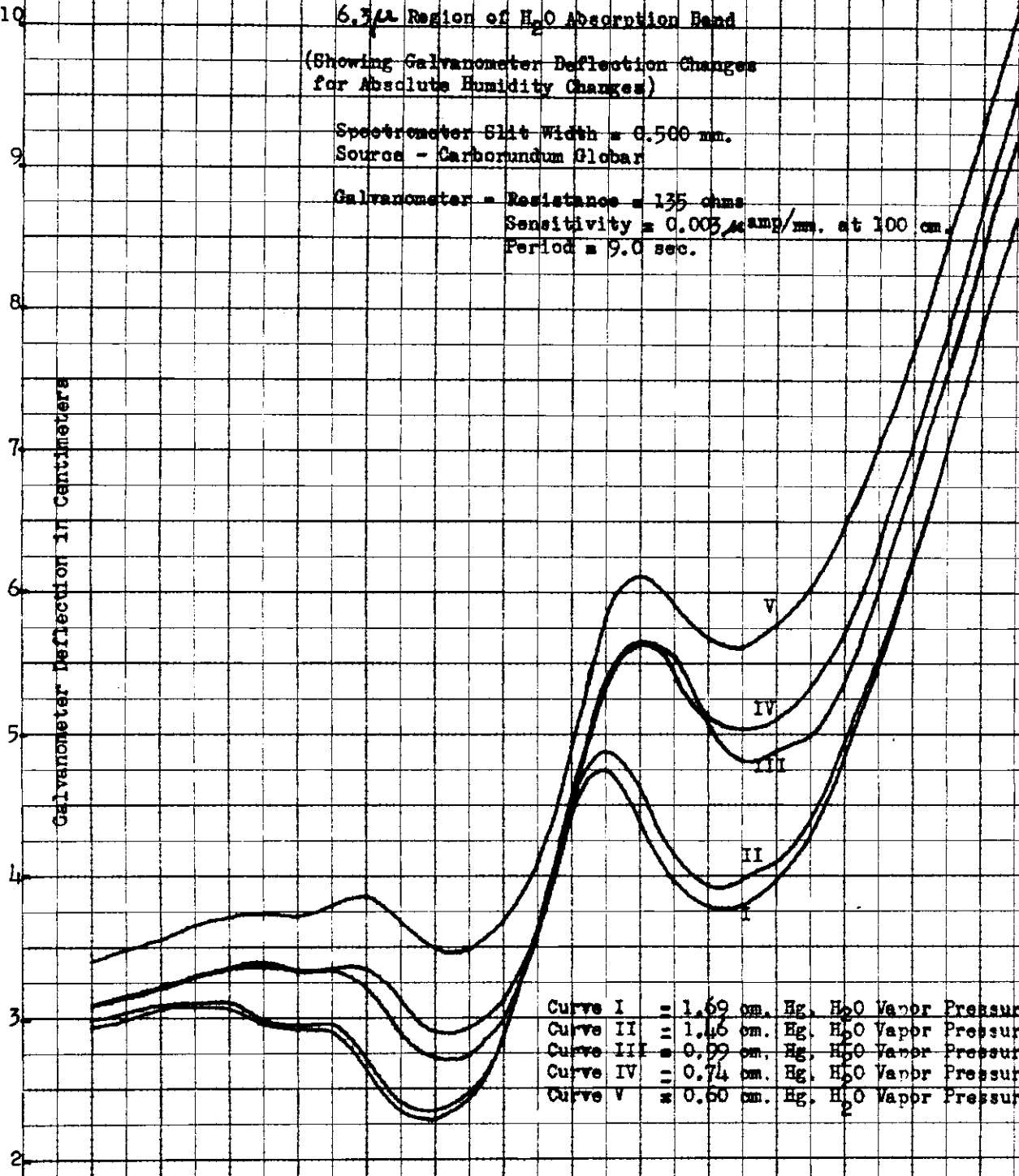
6.3 μ Region of H₂O Absorption Band

(Showing Galvanometer Deflection Changes for Absolute Humidity Changes)

Spectrometer Slit Width = 0.500 mm.
Source - Carborundum Globar

Galvanometer - Resistance = 135 ohms
Sensitivity = 0.003 μ amp/mm. at 100 cm.
Period = 9.0 sec.

Galvanometer Deflection in Centimeters



- Curve I = 1.69 cm. Hg. H₂O Vapor Pressure
- Curve II = 1.45 cm. Hg. H₂O Vapor Pressure
- Curve III = 0.99 cm. Hg. H₂O Vapor Pressure
- Curve IV = 0.74 cm. Hg. H₂O Vapor Pressure
- Curve V = 0.60 cm. Hg. H₂O Vapor Pressure

Arbitrary Spectrometer Wave Length Scale

15.00 .2 .4 .6 .8 16.00 .2 .4
6.6 6.3 6.0
Wave Length in Microns

DATA FOR GRAPH III

Infra-Red Spectrometer Slit Width = 0.500 Millimeters

Table IV

Psychrometer:
 Dry Bulb = 79°
 Wet Bulb = 71°
 Relative Humidity = 68%
 Absolute Humidity = 1.69 cm. Hg.
 Water Vapor Pressure

Table V

Psychrometer:
 Dry Bulb = 78°
 Wet Bulb = 68°
 Relative Humidity = 59%
 Absolute Humidity = 1.46 cm. Hg.
 Water Vapor Pressure

| Spectrometer Wave Length Scale Arbitrary Units | Galvanometer Def- lection in cm. |
|---|-------------------------------------|
|---|-------------------------------------|

| | |
|-------|------|
| 15.10 | 2.93 |
| .15 | 2.99 |
| .20 | 3.07 |
| .25 | 3.08 |
| .30 | 3.07 |
| .35 | 3.95 |
| .40 | 2.91 |
| .45 | 2.91 |
| .50 | 2.63 |
| .55 | 2.34 |
| .60 | 2.28 |
| .65 | 2.43 |
| .70 | 2.86 |
| .75 | 3.63 |
| .80 | 4.48 |
| .85 | 4.75 |
| .90 | 4.39 |
| .95 | 3.96 |
| 16.00 | 3.78 |
| .05 | 3.80 |
| .10 | 3.97 |
| .15 | 4.26 |
| .20 | 4.83 |
| .25 | 5.43 |
| .30 | 6.18 |
| .35 | 7.03 |
| .40 | 7.89 |
| .45 | 8.61 |

| Spectrometer Wave Length Scale Arbitrary Units | Galvanometer Def- lection in cm. |
|---|-------------------------------------|
|---|-------------------------------------|

| | |
|-------|------|
| 15.10 | 2.97 |
| .15 | 3.03 |
| .20 | 3.08 |
| .25 | 3.10 |
| .30 | 3.11 |
| .35 | 2.97 |
| .40 | 2.94 |
| .45 | 2.96 |
| .50 | 2.70 |
| .55 | 2.40 |
| .60 | 2.35 |
| .65 | 2.46 |
| .70 | 2.83 |
| .75 | 3.58 |
| .80 | 4.47 |
| .85 | 4.87 |
| .90 | 4.61 |
| .95 | 4.15 |
| 16.00 | 3.93 |
| .05 | 3.99 |
| .10 | 4.08 |
| .15 | 4.36 |
| .20 | 4.93 |
| .25 | 5.51 |
| .30 | 6.23 |
| .35 | 7.08 |
| .40 | 7.95 |
| .45 | 8.67 |

DATA FOR GRAPH III (cont'd)

Infra-Red Spectrometer Slit Width = 0.500 Millimeters

Table VI

Psychrometer:
 Dry Bulb = 66.5°
 Wet Bulb = 58°
 Relative Humidity = 59.5%
 Absolute Humidity = 0.99 cm. Hg.
 Water Vapor Pressure

Table VII

Psychrometer:
 Dry Bulb = 69°
 Wet Bulb = 55.5°
 Relative Humidity = 41%
 Absolute Humidity = 0.74 cm. Hg.
 Water Vapor Pressure

| Spectrometer Wave Length Scale Arbitrary Units | Galvanometer Def- lection in cm. |
|---|-------------------------------------|
|---|-------------------------------------|

| | |
|-------|------|
| 15.10 | 3.10 |
| .15 | 3.14 |
| .20 | 3.22 |
| .25 | 3.28 |
| .30 | 3.35 |
| .35 | 3.40 |
| .40 | 3.34 |
| .45 | 3.39 |
| .50 | 3.21 |
| .55 | 2.88 |
| .60 | 2.73 |
| .65 | 2.73 |
| .70 | 3.00 |
| .75 | 3.65 |
| .80 | 4.40 |
| .85 | 5.35 |
| .90 | 5.66 |
| .95 | 5.55 |
| 16.00 | 5.10 |
| .05 | 4.82 |
| .10 | 4.88 |
| .15 | 4.99 |
| .20 | 5.31 |
| .25 | 6.01 |
| .30 | 6.70 |
| .35 | 7.54 |
| .40 | 8.52 |
| .45 | 9.43 |

| Spectrometer Wave Length Scale Arbitrary Units | Galvanometer Def- lection in cm. |
|---|-------------------------------------|
|---|-------------------------------------|

| | |
|-------|------|
| 15.10 | 3.08 |
| .15 | 3.14 |
| .20 | 3.20 |
| .25 | 3.30 |
| .30 | 3.36 |
| .35 | 3.34 |
| .40 | 3.31 |
| .45 | 3.36 |
| .50 | 3.35 |
| .55 | 3.11 |
| .60 | 2.90 |
| .65 | 2.93 |
| .70 | 3.12 |
| .75 | 3.61 |
| .80 | 4.52 |
| .85 | 5.38 |
| .90 | 5.65 |
| .95 | 5.37 |
| 16.00 | 5.10 |
| .05 | 5.03 |
| .10 | 5.10 |
| .15 | 5.34 |
| .20 | 5.70 |
| .25 | 6.33 |
| .30 | 7.04 |
| .35 | 7.84 |
| .40 | 8.75 |
| .45 | 9.59 |

DATA FOR GRAPH III (cont'd)

Infra-Red Spectrometer Slit Width = 0.500 Millimeters

Table VIII

Psychrometer:

Dry Bulb = 70.5°

Wet Bulb = 54°

Relative Humidity = 31.5%

Absolute Humidity = 0.60 cm. Hg.

Water Vapor Pressure

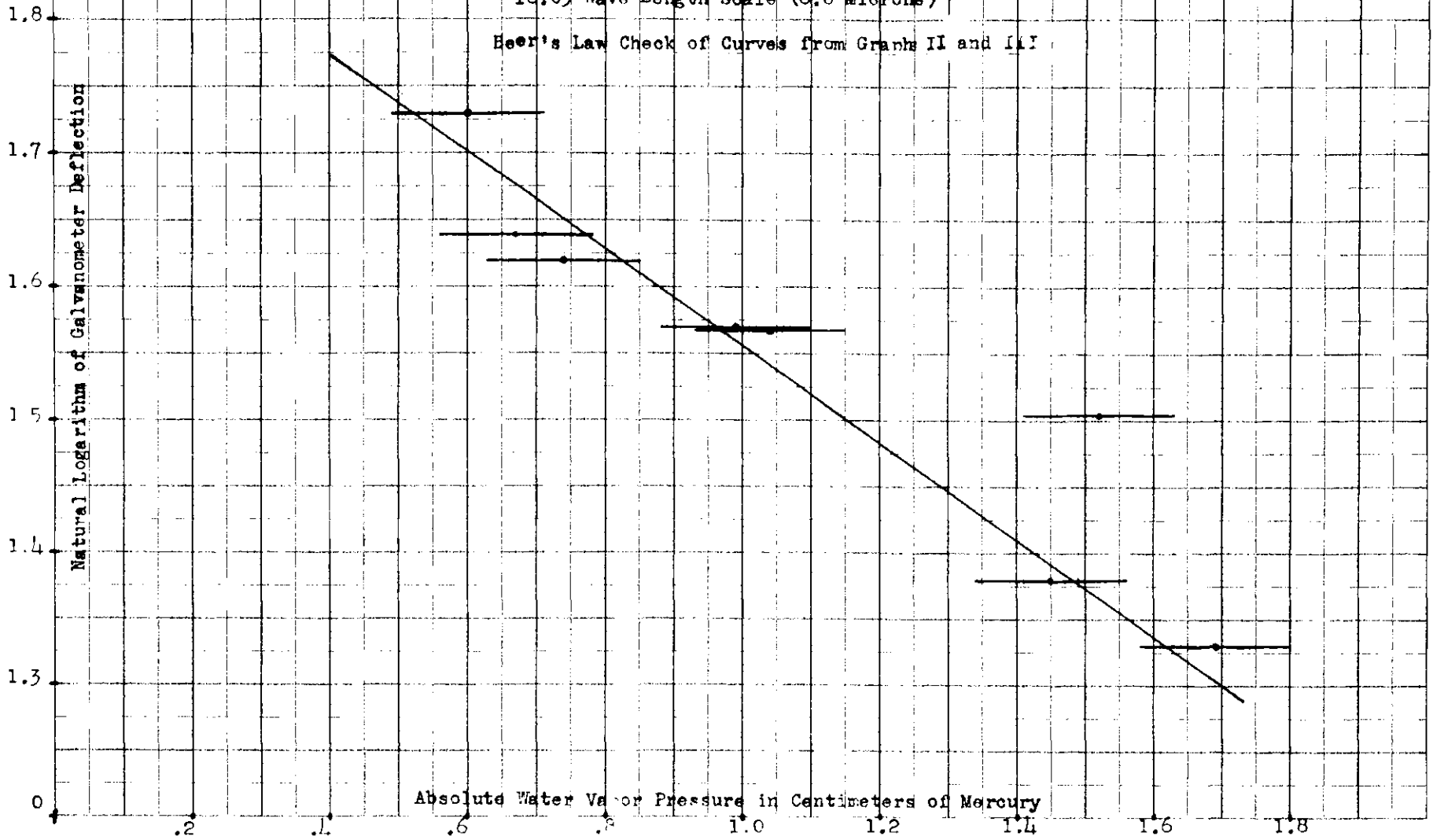
| Spectrometer Wave Length Scale Arbitrary Units | Galvanometer Def- lection in cm. |
|---|-------------------------------------|
| 15.10 | 3.80 |
| .15 | 3.43 |
| .20 | 3.55 |
| .25 | 3.65 |
| .30 | 3.72 |
| .35 | 3.74 |
| .40 | 3.72 |
| .45 | 3.79 |
| .50 | 3.86 |
| .55 | 3.67 |
| .60 | 3.48 |
| .65 | 3.50 |
| .70 | 3.68 |
| .75 | 4.11 |
| .80 | 4.92 |
| .85 | 5.82 |
| .90 | 6.11 |
| .95 | 5.90 |
| 16.00 | 5.69 |
| .05 | 5.60 |
| .10 | 5.77 |
| .15 | 6.02 |
| .20 | 6.47 |
| .25 | 7.03 |
| .30 | 7.71 |
| .35 | 8.48 |
| .40 | 9.33 |
| .45 | 10.20 |

Graph IV

Experimental Curves of Absolute Humidity Versus Natural
Logarithm of Galvanometer Deflection

(All Galvanometer Deflections Taken at
16.05 Wave Length Scale (6.0 Microns))

Beer's Law Check of Curves from Graphs II and III



DATA FOR GRAPH IV

Table IX

(From Graph II)

| Galvanometer Deflection for Different Curves at 16.05 Wave Length Scale (6.0 microns) in Centimeters | Natural Logarithm of Galvanometer Deflection | Water Vapor Pressure in cm. Hg. |
|---|--|---------------------------------------|
| 4.50 | 1.504 | 1.52 |
| 4.80 | 1.569 | 1.04 |
| 5.15 | 1.639 | 0.67 |

(From Graph III)

| | | |
|------|------|------|
| 3.80 | 1.33 | 1.69 |
| 3.99 | 1.38 | 1.46 |
| 4.82 | 1.57 | 0.99 |
| 5.03 | 1.62 | 0.74 |
| 5.62 | 1.73 | 0.60 |

CONCLUSIONS

The resonant cavity method, at least theoretically, offers good possibilities for use in direct measurement of the refractive index of air and indirect measurement of the absolute humidity (if existing temperatures and pressures are known). The problems of electrical adjustment and the weight and handling of the power supply and oscilloscope might offer some difficulty in a portable equipment, but application of the method in meteorological studies would certainly be desirable. Further experimental study of the method appears to be warranted.

Of the infra-red methods studied, the diffraction grating seems the most adaptable for use in a humidity instrument. The prism method would seem to be unsatisfactory, due to the very delicate handling necessary for the prisms. Furthermore, all the prisms used in the infra-red region are soluble in water, and humidities should be below 70 per cent to prevent rapid deterioration.

In the experimental studies using gratings, it was stated that positive indications were observed. It is believed that the method is fundamentally sound and practical. Use of an Echelette grating would concentrate energies in any desired water vapor absorption band, allowing greater overall energies to the thermocouple and hence greater measurable changes of energy due to humidity changes. Another type source, such as a globar, also might be desirable, but use of the Echelette grating might eliminate this need.

It is believed that better results in the experimental studies conducted with the infra-red spectrometer, might have been obtained. That is, greater galvanometer deflection changes for given absolute

humidity changes might have been possible. The spectrometer was not absolutely aligned (because of time limitation on the experimental work). Thus, an appreciable amount of resolution was probably lost, and, therefore, the magnitudes of the deflection changes with given humidity changes were probably reduced. Moreover, the galvanometer used was not entirely satisfactory, since the spectrometer is normally used with a special galvanometer of six ohms impedance. (The special galvanometer was not available.) In this case the resolution obtained was definitely less than that possible with proper equipment.

However, it is believed that the positive data obtained in the latter experimental method definitely indicate the practicability of the use of the infra-red method of absorption bands for sensitive, accurate, and rapid absolute humidity determinations.

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