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Evaluation of a Portable Chamber for Measuring Plant-Soil Evapotranspiration.

presented by

Gary A. Peterson

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George E. Merva
Major professor

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EVALUATION OF A PORTABLE CHAMBER FOR MEASURING PLANT- SOIL EVAPOTRANSPIRATION.

By

Gary A. Peterson

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Abstract

EVALUATION OF A PORTABLE CHAMBER FOR MEASURING PLANT- SOIL EVAPOTRANSPIRATION.

By

Gary A. Peterson

The purpose of this research was to evaluate the portable chamber as a method for measuring "instantaneous" soil-plant evapotranspiration (ET). Three objectives defined to carry out the purpose were as follows: 1) to study the transducer system used to measure changes in water vapor density under controlled conditions; 2) to study the chamber-transducer system used to measure changes in water vapor density under controlled conditions; and 3) to compare field evapotranspiration measured using the portable chamber with that measured using a lysimeter.

An aspirated psychrometer was chosen to measure changes in water vapor density within the portable chamber. Measurements of response to step changes of water vapor density were completed on psychrometers equipped with small fast response thermistor temperature sensors and a psychrometer equipped with inexpensive, slower responding integrated circuit (IC) temperatures sensors.

Laboratory tests were conducted to determine the response of the chamber and psychrometer response to changes in chamber air water vapor density in absence of plants. Results of the tests showed psychrometers measured only 67% of controlled water inputs. Calibration equations were developed from the laboratory data to correct for psychrometer measurement inefficiency. Some doubt about the applicability of the calibration equations to field measurements exists due to possible errors in experimental design.

Field measurement of cumulative ET for a lysimeter were compared to chamber measured cumulative ET on 4 days in 1984. Measurement with a 2.4 m (96 inch) tall chamber equipped with three psychrometers yielded nearly 1:1 cumulative ET when compared with a lysimeter on 1 day. Measurements with a 3.6 m (141 inch) tall chamber yielded approximately 78% of lysimeter cumulative ET for tests on 3 days.

Application of laboratory developed calibration curves proved unsatisfactory. Data collected with the 2.4m (96 inches) tall chamber overestimated lysimeter cumulative ET by 40-50%. Cumulative ET measured with a 3.6 m (141 inch) tall chamber was ±20% of lysimeter cumulative ET.

Investigations were conducted to determine the number of data points necessary to estimate ET rate for a single measurement and the length of time after chamber placement over a crop before valid data can be collected. Seven time intervals from 10 to 80 seconds were analyzed for maximum ET rate. Results showed that as the length of the analysis time interval increased, ET rate decreased. For data reported here an analysis time of 10 seconds gave maximum ET rates.

Analysis of the elapsed time from chamber ground contact until the start of the maximum ET rate analysis time bracket showed the average elapsed time from start to decrease with increasing length of analysis time bracket. .

Overall analysis found good agreement of the 2.4 m (96 inch) tall chamber with the lysimeter, but less than satisfactory comparison of the lysimeter with a 3.6 m (141 inch) tall chamber (78%).

Approved George E. Merva
Major Professor

Approved Donald M. Edwards
Department Chairperson

To Jeffery David Peterson

A brother whose early death gave others a new reason to live.

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Many people contributed to this work and I would like to take this opportunity to acknowledge there efforts. I would like to express appreciation to Dr. George Merva, my major professor, for his guidance, encouragement, and support. His guidance and suggestions were helpful in the development of the analysis procedures implemented.

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Finally, thanks to Eric Harmsen, a fellow graduate student, who with me, indulged the neurotic idea that we could build an ET chamber.

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CHAPTER 1

INTRODUCTION AND LITERATURE

1.1 INTRODUCTION

Evaporation from the soil surface and transpiration by plants occur simultaneously. Both processes remove water from the soil making it unavailable to the growing crop. For purposes of estimating water lost from the soil, evaporation and transpiration are grouped together as evapotranspiration.

Technically, evapotranspiration (ET) as defined by Burman et al. (1980) is " The combined process by which water is transferred from the earth's surface to the atmosphere. It includes evaporation of liquid and solid water from the soil and plant surfaces plus transpiration of liquid water through plant tissues expressed as the latent heat transfer per unit area or its equivalent depth of water per unit area."

The primary reason to measure ET is to estimate the quantity of water a growing crop needs to produce an acceptable yield. Measurements of ET can be used to verify ET estimates produced by seasonal ET models improving the quality of the seasonal estimate and increasing confidence in the ET model. The model can be used to estimate the water needs of a crop and to schedule irrigation. Since irrigation consumes energy and increases the cost of producing a crop, the reduction of the volume of water applied reduces costs.

One method of measuring ET is the use of chambers placed or built around growing crops. The measurement principle is simple in theory. A chamber covered with a transparent material, impervious to water vapor, surrounds a group of plants water converted to vapor via ET. Measurement instruments sense the quantity of water vapor present in chamber air. Increases in the quantity of water in vapor form in the chamber air as time passes are attributed to ET.

Several researchers (Musgrave and Moss, 1961; Decker et al, 1962; Puckridge,1978) have used the chamber technique. The first chambers were fixed. A chamber was erected around a

growing crop and left in place several hours to several weeks. This approach had several drawbacks, not the least of which was that it was very similar to greenhouse tests. The clear covering over the chamber permitted solar radiation to enter the chamber promoting crop growth. Like a greenhouse, the temperature inside the chamber had to be controlled if the chamber was to be used for any length of time. Outside air could not be circulated through the chamber to maintain the internal chamber temperature at the same temperature as the air in the surrounding field. Air conditioners successfully modified the chamber environment and eliminated a build up of heat within fixed chambers. The air conditioned environment created its own problem. The conditioning of the air removed water from the chamber air. Capture and measurement of the condensate did provide a convenient method of quantifying ET from the crop growing inside the chamber, but it also modified the chamber air relative humidity significantly from that of the outside air near the chamber.

Another drawback of the fixed chamber approach was the CO_2 depletion of the chamber air as a result of plant photosynthesis. Elaborate systems to inject CO_2 (Musgrave and Moss, 1961; Sakamoto and Shaw, 1967) into the chamber were devised to maintain the CO_2 concentration at some preset level.

Most of the problems with the fixed chambers were the result of the length of time the chamber remained over the crop. The fixed chambers permanently altered the environment of the crop whose ET was to be measured, making comparison of chamber measured ET to field ET questionable.

Peters, et al. (1974) attempted to reduce the problems associated with fixed chambers by mounting a chamber on tracks. The track mounted chamber had door at each end. The chamber was moved from test plot to plot. At each plot the doors were closed and a 60 to 120 second measurement of water vapor accumulation within the chamber was made. The shortness of measurement reduced the need for conditioning the chamber air or adding CO_2. Using the track mounted chamber many measurements of several plots could be made daily, increasing the number of repetitions of ET measurement, increasing confidence in measured ET over the fixed chamber measured ET.

Reicosky and Peters (1977) took the track mounted chamber design a step further by

mounting a chamber on a farm tractor. The measurement instruments which had previously been housed in fixed instrument shelters were also mounted on the tractor. This provided complete portability of the ET measurement system.

A schematic of a portable chamber system as shown by Harmsen et al. (1983) is shown in Figure 1-1.

The portable chamber system consists of a chamber frame and covering, air mixing fans to prevent moisture stratification, measurement transducer or transducers, data collection equipment, and a suspension structure to assist in chamber placement.

A portable evapotranspiration (ET) chamber like its fixed predecessor is designed to measure evaporation from the ground surface and transpiration from crops. When the chamber is lowered over a group of plants, all the water liberated by evaporation at the soil surface and transpired by the plants is trapped. After 30 to 120 seconds the chamber is removed from the

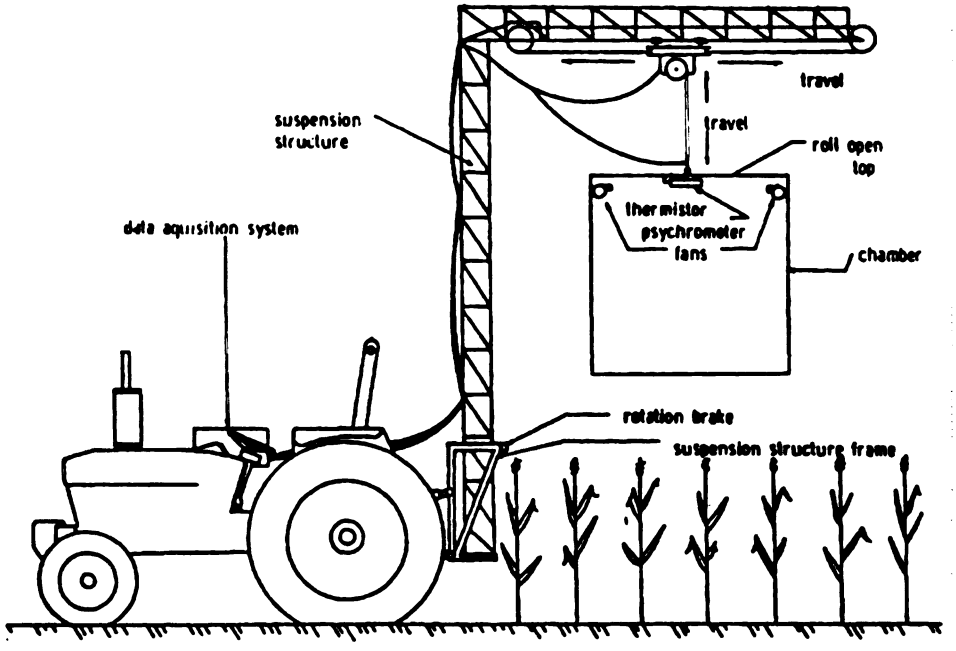

Figure 1-1 Schematic drawing of a the components of a portable ET chamber as drawn by Harmsen (1983).

crop. A integration of individual measurements over a day provides an estimate of cumulative ET.

Harmsen (1983) pointed out a difference between the fixed and portable chamber techniques that the pioneers of the technique (Reicosky and Peters, 1977) fail to mention. The portable chamber is said to be "instantaneous" because the measurement is made over a short period of time. The measured ET flux is taken to be a reasonable estimate of the ET flux for a given point in time.

1.2 PURPOSE

The purpose of this research was to evaluate the portable chamber as a method for measuring "instantaneous" plant-soil evapotranspiration.

1.2.1 Objectives

The research had three major objectives:

1) to study the transducer system used to measure changes in water vapor density under controlled conditions;

2) to study the chamber-transducer system used to measure changes in water vapor density under controlled conditions;

3) to compare field evapotranspiration measured using the portable chamber with that measured using a lysimeter.

1.2.2 Organization

Chapter 1 presents a review of the literature dealing with portable evapotranspiration chambers, plant use of water, and measurement of water vapor density. Three chapters treating each of the three major objectives follow, containing literature, methods, results, and discussion pertinent to each objective. Chapter 2, covering objective 1, details the selected measurement transducer, its construction and calibration. Chapter 3, covering objective 2, details laboratory test of the measurement transducer, data collection equipment and chamber ability to measure known inputs of water independent of transpiring plants. Chapter 4, covering objective 3, addres-

ses field comparisons of chamber ET to weighing lysimeter ET for maize (corn). Chapter Five relates each objective to the purpose of the research.

1.3 REVIEW OF LITERATURE

1.3.1 Field Verification of Portable Chambers

Reicosky and Peters (1977) first reported the development of a portable chamber for measurement of plant transpiration. The chamber consisted of a rectangular metal frame 1.83m (72 inches) deep by 2.03m (80 inches) wide by 1.37m (54 inches) high, covered with clear mylar film. The frame was mounted on the front of a small farm tractor. The chamber was raised and lowered over the crop with a small battery-powered winch. Air inside the chamber was mixed with four fans, which were mounted near the bottom of the chamber in each corner. These provided a mixing rate of nine chamber volumes per minute.

The rate of water vapor accumulation in the chamber was measured with an aspirated thermistor psychrometer. The portable chamber was placed over plants grown in a hydroponic solution. Measurements of the rate of change in water vapor concentration within the chamber in one minute were repeated every 10 minutes. The chamber was removed from the plants between measurements.

A plot of the chamber transpiration rate against the solution uptake rate yielded good results for data collected on a clear day. A simple regression line through the data gave an r^2 of 0.98. Results for data collected on a partly cloudy day were not presented quantitatively, but the authors stated that chamber-measured ET rates were "considerably more scattered." The authors hypothesized that temporary water storage in the plant stems caused a smoothing of the fluctuations in measurements of solution uptake rates.

Chamber-measured transpiration rates, more tightly coupled to solar radiation, showed greater variation due to radiation changes caused by passing clouds. A mathematical error analysis (Doebelin, 1975) yielded theoretical limits of accuracy of the aspirated psychrometer of 19 percent and a probable error of 11 percent. No independent tests of the chamber-transducer measurement system were attempted.

Field tests with alfalfa near a lysimeter at St. Paul, Minnesota provided a comparison with a portable chamber (Reicosky et al., 1981). Measurements of ET under clear skies were made at 10 minute intervals throughout the daylight hours. Hourly averages of ET from a nearby lysimeter and calculated hourly ET using the Penman equation were compared with chamber measured ET. Chamber and Penman ET were 7.8 mm / day (0.30 in/day) compared with 8.0 mm / day (0.31in/day) measured with the lysimeter.

Reicosky (1985) collected ET data while comparing soybean row spacings. He cited difficulty evaluating measurements for conditions other than clear sky, confirming that the relationship of the chamber to ET under variable radiation conditions is complex.

Harmsen (1983) described criteria for design of a portable chamber used at Michigan State University. This portable chamber was modified from the original described by Reicosky and Peters (1977). An aluminum frame was covered with Propafilm C, a clear plastic film having properties similar to mylar. However, unlike mylar, Plexiglas, and lexan, Propafilm C has a high transmittance of infrared radiation in the 0.2 to 10 micron wavelength.

The chamber was suspended from a tractor mounted boom and was raised and lowered with a 12 volt DC winch. A top was added that remained open between measurements, closing only after the chamber contacted the ground over the crop at the start of a measurement. The open top was supposed to prevent expulsion of canopy air by air trapped in the fixed top chamber during placement. Since a single aspirated psychrometer was used for measurement, no verification of transducer function was available.

Laboratory measurements by Harmsen (1983) showed that this portable chamber resulted in an estimate of controlled input of water vapor that was too high by 30 percent. Field comparison of the chamber system was attempted for corn near a lysimeter at Coshocton, Ohio. The results of one day's tests for clear sky conditions showed chamber-measured ET in excess of lysimeter- measured ET by 13 percent. The measurement transducer was a single aspirated psychrometer. These two tests indicated that the chamber with an openable top overestimated actual water vapor concentrations within the chamber regardless of the source of the water vapor.

1.3.2

Plant Use Of Water

Accurate measurements of evapotranspiration are important for calibration of procedure used to estimate ET. When ET values are combined with measurements of irrigation water, rainfall, and anticedent soil moisture, a running balance of soil moisture available to a plant can be maintained.

Evaporation of water from the soil surface can contribute significantly to soil water removal early in the growing season when the canopy ground cover is minimal. As the crop canopy develops, the ground surface is shaded, significantly reducing the radiation reaching the ground surface and the amount of soil evaporation.

For most crop canopies, the water evaporated from the soil surface is considerably less than the transpired water. This occurs for two reasons. First, the ground is usually shaded by the crop, resulting in a reduction in the energy reaching the surface. Secondly, the availability of moisture to evaporate decreases significantly as the ground surface dries. Thus, transpiration is the major consumer of a soil moisture.

The dominant energy source driving transpiration is solar radiation. Transpiration transforms sensible heat into latent heat of vaporizationthus providing primary temperature regulation mechanism for the plant leaf. Along with other passive energy transport processes, transpiration stabilizes leaf temperature through evaporation from cell surfaces inside the leaf. Water transpired from the leaf removes heat stored in leaf tissues and fluids, cooling the leaf.

1.3.3 The Quantity of Water Vapor in a Volume of Dry Air

To effectively use the evapotranspiration chamber one must have an accurate method for measuring water vapor density in air. As this quantity is not directly measurable, it is important to understand the concepts associated with the determination of the partial pressure of water vapor in a volume of air. The science of measuring the moisture content of a substance is hygrometry. Hygrometry is not limited to measurements on gases but may also be made on solids. For example, wood must be dried before it can be used for construction. Wood with too much moisture

will have less than maximum strength; too little and it will snap like a twig. The volume of a solid can be measured, in most cases, rather easily. If, like many woods, the volume decreases with moisture loss, the new volume can be measured and used to calculate the true quantity of moisture per unit volume.

To measure the quantity of water in moist air the composition of dry air must be known. Atmospheric air varies in composition; thus, the exact content is arbitrary. Dry atmospheric air as defined by the Joint Committee on Psychrometric Data as reported by Harrison (1963a) is shown in Table 1-1.

The molecular weight of dry air is the sum of the products of the individual molecular weights times the fraction of that component present in a given volume at 0 ° C. A mole of a substance is defined as 6.02×10^{-23} molecules of that substance. One mole of a gas will occupy 22.41 liters (L) at 0 °C and 1 atmosphere of pressure. The mole-fraction of a particular gas is the portion of a gas mixture accounted for by that gas. Water in vapor form is a gas and is present in the earth's atmosphere in quantities of less than 0.001 percent to a maximum of 5 percent by volume, but is usually 1 to 1.5 percent (Harrison,1963a). The perfect gas law and Dalton's Law form the basis for the thermodynamic understanding of a mixture of dry and moist air.

Table 1-1. The composition of dry air.

Component	Molecular Weight	Mol-fraction	Partial Mol. WT. dry air
Oxygen	32.000	0.2095	6.704
Nitrogen	28.016	0.7809	21.878
Argon	39.944	0.0093	0.371
Carbon Dioxide	44.01	0.0003	0.013
Total			28.966

The perfect gas law is:

$$PV = nRT = \frac{m}{M} RT \qquad (1)$$

where

P = pressure of the gas, in kPa

V = volume of the gas, in L

R = the gas constant, in kPa-L $mole^{-1}$-K^{-1}

T = the absolute thermodynamic temperature of the gas, in °K

m = mass of gas, in grams

M = molecular weight of the gas, in grams / mole

Ambient air can be assumed to be a perfect gas if two factors apply. First, Boyle's law states that for real gases at low pressure (the pressure of a gas as the pressure approaches zero as a lower limit), a fixed mass of gas maintained at constant temperature will have a constant product of the pressure times the volume. Second, at low pressures the internal energy of a fixed mass of gas is independent of the volume and pressure (Harrison,1963b).

Dalton's law allows the perfect gas law to be expanded to reflect the total pressure of gas in a volume. It states that the partial pressure of each gas in a mixture is independent of other gases and exerts its own partial pressure. Water vapor in a mixture will diffuse to fill a fixed volume, equalizing its pressure throughout the volume. The speed of diffusion will vary depending on the entropy differences of the mixing gases. In a mixture of gases, water vapor will uniformly distribute throughout the volume and will be at the temperature of the other gases in the volume.

The standard measurement technique for determination of the water quantity in a volume of moist air is the gravimetric method. The gravimetric method is very accurate and does not reduce the measured volume. A known volume of moist air is passed through a coil bathed in liquid nitrogen, condensing the vapor in the air. The condensed water vapor is weighed to determine the mass of water present in an equivalent volume of dry air. Because water vapor disperses uniformly in a gas mixture, it is impossible to remove all water vapor from a volume of air. Even after supercooling the air passed through the coil, some moisture is not removed from the gas.

Because gravimetric sampling is laborious and time consuming, other indirect methods are used when extreme accuracy and precision are not needed. These methods involve measuring quantities and properties which can be substitued into the perfect gas law. The partial pressure of water vapor in moist air is not directly measurable but can be calculated if other measureable factors are known. Using the perfect gas law and three measurable factors the fourth can be calculated, allowing the quantity of moisture in a fixed volume to be estimated. The next task will be to find a transducer that will measure properties needed to calculate the partial pressure of water vapor in the portable chamber.

CHAPTER 2

TRANSDUCER SELECTION AND TESTING

2.1 OBJECTIVE 1

The first objective was to study the transducer system used to measure changes in water vapor density under ambient conditions.

2.2 INTRODUCTION

In this chapter, transducers used to measure humidity are briefly reviewed. A summary of the theory and development of psychrometrics follows, including a review of errors associated with the use of aspirated psychrometers and their time response characteristics. The method used to evaluate the transducer used for the research is presented and the results of the evaluation are discussed.

2.2.1 Transducer Selection

Various types of transducers were considered for use in this research. The transducer selected had to meet the following criteria:

1) not destructive of the environment being measured;

2) sufficiently accurate and precise to warrant use in a growing crop canopy;

3) capable of performing rapid measurements;

4) easily interfaceable with electronic data collection equipment;

5) portable; and

6) affordable.

Oliver (1971) provided an excellent review of humidity measurement transducers; for functional details of the transducers discussed below, the reader is referred to this reference.

Hair hygrometers measure the expansion/contraction of strands of human hair with changes

in humidity. As hair hygrometers are unable to provide electronic output, they were not appropriate for this research.

Electrolytic cells depend on the absorption of moisture from a gas passing over them. These could not be used because of their large size, high electric potential requirements, and long (1 1/2 to 2 minutes) response times.

Capacitive effect sensors were not selected because they require AC voltage and have measurement times in excess of one minute. Surface resistivity sensors sense changes in humidity as a function of adsorbed moisture changing the electrical resistance. The requirement of AC voltage and long lag time to equilibrium (30 seconds under calm conditions) made these sensors undesirable.

The cooled surface dew point detector was a good candidate for humidity measurement. The measurement principle used is as follows: atmospheric gas, when passed over the surface of a nonabsorptive mirror surface, will condense to dew or frost on that surface. The presence or absence of dew is sensed with an optically coupled photocell. The temperature of the surface when a constant thickness of dew is achieved corresponds to the saturated vapor pressure which is equal to the partial pressure of water vapor in the air sample. Though very promising, the long time for measurement (30 seconds), though better than previously listed transducers, coupled with the high costs ($2,500-$3,000 in 1982), eliminated this transducer from consideration.

The infrared gas analyzer is the best transducer available for measurement of water vapor in atmospheric air in humid climates. The accuracy is high, measurements could be taken rapidly (several measurements per second were possible), and the measurement sensitivity increased with decreasing water vapor content. The instrument was not used because its cost was prohibitive ($7,500 in 1982) and it was difficult to obtain and maintain.

One of the oldest and best-known transducers, the psychrometer, was finally chosen. A psychrometer is a device consisting of two similar thermometers with the bulb of one being kept wet so that evaporative cooling makes it register a lower temperature than the dry bulb; the difference between the readings constitutes a measure of the dryness of the atmosphere.

The transducer used in this research was an aspirated wet bulb-dry bulb psychrometer. The term aspirated refers to a fan-forced air current drawn over the wet and dry temperature sen-

sors, enhancing evaporation from the wetted wick. The basic psychrometer consisted of a small tube with a fan attached to the end. Two temperature sensors were inserted perpendicularly into the air stream through the pipe wall, with the ambient temperature sensor upstream from the evaporatively cooled sensor. A cotton wick leading to a water reservoir covered the sensor and instrument leads downstream, providing moisture for evaporative cooling.

2.3 LITERATURE

2.3.1 History and Psychrometric Theory

Early practice and psychrometric formulas were based on the classical convection theory (Harrison, 1963b). Harrison stated that air passing the moistened wick of a wet bulb will be cooled from the dry bulb temperature to the wet bulb temperature, giving up enough heat to evaporate water from the wet bulb. The air in the vicinity of the wet bulb was assumed to remain at the wet bulb temperature. Radiation effects were ignored.

The psychrometric formula presented by August (1835) and Apjohn (1835) as reported by Harrison (1963a) is

where:

$$e = e_w - \gamma P \ (t - t_w) \qquad (2)$$

e = vapor pressure, kpa

e_w = saturated vapor pressure, kpa,

γ = the psychrometric constant with respect to water

P = atmospheric pressure, kpa

t = ambient temperature, °C

t_w = wet bulb temperature, °C

Ferrel (1886) showed that the psychrometric constant was dependent on the wet bulb temperature and atmospheric pressure. The psychrometric constant could vary by 3 percent at high temperatures and humidity. Ferrel verified his estimate of the psychrometric constant with sling psychrometer measurements.

Early psychrometric formulas were combinations of theoretical and empirical formulas. Bindon (1963) accurately assessed the deviation between theory and practice in the following quote:

> "When an attempt is made to provide a satisfactory theory for the real wet bulb process, it becomes obvious that classical thermodynamics cannot be directly applied. This theory is generally applicable only to closed systems in equilibrium, whereas the real wet bulb process is an open system in a stationary state rather than in thermodynamic equilibrium in the classical sense. To solve the real problem, it is necessary to make a detailed accounting of the heat and mass exchange between the wet bulb and the ambient atmosphere. The most satisfactory theoretical attempt to follow along these lines was made by Arnold. Other writers have extended the Arnold theory, and it is possible that further work might be done if all the resources of modern heat and mass exchange theory were applied to the problem. In view, however, of the many sources of error in the real psychrometer, it is doubtful if any appreciable gain in accuracy would result from a more detailed theory."

The current psychrometric equation, often credited to List (1958), is really Equation 3 with revisions by Ferrel (1886) as reported by Harrison (1963a). For temperature measured in °C, the equation is

$$e = e_w - \gamma P (t - t_w) \ (1 + 0.00115\ t_w) \qquad (3)$$

The terms in the last set of parentheses represent a correction for the difference between the latent heat of vaporization at 0 °C and the latent heat of vaporization at the wet bulb temperature. Although the psychrometric constant is actually not constant, Harrison (1963b) and others stated that the psychrometric constant may be regarded as fixed when the wet bulb ventilation exceeds 3 m/sec under ordinary conditions of pressure and temperature at sea level. Harrison stated:

> "Experiments with various fluids in addition to water, and with various carrier gases in addition to air, have indicated that the theory of adiabatic saturation is accurate as a basis for the psychrometric formula when the ratio of the **thermal diffusivity (K)** to the **diffusion coefficient (D)** is equal to unity, which is nearly true in the special case of the sys-

tem water-air, but is not generally true in the case of systems consisting of most other combinations of fluids and carrier gases under realizable ventilation rates."

2.3.1.1 Errors associated with the use of aspirated psychrometers

Tanner (1971) presented the material below in more detail. The purpose of this summary is to indicate the four major errors made when designing and building aspirated psychrometers and to note solutions that eliminate or reduce the errors. The mathematical derivations are included only when necessary; otherwise, the reader should consult Tanner (1971).

Using theory presented by Stewart (1963), Tanner (1971) discussed four major sources of error associated with the use of aspirated psychrometers:

1) inadequate ventilation;

2) inaccurate measurement of wet and dry bulb temperature;

3) temperature measurement errors from external radiation sources; and

4) inadequate wetting of the wet bulb wick.

2.3.1.1.1 INADEQUATE VENTILATION

Figure 2-1 shows the effect of increasing ventilation rate on wet bulb depression. Each curve represents data for a wet bulb with the given diameter. From the figure it is apparent that a small wet bulb diameter combined with a high ventilation rate provides optimum results. Ventilation rates in excess of 3 m/sec (590 ft/min) with wet bulb diameters of less than 1 mm should be used.

2.3.1.1.2 INACCURATE MEASUREMENT OF TEMPERATURE

Obviously, a bad measurement of temperature in either the wet or dry bulb will introduce errors. Errors resulting from temperature measurement are illustrated in Figure 2-2 , which was constructed from data supplied by Tanner (1971). The curves shown reflect the percent error in estimation of relative humidity for an error of ±1°C in the dry bulb, the wet bulb, and a ±1°C error in the depression (dry bulb - wet bulb) measured differentially, for air at 40 percent relative humidity at 25°C. By varying the dry bulb temperature, the relative humidity can be made to increase as the dry bulb temperature decreases and vice versa. Figure 2-2 illustrates two important points. First, inaccurate measurement of the wet bulb temperature is of greater significance at

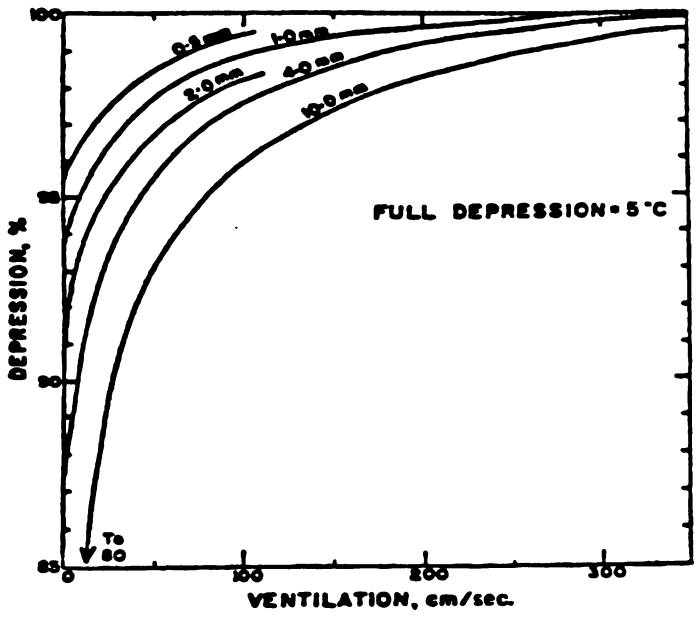

Figure 2-1 Errors in wet bulb temperature measurement due to inadequate wet bulb aspiration velocity for wet bulbs with diameters of 0.5, 1.0, 2.0, 4.0 and 10.0 mm.

lower temperatures and higher humidity than a similar error in dry bulb temperature. Second, significant gains in accuracy can be made if the depression (dry bulb-wet bulb temperature) is measured with a differential thermometer.

Additional temperature errors may be caused by heat conducted up the leads of the temperature sensors themselves and from the water feeding the wick. Heat conduction can be minimized by exposing a section of the wick downwind from the wet bulb. If the supply water is at a temperature higher than the wet bulb (generally the case), a reduction of the conduction error is possible by providing an extended evaporating surface downstream from the wet bulb sensor, cooling the water entrapped in the wick and the sensor lead wires.

A seemingly obvious, though often overlooked point, is to place the dry bulb sensor upstream of the wet bulb sensor to avoid changing the temperature of the airstream in the vicinity of the dry bulb.

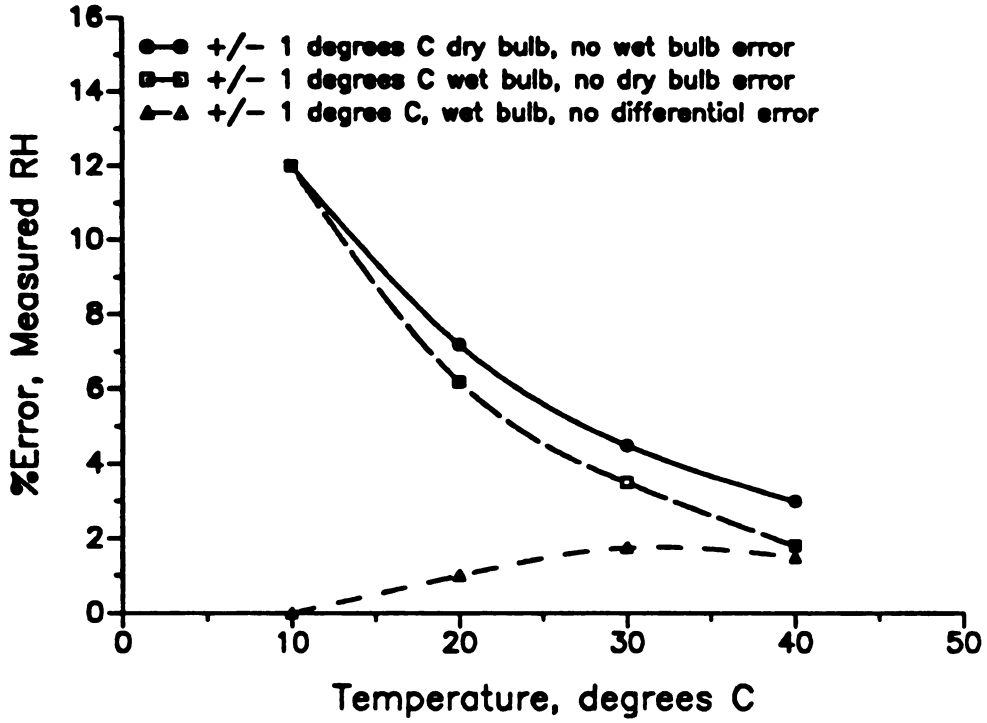

Figure 2-2 Relative humidity measurement errors resulting from error in measurement of ±1°C dry bulb, the wet bulb, and a ±1°C error in the depression (dry bulb - wet bulb) measured differentially, for air at 40 percent relative humidity at 25°C.

2.3.1.1.3 EXTERNAL RADIATION SOURCES

The error of temperature measurement from an external radiation source is directly proportional to the ratio of the area normal to the incident radiation to the total sensor area and is inversely proportional to the convective heat transfer coefficient (Tanner, 1971). If the sensor size is reduced, the area normal to the incident radiation is reduced, resulting in less measurement error. The convective heat transfer coefficient increases sharply as the ventilation rate increases. Since the convective heat transfer coefficient is inversely proportional to the measurement, an error increase in ventilation velocity will decrease measurement error.

To reduce external radiation errors, a psychrometer should have a high ventilation velocity , a small sensor, or both. A radiation shade reduces the solar radiation flux and the temperature measurement error greatly. Without a radiation shade, serious wet bulb temperature errors occur at sensor diameters in excess of 0.1 mm (Tanner, 1971).

2.3.1.1.4 WET BULB TEMPERATURE MEASUREMENT ERRORS

Tanner (1971) listed the following measurement errors for wet bulb temperatures:

1) use of contaminated water to supply the wick; and

2) wick solute build-up from salts left behind as water is evaporated.

Contamination of the water supply can create substantial errors (Wylie, 1968, cited by Tanner, 1971). Wylie spread thin films of oleic acid and grease from human skin on the surface of the wick water supply. The oleic acid only changed the psychrometric coefficient 1.4 percent, but the grease introduced an 18 percent error. A flush with clean water restored the wicks to original performance. Hand contact with wicks during replacement or cleaning can alter the results and should be followed with a thorough rinsing with distilled water.

Problems associated with wick solute build up can be minimized by proper choice and preparation of the wick. Important differences exist in wick materials. Although cotton yarn, cotton sleeving, ceramics, or even filter paper have been tried, wicks are usually made of cotton. Tanner (1971) indicated that an adequate wick can be constructed from a white cotton shoelace first boiled in $NaCO_3$ to remove sizing and starch and then boiled in clean water.

Adequate wetting of a wick material is sometimes hard to determine. After some research, Wylie (1968) as reported by Tanner (1971), stated that at capillary water tensions of 1 to 2 centimeters, a wick will glisten when completely wet and adequately conductive.

In the previous discussion of errors caused by inadequate ventilation, it was noted that the ventilation rate necessary for full depression of the wet bulb increases as the wet bulb diameter increases. To reduce the wet bulb diameter, Tanner suggested that a cotton wick be used near the sensor. The sensor surface is covered by two layers of facial tissue laid over the sensor, in close contact with the cotton wick. This will provide adequate water supply to the wet bulb while minimizing the increase in diameter caused by the wick. The tissue paper is easily replaced reducing solute build-up due to salts left behind. The use of distilled water will significantly reduce salt deposition in the supply wick.

2.3.1.2 Time response characteristics

One final parameter should be considered when working with an aspirated psychrometer: the length of time taken by the temperature sensors to respond to a change in temperature. This can be measured and approximated mathematically as a function of τ, the time constant. A reasonable assumption is that the time constant for the wet bulb will be different (less) than the time constant for the dry bulb.

The following equations express that function (Tanner, 1971):

$$\tau_w = \frac{C_{wb}}{(1+ \Delta_w/\gamma\ P)\ (K_h + K_L)} \tag{4}$$

$$\tau_d = \frac{C_{db}}{(K_h + K_L)} \tag{5}$$

where

C_{wb} = heat capacity per unit area of wet bulb

C_{db} = heat capacity per unit area of dry bulb

τ_w = time constant of wet bulb

τ_d = time constant of dry bulb

Δ_w = slope of saturation vapor pressure curve at the wet bulb temperature

γ = psychrometric constant

P = pressure

K_h = convective heat transport coefficient

K_L = thermal radiation transport coefficient

This means that the wet bulb will respond $(1 + \Delta_w/\gamma\ P)$ times faster than the dry bulb if $C_{wb} = C_{db}$, which is usually true. The rate of improvement of τ_w is a function of the slope of the saturation vapor pressure at the wet bulb temperature. As the wet bulb temperature increases, so does the value of τ_w relative to τ_d.

A temperature fluctuation with a duration longer than four times τ_w will allow the sensor to respond to 98 percent of the fluctuation, while at time equal τ_w only 15 percent of the fluctuation

will be measured. It is therefore important to have temperature sensors with short response times (τ) to measure rapid changes in water vapor density occurring inside the portable chamber.

When the portable chamber is placed over a group of plants, the moisture transpired by the plants is trapped with minimal disturbance of the microclimate. The accumulation of water vapor in the chamber should increase at some steady rate, resulting in a curve of water vapor density versus time like that shown in Figure 2-3. The curve actually resembles a ramp. Temperature sensors must respond quickly to measure the change in the wet bulb temperature associated with the increasing water vapor density within the chamber.

In a mathematical model, electrical temperature sensors are first order instruments. Doebolin (1975) presented a simplified mathematical model of the response of a first order sensor to a step change and to a ramp change. Using the first order mathematical model, the following equation was derived for measurement error:

$$e_m = -q_{is}\,\tau\, e^{(-t)/\tau} + q_{is}\,\tau \qquad (6)$$

where

e_m = measurement error

q_{is} = rate of change of the measured quantity

τ = time constant

t = time

Figure 2-4 illustrates how a first order sensor will react to a ramp. The term $q_{is}\,\tau\, e^{(-t)/\tau}$ is the transient error and will disappear as time approaches 5τ as is seen by the curved line at the start of measurement. Eventually, the sensor tracks the input but is in error by a constant value $q_{is}\tau$, the steady state error. To effectively measure the value of a ramp input, a small τ, the time constant, is required to minimize the steady state error. A small τ will also reduce the time duration of the transient error, allowing measurement of the ramp to begin sooner.

The approximation of the time constant of the temperature sensors is important. Theory states that the value of the response of a first order instrument to a step input, will be eventually equal to the step. Further, theory indicates that τ, the time constant, will occur at 63.2 percent of response to a step input. This means that τ can be estimated from a plot of sensor response to a step input versus time.

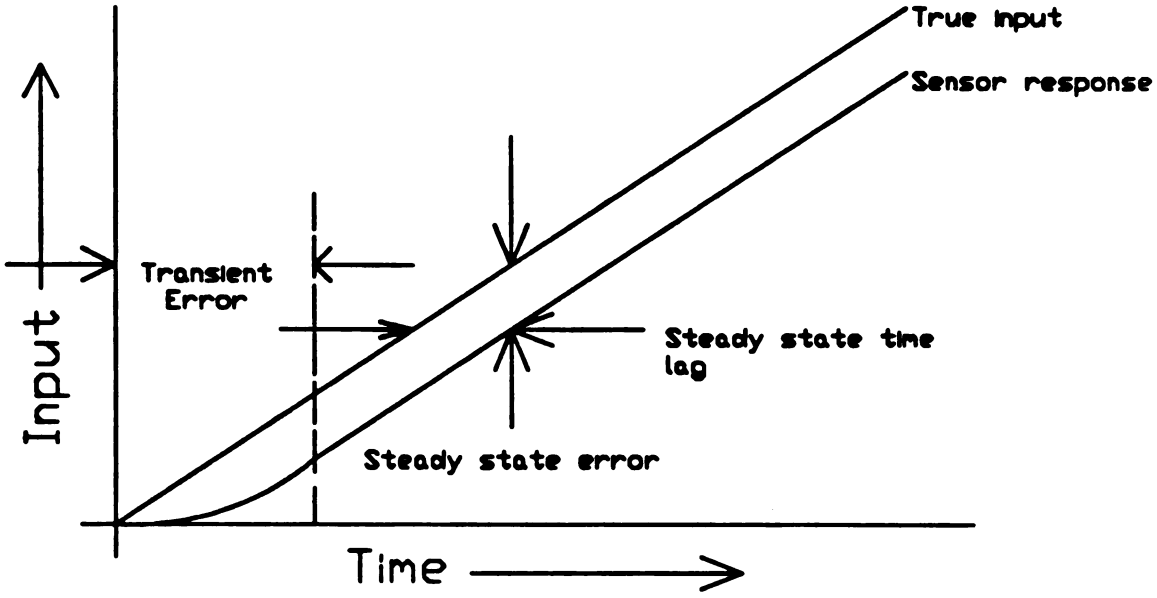

Figure 2-3 Theoretical response of a first order sensor to a ramp input.

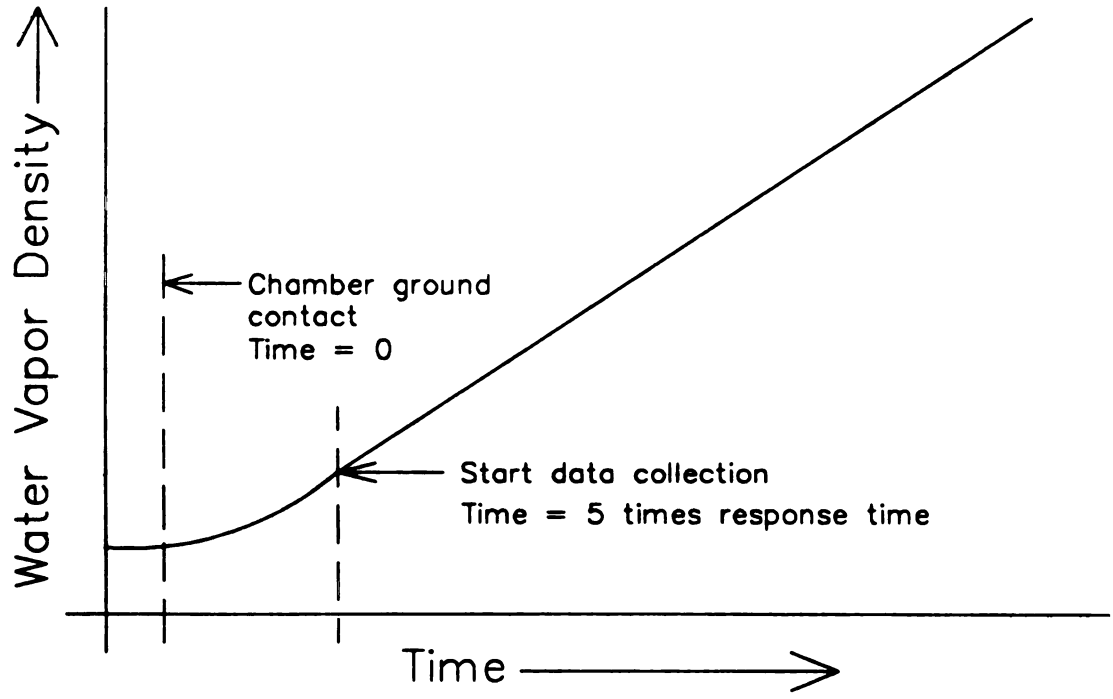

Figure 2-4 Theoretical accumulation of water wapor in the portable chamber during a field measurement.

2.4 METHODS

The purpose of this section is to describe the equipment and apparatus used to arrive at the results. This section will describe the data collection equipment, amplifier and transducer combination, calibration of transducers, and the apparatus for the step and ramp tests.

2.4.1 Data Collection Equipment

The data were collected with a microcomputer based analog to digital converter (A/D) . The computer and A/D were IEEE 696 S-100 bus, board-level components housed in an enclosure (Figure 2-5). The microcomputer card was a Cromemco Single Board Computer with a Z- 80 microprocessor. The computer card had a 4 kilobyte (K) BASIC interpreter, 3 parallel and 1 serial communications ports, and 2K of RAM memory. The A/D board was a Tecmar A/D 212 with input ranges of 0 to 1, 0 to 5, 0 to 10 and -5 to +5 volts. Resolution in any input range is ±1 part in 4096. A programmable timer on the A/D board provided time of day and sample timing. Additional memory for storage was provided by a California Computer Systems 16K static RAM board interfaced to the IEEE 696 system bus. Permanent data storage was supplied by a parallel port, interfaced digital tape recorder manufactured by ADPI. The tape was mounted on brackets inside the bus enclosure cabinet.

Software to drive the tape deck was written. Data collected was written to memory by a BASIC program. After measurements were taken, RAM memory holding raw data was written directly to tape for permanent storage. The IEEE 696 computer bus provided the power supply and communication bus for the computer board, A/D Board and the RAM memory board, as well as power and secure mounting for the digital tape deck. The microcomputer communicated with the user via a Texas Instruments Silent 700 thermal paper printing terminal connected to the serial port.

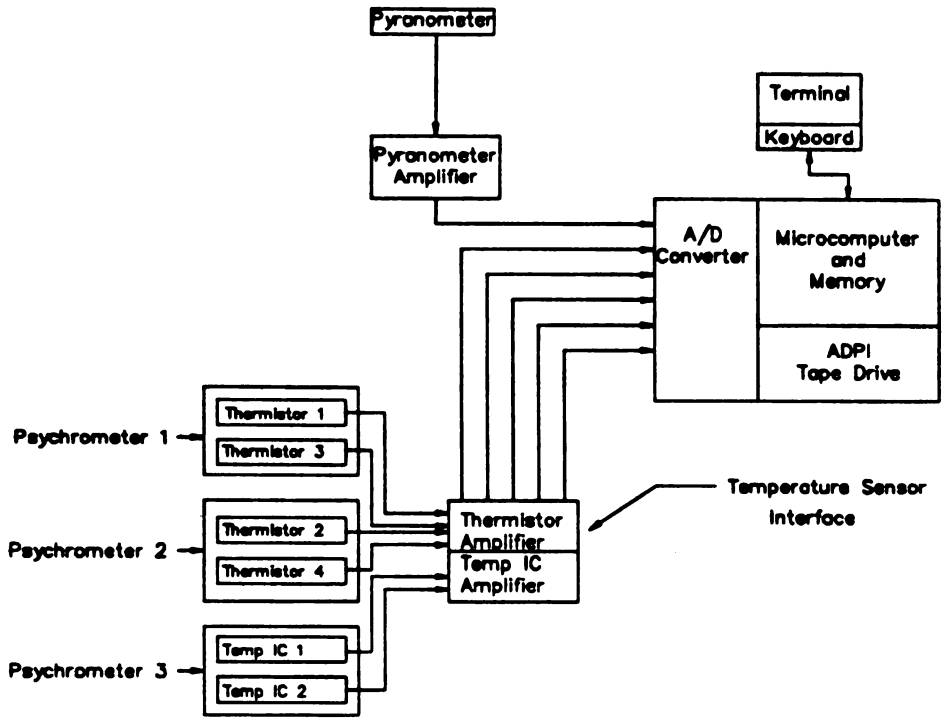

Figure 2-5 Block diagram illustrating components of the measurement transducer and data collection and recording equipment.

2.4.2 Transducer Construction Details

2.4.2.1 Thermistor temperature sensors

Two types of temperature transducers were used: 1) glass bead thermistors and 2) plastic encased temperature sensitive integrated circuits (IC's). Thermistor sensors were chosen because a small change in temperature causes a large change in electrical resistance. Thermistors, when coated with a thin layer of glass, are very rugged and can be made very small. However, thermistors have two drawbacks: 1) the resistance change with temperature is non-linear; and 2) the manufacturing resistance tolerance is high (±20%), requiring a complicated calibration process for each sensor.

By contrast, the temperature IC's are linear output devices encased in plastic housings used for transistors. The high thermal capacity of the plastic case slows response to temperature

fluctuations.

WARNING: The construction details for thermistor probes that follow describe how the probes were connected and interfaced to the A/D. The author strongly recommends **against** this procedure. Late in the study a source of affordable precision-matched thermistors with excellent resistance-versus-temperature characteristics and a low manufacturing resistance tolerance (±0.01%) permitting thermistor interchangeability, was discovered. The procedure outlined below will not result in the construction of interchangeable probes.

A thermistor acts like a temperature dependent resistor. As the temperature in the region of the thermistor and of the thermistor itself fluctuates, the resistance of the thermistor varies inversely. The goal was to create a temperature-dependent circuit with a voltage output in the 0 to 10 volt input range of the A/D converter. Specifically, the circuit output needed to span the A/D voltage input range for temperatures between 10 and 45°C. This range covered the field-specified range while allowing for some error.

An inverting operational amplifier circuit was chosen (Figure 2- 6). Substituting a thermistor (Raw thermistor beads of 20K±20% resistance were obtained from Thermometrics, Inc.) for the feedback resistor in the circuit created a temperature sensitive electronic circuit with an output characterized by the following equation:

$$V_{output} = - \frac{R_{th}}{R_{in}} (V_{input}) \qquad (7)$$

where

R_{th} = the thermistor resistance

R_{in} = the resistance of the input resistor

V_{input} = the input voltage to the circuit

V_{output} = the output voltage

Substituting actual values yields

$$V_{output} = - \frac{R_{th}}{220 \times 10^3} \quad (2.5) \qquad (8)$$

The size of R_{in} is a function of the heat dissipation constant of the thermistor and the excitation or input voltage. R_{in} was adjusted to provide current through R_{th} below the value necessary to raise the internal temperature of the thermistor above the specified precision of measurement (±0.01°C) due to self heating. The thermistor was active in the circuit. The self heating due to current flow was a function of the product of the square of the current through the thermistor and the resistance of the thermistor (Watts = current^2(resistance)). Maximum resistance occurs at the minimum temperature. If the current (I) allowed by R_{in}, squared, times the resistance of the thermistor (R_{th}) is less than the thermistor thermal dissipation constant (watts/sec), the self heating of the thermistor will not affect the temperature measurement.

Stage 1, Figure 2-6, created a negative output signal, eliminated temperature measurement error due to thermistor self heating, and provided a buffered output for Stage 2. Stage 2, Figure 2-6, provided positive offset voltage to the incoming negative signal, amplification, signal inversion, and passive filtering.

The negative output of stage 1 is not zero unless R_{th} is zero, an unlikely occurrence. The output of stage 1 needed to be offset to near zero at the minimum output voltage of stage 1 (R_{th} =

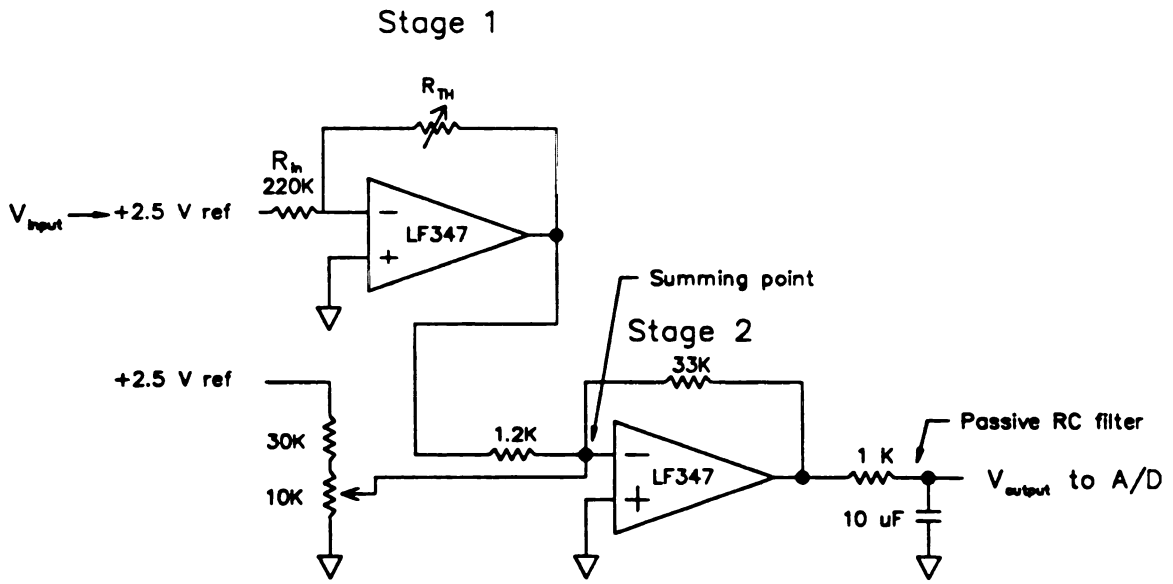

Figure 2-6 Thermistor temperature and amplifier circuit.

maximum resistance = temperature at minimum measured value). Stage 2 was connected to an adjustable voltage source constructed from a 2.5 volt reference in series with a 30 K±2% resistor and a 10 K potentiometer to ground. The adjustable leg of the potentiometer connected to the stage 2 input at the summing point. The 10 K potentiometer provided some adjustment of offset. A 30 K resistor was used to reduce the size of the potentiometer needed. This reduced the effect of component temperature variations on the output voltage because the temperature variability of the fixed resistor was much less (10 ppm/°C) than the potentiometer (200 ppm/°C) .

The output of stage 1 was amplified 27.5 times (after removing the offset) to match the 0 to 10 volt input range of the A/D for thermistor temperatures between 10 and 30°C. A desirable side effect was the inversion of the negative input signal.

The last job done in stage 2 was the filtering of noise from the signal. The original circuit board did provide two additional operational amplifier stages for active filtering, if necessary. The circuit design was simple and the expected environment did not warrant the use of an active electronic noise filter. A simple passive resistor-capacitor (RC) filter proved adequate.

2.4.2.2 Temperature IC's

At the field temperature (20°C), the output of the temperature IC was about 2.5 volts (10 mV/°K). The output voltage was offset to near zero with - 2.5 volt reference circuit (Figure 2-7). The resulting positive signal from the temperature IC was amplified with a non-inverting operational amplifier circuit to provide a signal in the 0 to 10 volt A/D input range for temperature IC temperatures from 10 to 35°C . The output of the amplifier was filtered with a passive RC filter identical to that used for the thermistors. The LM and LF part numbers specified in Figures 2-6 and 2-7 refer to National Semiconductor listings.

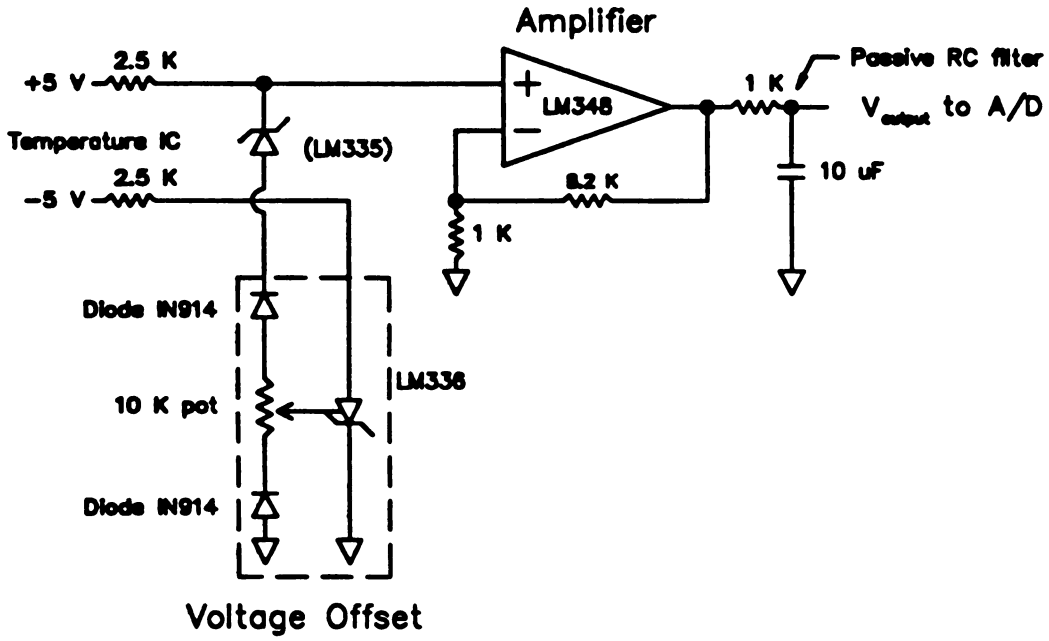

Figure 2-7 Temperature IC and amplifier circuit.

2.4.3 Psychrometer Construction Details

The psychrometer built for use with the portable chamber was a variation of that presented by Richardson (1971). It consisted of a 25.4 mm (1.0 inch) inside diameter plexiglas tube attached by one end to the center of the face of a 114 mm (4.5 inch) by 102 mm (4.0 inch) by 6.4 mm (0.25 inch) thick clear plexiglas block. A 25.4 mm (1 inch) diameter hole through the block, coaxial with the tube, provided a passage for a Ripley 12 volt DC squirrel cage fan to draw air through the aspiration tube. Two 63.5 mm (3.5 inch) wide by 102 mm (4 inch) long by 19 mm (0.75 inch) thick plexiglas pieces were sandwiched together and a hole the same size as the outside diameter of the plastic tube was bored lengthwise(Figure 2-8). Additional holes were drilled in the corners of the rectangular face of each sandwich piece and threaded to accept 6.4 mm by .78 threads/mm (1/4-20) bolts. One rectangular plate was fitted around the tube to the end plate. The end plate was drilled and tapped to secure the rectangular plate (the lower half of the sandwiched pieces) perpendicular to the end piece.

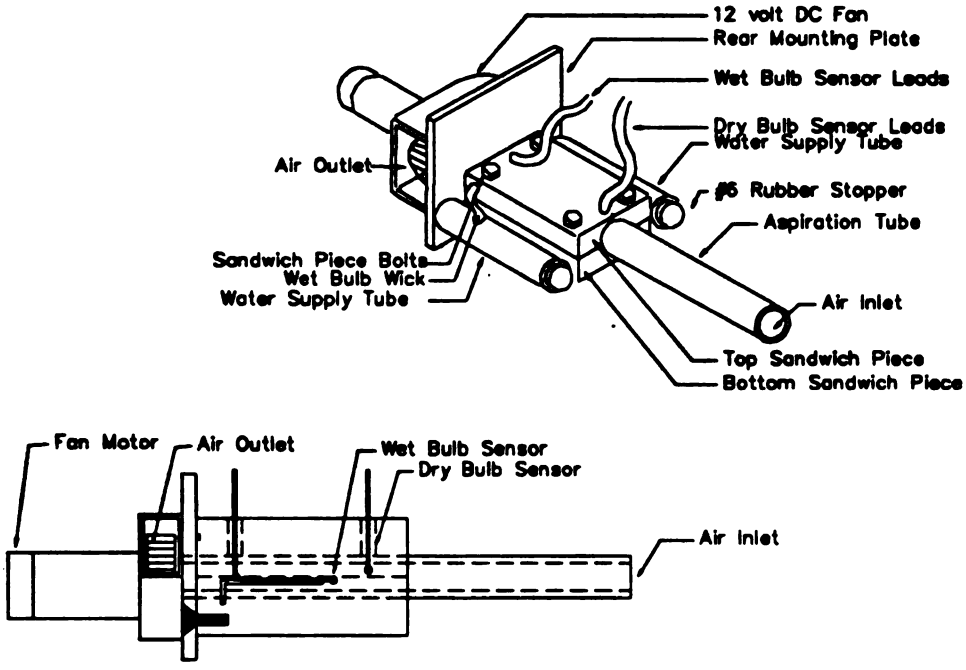

Figure 2-8 Aspirated psychrometer drawing.

The top half of the aspiration tube was removed 89 mm (3.5 inches) from the end plate to the end to facilitate sensor maintenance and mounting. The top half of the sandwich piece could then be put in place, sealing the aspiration tube. With the top sandwich piece off, holes were drilled to support a wire stand that allowed 38 mm (1.5 inches) of the wet bulb sensor, leads, and wick to be mounted transversely in the center of the tube. A hole drilled in the center of the bottom support plate allowed access for the wet bulb sensor leads.

The dry bulb sensor was positioned forward of the wet bulb by drilling a hole in the upper sandwich piece and inserting the sensor and leads through it perpendicularly, into the center of the air stream. The water reservoirs for the dual wicks were at either side of the bottom support piece and were made of 19 mm (0.75 inch) inside diameter by 89 m (3.5 inch) long plexiglas tubes, glued to the end plate at one end and plugged with a No. 6 rubber stopper at the other. A tube on each side was positioned to reduce water tension when full to less than 1 cm (0.39 inch).

A cotton shoelace wick passed from each water tube into the aspiration tube and was secured to the wet bulb sensor lead stopping very near the sensor tip. Two layers of facial tissue were layered over the surface of the sensor and onto the wick. The wick and tissue were wetted

with clean, distilled water and the water reservoirs were filled with distilled water.

For field use, a sun shade of 102 mm (4 inch) diameter corrugated drain tubing was painted white and fitted with two wire mounts that slid over the aspiration tube. Air drawn through the aspiration tube passed over the dry bulb, over the wet bulb, over the wick, through the fan intake, and was then exhausted.

2.4.4 Errors Associated with the Measurement System

The measurement system can be divided into three areas that may introduce measurement errors: 1) the temperature sensors; 2) the A/D converter and the amplifier circuits; and 3) the psychrometer assembly.

2.4.4.1 Temperature sensor errors and calibration

Errors caused by sensors are usually the result of bad calibration or no calibration. For this experiment, the temperature sensors had to be able to measure temperature within ±0.1°C with a repeatability of 0.05°C.

Both thermistors and temperature IC's were calibrated using the same technique. The field working range of temperature was 10 to 35°C, a temperature easily obtained using an insulated water bath. All temperature sensors were tied together in contact with either a mercury in glass thermometer calibrated to the nearest 0.05°C or a platinum resistance thermometer. Glass thermometers were used as a reference. Later, a platinum resistance thermometer was obtained. The platinum thermometer was chosen because " it is the accepted international standard for interpolating basepoint temperature in the range 195 - 650°C on the standard scale" (Course notes, Chem 372, 1980).

A small submersible pump placed in the water bath agitated the water continuously. Ice was added to the water bath to lower the water temperature below 10°C. The water bath temperature was increased in 0.5 to 1.0°C increments up to 40°C. The mixing pump increased the water bath temperature 0.10°C every 10 minutes providing a 30 second window for measurement of water temperature with an uncertainty of ±0.01°C .A measurement of the temperature either from the glass thermometer or the platinum thermometer was recorded along with the A/D

count for each sensor at each water bath temperature increment.

The data for each sensor consisted of a value between 0 and 4096 from the A/D and the measured water bath temperature. Initially nonlinear equations fit to the data were of the form

$$\ln R_T = \frac{1}{T} \qquad (9)$$

where

R_T = thermistor resistance (directly proportional to A/D counts)

T = Temperature ,°C

In practice, 1/T was replaced by a polynomial expansion of 1/T. The order of the polynomial was dependent on the temperature range and the nonlinearity between Ln R_T and 1/T (Sapoff, 1980).

On the basis of work by Campbell (1982), calibration curves were developed using a fifth order polynomial to approximate the temperature versus count relationship.

2.4.4.2 Measurement Instrument temperature drift

Measurement errors associated with electrical amplification and conversion equipment (A/D converter) are usually associated with changes in the operating temperature of the individual components. All electrical or electronic circuits vary their output as the individual components change temperature from the temperature at which the baseline measurements were made. Since the control of temperature in the field is difficult, the goal in building or choosing an electrical or electronic device to do data conversion is to reduce the temperature-dependent shift in output to a quantity less than the required precision of measurement, thereby minimizing temperature-induced errors. In this experiment, the maximum change in output induced by variation in field temperature should be less than 0.05°C.

During the growing season, the daily ambient temperature varies from 10 to 35°C. The response of the A/D and amplifier circuits vary with changes in ambient temperature. The components of the amplifier and A/D gain heat as a result of the heat generated by the electric current they consume. Heat generated by the computer and RAM memory card add to the heat load in their respective enclosures. If the enclosures are not shielded from direct radiation, additional ab-

sorbed radiation could raise the enclosure temperature significantly above ambient temperature. To combat temperature induced variations, components used to build the A/D and amplifier were selected to produce a worst case error less than the specified precision over the desired operating temperature range. Manufacturers generally report conservative specifications; therefore, the product meets or exceeds the specifications at least 50 percent of the time.

The A/D convertor's manufacturer's specifications easily met the field measurement requirement for temperature induced variation in the 10 to 35°C range. The amplifier circuits, built in-house, were suspect until tested.

A test of the variation of the measurement system with temperature was conducted using an environmental chamber. The thermistor temperature sensors, configured as resistive elements, could be easily replaced by fixed resistors with little resistance variance with temperature to determine if temperatures in the range of field conditions (10-35°C) would effect the A/D and amplifier circuit. The result of any measurement of temperature was a number between 0 and 4095 with 0 corresponding to a 0-volt output and 4095 corresponding to 10- volt output from the amplifier.

The thermistors were replaced by 18K±1% resistance, 10 ppm/°C resistors. The resistors substituted for the thermistors were selected to duplicate the thermistor resistance at the midpoint of the field temperature range (°C). The computer enclosure and amplifier box were placed in the environmental chamber. The computer, A/D, and amplifier were tested together because that was the field configuration. The output of the A/D and amplifier circuit were expected to remain constant when the temperature of the ambient air was in the 10-35°C range because the output of the voltage divider was constant. A ±1 count measurement error in the A/D converter was a function of the A/D converter conversion process. Additional counts were a function of A/D and amplifier temperature induced drift. Individual measurement channels on the A/D were checked to insure that estimates of error were conservative.

2.4.4.3 Errors associated with the psychrometer assembly

2.4.4.3.1 PSYCHROMETER ASPIRATION VELOCITY

The psychrometer construction details explain how several of the errors associated with use of psychrometers are reduced or eliminated. Proper choice of tube sizes and aspiration fans can eliminate the errors associated with inadequate ventilation of the wet bulb. Thus, the air velocity in the aspiration tube of the psychrometer was measured to ensure that it was adequate.

The measurements were made on a thermistor-equipped wet bulb psychrometer with an incline micro-manometer manufactured by E. Vernon Hill, Inc. A pressure tap was applied to the aspiration tube at a distance of four tube diameters from the inlet. The negative pressure developed in the tube was measured with the manometer referenced to atmospheric pressure. The pressure in mm of H_2O was converted to velocity using a nomograph supplied with the manometer.

2.4.4.3.2 PSYCHROMETER RESPONSE TIME TEST

After the psychrometer was built, the temperature sensors were calibrated, and the aspiration velocity of the psychrometer was tested, one more test was necessary before the psychrometer could be used in the chamber.

The goal of the psychrometer response time test was to determine the time constant, τ, for the psychrometer. To complete the test, a growth chamber 0.61 m (24 inches) wide by 1.52m (60 inches) deep by 0.91 m (36 inches) high was cleaned and the air inlet and outlets were sealed with plastic and tape. Inside the chamber, a 3.1 m^3/min (110 $ft.^3$/min) squirrel cage fan mixed the chamber air. A 3 cm^3 vial of water was dumped onto a small hot plate inside the growth chamber to simulate an instantaneous step change in water vapor density. Air from the chamber was drawn out a hole in the door through the psychrometer. By this means, a quantity of water could be evaporated into a "fixed" volume, continuously mixed, and sampled by the psychrometer. The intent of the experiment was not to establish an exact time constant for each psychrometer, but to verify the theoretically expected range of time constants and establish an estimate of how long to wait after chamber placement on a crop before starting a measurement.

2.5 RESULTS AND DISCUSSION

2.5.1 Thermistor Calibration Results

In this section the results of the attempts to calibrate each sensor are discussed. First, a discussion of the curve fitting procedure used and the criteria for assessing a good curve fit are presented. Next, a comparison of the reference thermometer to a commercial temperature probe is presented. The results of the curve fits for individual sensors for each of three days of calibration data are summarized, indicating the quality of a curve fit for a given sensor on a given day. A curve fit for each sensor using all the calibration data will be presented to assess the short term sensor stability and the accuracy range of each sensor. A comparison of a residual plot for sensors meeting the design criteria (0.05°C) with that of a sensor not meeting the design criteria will be presented to illustrate sensor short term drift.

2.5.1.1 **Curve fitting.**

During the course of data collection, the temperature sensors were calibrated many times for reasons varying from sensor breakage (glass covered beads) to seasonal recalibration. The calibrations discussed in this document are the result of data collected on 7/21/84, 7/23/84, and 7/24/84. These calibrations cover the interpretation of lab and field data presented in later chapters. Six sensors were calibrated: four thermistors and two temperature IC's. Polynomial curves were fitted to individual sensor calibration data in the 15 to 40°C temperature range.

The calibration of the raw thermistors yields a mathematical relationship between thermistor resistance at a given temperature (represented as a count from the A/D) and the temperature. The equations developed have a desired design error of ±0.05°C. Many forms of equations can be used to represent the relationship of thermistor resistance (A/D count) to temperature. A polynomial curve was chosen based on previous research and ease of computer fitting. The temperature range of the curve fit was sufficiently narrow (15 to 40°C) that little difficulty in obtaining a good curve fit was anticipated.

As a polynomial curve can be expanded to many terms, some criteria must be used to deter-

mine when additional coefficients are needed to explain variability. The data for each sensor on each day of calibration were fit to a curve with the BMDP statistical package. BMDP is a large group of statistical programs that use English-like control language and run on the Cyber 750 mainframe at Michigan State University. BMDP5R is a polynomial regression program capable of fitting 1 to 15 coefficients to a data set. BMDP5R prints several statistics which aid in determining when enough coefficients have been fit.

A standard F test can be performed on each coefficient. The numerator sum of squares is the sum of squares attributed to all higher degree polynomials. The denominator sum of squares is the residual sum of squares. A significant F value indicates that a higher order polynomial should be considered. The proper degree polynomial can be determined statistically by adding coefficients until the F test is either no longer significant at the chosen significance level or no improvement is seen. In general, a F value of two or less means that little improvement can be gained by adding another coefficient.

Although the F test is a good indicator of the number of coefficients to fit, the interpretation used in practice was slightly different. No specific level of significance was chosen for F; instead, the rate of improvement in the F value was used to indicate an adequate fit. When the magnitude of the F value decrease with an increase in polynomial coefficients became very small or nonexistent, no higher order coefficients were useful.

The residual values of a curve fit show the distribution of the error in the curve and are helpful for locating data points which are incorrect, biasing the resulting equation. The residuals illustrates the span of the data and the ability of the calculated polynomial equation to predict the temperature within some tolerance band.

2.5.1.2 Reference thermometer verification

To assure that the platinum thermometer was properly calibrated, a temperature probe manufactured by Campbell Scientific, Inc., of Logan, Utah was compared to readings from the platinum thermometer. The Campbell probe was used as a secondary temperature standard throughout the calibration. The Campbell probe was an interchangeable temperature probe with an accuracy of ±0.1°C and a reproducibility of ±0.05°C. The manufacturing tolerances of the

Campbell probe had to be very small to allow interchangeability with high accuracy and repeatability. For these reasons, the Campbell probe should have been very stable over periods of 1 to 2 months. If the platinum thermometer and the Campbell probe measured the same temperature, a polynomial regression should yield an equation with two coefficients, a slope, and an intercept. The F value should not show any significant improvement after the second coefficient.

The platinum thermometer was calibrated each time it was used. Three calibration points (ice point - 0.0°C; Na_4SO_4-Na_4SO_4-10 H_2O point - 32.38°C; and the boiling point of pure water - 100.0°C) were used to estimate the coefficients of the thermometer calibration equation. Slight inaccuracies in determination of a calibration point could have biased the calibration curve. Assuming that the Campbell probe was stable day to day, a plot of the residuals of a first order polynomial curve fit of the Campbell probe against the platinum thermometer was made (Figure 2-9). If the residuals are plotted by day of calibration, the relative merit of a given day's calibration data can be assessed.

The residuals for 7/21/84 and 7/23/84 lie very near or on top of each other, indicating little difference in the data for those days. The portion of the residual plot contributed by data taken on 7/24/84 appears to be shifted downward several hundredths of a °C, indicating some difference in the calibration data from that of the other two days. The range of the residuals was within the ±0.05°C design error band with one exception. Therefore, the platinum thermometer readings are acceptable for use as calibration points for the sensors.

2.5.1.3 Daily calibration equation development

Polynomial curves for each of the six sensors were developed from the calibration data taken on 7/21/84, 7/23/84, and 7/24/84, resulting in three equations for each sensor. From the residuals for each sensor (not shown) on each day, an estimate of the individual sensor error was developed. Three groups were created: sensors with 90 percent of residuals less than ± 0.05°C, sensors with 90 percent of residuals less than ± 0.1°C, and sensors with 90 percent of residuals >0.1°C. These groups corresponded to the design error band, twice the design error band, and greater than twice the design error band.

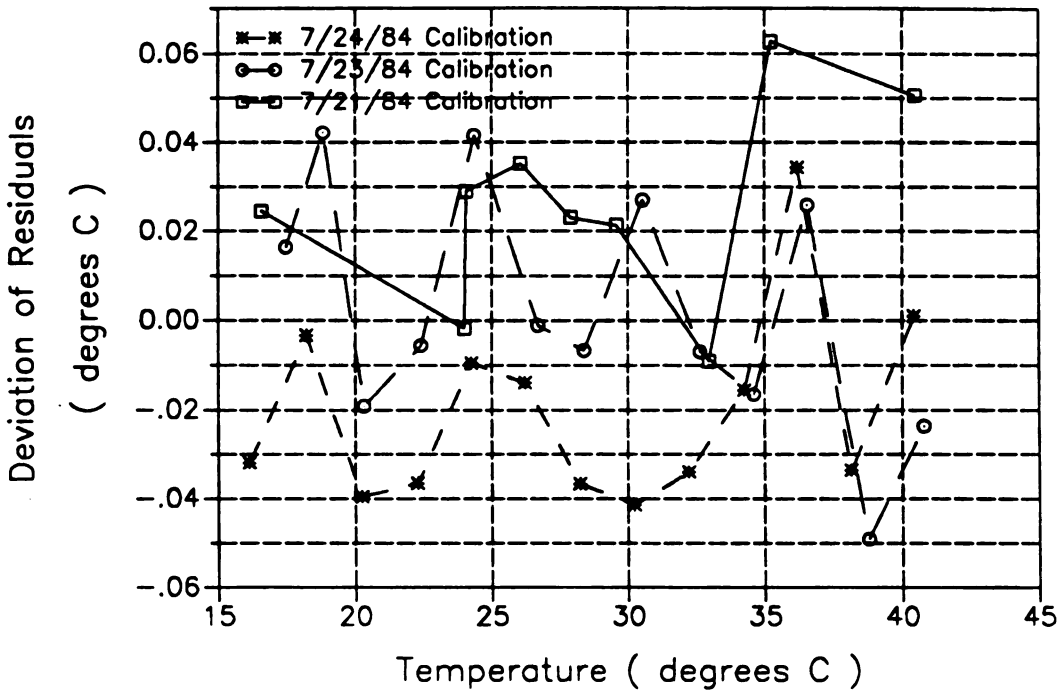

Figure 2-9 Residual Plot for the Campbell thermistor probe vs a platnium resistance thermometer for 3 calibration tests.

The results of the analysis of the residual showed all sensors to be within the design error band (90 percent of all residuals ±0.05°C) for data taken on 7/23/84 and 7/24/84. Data taken on 7/21/84 showed sensors 1,2,and 4 to be in the ±0.05°C band, with 3,5, and 6 in the ±0.1°C band. Difference in the time between reading on 7/21/84 and 7/23/84 or 7/24/84 account for the daily calibration differences. On 7/23/84 and 7/24/84, 90 seconds were allowed before a measurement, in contrast to a 30-second equilibrium time on 7/21/84. It is probable that the platinum thermometer was not at equilibrium with the water bath on 7/21/84.

The results of the daily calibration were good, indicating acceptable calibrations, but each calibration equation was slightly different for each sensor on the 3 days of calibration.

2.5.1.4 Pooled calibration data interpretation

In this section equations are fit to the pooled temperature data for each sensor. An estimate of the sensor performance is made from the plot of the residuals for each sensor and an estimate of the quality of the calibration data is presented.

Pooling the data from the daily calibrations can help to indicate short term instability or drift for a given temperature sensor and expand the measurement error information significantly. Equations derived from the pooled data helped determine if the sensors and amplifiers had any significant short term drift that would cause data interpretation errors in lab and field tests.

Each sensor was fitted to the pooled calibration data with a polynomial expansion. As before, lack of reduction of the F statistic for added coefficients was used to determine the number of coefficients to fit. The quality of the fit and an estimate of sensor accuracy was made by observing the pattern and range of the residuals.

A plot of the predicted temperatures for a thermistor and a temperature IC sensor against A/D count illustrates the nonlinearity of the thermistor temperature sensor (Figure 2-10). The thermistor temperature sensors predict larger temperatures as the count from the A/D decreases. The temperature IC, on the other hand, predicts increasing temperatures with increasing A/D count. The nonlinear, inverse relationship of the thermistor temperature sensor to A/D count made approximations of the predicted temperature without the polynomial equations very difficult.

The polynomial curve fit for sensor 5 yielded residuals well outside the ±0.05°C design error band (Figure 2-11). The residual plot clearly showed a pattern of separation of residuals by date of data collection. Comparing the residuals for sensor 5 calibration to the residuals for sensor 2 (Figure 2-12) brings the magnitude of the temperature error for sensor 5 was brought into perspective. Sensor 5 was not stable under the calibration conditions on a daily basis. Sensor 5 must be assumed to have an error band of ±0.5°C, approximately ten times the design value. Sensors 1, 2, and 4 were within the design error range, sensors 3 and 6 were less than 2 times the design error range, and sensor 5 was outside the design error range consistently. Analysis of the residuals of sensor 5 compared to a typical residual plot (sensor 2) indicated day to day shifts in sensor 5 were occurring. The error in sensor appears to be a construction flaw in the bead to

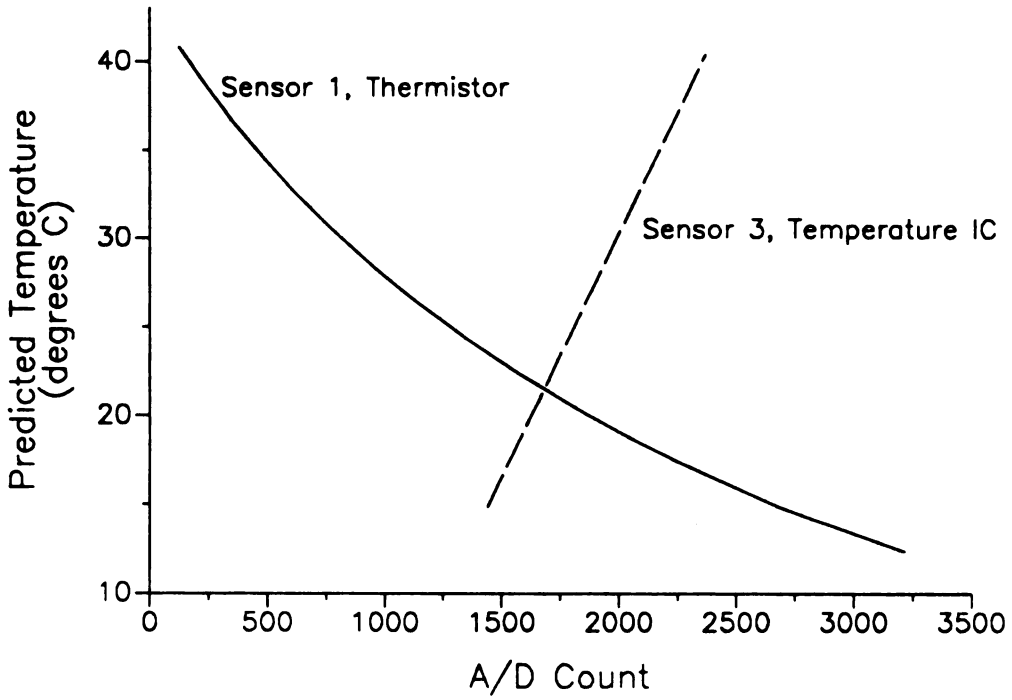

Figure 2-10 Predicted thermistor and temperature IC sensor temperatures versus A/D count for sensors 1 and 3.

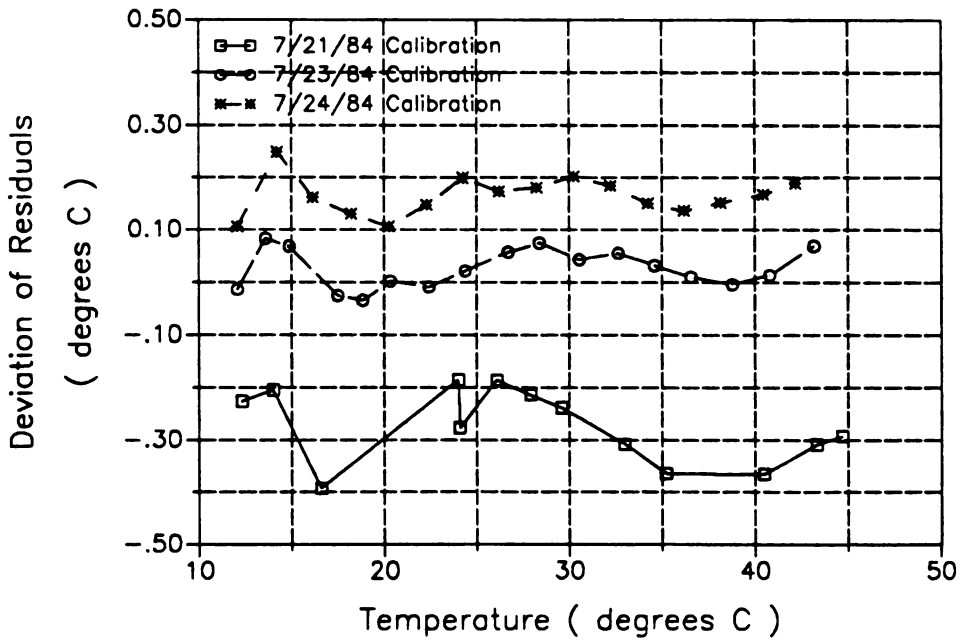

Figure 2-11 Residuals vs platnium resistance thermometer temperature for sensor 5 from a single polynomial cure fit using the pooled calibration data from 7/21/84, 7/23/84, and 7/24/84.

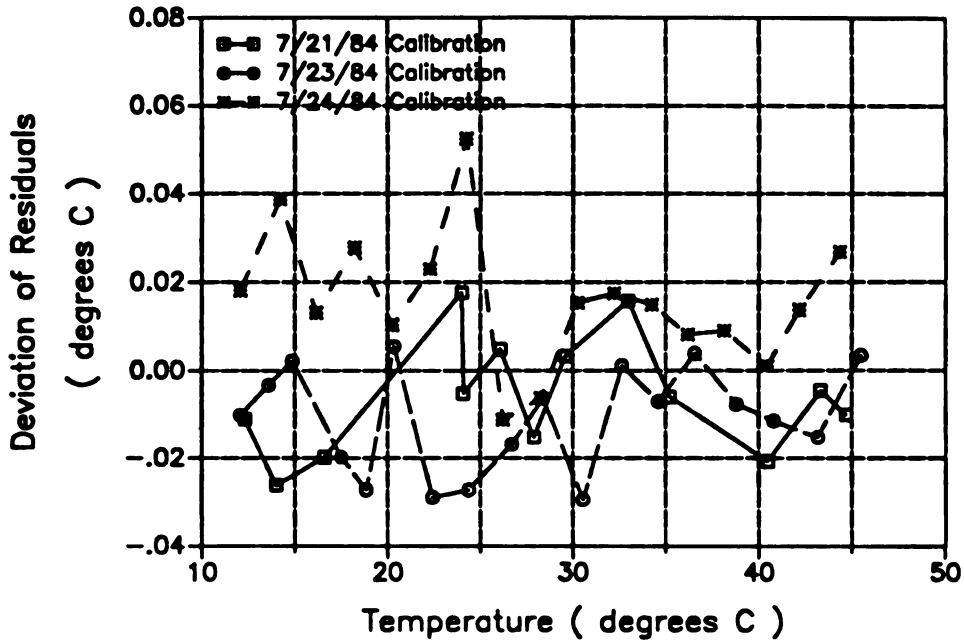

Figure 2-12 Residuals vs platnium thermometer temperature for sensor 2 from a single polynomial cure fit using the pooled calibration data from 7/21/84, 7/23/84, and 7/24/84.

lead wire seal, allowing water leakage into the thermistor electrical connections.

The sensors were grouped into three accuracy bands: those with 90 percent of residuals ±0.05°C, 90 percent ±0.1°C, and 90 percent >0.1°C. Sensors 1, 2, and 4 were ±0.05°C, 3 and 6 were ±0.1°C, and sensor 5 was> 0.1°C (±0.5°C,).

Pairing of temperature sensors in a psychrometer is important. The wet bulb sensor should be the temperature sensor with the greater accuracy because errors in the wet bulb temperature measurement contribute more to the measurement error than does a similar error in dry bulb temperature measurement. Using the results of the grouping of residuals from the polynomial curve fits the following wet bulb - dry bulb pairing of psychrometers was developed: thermistor sensors 2 and 4 in psychrometer 1; thermistor sensors 1 and 5 in psychrometer 2; and temperature IC sensors 3 and 6 in psychrometer 3.

The polynomial equations derived from the pooled calibration data will be used to calculate temperatures from the field A/D count data. They are listed, by sensor, in Appendix 1.

2.5.2 Measurement Instrument Temperature Drift

The purpose of this test was to determine the amount of error in a given measurement resulting from the A/D and amplifier circuits being at a temperature different than the calibration temperature (20°C).

Table 2-1 shows the error in temperature measurement due to variation in the temperature of the components that comprise the measurement system other than the thermistors. The approximate temperature error was calculated as the difference of the calculated temperature from the A/D count at room temperature (20°C) and the temperature calculated from the A/D count at the test temperature.

At 10°C all thermistor amplifier circuits and A/D channel temperature errors were less than 0.05°C. At the other end of the field temperature range, 40°C, all amplifier circuits exceeded the 0.05°C target. The deviation was not judged large enough to warrant redesign of the amplifier circuit. Instead, a field radiation shield for the amplifier and computer box was constructed, and the amplifier box was insulated with 19 mm (0.75 inch) foam. This was done to reduce the possibility that the computer and amplifier box would experience high internal temperatures due to heat gain from incident solar radiation. Clearly, as the temperature of the amplifier and A/D components increases, the temperature measurement errors increase, but given the measures taken to minimize additional heat load, the current design is acceptable.

Table 2-1. Temperature measurement error induced by temperature variations between 10 and 40°C

Temperature	10°C	40°C
Sensor	Error (°C)	Error (°C)
1	-0.02	+0.06
2	-0.02	+0.06
3	-0.02	+0.06
4	-0.02	+0.06

2.5.3 Errors Associated with Psychrometers

2.5.3.1 Psychrometer aspiration velocity tests

Measurements of the air velocity in the thermistor-equipped wet bulb psychrometer are summarized in Table 2-2. The aspiration velocity test was performed to verify that the psychrometer tube inside diameter and aspiration fan air capacity resulted in an air velocity in the tube of greater than 3 m/sec.

Manometer measurements were taken at three fan input voltages. The lowest voltage (10.5 volts) represented a discharged 12-volt DC lead acid battery at the minimum potential before damage to the battery is permanent. The highest potential (13.5 volts) represented a battery at maximum charge.

Table 2-2. Relationship of the aspiration motor to the air velocity in the vicinity of the wet bulb.

Voltage	Manometer	Velocity
	mm, H_2O	m/sec
10.5	3.3	7.2
12.0	4.3	8.3
13.5	5.3	9.1

The manometer readings were not adjusted for air density because the measured values were twice the minimum 3 m/sec required for full wet bulb depression. Air density correction affects the measured value by a maximum of±20 percent. The psychrometer design clearly met the minimum air velocity requirement to obtain full wet bulb depression at all expected fan excitation voltages.

2.5.3.2 Psychrometer response time test

The purpose of the psychrometer step test was to determine the time from the introduction of a change in water vapor in the air passing through the psychrometer until an accurate measurement could be made. The time lag until measurement is a function of the transient error duration which can be approximated by five times the wet bulb sensor's response time (Doeblin, 1975).

Response times for thermistor and temperature IC's were estimated using graphical solutions (Figure 2-13). The sensor temperature was plotted against the time of measurement. The magnitude of the step was determined from the data. Using maximum and minimum temperatures from the measurements, the value of temperature at 63.2 percent of the step temperature change was determined.

The response of the wet bulb for both thermistors and temperature IC's was faster than the dry bulb (Table 2-3). Although the response time of the temperature IC wet bulb was longer than the thermistor, the temperature IC was still usable. The delay before beginning measurement should be five times τ to reduce the transient error and measure the true response. Using the wet bulb as a conservative estimate of psychrometer response, a time delay of 18 seconds should be allowed before assuming data from a thermistor is valid. For the temperature ICs, a delay of 47.5 sec was required. The serviceability of the temperature IC was marginal for fast responding systems. The longer response time was probably due to the greater mass of the temperature IC when compared to the thermistor. An alternative package could reduce the mass significantly, thereby reducing the thermal lag caused by the current package.

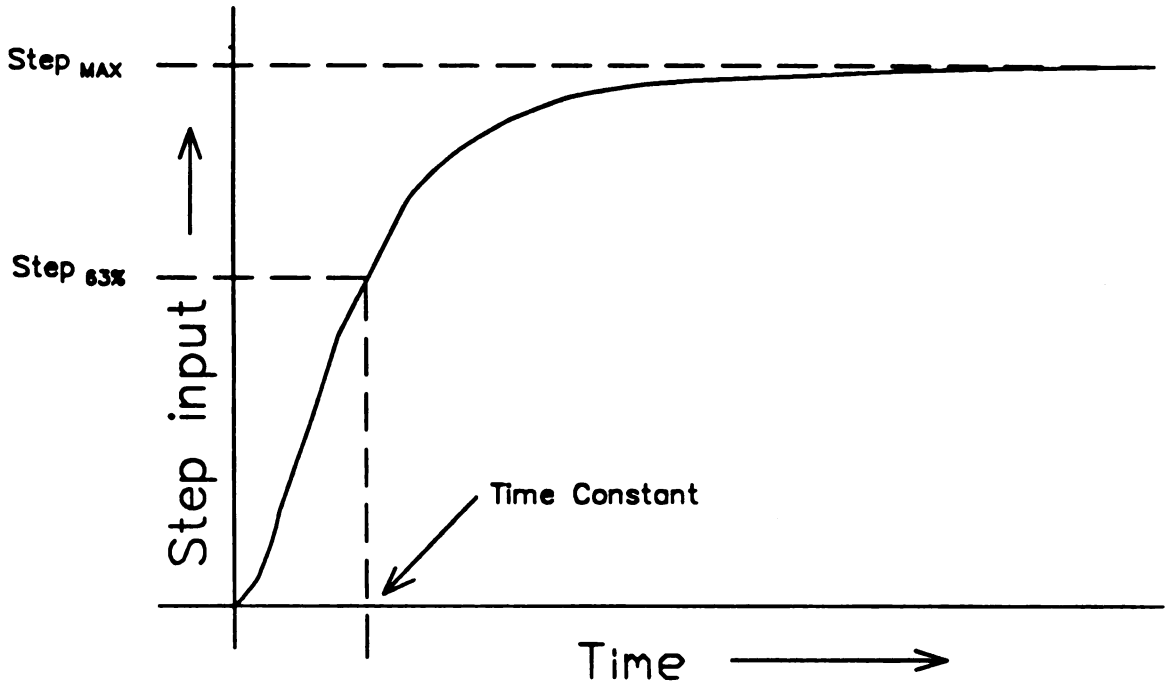

Figure 2-13 Graphical solution technique for estimation of τ.

Table 2-3 Response times (τ) of thermistor and temperature IC equipped psychrometers.

	Response Time	
Sensor Type	Wet bulb (sec)	Dry bulb (sec)
Thermistor	2.5	3.6
Temperature IC	8.5	9.8

CHAPTER 3

LABORATORY EXPERIMENTS

3.1 OBJECTIVE II

The second objective was to study the chamber-transducer system used to measure increases in water vapor density in the chamber.

3.2 INTRODUCTION

In this section, the chamber-transducer system is described, including the fans used for mixing air, the plastic chamber cover, the foam ground seal, and the three psychrometers. A description of the equipment used to create step and ramp inputs of water vapor into the chamber and the results of the step and ramp tests for specific water vapor densities is presented.

3.3 METHODS

3.3.1 The Portable Chamber

The discussion and description of the test equipment thus far has centered on the data collection and storage equipment, including the microcomputer, terminal, A/D convertor, ADPI tape drive, and the psychrometers.

A description of the chamber design used in the first season of data collection was given by Harmsen (1983). The following description details the most recent chamber design. Experience during the first year spurred redesign of the original chamber to improve transportability and serviceability, and to repair damage caused by a mechanical failure which partially crushed the original chamber.

3.3.1.1 Frame

The new chamber was built in modules. Rectangular frames 1.22 m (48 inches) by 1.5 m (60 inches) were constructed for the top and bottom frames from 25 mm (1 inch) 18-gauge (thin wall) square steel tubing. Side poles of 25 mm (1 inch) 18-gauge square tubing were cut in lengths of 1.2 m (46 inches), 2.4 m (84 inches), and 3.6 m (141 inches). Eighteen-gauge square tube pegs 22 mm (7/8 inch) on a side by 102 mm (4 inches) long were welded to the corners of the top and bottom rectangles, forming posts over which the 25 mm (1 inch) square tube poles fit. The pole length was matched to the crop height to construct chambers of appropriate dimensions. Diagonal cross braces equipped with turnbuckles gave the frame rigidity and provided square adjustment (Figure 3-1).

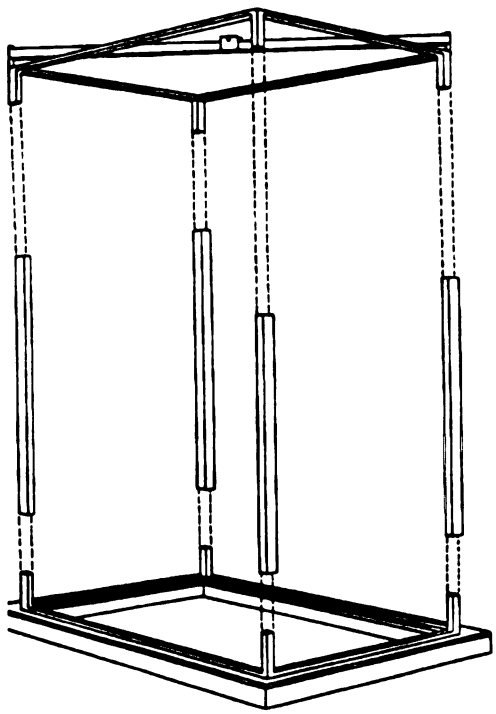

Figure 3-1 Chamber base and frame construction detail.

3.3.1.2 **Base**

The ground seal was made from oak stock 19 mm (3/4 inches) thick by 89 mm (3 1/2 inch) wide. The oak frame itself was 1.17 m (46 inches) wide and 1.47 m (58 inches) long. Upholstery foam, 89 mm (3 1/2 inch) wide by 102 m (4 inch) thick, was glued to the face of the oak frame. The oak frame was secured to the chamber base tube frame with 6.3 mm (1/4 inch) diameter bolts which passed through the frame and the oak base, to a tee nut fastener. This blind fastener allowed the frame to be easily removed or replaced if it became damaged.

3.3.1.3 **Covering**

Ideally the chamber covering should transmit all incident radiation in the 0 to 16 micron wave length. A summary of various coverings used by other researchers was presented by Harmsen (1983). His findings indicated the need for a flexible covering material for use on the modular chamber. Work by Sestak et al. (1971) suggested that a polyvinylindene chloride coated polyprolene (propafilm C) film was desirable because of its ability to transmit substantially greater quantities of infrared radiation than other films. A comparison of the transmission of radiation in the 2.5 to 16 micron range for propafilm C, Plexiglas, and lexan, showed an integrated average transmissivity of 75 percent for propafilm C, but only 10 percent for lexan and Plexiglas. Propafilm C was chosen for this system to minimize the trapping of re-radiated infrared energy within the chamber. The propafilm C was wrapped around the skeleton and secured to the chamber uprights with double stick tape. This method of attachment provided easy replacement of the sides or top when torn or dirty and provided an excellent seal. For the 2.4 m (96 inches) and 3.6 m (141 inches) tall chambers, five cm (2 inch) wide scotch tape was used to seal the seams of stacked widths of 1.2 meter (48 inch) width propafilm C.

3.3.1.4 **Fan placement and air mixing**

To accurately measure water transpired by plants in the chamber, no vapor gradient can exist. Fans were used to provide a uniform mixture of air and water vapor during measurement.

For the step and ramp tests, two axial flow fans powered by 12 volt DC motors with 0.41 m (16 inch) blade diameters rated at 64 m^3/min (2275 cfm) each were used. The axial fans were mounted on ball joint supports 0.30 m (1 foot) down from the top of vertical poles diagonally opposite each other. The ball joint mounts allowed the fans to be easily positioned to obtain maximum mixing.

3.3.1.5 Sensor mounting

Three psychrometers, two equipped with thermistor temperature sensors and one with IC temperature sensors, were mounted on a tee bar. The top of the tee was attached to the top of the chamber frame at the midpoint of the long side, with the leg extending downward 0.46 m (18 inches). Each psychrometer was mounted on a different face of the downward protruding bar, creating a tree of psychrometers with the inlets 114 mm (4.5 inch) and 90 degrees apart.

3.3.1.6 Supports

Raising and lowering the chamber over a crop canopy was accomplished by adding a 25 mm (1 inch) square steel tube with 32 mm (1/8 inch) walls which spanned the top rectangular frame diagonally. Holes were drilled in two opposite corners to accept 152 mm (6 inches) of 13 mm (1/2 inch) diameter threaded rod. The diagonal support rod was drilled at both ends and bolted to the threaded rods. An attachment bracket and pin at the center of the bar provided a point for connection of a lifting cable (Figure 3-1). The chamber was properly balanced by adjusting the support bar at the corners while the chamber was suspended.

3.3.2 Step and Ramp Tests

The purpose of the step and ramp tests was to determine if the transducer-chamber system could accurately measure a known change in moisture content introduced instantaneously or gradually over a short time. It was felt that before the measurement system could be used in the field, it had to function adequately in the laboratory. The step and ramp tests were used to validate the chamber's performance and applicability in practice.

3.3.2.1 **Step test**

In this section, the equipment and techniques used to introduce liquid water into the chamber air volume, the fan placement and air mixing, and the water quantities used are described. The equipment for performing the step test included a 0.91 m (36 inch) tall chamber equipped with axial fans, the foam base, and the psychrometers and associated electronics, including the microcomputer.

The purpose of the step test was to determine the response of the chamber-transducer system to a known pulse of water vapor. In theory, rapidly changing the water vapor density of the air within the chamber a known amount should provide an estimate of the system response time. Of more importance to this research was the ability of the transducers to accurately measure the volume-equivalent of moisture introduced into the chamber.

3.3.2.1.1 WATER INJECTION EQUIPMENT

Additional equipment was required to "inject" the water vapor directly into the chamber. A crude water injection system was constructed using a 1500 watt stainless steel frying pan as an evaporating surface attached to a painted plywood base (Figure 3-2). A hole in the center of the base provided access to the frying pan surface. The injection system consisted of a medical syringe, of appropriate size for the desired sample, coupled to a length of tygon tube. The tygon tube ran to a loop of 0.9 mm (0.035 inch) diameter teflon tubing. Small holes 0.4 mm (0.015 inch) in diameter and 25 mm (1 inch) apart were made around the loop. A water source connected to a three-way valve in the tygon tube, between the loop and the syringe, permitted the syringe to be refilled without disconnecting the tube. The loop of teflon tubing was suspended over the frying pan surface with the outlet holes toward the hot pan. The syringe was repeatedly filled with distilled water and the tubes charged with water until all air bubbles were forced from the tubes and syringe. Using a properly sized syringe, a known volume of water could be discharged on to surface of the frying pan for rapid evaporation, crudely imitating a step input. Surface tension of water retained in the tygon and teflon tubing prevented water from dripping out the holes onto the frying pan surface after the syringe had been emptied.

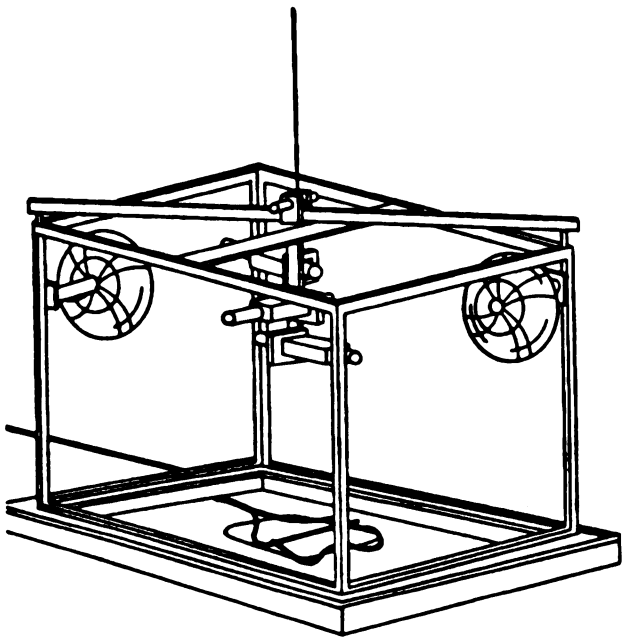

Figure 3-2 Chamber and water injection system used for laboratory tests.

3.3.2.1.2 FAN PLACEMENT

Two 0.41 m (16 inch) diameter axial fans were used to mix air in the 0.91 m (36 inch) tall chamber. The fans were located 0.30 m (12 inches) down from the top of the chamber in opposite corners. Ball joint fan mounts were adjusted to create a swirl of air in the chamber center. The fans were operated at both high and low velocities to test the affect of air mixing velocity on the accuracy of the measurement of water vapor within the chamber.

3.3.2.1.3 TEST PROCEDURE

The axial fans provided a free air mixing rate of 62.6 m^3/min (2235 cfm) each. Distilled water in 2, 15, and 30 cm^3 volumes was delivered to the hot plate as rapidly as the injection system allowed. The time required to empty the syringe and the time to evaporate all water from the

frying pan was recorded. Wet and dry bulb temperatures were recorded for 2 minutes. After each test, the chamber air was purged. Additional fans in the vicinity of the experimental setup were used to circulate room air. Five repetitions of each volume were completed.

The fan voltage was reduced to 8 volts DC, reducing the air mixing velocity by about one half(31 m^3/min). The step test, as described above, was repeated.

3.3.2.2 **Ramp test**

The purpose of the ramp test was to determine the response of the chamber-transducer system to a known ramp input of water vapor. The ramp test best simulated the expected response of plants transpiring in the chamber. Supplying water vapor to the chamber at a known rate and volume provided an estimate of psychrometer performance and data for creation of calibration curves, if needed.

The equipment for the ramp test was the same as for the step test with one exception. The syringe used to inject water in the step test was replaced by a 50 cm^3 burette. The stop cock of the burette was used to control the flow rate of input water. The volume of water introduced into the chamber was measured to the nearest 0.1 cm^3.

The axial mixing fans were driven at 12 volts DC, providing free air mixing rates of 62.6 m^3/min (2235 cfm). Distilled water in 2, 4, 8, 15, and 30 cm^3 quantities was delivered to the hot plate. The flow of water delivered to the hot plate was controlled to supply the desired volume in 60 seconds. The time required to evaporate all water from the frying pan was recorded. Wet and dry bulb temperatures were recorded for two minutes. After each test, the chamber air was purged with the fans. Additional fans near the experimental setup were used to circulate room air. Five repetitions of each configuration were completed.

The fan voltage was reduced to 8 volts DC, effectively reducing the motor rpm and the fan air throughput by about one half. The ramp test, as described above, was repeated.

3.3.2.3 Calculations

To determine the change in the chamber moisture content, the raw count data from the A/D converter was first changed to temperature in degrees centigrade. Then, the wet bulb temperature was used to calculate the saturated vapor pressure (e) in Pa, using the following equation by Dilley (1968):

$$e = 610.78\ EXP\left(17.269\ \frac{T_{wb}}{T_{wb} + 237.3}\right) \qquad (10)$$

The actual vapor in Pa was calculated with the equation by Ferrel (1865) as reported by Harrison (1963a):

$$e^{\circ} = e - [65700(P)(T_{db} - T_{wb})(1 + 0.00115T_{wb}) \qquad (11)$$

where e° = Vapor pressure, Pa

P = barometric pressure, Pa

T_{db} = dry bulb or ambient temperature, °C

T_{wb} = wet bulb temperature, °C

The volume of water in the chamber was calculated by

$$cm^3 = 18.0\ e^{\circ}\left(\frac{V}{RT\rho}\right) \qquad (12)$$

where cm^3 = volume of water in chamber

V = chamber volume in cm^3

R = , the gas constant, in Pa-cm^3 / mole-K

T = temperature in °K

ρ = density of water = 1g/cm^3

If the depth of water accumulated in the chamber is needed, as it is for the rate calculations for the ramp experiment and the field data, the perfect gas law is used but the volume of water calculated is divided by the ground area covered by the chamber in cm^2.

$$\text{Depth} = 180\ VP\left(\frac{V}{ART\rho}\right) \qquad (13)$$

where: Depth = equivalent depth of water over the chamber base area, mm

A = area of chamber base, cm^2.

3.4 RESULTS AND DISCUSSION

In this section, the results of the step and ramp tests are presented. An explanation of data that was excluded from further analysis is also provided.

Data needed to be excluded because of a calculation error when preparing the experiment. The step test methodology listed water input of 2, 15, and 30 cm^3. The 30 cm^3 test far exceeded the field evapotranspiration (ET) levels. A 20 cm^3 input would have better represented the largest volume of water accumulated in one minute field tests in the semi-humid climate of Michigan. Determining the function of the psychrometers at this, or higher input volumes, was of no value for comparing input volumes with measured water volumes. However, initial analysis of the 30 cm^3 data does provide some insights that, though irrelevant to the construction of calibration curves, does merit discussion.

3.4.1 Experimental Apparatus Induced Error

Figure 3-3 shows a plot of the data for psychrometers 1, 2, and 3 at 2, 15, and 30 cm^3 water input levels. Ideally, the addition of water vapor to the chamber should produce a one- to-one line passing through the origin. The straight line regression curve is clearly not the best type of curve to match this data. The slope of the linear regression curve is far from one. The curvilinear dashed line representing a second order polynomial equation passes through the center of each cluster of data points and is noticeably better. The figure shows that the psychrometers did not measure the theoretical step volume inputs correctly and the result was too low an estimate of the input volumes.

Calculation of the chamber saturation moisture content and subtraction of the moisture content at the starting wet and dry bulb temperatures yields a theoretically maximum possible addition of moisture for the chamber in cm^3. For all repetitions at 30 cm^3, the input moisture exceeded

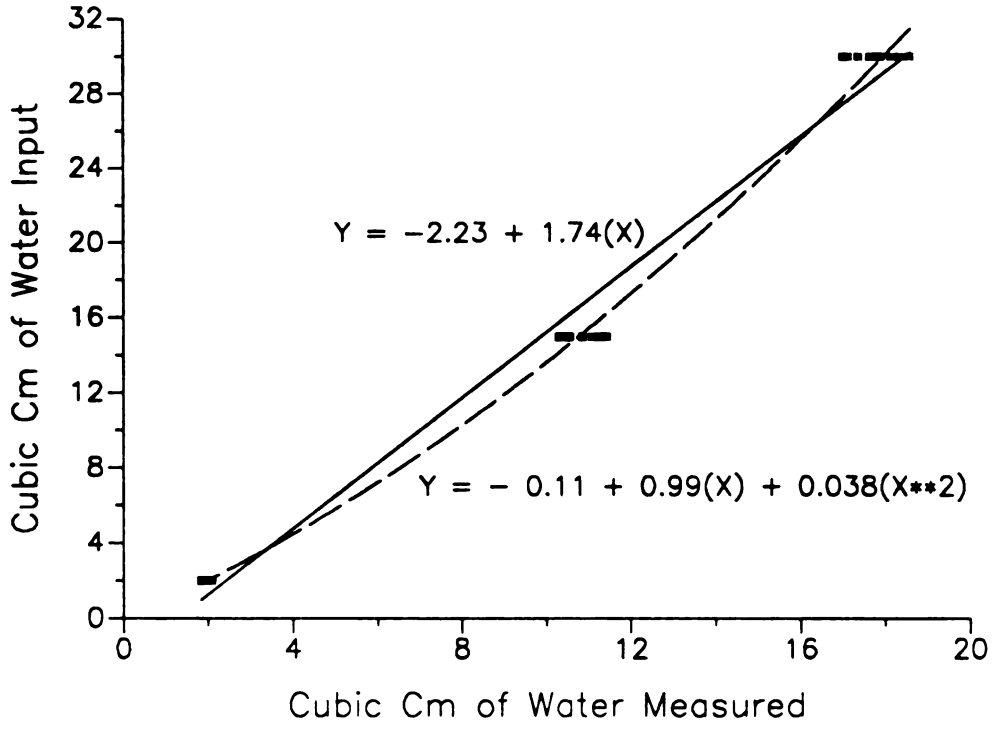

Figure 3-3 A plot of the pooled 2 ,15, and 30 cm^3 step input data for psychrometers 1, 2 and 3 fit to first and second order polynomial equations using a least squares technique.

the capacity of the chamber to hold moisture, thus saturating the chamber. At both high and low air mixing velocities (nine repetitions), the measured moisture content of the chamber was less than the input moisture volume. At the end of a repetition, the dry bulb temperatures had increased 2 to 3 degrees C. The increase in the temperature of the dry bulb was first attributed to heating of the ambient air by the frying pan surface after all the water had been driven off, but before the end of data collection for a given repetition. A computer program was written to test the calculations used to determine chamber moisture content. After comparing the program results with values from a psychrometric chart, the program was pronounced correct.

The program was modified to iterate to the correct final wet bulb temperature for a given increase in chamber moisture content. The program inputs were the starting wet and dry bulb temperatures and the end dry bulb temperature. The starting wet bulb temperature was increased 0.01 degrees C until the calculated final moisture content was equal to the starting moisture con-

tent plus the desired increase. For all runs at 30 cm^3, at high and low air mixing velocities, the calculated final wet bulb temperature was within 0.05 degrees C of the measured final dry bulb temperature. The chamber must have been saturated.

Figure 3-4 shows the wet and dry bulb values while Figure 3-5 shows the moisture accumulation in cm^3 calculated from the wet and dry bulb temperatures at each sample point. Analysis of Figures 3-4 and 3-5 suggests that all the water driven off the frying pan did not evaporate. If the water had evaporated as planned, the water accumulation curve of Figure 3-3 would have been a smooth line.

There are several explanations that could account for some of the "missing" water:

1) atomization of water prevented it from entering the vapor state;

2) psychrometers become unreliable at relative humidities in excess of 90 percent, as Tanner (1971) reported that Wylie (1968) found. This is clearly the case in all the tests if atomization is not a factor;

3) the time of measurement was too short to allow the wet bulb to respond to the large temperature change (10 degrees C);

4) at the end of the test, the wet bulb may have been extracting heat from the ambient air, thus condensing moisture rather than evaporating water. This was indicated by the final wet bulb temperature, which in most cases, was higher than the starting dry bulb temperature; and

5) some water may have been absorbed by the plastic chamber covering and the base foam and desorbed between measurements.

Atomization of a portion of the input water is the probable cause of the inaccuracy of the psychrometer measurements. If water is suspended in the air in liquid form, it cannot contribute to the partial pressure of water vapor in the chamber. Since the psychrometers respond indirectly to the chamber vapor pressure, water in suspension cannot be measured. The previous discussion of the coincidence of wet and dry bulb final temperatures and the ripples in the wet and dry bulb temperature plot and moisture accumulation plot strongly support the atomiziation hypothesis.

Determination of the actual cause of the "missing water" is compounded by the fact that the chamber would have been saturated if atomiziation did not occur, indicating that the

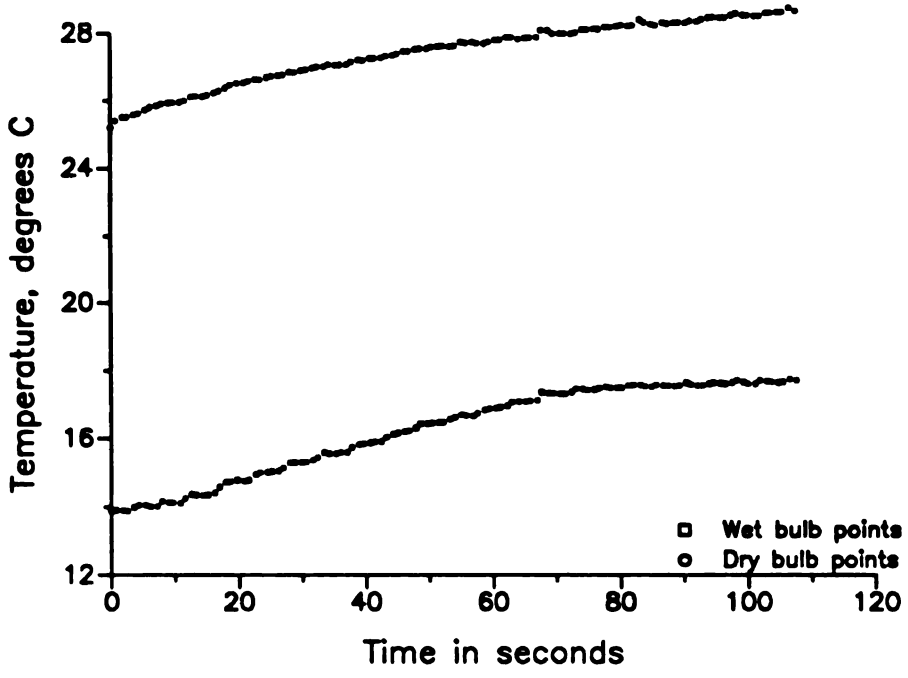

Figure 3-4 Wet and dry bulb temperatures for a 0.28 mm/hr ramp input at the low air mixing velocity.

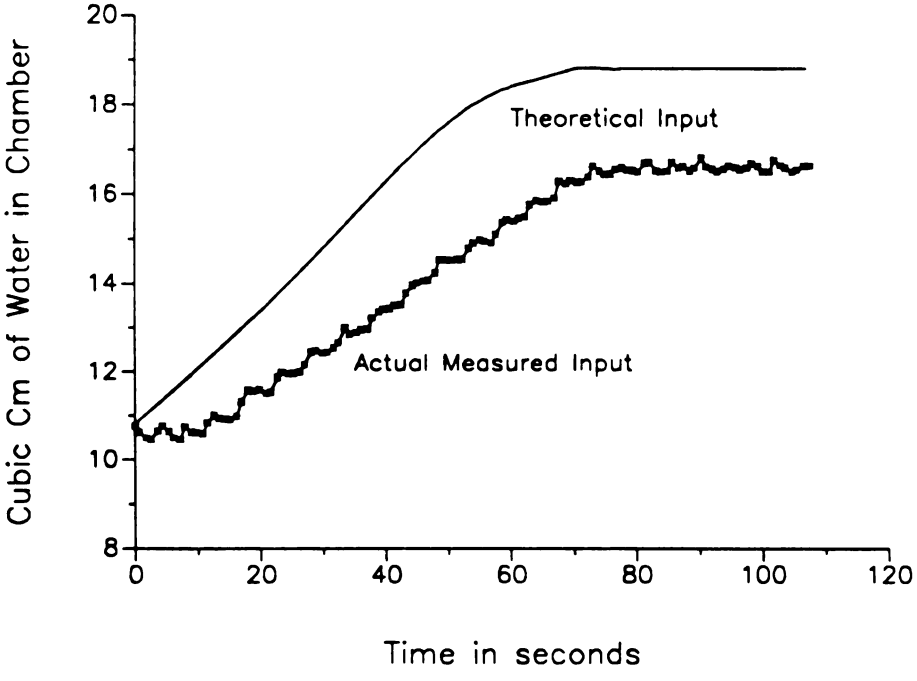

Figure 3-5 Theoretical and measured accumulation of water (mm) in the chamber for a 0.28 mm/hr (8 cm^3 by volume)ramp input at the low air mixing velocity.

psychrometers were operating outside their sensitivity range. Whether water atomization at the lower levels of water input occurred is unknown and, at this point, indeterminable. The results of the 30 cm^3 analysis, though not used for comparison of the actual water volume input versus the measured chamber moisture increase, were valuable and indicated uncertainties in the measured data that must be considered.

3.4.2 Step Test Results

Table 3-1 summarizes the results of the step test for the 2 and 15 cm^3 water inputs. For both input volumes, the psychrometers functioned better at the higher air mixing velocity. A comparison of the high to low air mixing velocity data shows all psychrometers returning lower average water volumes at the lower velocity. The standard deviations of the higher air mixing velocity data are approximately half those of the lower air mixing velocity data. Clearly, the higher air mixing velocity is desirable to obtain good quality measurements.

Table 3-1 Average yield and standard deviation of water in cm^3 for 5 repetitions of step inputs of 2 and 15 cm^3, at high and low air mixing velocities for psychrometers 1, 2 and 3.

	2 cm^3		15 cm^3	
Psychrometer	High	(Low)	High	(Low)
	cm^3		*cm^3*	
1	1.89±0.07	(1.64±0.14)	10.50±0.22	(9.31±0.56)
2	2.01±0.07	(1.54±0.12)	10.80±0.21	(9.51±0.40)
3	2.00±0.07	(1.74±0.15)	11.04±0.40	(10.20±0.42)

Psychrometer 2 and psychrometer 3 (the IC psychrometer) measured the 2 cm^3 water input accurately, and psychrometer 1 was within six percent of the correct value for water input. The performance of the psychrometers at the 15 cm^3 water input volume was much worse than

expected. All psychrometers measured approximately two-thirds of the input water volume. As noted earlier, it is not known if the input water was atomized. Using the step data to create calibration curves to correct the measurement error was not desirable because only two water input volumes were measured. It is well-known that two points define a straight line but, without additional points, the use of a line constructed from two points cannot be used with any confidence.

3.4.3 Ramp Test Results

The ramp data collected for the 0.07, 0.14, 0.28, and 0.52 mm/hr input rates were plotted for each repetition. The data collected at the lower air mixing velocity were noticeably more variable than at the higher air mixing velocity data for selected psychrometers (Figure 3-6).

A simple statistical test was used in an effort to measure the quality of the data. The mean and standard deviation of the change in the measured rate of water accumulation within the chamber between individual data points was calculated. From the mean and standard deviation, the

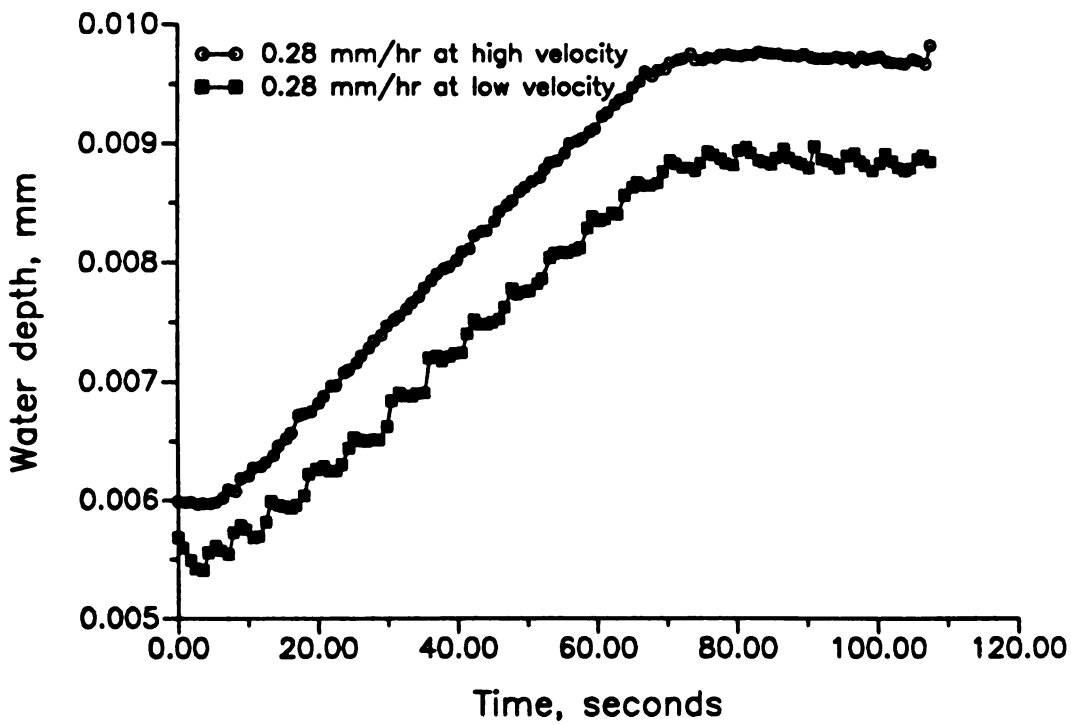

Figure 3-6 Ramp accumulation of water in the chamber at 0.28 mm/hr input at high and low air mixing velocities.

coefficient of variation (CV) of the rate of water accumulation within the chamber was calculated for each repetition. The purpose of the CV analysis was to provide an indicator of the variability of the data associated with individual repetitions and to provide insights into analysis of the calculated rate data.

The average CV for the five repetitions at each water input rate was computed for the high and low air mixing velocities (Table 3-2). The values of all entries in the table were large, indicating much variability in the measured rate of water vapor increase for evenly spaced points. Psychrometers 1 and 2 behaved similarily, confirming the similarity of the response of the temperature sensors used. Psychrometer 3 exhibited very large CV values at input rates less than 0.28 mm/hr. At the 0.28 mm/hr rate and above, psychrometer 3 had CV values similar to those of psychrometers 1 and 2. One possible cause for the poor performance at the 0.07 and 0.14 mm/hr input rates was the location of psychrometer 3. It was closest to the chamber base and the frying pan surface. The psychrometer may have been receiving radiant heat directly from the frying pan surface, contributing to variation in the measured temperatures.

If heat energy radiated from the frying pan affected psychrometer 3, it would seem likely that psychrometer 2, located 114 mm (4.5 inches) above psychrometer 3, would also show some response. The CV values for psychrometer 2 were similar to those of psychrometer 1, located above it. The lack of a uniform gradient between the psychrometers indicated that heat radiated from the frying pan was probably not responsible for the observed variation.

Table 3-2 Average coefficient of variation (%) for 5 repetitions for psychrometers 1, 2 and 3 at high and low air mixing velocities.

Psychrometer	1		2		3	
Rate	Fan		Fan		Fan	
mm/hr	*High*	*(Low)*	*High*	*(Low)*	*High*	*(Low)*
0.07	145	(127)	166	(134)	387	(520)
0.15	104	(126)	74	(89)	223	(229)
0.28	98	(223)	111	(215)	132	(183)
0.52	78	(104)	58	(66)	78	(85)

It is more likely that the errors were due to the larger thermal mass of the temperture IC's used as sensors in psychrometer 3.

3.4.3.1 Endpoint analysis

Two methods for evaluating the data collected for the 0.07, 0.14, 0.28, and 0.52 mm/hr ramp inputs were considered. One method consisted of comparing the slope of the change in water vapor density with the slope of the known input of water over time. For the second method, the final water vapor density is subtracted from the initial water vapor density, and with suitable conversion factors, the total change in water volume of the chamber is calculated. The total water volume change divided by the time elapsed yields the rate in mm/hr. This method is an endpoint analysis.

Using this method, the data from the ramp tests could be fitted to linear prediction equations for each psychrometer. If the measured water inputs were used as the independent or x value in the linear equation model $y = a + b(x)$, the value of the predicted dependent variable y could be calculated. Figure 3-7 shows the data and curves that represent each linear regression model derived from data for individual psychrometers at the higher air mixing velocity. The measured water input always needed to be multiplied by a coefficient greater than one, indicating that all psychrometers underestimated the known water input. These equations describing the performance of the psychrometers can be used to adjust the field measured data. As such, the equations are a calibration of each psychrometer's response to the chamber and the air mixing velocity. Figure 3-8 illustrates a similar analysis at the lower air mixing velocity. Note that the multiplier or slope is larger at the lower air mixing velocity.

The equations in Figures 3-7 and 3-8 are not directly applicable to the data calculated during a field measurement. To estimate total daily ET from field data, the rate of water vapor increase per hour was calculated for each run. The individual rates were assumed to be the ET rates for the time interval between runs. Integration of these measurements over the total time of measurement yielded a cumulative field ET, in mm.

The calibration equations presented in Figures 3-7 and 3-8 can be used to adjust the field-calculated ET rate. First the measured field rate has to be converted to a volume, using one

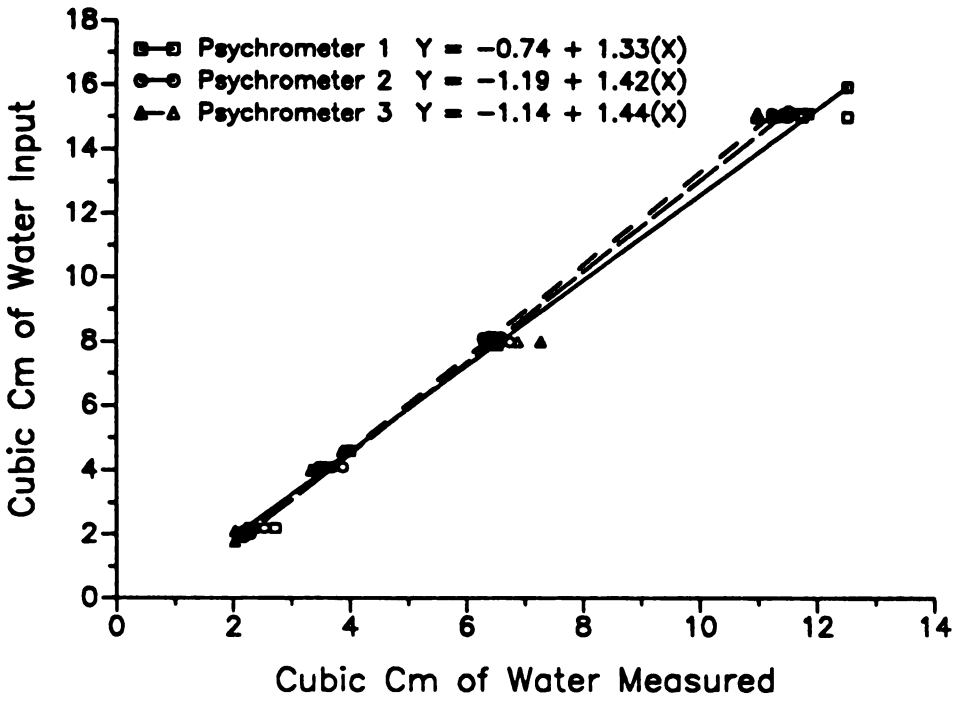

Figure 3-7 Data and linear regression lines for psychrometer 1, 2, and 3 at 2, 4, 8 and 15 cm^3 water input rate at high air mixing velocity.

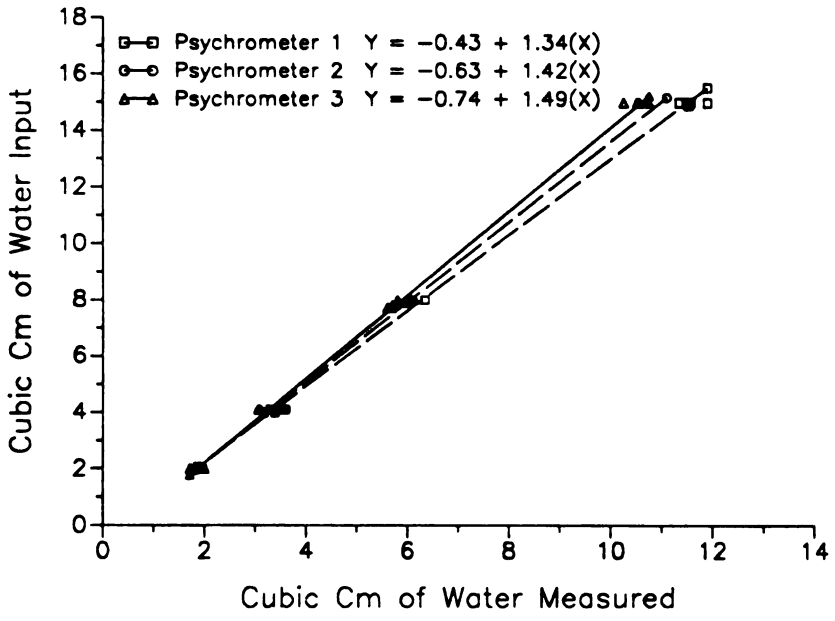

Figure 3-8 Data and linear regression lines for psychrometer 1, 2, and 3 at 2, 4, 8 and 15 cm^3 water input rate at low air mixing velocity.

minute for the time interval. Then the calibration equation could be applied, the volume adjusted, and the new adjusted field rate could be calculated. Although this was a workable solution, converting the field rates was a drawback.

The rate of water increase with time is a rate function. The calibration equations adjust the volume of water measured. The volume is really the integral of the rate of water accumulation for some fixed lower and upper bound. Since the field data were calculated as the rate of water accumulation over time (mm/hr), it was reasonable to develop calibration equations that adjusted the calculated rate, reducing the errors that could occur when using volume-based calculations.

3.4.3.2 **Rate calibrations**

The theory behind the interpretation of measurements of ET made with the portable chamber is simple. Many short measurements of ET rate over the span of the active evapotranspiration time need to be made. The short measurements (two minutes) will change the environment around the transpiring leaves minimally. Toward end of each chamber measurement , the water accumulation in the chamber should affect plant transpiration, decreasing the ET rate. Early in the measurement, the plant's transpiration rate should be unaffected by the chamber. This maximum rate of ET, if measured, can provide an estimate of field ET rate.

The concept of analysis of field data to determine a maximum ET rate emerged from discussions with other investigators (D.C. Reicosky, personal communication, 1984; F.L. Charles, personal communication, 1987). An analysis approach is not well documented in the literature, but was used by F.L. Charles, et. al. (1987) in the analysis of phreatophyte ET in the San Luis Valley in Colorado with good results.

The ramp test conducted in the laboratory supplied the data necessary to create linear calibration equations relating the measured rate of input to the known rate of input. To use the maximum-slope concept of ET estimation for the field data analysis, some additional analysis of the laboratory data might prove useful for interpreting the field results. Plots of the laboratory repetitions did not suggest that any section of the resulting water accumulation curve would yield a maximum slope consistently.

The maximum slope concept presented two interpretation problems for field data:

1) If a maximum slope existed, over what range of points should it be calculated?

2) Is the maximum in any time bracket dependent on the point at which the regression started?

To determine if using different time brackets would result in different maximum slopes, seven time brackets were chosen. The time brackets reflected the range from the shortest reasonable time of field measurement for the chamber and psychrometers to twice the usual analysis time used in previous field studies. The brackets were 10, 15, 20, 30, 40, 60, and 80 seconds.

To determine if the maximum calculated rate was dependent on the starting point of the analysis, least squares linear regressions were performed on the points that fell in the 10 second analysis time bracket for all possible starting points on the data curve by sliding the chosen analysis time bracket up the curve until a regression could not be performed because of insufficient data (Figure 3-9). The maximum rate and starting point on the data curve was recorded. The precedure was repeated for each analysis time bracket. Trials on low air mixing velocity data gave very large or negative slopes when the time bracket for the linear curve fit was very short (10 seconds). These initial trials indicated the necessity of developing a measure of the variability of the dāta, resulting in the CV analysis previously mentioned.

Criteria for selecting the maximum slope were established to prevent aberrations in sections of the collected raw data from providing spureous results. The slope had to be larger than the previous maximum slope and have an r^2 greater than 0.90. It is important to note that slopes calculated with this procedure, although maxima, did not need to be statistically significantly different from other slopes calculated for the same time interval. The goal of the analysis was to try to establish an average maximum slope and average starting point on the data curve, if in fact they existed.

The time interval and starting point analysis on the laboratory-collected ramp data was anticipated to indicate differences or similarities between psychrometers without the added uncer-

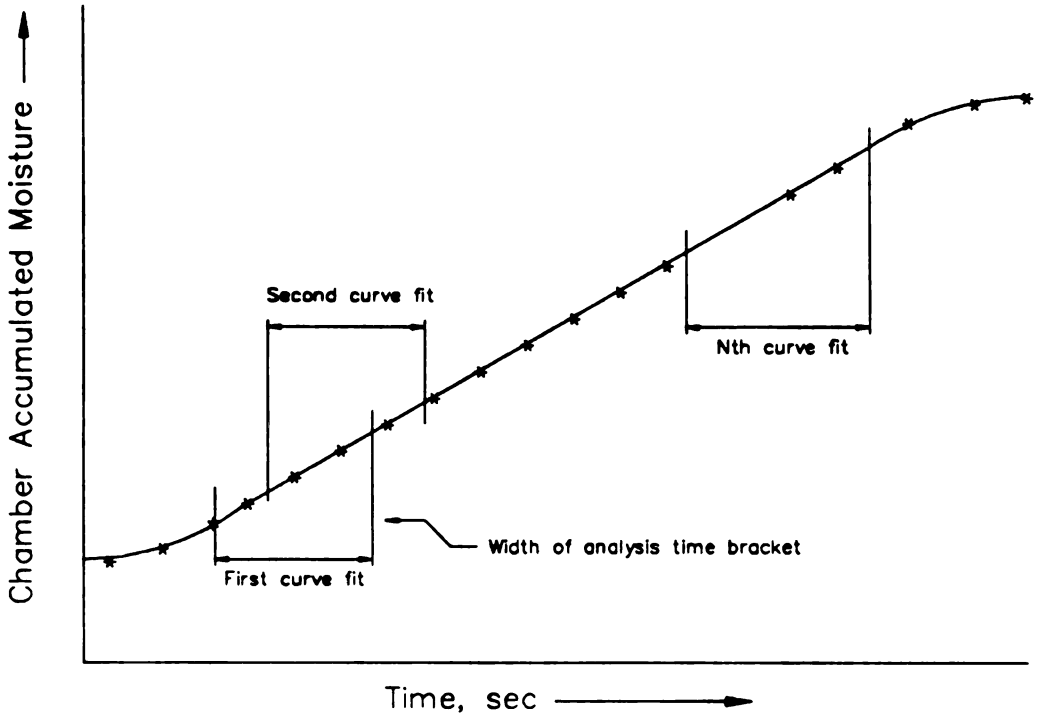

Figure 3-9 Calculation of the maximum ET rate for a given analysis time bracket using a sliding analysis time bracket.

tainties that plants introduce. Table 3-3 presents the average starting data point for psychrometers 1, 2, and 3 at 0.07, 0.14, 0.28 and 0.52 mm/hr water input rates for each time bracket.

Scanning down the columns of Table 3-3, it is evident that the starting point for any psychrometer at any water input rate moves toward the start of data collection regardless of air mixing velocity. The average starting point of the maximum slope time interval was much closer to the start of data collection for psychrometer 1 than for psychrometers 2 or 3. Psychrometer 1 was affected marginally by the reduction in air mixing velocity. The reduction in air mixing velocity did not seem to affect the starting point for psychrometers 2 and 3. The difference between the average starting points for psychrometers 1 and 2 was unexpected. Both psychrometers used thermistor temperature sensors with similar time response characteristics

Table 3-3 Average time (sec) for 5 repetitions to the start of maximum rate for psychrometers 1, 2, and 3 at 4 input rates and 7 analysis time brackets.

Psychro-	Time	Rate							
meter	bracket	0.07 mm/hr		0.14 mm/hr		0.28 mm/hr		0.52 mm/hr	
(#)	(sec)	High*	[Low**]	High	[Low]	High	[Low]	High	[Low]
	10	18.6	[25.4]	14.8	[28.4]	22.6	[32.4]	15.2	[24.6]
	15	18.2	[26.0]	15.6	[29.4]	20.0	[30.0]	13.0	[19.6]
	20	13.4	[17.6]	14.2	[26.4]	17.6	[31.0]	10.4	[15.6]
1	30	8.6	[11.6]	11.4	[15.4]	14.2	[19.6]	9.2	[10.2]
	40	5.6	[7.4]	8.0	[12.6]	10.4	[14.8]	7.4	[7.6]
	60	5.0	[6.6]	6.2	[9.0]	7.4	[10.0]	5.4	[5.6]
	80	5.0	[5.0]	5.0	[5.0]	5.0	[5.0]	5.0	[5.0]
	10	50.0	[58.4]	54.4	[58.2]	48.6	[52.8]	52.6	[52.8]
	15	54.0	[55.6]	52.8	[54.2]	49.4	[50.0]	45.8	[52.6]
	20	50.6	[48.6]	51.8	[48.2]	52.2	[45.2]	48.2	[53.0]
2	30	42.2	[44.8]	44.4	[43.8]	42.2	[41.8]	39.4	[44.6]
	40	35.6	[35.8]	36.2	[35.0]	33.6	[33.4]	34.4	[35.0]
	60	21.4	[20.8]	20.4	[19.6]	15.4	[17.4]	19.6	[19.2]
	80	10.4	[9.8]	9.2	[8.6]	5.0	[5.2]	6.4	[6.6]
	10	68.4	[62.2]	67.6	[62.8]	61.0	[67.4]	61.0	[63.2]
	15	63.8	[60.8]	63.4	[54.8]	58.4	[62.4]	58.4	[59.0]
	20	61.8	[56.4]	60.2	[58.6]	55.4	[59.8]	54.8	[55.8]
3	30	56.8	[55.0]	52.4	[50.4]	48.0	[51.4]	49.8	[51.6]
	40	51.6	[46.4]	44.4	[42.0]	40.8	[44.0]	42.6	[43.6]
	60	38.6	[38.6]	31.2	[29.4]	27.2	[33.4]	30.8	[31.8]
	80	28.4	[28.4]	19.4	[19.6]	15.2	[22.6]	18.0	[18.8]

*High air mixing velocity
**Low air mixing velocity

that should have resulted in similar average starting points. The longer response times of the IC sensors in psychrometer 3 were expected, but the similarities in the average starting points for psychrometers 2 and 3 suggest that some other factor may be important.

The other major difference between the psychrometers was the mounting position. Psychrometer 1 was closest to the top. It is possible that water vapor from the frying pan migrated to the top of the chamber rapidly and then was mixed with chamber air. Psychrometers 2 and 3, mounted lower in the chamber, may not have encountered the more completely mixed air until later in the data collection time interval. However, observation of white chemical smoke released near the water evaporation surface did not confirm the position sensitivity of the psychrometers. The smoke quickly dissipated at both low and high air mixing velocities with no evidence of stratification or decreased mixing in the chamber.

The difference between psychrometers 1 and 2 was probably not due to differences in wicking. The data for the 0.07 mm/hr rates was collected three days before the 0.14, 0.28, and 0.52 mm/hr data. Before each test the psychrometers were torn down and fresh "Kleenex" brand tissue (other brand names were tried and did not work well) double layer wicks were applied to the wet bulbs. It is unlikely that an identical wick problem would occur on two days.

Two other expected trends not reported in Table 3-3 occurred. The average maximum rate and its associated r^2 decreased with an increase in the interval of measurement for all water input rates and air mixing velocities. Both the average maximum rate and r^2 were larger for the higher air mixing velocity for all water input rates.

3.4.3.3 Ramp calibration curves

Use of the volume-based calibration curves shown in Figures 3-7 and 3-8 was not desirable because of the possible propogation of errors when using the adjusted data to calculate cumulative ET. The alternative was to develop calibration curves that corrected the measured ET rate to some known ET rate. Linear predictive equations were developed from the known ramp input data and the measured ramp input data using least squares linear regression analysis. This analysis resulted in a calibration equation for each psychrometer.

The development of calibration equations was complicated by the time interval analysis. Calibration equations could be developed for each psychrometer at each time interval, resulting in 21 equations. Statistically, the rate values calculated for a time bracket might not be different. The choice of the time bracket for which calibration equations were developed was arbitrary. The application of known characteristics of the psychrometers (response time, sensor type), measurements of data variability (CV), and judgment (common sense) gained by experience, did suggest the choice of a reasonable time interval.

Based on the psychrometer response times and the data variability of laboratory ramp tests, the 20 second time interval was chosen for psychrometers 1 and 2. The 30 second time interval was used for psychrometer 3 because of the increased response times of the IC temperature sensors used. Calibration equations were constructed for each psychrometer using the data from the 20 second time interval for psychrometers 1 and 2, and 30 second time interval for psychrometer 3. Figures 3-10 and 3-11 illustrate the data and regression lines for the high and low air mixing velocities. The high air mixing velocity calibrations equations will be applied to rates calculated from field data to determine if adjusting field values yields ET rates which better estimate the actual ET.

The applicable equations are:

Psychrometer 1adjusted ET rate, mm = -0.05 + 1.34(Measured ET)

Psychrometer 2 adjusted ET rate, mm = -0.05 + 1.63(Measured ET)

Psychrometer 3 adjusted ET rate, mm = -0.05 + 1.71(Measured ET).

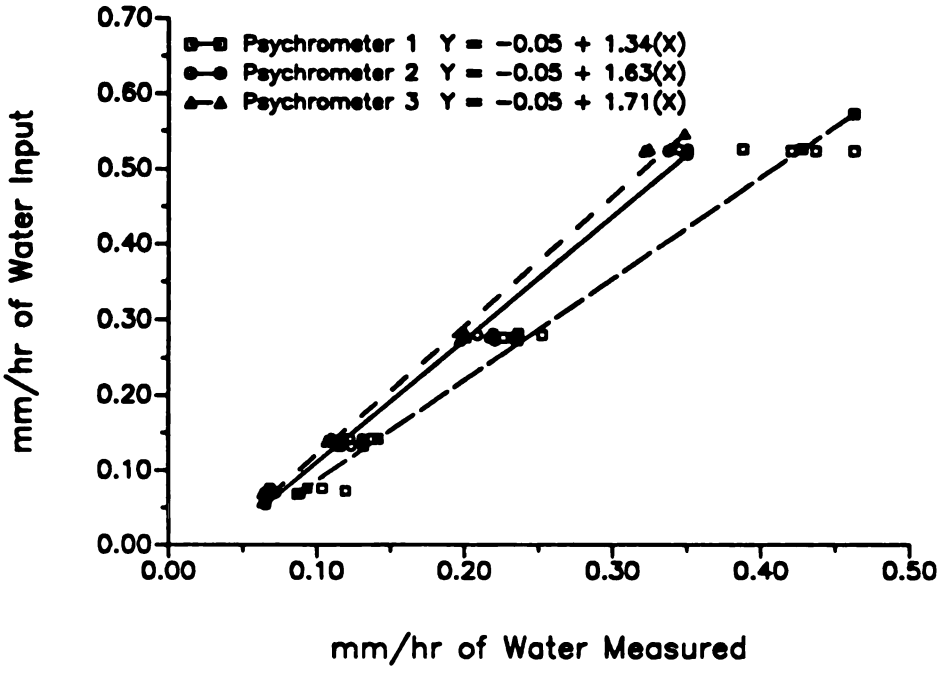

Figure 3-10 Data and linear regression lines for psychrometers 1, 2, and 3 at 0.07, 0.14, 0.28, and 0.52 mm/hr water input rate at high air mixing velocity.

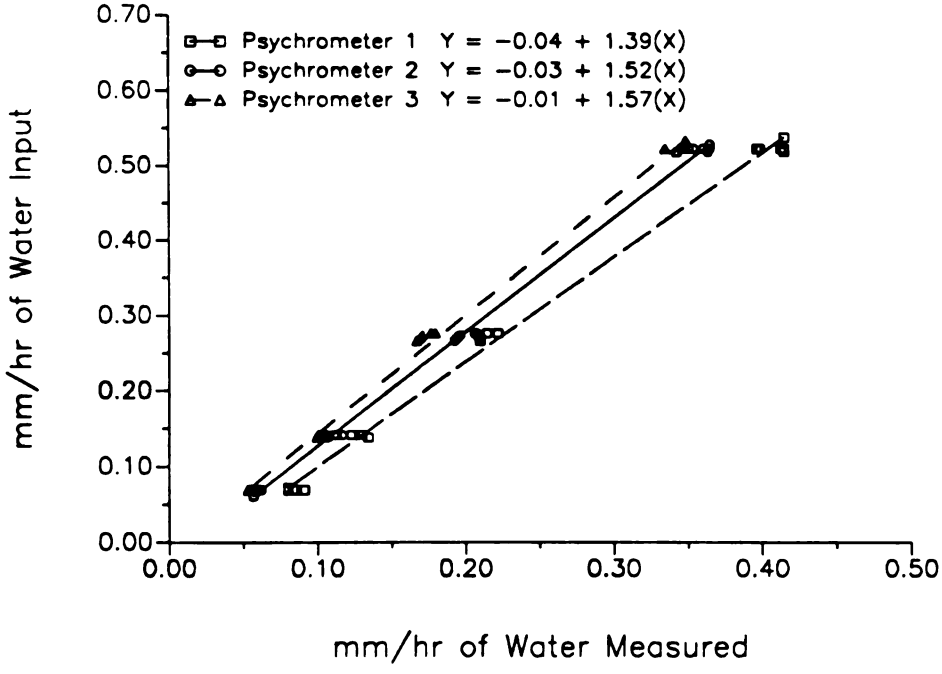

Figure 3-11 Data and linear regression lines for psychrometers 1, 2, and 3 at 0.07, 0.14, 0.28, and 0.52 mm/hr water input rate at low air mixing velocity.

CHAPTER 4

FIELD EXPERIMENTS

4.1 OBJECTIVE III

The third objective of the research was to compare field evapotranspiration measured with the portable chamber with lysimeter-measured evapotranspiration.

4.2 INTRODUCTION

This chapter describes the field tests of the portable evapotranspiration chamber. First, the literature detailing field tests of portable chambers by other researchers is presented. The description of the chamber-measurement system is updated from that given by Harmsen (1983). Then, the reference field lysimeter and the calibration procedure used is described. Finally, the method for taking field measurements and the interpretation of the measurements is discussed.

4.3 REVIEW OF LITERATURE

Reicosky and Peters (1977) first attempted to compare evapotranspiration measured with a portable field chamber with that measured by a lysimeter using a test plot of soybeans. The soybeans were grown in Hoaglands solution in a solution uptake tank. The soil surface of the soybean plot was covered with polyethylene sheets to prevent evaporation. The portable chamber was placed over the soybean plot and the water vapor density within the chamber was measured with a single aspirated psychrometer. Water vapor density measurements were taken at the start and after one minute had elapsed, coinciding with measurements of soybean solution uptake. Using the beginning and ending measured water vapor density, the absolute water volume change in the chamber during the measurement interval was estimated. This volume was converted to a rate using the elapsed time during the measurement. The chamber-measured rates were plotted against solution uptake measurements for the measurement inter-

val. A least squares regression line fit to the data showed r^2 of 0.98, a slope of 0.98, and an intercept of 0.009 (almost 1 to 1) for data collected under clear skies. Additional measurements on cloudy days did not produce good results. The researchers stated that data taken for conditions other than clear sky were probably not interpretable and should not be used.

Reicosky et al. (1981) reported the comparison of a portable chamber with a weighing lysimeter located near St. Paul, Minnesota. The lysimeter was covered with 0.70 m (27 inches) tall alfalfa which was irrigated with 50 mm (2 inches) of water, one day prior to measurement. Measurements with the portable chamber were taken near the lysimeter at 10 minute intervals and averaged to yield an hourly ET rate. Results were good for days with mostly clear skies (Reicosky et al., 1981; Reicosky ,1985). ET rates for the chamber and lysimeter compared favorably to Penman calculated hourly ET.

Hourly ET fluctuations measured by the chamber and lysimeter during the course of the day produced a bell-like pattern corresponding to available solar radiation. The maximum hourly ET for the chamber (0.85mm [0.03 inches]) was comparable to lysimeter-measured ET for the same period (0.8mm [0.03inches]). The general agreement of chamber-measured ET with lysimeter-measured ET on an hourly and daily basis led Reicosky to conclude that the chamber could accurately measure ET.

Harmsen (1983) reported the results of comparison of a portable chamber with a lysimeter in Coshocton, Ohio. Chamber cumulative ET was greater than lysimeter ET by 16 percent for measurements made with a chamber equipped with an openable top. Harmsen stated he believed that the overestimation of ET occurred because of the time required to close the openable top (nine seconds).

The results emphasize the importance of making field comparisons between portable chambers and reference devices for verification of measurements. The reader is cautioned to note that all comparison data cited were obtained under clear sky conditions. The frequency of such clear days may limit the usefulness of a portable chamber in humid climates.

4.4 FIELD MEASUREMENTS

4.4.1 Equipment and calibration

This section consists of a description of the equipment used to make measurements in the field and its calibration. The equipment consisted of the chamber, including the suspension structure, power supply, and power delivery; the lysimeter, mass measurement equipment, and calibration procedure; the pyranometer;and the equipment for data collection in the field and for data reduction in the laboratory.

4.4.1.1 Chamber

All components of the chamber system used for field tests were the same as those used for laboratory tests. Extension units 2.4 m (96 inches) and 3.6 m (141 inches) tall were used to accommodate corn during the growing season.

4.4.1.2 Suspension structure

The chamber suspension system consisted of the chamber and a tractor-mounted boom. The following description and illustration were taken directly from Harmsen (1983) (Figure 4-1).

> "A tractor mounted suspension structure was built to suspend the chamber above the crop and lower it into place for measurement. The suspension structure is shown in Figure 4-1 [also Figure 4-1 in this publication], along with the chamber and farm tractor used for support and mobility. Rigid television antenna tower sections were used for the suspension tower. The tower sections could be increased in height to accommodate the tall chamber by adding additional sections. The original cross bracing was reinforced at points of critical stress. A 37.3 watt (1/20 HP) permanent magnet reversible motor was used to move the chamber laterally on a trolley set inside a heavy-duty rolling door track on the horizontal boom section. The chamber was raised from or lowered to the ground using a braided wire cable connected to a 4450 Nt (1000 pound) capacity 12 volt DC winch. The winch was rigidly attached to a plate on the trolley in the door track.

The vertical portion of the tower structure rested in a steel three point hitch connected frame which prevented the tower from tipping and provided for rotation. The bottom of the tower was positioned on a steel plate which rested on a rotation bearing. The structure was made to rotate about its vertical axis by use of a manual operated chain and sprocket attached to the lower portion of the suspension structure support frame. After the boom was rotated to the desired position a brake could be set to avoid further rotation."

4.4.1.3 Power supply

The power supply was provided by a battery pack with four six-volt DC golf cart batteries wired series-parallel to deliver 12 volts DC, mounted from a bracket attached to the tractor side cultivator mount. The battery pack capacity was adequate for four hours of operation without recharging. A 60-amp self-regulating 12-volt DC alternator was added to the tractor. The alter-

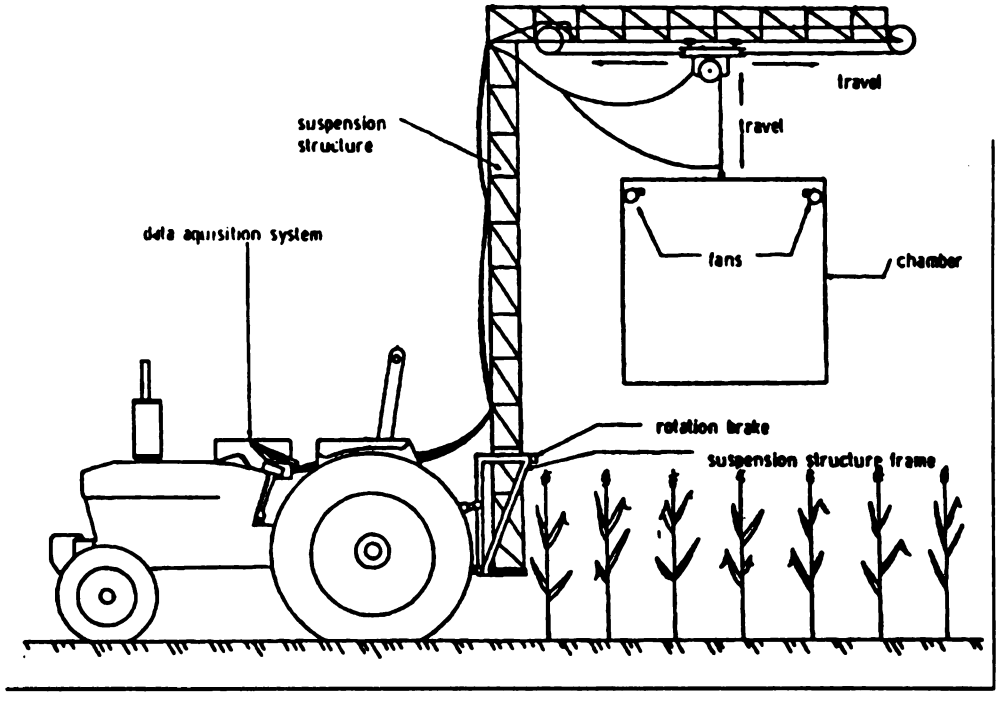

Figure 1 Portable chamber and suspension structure in the field.

nator mount was isolated from the tractor electrical system to prevent imbalance problems with the tractor battery. The alternator charged the battery pack between field measurements.

Power for the data collection equipment was supplied by a 12-volt DC to 110-volt AC, 300-watt square wave inverter. The DC voltage supply for the inverter was taken from the battery pack.

4.4.1.4 Chamber air mixing

Both axial and centrifugal fans were used to provide a uniform mixture of air and water vapor during measurement. Axial fans with 0.41 m (16 inch) blade diameters rated at 64 m^3/min (2275 cfm) were used. Two axial fans were mounted on ball joint supports 0.30 m (1 foot) down from the top of vertical chamber corner poles opposite each other. The ball joint mounts allowed easy positioning of fans to obtain maximum mixing in the top of the chamber.

Twelve-volt DC centrifugal fans with 3 m^3/ min (110 cfm) capacity were mounted 0.3 m (1 foot) above the chamber base frame from each chamber corner vertical support pole. These four fans provided 12 m^3/min or three chamber volume mixes per minute for the 2.4 m (96 inch) tall chamber and two chamber volume mixes per minute for the 3.6 m (141 inch) tall chambers.

4.4.1.5 Power delivery

Power to drive the boom winch was delivered through number 2 electric welding cable. The current to the boom winch (100 amps) was switched on and off with 12-volt DC starter motor solenoids from a control panel near the tractor operator.

Power to drive the fans was delivered to the chamber with number 2 electric welding cable. The fans rpm and air output was dependent on the voltage potential at the fans. The six fans required 29 amps of current at 12 volts DC to maintain their rated air output capacity. The welding cable provided flexible, low resistance, high current capacity, dropping the 12-volt DC supply only 0.5 volts DC at the fan motor. With the battery pack at full charge, the voltage potential was 13 to 13.5 volts DC, providing adequate voltage potential at the fans after the potential losses due to supply wire resistance.

4.4.2 Lysimeter

A large weighing lysimeter located in an irrigated field at the Kellogg Biological Research Station near Hickory Corners, Michigan was used as the standard against which chamber measured ET was compared (Figure 4-2). The surface dimensions of the lysimeter were 3.05 m (10 feet, i.e. four corn rows) wide by 1.9 m (6 feet 4 inches) long, accommodating 42 corn plants at a plant population of 7.2 plants/m^2 (29,000 plants/acre). The depth of the lysimeter was 1.52 m (60 inches) with 90 mm (3 and 5/8 inches) of dense fired clay bricks laid on edge to form a drainage matrix at the bottom of the soil block.

The undisturbed soil core for the lysimeter was taken from an area in the field near the lysimeter, after determining that the soil profile in that area was the same as that for the lysimeter. The soil core of the lysimeter was Kalamazoo loam. The Kalamazoo loam profile consisted of approximately 250 mm (10 inches) of loamy top soil, 400 mm (16 inches) of clay loam, 50-100 mm (2 to 4 inches) of loamy sand, and sand below.

4.4.2.1 Lysimeter mass measurement equipment

The weighing device for the lysimeter was an agronomy scale marketed by the Cardinal Scale Company for large weighing lysimeters and described by Ritchie and Burnett (1968). A 45 kg (100 pounds) strain gage located on a counter balance arm of the scale provided the output signal for mass determinations. The output of the strain gage was converted to a mass change by an analog to digital converter (A/D) manufactured by Cardinal Scale Company. The strain gage attachment point on the scale tare arm provided a measurable range of scale mass change of 909 kg (2000 pounds). The balance of the scale mass was counterbalanced with lever arms and tare masses. The Cardinal A/D resolved the strain gage output into 80,000 parts or 0.010 kg (0.025 pound). The combination of the agronomy scale and Cardinal A/D provided a precise tool for measurement of scale mass changes.

A serial communication port on the Cardinal A/D allowed transmittal of the mass measurement to a microcomputer. A time of day clock associated with the microcomputer allowed the microcomputer to request a scale measurement at specific time intervals. Data from the scale

were stored in memory for later transfer by phone to a host computer. A printer attached to the microcomputer logged each scale measurement on paper, providing a backup in the event a power failure caused loss of the computer memory.

4.4.2.2 Lysimeter calibration

The Cardinal A/D used was a dedicated purpose microcomputer with a self calibration program. This simplified conversion of the mass change of the scale to a numeric value which could be displayed or transmitted. Reference weights were constructed from 0.018 m^3 (5 gallon) buckets by filling each of 10 buckets with 23 kg (50 pounds) of dry sand. After filling the buckets, tops were placed on them to prevent mass changes due to moisture loss or gain of the sand. Each bucket was weighed to the nearest 0.02 kg (0.05 pounds) at a commercial scale calibration station. The buckets were then transported to the lysimeter field site. The calibration procedure consisted of initializing the Cardinal A/D internal calibration program, specifying the desired output units, establishing a base mass measurement, loading the scale with ten buckets, initiating the measurement of scale mass, and displaying the two calibration numbers on the Cardinal A/D .

Precautions were taken to insure accurate calibration. For example, wind in the area of the lysimeter could cause extreme fluctuation of the scale output. The calibration was done near midnight, when wind speed was lowest, to reduce the possiblity of wind induced calibration errors. The entire calibration procedure was repeated until calibration coefficients from the previous calibration matched the coefficients for the calibration in progress. Independent verification of scale mass measurements at mass changes less than 23 kg (50 pounds) were confirmed with masses of 0.45 kg (1 pound), 2.3 kg (5 pound), and 12.2 kg (22 pounds). For all masses measurements were ±0.01 kg (0.25 pounds).

4.4.3 Pyranometer

Solar radiation (irradiance) measurements were made with a LiCor Li200s pyranometer. The output of the pyranometer was amplified to the input range of the A/D (0 to 10 volts) with an Analog Devices 2B30 strain gage/RTD signal conditioner. The 2B30 had an adjustable gain of 1 to 2000 volts/volt input, 0.5 microvolt/degree C temperature drift, and an adjustable low pass

noise filter. The amplified output signal of the 2B30 was connected to one A/D input channel. Amplification level of the input signal was calculated from the calibration data supplied with the pyranometer. The pyranometer was not independently calibrated; therefore, its precision was not in question but its accuracy was. It provided data which could be used to compare the field measurements on a relative basis.

4.4.4 Data Collection Equipment

4.4.4.1 Field equipment

The field data collection equipment was the same as that used in the laboratory tests. The microcomputer, analog to digital converter (A/D), temperature sensor amplifier and filter box, ADPI tape drive, and Silent 700 terminal were mounted on a table attached to the battery pack frame (Figure 4-1). This provided the tractor operator with convenient access to the data logging equipment.

4.4.4.2 Laboratory equipment

The laboratory equipment for field data reduction consisted of a California Computer Systems Z80 based SIOO computer with an interface to an ADPI tape drive. Field data collected on tape were transferred via the ADPI tape drive to the SIOO Computer.

4.5 Method

This section describes the method used for data collection, including the field conditions, the data collected, the procedure used to collect data, and the analyses performed on the data.

4.5.1 Field Conditions

Lysimeter and field ET measurements were made on corn on July I9 and August I3, I5, and 20, I984. For all days of data collection except August I5, the corn was irrigated with 25 mm (1 inch) of water the day before. The corn varied in size and maturity for the dates of data collection. On July I9 the corn was only 2.1 m (84 inches) tall, allowing the use of the 2.4 m (96 inches) tall chamber. On August 13, 15, and 20, the corn was 3.2 m (126 inches) tall, requiring use of the

3.6 m(141 inches) tall chamber. Estimates of the percent ground cover from above the corn on the lysimeter and in the test area were the same.

The corn on the lysimeter and in the test area near the lysimeter looked similar in July. For all dates in August, the crop on the lysimeter differed in appearance from the crop in the test area. The difference was caused by rootworm damage to the corn on the lysimeter. Corn had been planted in the field in which the lysimeter was situated for eight years prior to installation of the lysimeter in l983. The corn on the lysimeter was first planted in 1984. This hand planted corn did not receive insecticide. The corn on the lysimeter lodged badly as a result of the rootworm damage and stakes were used to support individual corn plants. The corn near the lysimeter was planted mechanically and did receive insecticide.

A university agronomist (M. Vitosh, personal communication, l984) was consulted about the difference in the appearance of the corn. He stated that the corn on the lysimeter, though different in appearance from the corn in the surrounding test sites, was still actively growing, and the data collection proceeded in August. Because of the lodging of corn on the lysimeter, the ground cover for corn on the lysimeter was about l0 percent less than for corn in the test area.

The soil type in the vicinity of the lysimeter and on the lysimeter was the same. Thus, the availability of moisture to the corn on the lysimeter and the corn planted near the lysimeter was assumed to be equal.

4.5.2 Data Collected

4.5.2.1 Field data collected

Solar irradiance and wet and dry bulb temperatures for the three psychrometers were recorded during each field measurement. Notes were made on test site location, number of plants, estimated percent ground cover, and cloud cover.

4.5.2.2 Quantity of data collected

The control BASIC supplied by Cromemco allowed the collection of one data point every 0.8 second per channel. During a measurement 120 data points were collected from 7 channels.

4.5.2.3 Lysimeter data collected

The data collection system for the lysimeter produced one average scale mass measurement every five minutes. This was an average of the 20 scale mass samples. Scale mass conversion and averaging required two minutes for completion of the 20 sample average.

4.5.3 Chamber Data Collection Procedure

The test plants were selected, the chamber was positioned above the plants, and the fans were turned on to purge the air within the chamber. The data collection was begun with the chamber located above the crop. At five seconds into the data collection interval, the chamber was lowered over the crop. The time of ground contact and the quality of the ground seal were noted and recorded. The data collection proceeded until the desired number of points was collected. The number of points used was 120 for both the 2.4 and 3.6 m (96 and 141 inches) tall chambers. Data collected were temporarily stored in the computer memory. The chamber was lifted off the crop and the boom was rotated to insure that the chamber would not be located over the test plot during the time between measurements. The data in the computer memory were transferred to tape storage for laboratory analysis.

In the laboratory, the data were read from the tape to disc storage. The wet and dry bulb temperatures for each channel were calculated. Wet bulb temperatures were converted to saturated vapor pressure, the vapor pressure deficit was calculated, and the vapor pressure in kpa in the chamber was obtained. The chamber vapor pressure was converted to an equivalent depth of water over the base area of the chamber, utilizing a conversion based on the perfect gas law (see Chapter 3).

The maximum ET rate and elapsed time to start were calculated for each field measurement using the procedure described in the laboratory analysis. The maximum ET rates for an analysis

time bracket were integrated to compute a cumulative ET using a trapezoidal estimation. In addition to cumulative ET, a confidence interval for the integrated cumulative ET was calculated.

The linear regression procedure used to calculate a maximum ET rate allowed statistical estimation of the upper and lower limits of the ET rate based on the desired percentage of correct values (confidence interval or CI). The larger the percentage of correct values desired, the wider the tolerance band around the measured ET rate had to be.

The size of the confidence interval around a predicted value is a function of the number of points in the analysis time bracket. For normally distributed data, assuming random variation, the size of the confidence interval around a predicted value should decrease as the number of points used in the regression increases, up to some number of points. The 20 second analysis time bracket encompasses approximately twice the number of points in the 10 second analysis time bracket. An upper and lower bound on cumulative ET (confidence interval) was calculated with the field measured ET rates for the 10 and 20 second analysis time bracket at 95 percent confidence to determine which time bracket would adequately compare to lysimeter cumulative ET.

4.5.4 Analyses

4.5.4.1 Cumulative ET analysis

Data collected on July 19 and August 13, 15, and 20 of 1984 were used for analysis of cumulative ET. On each day, measurements of the lysimeter mass were made every five minutes. A mass change of 6.04 Kg was equal to a 1 mm decrease in the soil water content f the lysimeter. Therefore, a mass change of the lysimeter could easily be converted to an equivalent depth of water by dividing by 6.04.

Measurements of solar radiation (W/m^2) and ET rate (mm/hr) were also made while each lysimeter mass measurement was being made. Solar radiation was measured directly. No solar radiation measurements were made between runs. ET rate (mm/hr) was measured indirectly with the psychrometers in the chamber and calculated as previously discussed.

The 2.4m (96 inch) tall chamber was used on July 19. The 3.6m (141 inches) tall chamber was used for all other days. The time between measurements was 10 minutes for data collected on July 19 and August 13 and 20. On August 15, the time between measurements was 5.5

minutes. More measurements were taken when the shorter time interval was used, allowing the affect of the number of measurements on the cumulative ET measured to be determined.

4.5.4.2 Hourly ET comparison

The chamber performance was evaluated on an hourly basis to estimate the usefulness of the chamber for short measurement intervals.

The data for hourly ET comparisons were calculated from the cumulative chamber and lysimeter ET data. Cumulative ET data for each hour were obtained by interpolating between the data points which fell closest to the hour for each psychrometer and for the lysimeter. Interpolation for each hour yielded eight hourly data points on July 19 and six hourly data points on August 13, 15, and 20. Using these values, a percent error of lysimeter hourly ET was calculated for each psychrometer and for the error of the average of psychrometers 1, 2, and 3. Percent error estimates allowed comparison of chamber performance for all hours of the date of collection and across days of collection.

4.6 RESULTS AND DISCUSSION

4.6.1 Time to Start and Time Bracket Analysis

Using a measurement instrument properly and collecting accurate data while minimizing the destruction of the sampled area is highly desirable when working with green plants. The goal of the time to start analysis was to determine how much time should elapse between chamber placement and the occurrence of the maximum measured ET rate. The goal of the time bracket analysis was to determine which of the eight time brackets yielded the maximum measured ET rate using the selected measurement equipment.

The data analysis was similar to that presented for the laboratory data. Maximum ET rates were calculated for analysis times of 10, 15, 20, 30, 40, 60, and 80 seconds for each field measurement. Time to start, maximum ET rate, and standard error for each analysis time bracket were averaged for each psychrometer by date. Table 4-1 shows the average time to start for each analysis time bracket for each psychrometer on each date. For all psychrometers on all dates,

the average time to start decreased as the length of the analysis time bracket increased. Average time to start for each psychrometer in each analysis time bracket across the days of data collection was consistent within a range of 20 seconds. Large differences in the average time to start among psychrometers by day, were not apparent.

In the laboratory analyses, psychrometer 1's average time to start was much less than that of psychrometers 2 or 3. This led to the assumption that psychrometer 1 would behave differently than psychrometer 2 in the field, even though psychrometers 1and 2 shared the same construction and type of temperature sensors. The data in Table 4-1 do not confirm that assumption. The larger number of field data samples indicated that temperature sensor differences between psychrometers 1, 2, and 3 did not affect the average time to start. Differences between psychrometers 1 and 2 (using the same type of temperature sensors), shown in the laboratory data, do not exist in the field data. The problems associated with the water injection methodology used in the laboratory tests may account for some of the discrepancy between laboratory and field data.

Table 4-1 is useful for assessing the amount of time elapsed from the start of a measurement until a maximum ET rate for a given time bracket can be calculated. To determine which analysis time bracket to use, a table of the average maximum ET rates for each psychrometer in each analysis time bracket was constructed (Table 4-2). The table shows that for any psychrometer on any date the average maximum ET rate decreases from a maximum as the analysis time bracket increases. For data collected on the same date, the average maximum ET rate among psychrometers in each analysis time bracket does not vary widely. Clearly the l0 second analysis time bracket yields the largest average ET, with an average l0 percent larger than the 20 second analysis time bracket used for laboratory calibration equation development. The choice of the l0 second analysis time bracket does not compromise the accuracy of the field measurements. The standard deviations of the average maximum ET rates are the same for all analysis time brackets and for all psychrometers.

From the data in Tables 4-1 and 4-2, it is reasonable to recommend that field maximum ET rate calculations be made for the l0 second bracket and that data collection not be less than 68 seconds. From Table 4-1, the maximum elapsed time from the start of measurement was 58

Table 4-1 Average time to start of analysis for 5 repetitions for psychrometers 1,2, and 3 in 10, 15, 20, 30, 40, 60, and 80 second analysis time brackets for data collected on July 19, August 13, 15, and 20, 1984.

Psychro-	Time	Elapsed Time from the Start			
meter	bracket	7/19/84	8/13/84	8/15/84	8/20/84
(#)	(sec)	(sec)	(sec)	(sec)	(sec)
	10	--	37	33	38
	15	--	34	29	33
	20	--	30	29	33
1	30	--	27	25	30
	40	--	23	20	24
	60	--	14	12	13
	80	--	25	5	4
	10	39	--	37	58
	15	36	--	31	55
	20	32	--	31	53
2	30	28	--	26	48
	40	23	--	22	43
	60	15	--	14	28
	80	18	--	7	9
	10	41	53	37	53
	15	42	50	36	53
	20	39	49	33	56
3	30	33	43	30	48
	40	28	36	24	42
	60	18	25	16	26
	80	10	10	6	9

Table 4-2 Average ET rate (mm/hr) and standard deviation from 5 repetitions for psychrometers 1,2, and 3 in 10, 15, 20, 30, 40, 60, and 80 second analysis time brackets for data collected on July 19, August 13, 15, and 20, 1984.

Psychro- meter (#)	Time bracket (sec)	ET Rate 7/19/84 (mm/hr)	8/13/84 (mm/hr)	8/15/84 (mm/hr)	8/20/84 (mm/hr)
	10	-.- -.-	0.34 ±0.1	0.52 ±0.1	0.42 ±0.1
	15	-.- -.-	0.32 ±0.1	0.50 ±0.1	0.44 ±0.1
	20	-.- -.-	0.31 ±0.1	0.49 ±0.1	0.42 ±0.1
1	30	-.- -.-	0.31 ±0.1	0.48 ±0.1	0.41 ±0.1
	40	-.- -.-	0.30 ±0.1	0.48 ±0.1	0.40 ±0.1
	60	-.- -.-	0.29 ±0.1	0.45 ±0.1	0.37 ±0.1
	80	-.- -.-	0.29 ±0.1	0.42 ±0.1	0.37 ±0.1
	10	0.56 ±0.1	-.- -.-	0.57 ±0.1	0.39 ±0.1
	15	0.54 ±0.1	-.- -.-	0.53 ±0.1	0.37 ±0.1
	20	0.53 ±0.1	-.- -.-	0.52 ±0.1	0.36 ±0.1
2	30	0.52 ±0.1	-.- -.-	0.50 ±0.1	0.35 ±0.1
	40	0.51 ±0.1	-.- -.-	0.49 ±0.1	0.35 ±0.1
	60	0.50 ±0.1	-.- -.-	0.47 ±0.1	0.33 ±0.1
	80	0.49 ±0.1	-.- -.-	0.45 ±0.1	0.32 ±0.1
	10	0.54 ±0.1	0.38 ±0.1	0.54 ±0.1	0.42 ±0.1
	15	0.51 ±0.1	0.35 ±0.1	0.51 ±0.1	0.37 ±0.1
	20	0.49 ±0.1	0.33 ±0.1	0.49 ±0.1	0.36 ±0.1
3	30	0.49 ±0.1	0.32 ±0.1	0.48 ±0.1	0.34 ±0.1
	40	0.48 ±0.1	0.31 ±0.1	0.47 ±0.1	0.33 ±0.1
	60	0.47 ±0.1	0.31 ±0.1	0.44 ±0.1	0.31 ±0.1
	80	0.46 ±0.1	0.30 ±0.1	0.42 ±0.1	0.30 ±0.1

seconds for the 10 second time bracket; adding 10 seconds to this value yields 68 seconds for a minimum for data collection time.

The data also indicate that the use of faster responding thermistor temperature sensors in psychrometers 1 and 2 was not better than the slower responding temperature IC's used in psychrometer 3. Further, the lack of differences in the standard deviations of the maximum average ET rate between psychrometers indicates that using thermistor temperature sensors with greater measurement accuracy is not warranted.

4.6.2 Cumulative ET Analysis

Comparing chamber-measured cumulative ET in the field with lysimeter-measured cumulative ET entails three analyses which yield information about individual psychrometer performance across the days of data collection, the affect of the elapsed time between field measurements, and the accuracy of chamber-measured cumulative ET compared to lysimeter- measured cumulative ET.

A comparison of the cumulative lysimeter-measured ET with cumulative ET measured by psychrometers 1, 2, and 3 for all dates of data collection is shown in Table 4-3. The chamber data was calculated from the results of the 20 second time bracket, which the laboratory analysis indicated should be used. Cumulative chamber ET was calculated as a percentage of lysimeter ET to permit comparison between psychrometers and across days of collection. Psychrometer 1 data were not reported on July 19, 1984 because the wet bulb wick dried out, preventing full depression. No data were available for psychrometer 2 on August 13, 1984 as it was disconnected.

On July 19, chamber-measured ET was very close to lysimeter- measured ET using the 2.4 m (96 inches) tall chamber. Cumulative ET for August l3, l5, and 20 clusters well around 70 to 80 percent of lysimeter ET. The only equipment difference for the four data collection dates was the change of chamber height in August. For all days of data collection, individual psychrometers compared well with each other except psychrometer 1 on August 20. The thermistor temperature sensors equipped with psychrometers (psychrometers 1 and 2) did not perform better than the IC sensor (psychrometer 3) psychrometer.

On August 15, the measurement frequency was increased to determine if measurements spaced closer than 10 minutes would improve ET estimation. Improvement due to increased measurement frequency was not apparent in the data from Table 4-3. Using an elapsed time of ten minutes between measurements resulted in no worse a measurement of cumulative ET as a percent of lysimeter ET than using an elapsed time of 5.5 minutes between measurements.

Table 4-3 Average cumulative chamber ET and confidence interval from the 20 second analysis time bracket vs. cumulative lysimeter ET for psychrometers 1, 2, and 3 for data collected on July 19, August 13,15, and 20, 1984 at 80 percent confidence.

		Psychrometer					
Date	Lysimeter	1		2		3	
	(mm)	*(mm)*	*(%)*	*(mm)*	*(%)*	*(mm)*	*(%)*
7/19	5.6	———		5.5±0.1[1]	(99±2)	5.1±0.2[1]	(93±2)
8/13	3.5	2.4±0.1[2]	(69±1)	———		2.6±0.1[2]	(74±4)
8/15	4.5	3.3±0.1[2]	(73±3)	3.5±0.1[2]	(78±2)	3.3±0.1[2]	(75±1)
8/20	3.6	3.0±0.1[2]	(84±3)	2.5±0.1[2]	(71±2)	2.6±0.2[2]	(72±6)

[1] 2.4 m (96 inch) tall chamber

[2] 3.6 m (141 inch) tall chamber

Laboratory testing of the chamber measurement systems resulted in the creation of calibration equations for the 20 second analysis time bracket for psychrometers 1 and 2 and the 30 second analysis time bracket for psychrometer 3. In Table 4-4, the results of using the equations to correct cumulative chamber ET are presented for all psychrometers on all collection dates. From the table it is apparent that application of the correction equations to data collected on July 19 was not helpful. The adjusted ET values for psychrometers 2 and 3 significantly overestimate lysimeter ET.

Field measurements in August, when adjusted, more closely matched cumulative lysimeter ET. Measurements from psychrometers 2 and 3 resulted in ET being overestimated by 19 per-

cent, while measurements from psychrometer 1 resulted in ET being underestimated by as much as 18 percent.

Table 4-4 Adjusted cumulative chamber ET and confidence interval from the 20 second analysis time bracket vs. cumulative lysimeter ET for psychrometers 1, 2, and 3 for data collected on July 19, August 13, 15,and 20,1984 at 80 percent confidence.

		Psychrometer		
Date	Lysimeter	1	2	3
	(mm)	*(mm) (%)*	*(mm) (%)*	*(mm) (%)*
7/19	5.6	———	8.5±0.2[1] (152±4)	8.2±0.2[1] (146±3)
8/13	3.5	2.8±0.1[2] (82±2)	———	3.8±0.1[2] (110±4)
8/15	4.5	4.1±0.1[2] (92±2)	5.3±0.2[2] (119±4)	5.2±0.1[2] (116±3)
8/20	3.6	3.6±0.2[2] (101±4)	3.8±0.1[2] (106±3)	3.8±0.2[2] (106±4)

[1] 2.4 m (96 inch) tall chamber

[2] 3.6 m (141 inch) tall chamber

A comparison of cumulative chamber ET versus cumulative lysimeter ET for the 10 second analysis time bracket provided further information on the use of the data for determining cumulative ET.

The results of the analysis of the average time to start and the average ET rates for each time bracket are presented in Table 4- 1 and 4-2. They indicate that the use of the 10 second time bracket was desirable because it yielded 10 percent greater ET rates when compared to lysimeter ET without a loss in measurement precision. Table 4-5 presents the cumulative ET for lysimeter and chamber field measurements for all psychrometers on all field collection dates using the 10 second analysis time bracket. All chamber cumulative ET's were greater than those calculated at the 20 second analysis time bracket. Cumulative ET data collected on July 19 shows 100 to 106 percent of cumulative lysimeter ET. Data collected on August 13, 15, and 20 show a 4 to 12 percent improvement in cumulative ET estimation, not as large as the 10 percent increase of average ET rates for the 10 second analysis time bracket over the 20 second analysis

time bracket, but still an improvement. Data for the 3.6 m (141 inch) tall chamber cumulative ET on August 13, 15, and 20 are still similar to that seen in Table 4-4, supporting the choice of the 10 second analysis time bracket for field data interpretation. However, the errors in estimation of cumulative ET do increase. In particular psychrometer 3 (using the temperature IC's) shows errors of 8 to 16 percent compared to 3 to 4 percent error if the 20 second analysis time bracket is used.

Table 4-5 Cumulative chamber ET and confidence interval from the 10 second analysis time bracket vs. cumulative lysimeter ET for psychrometers 1, 2, and 3 for data collected on July 19, August 13, 15,and 20,1984 at 80 percent confidence.

		Psychrometer		
Date	Lysimeter	1	2	3
	(mm)	*(mm)* *(%)*	*(mm)* *(%)*	*(mm)* *(%)*
7/19	5.6	———	5.9±0.3[1] (105±5)	5.6±0.5[1] (100±8)
8/13	3.5	2.5±0.1[2] (73±4)	———	2.9±0.4[2] (84±12)
8/15	4.5	3.5±0.2[2] (78±4)	3.8±0.3[2] (85±6)	3.7±0.4[2] (82±8)
8/20	3.6	3.3±0.3[2] (91±8)	2.7±0.2[2] (76±6)	3.0±0.6[2] (84±16)

[1] 2.4 m (96 inch) tall chamber

[2] 3.6 m (141 inch) tall chamber

4.6.3 Average Cumulative ET

Making practical use of the field measured ET is difficult if one must choose one of the three psychrometers to calculate cumulative ET. Since the psychrometers measured ET rates simultaneously, the differences in cumulative ET represent a possible range of cumulative values. If the cumulative ET from all psychrometers is averaged for each day of data collection, a representative cumulative chamber ET by day can be calculated.

Table 4-6 presents average cumulative ET for all psychrometers by date of collection. The average cumulative ET for the 10 and 20 second analysis time brackets are expressed as a percentage of cumulative lysimeter ET, for comparison across days of data collection. Solar radiation measurements expressed as cumulative mm of water depth equivalent are also presented for comparision between days. An instrument malfunction prevented solar radiation data reporting on August 13, 1984. Lysimeter cumulative ET was reported as a percentage of solar radiation for comparison of microclimatic conditions. Trends in Table 4-6 are the same as those for Table 4-3. Chamber ET on July 19 was 95 percent of field ET with a two percent margin of error at an 80 percent confidence level. Cumulative ET data for the August 13, 15, and 20 measurements show excellent agreement. across days for the 20 second analysis time bracket.

An outside source of solar radiation measurements was sought for August 13, 15, and 20 to compare to chamber-measured solar radiation. Unfortunately, the reference radiation instrument was out of service on August 13. Field notes for August 13 indicate the cloud cover and wind speed were similar to those for August 15 and 20. Using the field notes, a solar radiation value of 6.2 mm was assumed reasonable for August 13. Measurements on July 19 and August 15 and 20 corroborate the relationship of solar radiation measured with the chamber sensor to measurements from the comparison source, confirming the relative correctness of the chamber solar radiation measurements across days of data collection.

As is shown in Table 4-6, if data from the 10 second analysis time bracket is used to calculate average cumulative ET,the values are within a range of 27 percent across all days. For days when the 3.6 m (141 inch) tall chamber was used for measurements, calculated cumulative chamber ET has a range of six percent with average performance of 81 percent of lysimeter ET.

Table 4-6 Average cumulative chamber ET for the 10 (ET_{10}) and 20 (ET_{20}) second analysis time bracket in mm and as a percentage of cumulative lysimeter ET in mm; cumulative lysimeter ET as a percentage of solar radiation

Date	Solar	Lysimeter		ET_{20}		ET_{10}	
	(mm)	(mm)	(% of solar)	(mm)	(%)	(mm)	(%)
7/19	9.0	5.6	(62)	5.3±0.1	(95±2)	5.8±0.4	(104± 7)
8/13	6.2[1]	3.5	(52)	2.5±0.1	(74±3)	2.7±0.2	(77± 8)
8/15	6.2	4.5	(70)	3.4±0.1	(76±2)	3.7±0.3	(82± 6)
8/20	6.7	3.6	(54)	2.7±0.1	(75±3)	3.0±0.3	(83± 10)

[1] Estimated solar from field notes.

4.6.4 Hourly ET Results

The average percent error of hourly chamber-measured ET versus lysimeter hourly ET is given in Table 4-7 for four days of data collection. Again, data collected on July 19 with the 2.4 m (96 inch) chamber showed less error than data collected with the 3.6 m (141 inch) chamber in August. On a given day of collection the hourly percent error was comparable between psychrometers, in particular on August 13 and 15. The average chamber hourly ET error was 25 percent when all days of data collection were averaged. If averaged by chamber size, the 2.4 m (96 inch) tall chamber had a 13 percent error while the 3.6 m (141 inch) tall chamber was 27 percent in error.

Comparison of chamber-measured hourly ET to lysimeter-measured hourly ET was good for the 2.4 m (96 inch) chamber and would allow field measurement of ET for short (hourly) time spans without unreasonable error. The data for the 3.6 m (141 inch) chamber exceeded the desired maximum error of 20 percent (T.L. Loudon, personal communication, 1984), but could be used if adjusted upward.

Table 4-7 Average percent error of hourly cumulative chamber ET versus hourly cumulative lysimeter ET for July 19, August 13, 15, and 20, 1984.

	Psychrometer			Average Chamber
Date	1	2	3	Error
	(%)	(%)	(%)	(%)
7/19	—	8.6	16.6	12.6
8/13	35.4	—	33.4	34.4
8/15	23.8	20.4	23.8	22.6
8/20	14.1	28.4	31.9	24.8

4.6.5 Summary of Field Performance

The performance of the chamber in field tests was mixed. ET values obtained using the 2.4 m (96 inch) tall chamber were more than 90 percent of ET measured by the lysimeter, but only one day's data exist. Three days' field data collected with the 3.6 m (141 inch) tall chamber yielded 70 to 80 percent of the lysimeter-measured ET.

These data indicate that the chamber performed similarly on days with similar solar conditions. The improved performance of the chamber on July 19 may be partially due to the fact that 25 % more solar radiation was available on that date than any other day measured.

Also, there was reduced mixing of the air in the taller chamber. The air in the upper one third to one half of the large chamber was thoroughly mixed with the axial fans. I had assumed that the centrifugal fans used in the lower portion of the chamber adequately transported air from the lower portion of the chamber upward to the axial fans for mixing. The increase in chamber volume due to the increase in chamber height from 2.4 m (96 inches) to 3.6 m (141 inches) reduced the air turnover rate in the chamber from 3.7 cycles per minute to 2.5 cycles per minute. It is possible that some lower air mixing velocity exists below which measurement accuracy decreases.

Reicosky and Peters (1981) used fans which mixed and recycled the air nine times per minute. Results of calibration tests against solution uptake for soybeans were excellent (r2=0.98, slope= 0.98, intercept= 0.009, or essentially 1 to 1). Harmsen (1983) reported a 16 percent overestimation of lysimeter ET for an operable top chamber using one air cycle per minute. Larson (1980), using a mobile chamber developed by Peters et al. (1974), measured transpiration for soybeans using air cycling ratios of 1.7 volumes per minute. The author indicated that the exchange rate was too low, reducing the accuracy of the results.

The close agreement of the psychrometers for each day of measurement confirms that chamber height does cause a difference in measurement accuracy. Although it cannot be proven that the reduced air mixing ratio caused the reduction in measurement accuracy, the most probable cause of the difference is the the reduction of lower canopy air mixing when using the 3.6 m (141 inch) tall chamber.

Differences in the crop on the lysimeter and in the test plot area for measurements made in August may have been significant enough to contribute to the reported performance difference. Observation of the crop on the lysimeter would have suggested that the test plot area was healthier and should have used more water.

4.6.6 Problems

Several problems arose while using the equipment selected for the chamber-measurement system. The microcomputer selected supported only integer-math functions, whereas the calibration equations used real numbers. This made field determination of temperature difficult. The nonlinearity of thermistor output over the temperature range further complicated the issue. These two factors made it difficult to assure that the psychrometer wick was adequately wetted. Field temperature output for the different psychrometers would have provided a means of comparison of wet bulb temperatures, eliminating situations where uncertainty about wet bulb depression forced elimination of data.

Also, the data collection system used was bulky and cumbersome. The software was crude and difficult to use even with adequate training. In defense of the data collection system, no other system offered the capabilities needed to collect the data in the field at an acceptable cost.

The chamber transport system and lift mechanism required substantial time for setup and the services of a small farm tractor for the entire measurement period. Many attempts to collect data for lysimeter comparsion with the portable chamber were foiled by changes in the weather conditions. As previously mentioned, data collected under cloudy conditions led to unexplainable results for other researchers. The location of the test site downwind of a large body of water (Lake Michigan) and the prevailing winds across the lake led to few long clear-sky periods and fewer clear days.

Chapter 5

DISCUSSION AND CONCLUSIONS

5.1 Introduction

The purpose of this chapter is to summarize the discussions in the previous chapters, to delineate the procedure for optimum field use of the chamber, and to recommend improvements to the portable chamber measurement system.

5.2 Discussion

5.2.1 Objective 1

The first objective of the research was to study the transducer system used to measure changes in water vapor density under controlled conditions. An aspirated psychrometer was chosen as the measurement transducer because it best met the following criteria:

1) non-destructive of the environment;
2) sufficiently accurate and precise to warrant use in a growing crop canopy;
3) capable of performing rapid measurements;
4) easily interfaceable with electronic data collection equipment;
5) portable; and
6) affordable.

The use of thermistor temperature sensors constructed from raw thermistor beads provided small, fast response temperature sensors. Larger, integrated circuit (IC) temperature sensors were also used. The use of the thermistor and IC temperature sensors in the psychrometers provided an opportunity for comparing the accuracy of measurement of the temperature sensors as part of the second criterion for the measurement transducer. The temperature IC sensors displayed a linear response to changes in temperature while the thermistor temperature sensors did not. The IC's exhibited slower response and lower sensitivity to temperature adjustments. The

IC's were easier to use and required a simpler output amplifier. Although they were less expensive than the thermistor temperature sensors, the use of the temperature IC's reduced measurement accuracy.

The results of the temperature calibration tests showed the thermistor temperature sensors to be accurate within ± 0.05°C, while the temperature IC's were only accurate within ± 0.1°C. One thermistor temperature sensor (sensor 5) was significantly in error with residuals from calibration equation fitting in excess of 0.1°C. The thermistor temperature sensor amplifier circuit and analog to digital converter (A/D) were tested for field temperature errors and showed a maximum error of 0.06°C for a 30°C rise in temperature. This alleviated concern that field temperature shifts in components comprising the A/D and amplifier would cause temperature measurement errors.

The psychrometer assembly was tested with a manometer to assure that the minimum air velocity of 3 m/sec required for full wet bulb depression would be achieved. Velocities ranged from 7.2 to 9.1 m/sec for the expected range of aspiration motor operating voltages of 10.5 to 13.5 volts DC. At the time of testing, the velocities were considered adequate though not excessive.

Two psychrometers equipped with thermistor temperature sensors and a psychrometer equipped with IC temperature sensors were tested using a step moisture input to evaluate sensor response and performance (Table 2-3). The purpose of the test was to determine the approximate time after chamber placement at which the psychrometer could be assumed to be measuring plant transpiration. Results of the test showed the thermistor- equipped psychrometers reacted about three times faster than the IC-equipped psychrometer of similar construction. Measurement delays were 18 seconds for the thermistor-equipped psychrometers and 48 seconds for the IC- equipped psychrometer.

The psychrometer that was built met my performance criteria with one exception: affordability. The aspirated psychrometer was a good choice for a measurement transducer. In Chapter 2, the reader was cautioned that the method used did not result in interchangeable thermistor temperature probes. The warning does not stress the critical error I made in an effort to "build"

an affordable measurement transducer: failure to measure time as a cost item. This caused a violation of Gerrish's first law of instrumentation: "Don't build it if you can buy it!" (Gerrish, 1984)

The cost of the thermistor beads was $4.00 to $5.00 each, while the cost for the temperature IC's was $3.00 each. Commercial linearized thermistor and temperature IC probes, calibrated to ± 0.05°C, could have been purchased for $100 to $200 each. The cost of the time required to develop and calibrate the temperature probes was in excess of twice the cost of the commercial probes. Even though the parts that comprised the psychrometers were inexpensive (less than $40.00 total), the cost of the time spent calibrating the psychrometers made the approach used by this researcher much more expensive than was anticipated. This does not preclude future use of psychrometers as measurement transducers provided the mistakes of the past are not forgotten.

5.2.2 Objective 2

The second objective of the research was to study the chamber transducer system used to measure changes in water vapor density in the chamber.

The measurement system (chamber, fans, psychrometers, and A/D) was tested in two ways. Volumetric water inputs of 2, 15, and 30 cm^3 were used to test the ability of the psychrometers to respond to a known input of water vapor in a short time. The 30 cm^3 water input was too large to represent a reasonable field measurement. The data were not used to develop relationships between the chamber and the psychrometers, but they indicated that a problem existed with the moisture evaporation apparatus (a hot frying pan) used in the laboratory. Psychrometer water volume measurements were significantly in error at the 30 cm^3 input.

I hypothesized that the frying pan was causing about one- third of the water injected onto it to be suspended in the chamber air as liquid water particles. These small water particles were thought to be atomized. The psychrometers responded indirectly to changes in chamber water vapor density. If water from the frying pan were not vaporized, the psychrometers could not respond to the change in water vapor density.

The atomized liquid water should have evaporated at some time. Numberger (1972) reported results of two cloud models which related the radii of liquid water droplets to their time

before evaporation. The range of life times for the liquid water droplets was from 152 to 7950 seconds, depending on saturation. Since the chamber measurement was 120 seconds long, it is probable that if atomization occurred, the liquid water in suspension would not have completely evaporated by the end of the measurement. The 30 cm^3 input was sufficient to bring the chamber air very close to saturation. Measurements at this level were suspect because it was known that psychrometers give unreliable results at relative humidities in excess of 90 percent (Wylie, 1968).

The data from the 2 and 15 cm^3 step inputs were compared with the psychrometer measured volumes with almost 100 percent agreement for the 2 cm^3 inputs when using the high air mixing velocity. The results were not as good when the air mixing velocity was reduced, indicating that a relationship between psychrometer performance and air mixing velocity exists. The results of the 15 cm^3 input were similar for reduction of air mixing velocity. However, the water volume measured was only approximately two-thirds of the 15 cm^3 input volume even at the higher air mixing velocity.

The second test of the chamber and measurement system was a ramp input of water, meant to mimic the expected input of water from transpiring plants. Water input rates of 0.07, 0.14, 0.28, and 0.52 mm/hr were used to measure chamber performance. The intent of the ramp input test was to develop linear equations that related water input to measured water yield.

Initially linear equations were fit to the ramp data using an endpoint analysis approach. The endpoint analysis used the starting and ending water vapor density to calculate a volume change in water content of the chamber. Results of the 0.07, 0.14, 0.28, and 0.52 mm/hr input were fit to volume-based linear equations shown in Figures 3-4 and 3-5 for high and low air mixing velocities. The use of these equations to adjust field data would have necessitated the conversion of the field rates, in mm/hr, to a unit volume over some given time (still a rate, technically), adjustment of the volume,and conversion back to a rate. It is important to note that the linear equations for volume-based adjustment were very similar for the chamber tests with low and high air mixing velocities.

This would have been a workable solution; however, a rate-based correction was prefered and offered statistically simpler calculations of integrated ET confidence intervals. The results of

the step test and the ramp endpoint analysis made the need for calibration equations clear. Plots of the raw data during analysis indicated more variability for psychrometer 3 (IC- equipped) than for psychrometers 1 and 2 (thermistor-equipped). The increased variability was not entirely unexpected. The IC temperature sensors used in psychrometer 3 had a sensitivity to changes in temperature only one-half that of the thermistor temperature sensors. Analysis of the average temperature change per unit of time between data points was conducted to assess the magnitude of the difference between psychrometers. Data collected for psychrometers 1 and 2 had lower variability than that for psychrometer 3 at the 0.07 and 0.14 mm/hr input rate. At higher rates all psychrometers performed similarly (Table 3- 2).

The preferred calibration equations adjusted field measured rates to new rates using rate-based linear equations. The evaluation of the rate data to create calibration equations was complicated by the desire to locate the maximum slope of the chamber water vapor density increase. Instead of assuming that any good line fit (r^2=0.90) to the chamber water vapor density increase during measurement was the slope of the gradient increase, an analysis of seven time brackets from 10 seconds to 80 seconds was completed using the laboratory data (Table 3-3). The table showed that the average time required to wait before a maximum rate occurred was well into the measurement (50 - 70 seconds) and that the longer the analysis time bracket, the shorter the average time to start. Initially, using the longer analysis time brackets and moving the starting point forward seemed to be preferable, but the laboratory analysis also showed that as analysis time increased, average ET decreased. Some compromise had to be reached.

I recognized that the laboratory data might not resemble the field data. It was probable that errors introduced by the moisture evaporating apparatus (electric frying pan) biased the ramp test results. However, I assumed that the 20 second analysis time bracket best suited psychrometers 1 and 2, based on response times of the thermistor temperature sensors. The temperature IC's used in psychrometer 3 had longer response times, indicating that the 30 second time bracket should be used for this psychrometer. A first order linear equation was calculated from the ramp input laboratory data using 0.07, 0.14, 0.28, and 0.52 mm/hr input rates at the 20 second analysis time bracket for psychrometers 1 and 2, and at the 30 second analysis time bracket for

psychrometer 3 (Figures 3-6 and 3-7). The appropriateness of using the calibration equations to correct field data is still in doubt.

5.2.3 Objective 3

The third objective of the research was to compare the evapotranspiration measured in the field with the portable chamber to field- measured evapotranspiration from a lysimeter.

The field data was first analyzed to determine the length of time required to wait before a maximum ET rate could be calculated for a given analysis time bracket. Table 4-1 showed that for any date of analysis, increasing the time of analysis decreased the time to start. Table 4-2 showed that increasing the analysis time bracket resulted in a decrease in ET rates. The standard deviations of the average rates did not increase as the length of the analysis time interval decreased, leading to the conclusion that the shortest analysis time bracket was acceptable. Expected performance differences between thermistor- equipped psychrometers and the IC-equipped psychrometer were not apparent. Thus, use of the fast response thermistor temperature sensors did not improve ET rate measurement.

The longer times to start of analysis (Table 4-1) for the short analysis time brackets were unexpected. Conversations with F.L. Charles (1987), who used the technique for measurements on phreatophytes in the San Luis Valley in Colorado, indicated maximum ET rates for 10 second analysis time brackets occurred immediately after chamber placement. The time to start delay (about 48 seconds) does correspond well with delay times predicted for the IC-equipped psychrometer (psychrometer 3) based on wet and dry bulb response times. Average time to start (33 seconds or greater) for the thermistor- equipped psychrometers (psychrometers 1 and 2) was almost twice the expected 18 seconds calculated from wet and dry bulb response times. In fact, the thermistor-equipped psychrometers were not faster responding than the IC-equipped psychrometer for any time bracket.

The cumulative ET for each psychrometer was compared with the cumulative lysimeter ET on each day of data collection. Data collected on July 19 for the 20 second analysis time bracket were in excellent agreement with data from the lysimeter (99 percent for psychrometer 2 and 93

percent for psychrometer 3). The performance of the portable chamber on all other dates of data collection was not as good (70 to 84 percent of lysimeter ET).

The data for the 20 second analysis time bracket was adjusted with the laboratory based calibration equations with mixed results. Adjusted cumulative chamber ET for July 19 significantly overestimated cumulative lysimeter ET (146 to 152 percent). For data collected in August, use of the calibration equations resulted in ET being overestimated by as much as 19 percent for psychrometers 2 and 3, while psychrometer 1 underestimated cumulative ET by 18 percent. Had only the August data, which was collected with the taller 3.6 m (141 inches) chamber, been available, use of the calibration equations might have been recommended. With the inclusion of the 2.4 m (96 inch) tall chamber data, the usefulness of the calibration equations became doubtful.

The time to start analysis and the average ET rate analysis suggested that the 10 second analysis time bracket would be an acceptable choice for data analysis and that it added little uncertainty to the estimation of ET rates. The 10 second analysis time bracket ET rate data were integrated to calculate cumulative chamber ET for each psychrometer on each day of field data collection. The results of the average ET rate analysis showed a 10 percent increase in average ET rate when the 10 second analysis time bracket was compared with the average ET rate for the 20 second analysis time bracket. When the 10 second analysis time bracket ET rates were used to calculate cumulative ET, measurement accuracy increased, with the July 19 data at or overestimating lysimeter cumulative ET. The August data collected with the 3.6 m (141 inches) tall chamber increased 4 to 12 percent (Table 4-5).

The general increase in cumulative measured ET was expected. Accompanying the increase in cumulative ET was an increase in the measurement error. The maximum error of measurement for the 20 second analysis time bracket was 6 percent with an average error of 4 percent. When the 10 second analysis time bracket was used, the maximum error rose to 16 percent with an average error of 8 percent, or a doubling of the average error at the 80 percent confidence interval. Apparently more error was introduced when the shorter analysis time bracket was used.

The cumulative ET analysis did show the psychrometers to be returning similar measurements for a given date of data analysis. The probability that all psychrometers were in error for

any one date of data collection is low. This led to the conclusion that some difference in the ability of the chamber to accurately measure ET existed between the 2.4 m (96 inches) tall chamber and the 3.6 m (141 inches) tall chamber.

Analysis of the data for each psychrometer was not useful for evaluation of field measurements by the chamber. The data from the psychrometers were averaged to calculate a cumulative ET for the chamber in the 10 second and 20 second analysis time brackets. Average cumulative chamber ET followed the same trend as individual psychrometer data, with the July 19 measurements ranging from 95 to 104 percent of lysimeter ET. Data collected in August ranged from 77 to 83 percent and 74 to 76 percent for the 10 and 20 second analysis time brackets, respectively.

The last analysis of the chamber ET was done to estimate the performance of the chamber for hourly ET measurements. The results showed an average chamber error of 13 percent in a range of 9 to 17 percent on July 19. Average hourly chamber percent error was between 25 and 34 percent in August. The data using the 2.4 m (96 inches) chamber collected on July 19 was within the desired 20 percent error band and would allow hourly cumulative ET comparisons. The August data were outside the 20 percent error band for all psychrometers except psychrometer 1 on August 20. The average percent hourly ET error by date also exceeded the 20 percent error band, making hourly ET comparisons with the 3.6 m (141 inches) tall chamber suspect.

5.2.4 Problems

The previous discussion centered on the technical and quantitative aspects of the use of the portable chamber. A small section of the results and discussion dealt with problems involved with collecting the data. These should be stressed. A significant concern when using a portable ET chamber is the lack of data available to compare lysimeter ET to chamber ET on days with cloudy or varying sky conditions. All data collected for this study were for either clear skies or days with very high, sparse stratus clouds. The exact relationship between measurements with the portable chamber and changes in radiation is not known. It is hypothesized that changes in radiation will directly affect chamber-measured ET rates.

The portable chamber is essentially a point measurement tool. Measurements are assumed constant over some time period. If the conditions during the time period vary, the point measurement clearly can not adequately represent the time period. If conditions are highly variable when data is collected, the chamber-measured ET rate may not reflect the average ET for the time interval between measurements. Michigan's sky conditions during July and August are greatly influenced by the presence of Lake Michigan immediately to the west. Prevailing winds across the lake collect moisture from the lake surface, increasing cloud formation. The availability of clear days for calibration is severely limited, and the usefulness of the chamber on days with more variable conditions is suspect, as documented by several authors (Reicosky and Peters, 1977; Reicosky et al. 1981). It would seem that future use of the portable chamber, given the sky conditions necessary for data collection, would be limited in Michigan.

5.3 Conclusions

1) Psychrometers equipped with temperature sensors accurate to 0.05 °C did not yield better estimates of cumulative ET than did psychrometers equipped with temperature sensors accurate to 0.1°C.

2) A psychrometer with a response time of 10 seconds measured cumulative ET as well as a psychrometer with a response time of 3.6 seconds.

3) Laboratory tests under controlled conditions confirm that reductions in air mixing velocity reduce psychrometer measured ET rates.

4) Cumulative ET for periods in excess of 6 hours can be calculated from point in time measurements with the 2.4 m (96 inches) tall chamber equipped with air exchange rates of 5.2 cycles per minute with either thermistor or IC temperature sensors.

5) Hourly cumulative ET can be calculated from point in time measurements with the 2.4 m (96 inches) tall chamber equipped with either thermistor or IC temperature sensors.

6) For days with uniformly sunny skies, measurement intervals shorter than 10 minutes do not improve the cumulative ET measurement or reduce the cumulative measurement error.

7) Measured ET rates decrease as the time interval for which the rate is calculated increases.

8) The time to the start of slope analysis decreases as the time interval over which the slope is calculated increases for both the 2.4 and 3.6 m (96 and 141 inches) tall chambers.

5.4 Recommendations

Recommendations for Use and Improvement of the Existing ET Chamber in Order of Priority

1) Replace the existing A/D and psychrometers with a modern data collection system such as the Campbell Scientific CR-21X data logger and three Delta-T psychrometers. The Delta-T psychrometers offer small (25x100x75 mm), accurate (±0.1°C), interchangeable thermistor temperature sensor equipped psychrometers at a reasonable price ($450.00). Use three psychrometers to verify chamber measurements and prevent data loss due to loss of wick wetness in any one psychrometer. The Campbell CR- 21X which provides direct conversion and display of sensor input to temperature, allowing field sensor function verification.

2) Interface the data collection system to an MS- DOS based portable computer. An MS-DOS based computer allows the use of current data interpretation programs to complete field display and analysis of the data as it is being collected. Comparison of average wet bulb-dry bulb depression between psychrometers will indicate if a psychrometer wick is drying out and reducing wet bulb depression.

3) a. Replace existing 12-volt DC fans with 120- volt AC fans with chamber air turnover capacity of nine cycles per minute. Previous studies by Reicosky and Peters (1977) showed excellent results at this cycle rate.

b. Replace the DC power pack with a 5 to 7 kW AC generator. The battery pack could not deliver the power the fans needed for chamber air mixing at nine cycles with huge cables (#0). The AC generator is readily available and with the increased potential available, requires much smaller cables to transmit the same power. Be sure to vent all engine exhaust well above the crop canopy or keep the generator downwind of the test plots to prevent CO^2 from the generator exhaust from causing stomatal closure which can restrict transpiration.

c. Convert the boom winch and trolley motor to AC power to eliminate the need for the DC power pack. This would convert the entire system to AC power, which could create a greater hazard for the tractor operator and helper. This hazard can be minimized by using ground fault interrupt circuits near the AC generator to reduce electrocution hazard in the event of an accident or equipment breakage.

4) If chambers taller than 2.4 m (96 inches) are to be used, the suspension structure should be redesigned. The current boom is difficult to put together and erect safely. Flexure of the boom during use with the 3.6 m (141 inch) tall chamber and permanent deflection of the support tower indicate that very little safety margin for the operator and helper exists. Redesign should result in a chamber support system that does not require a helper to position the chamber over the test crop.

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Appendices

APPENDIX A

CALIBRATION EQUATIONS FOR EACH TEMPERATURE SENSOR ON EACH DAY OF CALIBRATION.

7/21/84

Sensor 1 = 0.43451013E2 - 0.22567099E-1CT + 0.10125473E-4CT^2 + 0.3945824E-8CT^3 + 0.91722337E-12CT^4 - 0.88530593E-16CT^5

Sensor 2 = 0.56419188E+02 - 0.36687060E-1CT + 0.19338681E-4CT^2 - 0.73516037E-8CT^3 + 0.15475007E-11CT^4 - 0.13250002E-15CT^5

Sensor 3 = 0.11830842E+02 + 0.57273579E-2*CT + 0.12092579E-4CT^2 - 0.21980047E-8CT^3)*100.0);

Sensor 4 = 0.52706427E+02 - 0.31423657E-1CT + 0.15300826E-4CT^2 - 0.55214055E-8CT^3 + 0.11175386E-11CT^4 - 0.92720970E-16CT^5

Sensor 5 = 0.56041017E+02 - 0.35823253E-1CT + 0.18629146E-4CT^2 - 0.68962802E-8CT^3 + 0.13937435E-11CT^4 - 0.11358045E-15CT^5

Sensor 6 = -0.25396904E+02 + 0.23205327E-1CT + 0.4415348E-6CT^2 - 0.52833743E-10CT^3

7/23/84

Sensor 1 = 0.43440323E2-0.22251514E-1*CT+0.93717702E-5CT^2 - 0.33081148E-8CT^3+0.69802405E-12CT^4 - 0.6213687E-16CT^5

Sensor 2 = 0.56099138E+02 - 0.35166337E-1CT + 0.1704151E-4CT^2 - 0.58829676E-8CT^3 + 0.11340122E-11CT^4 - 0.90155052E-16CT^5

Sensor 3 = -0.24695277E+02 + 0.27469804E-1CT

Sensor 4 = 0.5255175ED+02 - 0.30641977E-1CT + 0.14128244E-4CT^2 - 0.47879272E-8CT^3 + 0.91580967E-12CT^4 - 0.72478474E-16CT^5

Sensor 5 = 0.56181022E+02 - 0.34405069E-1CT + 0.16384965E-4CT^2 - 0.55369454E-8CT^3 + 0.10397438E-11CT^4 - 0.80231048E-16CT^5

Sensor 6 = -0.26205989E+02 + 0.24366198E-1CT

7/24/84

Sensor 1 = 0.43402283E2 - 0.22063576E-1CT + 0.88401277E-5CT^2 - 0.28729787E-8CT^3 + 0.55259869E-12CT^4 - 0.44826615E-16CT^5

Sensor 2 = 0.56137936E2-0.35283265E-1*CT + 0.17216581E-4CT^2 - 0.59830983E-8CT^3 + 0.11596748E-11CT^4 - 0.92617581E-16CT^5

Sensor 3 = - 0.24696747E+02 + 0.27453307E-1CT

Sensor 4 = 0.52672859E+02 - 0.31116421E-1CT + 0.1482774E-4CT^2 - 0.52096197E-8CT^3+0.10285187E-11CT^4 - 0.83556285E-16CT^5

Sensor 5 = 0.56350733E+02 - 0.34451868E-1CT + 0.16383278E-4CT^2 - 0.55190707E-8CT^3 + 0.10340753E-11CT^4 - 0.79730400E-16CT^5

Sensor 6 = -0.2618699E+02 + 0.24338182E-1CT

APPENDIX B

CALIBRATION DATA FOR TEMPERATURE SENSORS

Table A-1. Temperature sensor calibration data for 7/21/84.

		Sensor					
Campbell	**Platnium**	**1**	**2**	**3**	**4**	**5**	**6**
C	*C*	*count*	*count*	*count*	*count*	*count*	*count*
24.02	24.08	1381	1781	1771	1732	1804	2070
12.32	12.30	3162	3510	1342	3527	3575	1585
14.05	14.0	2827	3185	1405	3190	3245	1656
16.59	16.58	2384	2755	1499	2744	2786	1762
20.06	19.89	1889	2266	1625	2245	2317	1902
23.91	24.00	1392	1792	1769	1744	1823	2067
26.00	26.07	1174	1580	1844	1525	1605	2152
27.81	27.90	999	1409	1910	1348	1429	2226
29.49	29.58	853	1268	1971	1201	1282	2296
32.87	32.97	591	1014	2094	937	1020	2434
35.20	35.22	438	865	2175	784	868	2528
37.53	37.31	307	737	2254	654	738	2616
40.43	40.48	141	575	2366	486	574	2742
43.20	43.32	6	446	2496	351	442	2859
44.57	44.68	0	389	2531	294	383	2914

Table A-2. Temperature sensor calibration data for 7/23/84.

		Sensor					
Campbell	**Platnium**	**1**	**2**	**3**	**4**	**5**	**6**
C	*C*	*count*	*count*	*count*	*count*	*count*	*count*
12.04	12.07	3216	3558	1337	3578	3680	1570
13.52	13.58	2915	3265	1393	3275	3376	1632
14.84	14.86	2681	3040	1459	3040	3142	1685
17.46	17.48	2245	2617	1536	2600	2704	1793
18.83	18.84	2042	2419	1585	2397	2501	1849
20.25	20.33	1840	2223	1639	2193	2298	1910
22.33	22.41	1573	1964	1714	1924	2029	1994
24.32	24.37	1349	1748	1788	1699	1805	2077
26.59	26.7	1112	1518	1872	1461	1567	2172
28.27	28.39	957	1367	1933	1305	1411	2241
30.46	30.54	772	1189	2012	1120	1227	2331
32.54	32.64	615	1036	2087	961	1069	2415
34.50	34.60	480	904	2159	825	933	2496
36.50	36.56	356	785	2230	702	809	2576
38.64	38.79	229	661	2311	574	681	2667
40.68	40.8	124	560	2384	470	577	2750
43.02	43.17	13	452	2740	359	466	2847
45.23	45.47	*	358	2553	260	370	2940

Table A-3. Temperature sensor calibration data for 7/24/84.

		Sensor					
Campbell	**Platnium**	**1**	**2**	**3**	**4**	**5**	**6**
C	*C*	*count*	*count*	*count*	*count*	*count*	*count*
11.99	12.07	3202	3564	1338	3585	3711	1570
14.13	14.20	2786	3161	1416	3167	3291	1658
16.11	16.14	2445	2830	1487	2823	2944	1738
18.17	18.22	2121	2515	1563	2496	2616	1823
20.15	20.25	1833	2234	1638	2205	2323	1908
27.18	22.29	1578	1984	1712	1946	2063	1992
24.16	24.26	1359	1768	1783	1721	1837	2071
26.10	26.22	1152	1564	1856	1510	16.26	2154
28.09	28.24	960	1380	1929	1319	1434	2737
30.09	30.24	792	1216	2002	1149	1264	2318
32.09	32.22	639	1067	2074	994	1109	2400
34.15	34.25	499	928	2148	850	964	2483
36.14	36.19	377	807	2218	725	839	2563
38.02	38.15	266	696	2289	610	725	2642
40.34	40.44	145	578	2372	488	603	2736
42.14	42.18	53	497	2435	405	518	2808
44.11	44.35	0	404	2514	309	423	2896

APPENDIX C

DATA COLLECTION SYSTEM COMPUTER PROGRAMS

```
 1   REM INITIALIZATION OF TAPE
 4   FOR I=0 TO 5;IO=IN(10);NEXT I
 6   OUT ( 4 ) =0; OUT ( 4 ) = 1 ; RUN %56
 8   H=%18;RUN%54;RUN%56
10   H=%14;RUN%54
12   H=%30;C.%5880;H=%0D;C.%5880
16   RUN%55;RUN%56
20   H=%1A;RUN%54
22   H=%0D;C.%5880;RUN%55;RUN%56
30   ST.

LO.%52
10   REM SAVES @(10)-@(137) ON TAPE TR=D0,BL=C0
15   RUN%57
20   H=%14;RUN%54;H=(%30+D0);C.%5880
22   H=%0D;C.%5880;RUN%55;RUN%56
24   RUN%5A;H=%17;RUN%54
26   FOR I=0 TO 2;H=(%30+@(I));C.%5880;NEXT I
32   H=%2C;C.%5880;H=%30;C.%5880;H=%0D;C.%5880
38   RUN%55
40   FOR I=0 TO 255
42   H=&(20+I);C.%5880
44   NEXT  I
50   RUN%56
52   C0=C0+1
54   P.C0,D0;IF C0=1000 G.99
56   C0=0;D0=2
99   ST.

LO.%54
1    REM OUTPUT CONTROL BYTE TO TAPE DECK
2    C.%5800;OUT(10)=H
3    C.%5840;P=IN(10);IFP=94G.6
4    P.'ERROR NO CTRL ECHOED';G.9
6    C.%5840;P=IN(10);IFP=(H+64)G.9
8    P.#%,'ERROR, BE SENT=',H,'BYTE RCVD=',P
9    ST.

LO.%55
1    REM GET 0D-0A
4    C.%5840;P=IN(10);IFP=13G.6
5    P.#%,P,' RCVD. OD EXPECTED';G.9
6    C.%5840;P=IN(10);IFP=10 G.9
7    P.#%,P,' RCVD. 0A EXPECTED'
9    ST.

LO% 56
'
1    REM GET 07-0D-0A
2    C.%5840;P=IN(10);IFP=7 G.4
3    P.#%,P,' RCVD. 7 EXPECTED';G.9
4    RUN%55
9    ST.
```

```
LO.%57
5    REM CLEAR COMM. FROM TD.
10   GOS.99
20   OUT(10)=27;GOS.99
30   OUT(10)=8;GOS.99
40   E=24;RUN%54
50   RUN%56
90   ST.
99   FOR P=1 TO 9 ;Q=IN (10) ; NE. P; R.

LO.%5A
1    REM CONVERTS A BINARY NUMBER C0 TO 3 INTEGERS
4    @(0)=C0/100
6    @(1)=C0/10-@(0)*10
8    @(2)=C0-10*@(1)-100*@(0)
9    ST.

:LO.%5C
1    REM READ/WRITE TR=D0,BL=C0 CODE STARTING=E0
2    IF F0=1 G.7
3    RUN%5E
4    FOR I=0TO255;PUT(E0+I)=&(20+I);NEXT I
6    STOP
7    P. 'WARNING THIS SUBROUTINE WILL ERASE WHAT IS CURRENTLY'
8    P.'ON THE TAPE.  ENTER 1 TO CONTINUE'
9    INPUT F0
10   IF F0#1G.20
12   FOR I=0TO255;&(20+I)=GET(E0+I);NE.I
14   RUN%52
20   STOP

LO.%5E

1    REM READS @(1Z)-@(137) FROM TAPE FROM TR=D0,BL=C0
4    RUN%5A;H=%14;RUN%54
6    H=(%30+D0);C.%5880
8    H=%0D;C.%5880;RUN%55;RUN%56
12   H=%12;RUN%54
14   FOR I=0 TO 2;H=(%30+@(I));C.%5880;NEXT I
20   H=%2C;C.%5880;H=%30;C.%5880;H=%0D;C.%5880;RUN%55
30   FOR I=0 TO 255
32   C.%5840;H=IN(10);IFH#7G.40
36   C.%5840;P=IN(10);IFP=7G.40
38   P.'ERROR CODE DETECTED =',P;G.99
40   &(20+I)=H
42   NEXT I
44   RUN%56
99   ST.
LO. %14
1    REM READ K0 POINTS FROM A/D FOR L0 CHANNELS
4    A0=%3000
5    FOR K0=0 TO 95;P.K0,
6    RUN%52;PUT(A0)=A;PUT(A0+1)=B;PUT(A0+2)=C;PUT(A0=3)=D
7    PUT(A0+4)=E;PUT(A0+5)=F
8    A0=A0+6
10   O. (16)=04
20   FOR L0=0 TO 12
30   O.(18)=LO
40   O.(20)=00
50   IF IN(16)/128=O GOTO 50
60   A=IN(18) ; B=IN(20)
70   PUT(AO)=A;PUT(AO+1)=B
75   AO=AO+2
80   NE.  LO
100  NE.  KO
103  D0=0,E0=7
104  RUN%1D
```

```
110 ST.

Run .%52
5     REM GET TIME
10    O.(30.)=167;O.(30)=17;A=IN(28);B=IN(28)
20    IF(A0)+(B0)G.40
30    O.(30)=166
40    O.(30)=18;C=IN(28);D=IN(28);O.(30)=19
50    E=IN(28);F=IN(28)
70    STOP

Run %54
REM SET TIME OF DAY CLOCK
10    O.(30)=255;O.(30)=23 ;O.(28)=255
20    O.(28)=138;O.(30)= 01;O.(28)=57
30    O.(28)=15
40    O.(28)=00
50    O.(28)=00
60    O.(30)=2;O.(28)=61;O.(28)=0
63    P."THIS IS A PROGRAM TO SET THE A/D TIMER FOR TIME OF DAY OPERATION"
64    P.
65    P."ENTER DECIMAL NUMBERS PRECEEDED BY A % SIGN"
66    P.
70    P.'ENTER MINUTES-TENS AND ONES'
80    INPUT A
90    P.'ENTER HOURS-TENS ANDS ONES'
92    INPUT B
100   O.(28)=A;O.(28)=B
110   O.(30)=03;O.  (28)=57;O.(28)=00
120   P.'ENTER DAYS-TENS AND ONES'
122   INPUT A
130   P.'ENTER DAYS-1000S ANDS 100S'
132   INPUT B
140   O.(28)=A;O.(28)=B
145   O.(30)=67;O.(30)=09;O.(28)=00;O.(28)=00
150   O.(30)=10;O.(28)=00;O.(28)=00;O.(30)=68;O.(30)=39;
160   STOP
```

APPENDIX D

LABORATORY DATA ANALYSIS AND CONVERSION PROGRAMS

```
PROGRAM VAPOR;

{ This program calculates the liquid equivalent of the water
  trapped in the chamber.  It will adjust the wet bulb temperature
  upward until the dry bulb is reached or the target moisture
  content is reach.

  The program assumes a printer is attached to lpt1.

  You MUST use Turbo Pascal 3.0 or greater to compile
}

var
  wet, dry, satpress, dry_satpress :real;
  cmh20, ambpress, rh, mix_ratio   :real;
  barpress, cmm, dry2, wet2        :real;
  cmstart,cmstop,volmn             :real;
  a, page                          :integer;
  ch                               :char;


procedure calc(wett,dryt:real;var cm:real);
var cmdry    :real;
         begin
         SATPRESS:=6.1078*EXP((17.2693882*wett)/(wett+237.30));
         DRY_SATPRESS:=6.1078*EXP((17.2693882*DRYt)/(DRYt+237.30));
         AMBPRESS:=SATPRESS-0.000657*BARPRESS*((dryt-wett)*(1+0.00115*wett));
         CMH20:=((AMBPRESS/1013.0*18.0)/(82.05*(273.15+dryt)))*1000000.0;
         CMdry:=((dry_satPRESS/1013.0*18.0)/(82.05*(273.15+dryt)))*1000000.0;
         RH:=ambpress/DRY_SATPRESS*100.0;
         mix_ratio:= 0.622*(ambpress*0.1)/(101.35-(ambpress*0.1));
         cm:=cmh20*1.804;
         writeln(lst);
         writeln(lst,'     For wetbulb=',wett:6:2,' and drybulb= ',dryt:6:2);
         writeln(lst,'     Saturated vapor pressure [mb] at the wetbulb is
',satpress:6:3);
         writeln(lst,'     Saturated vapor pressure [mb] at the drybulb is
',dry_satpress:6:3);
         writeln(lst,'     The vapor pressure [ mb] is ',ambpress:6:3);
         writeln(lst,'     The equivalent volume of water [cu cm] in cubic m is
',cmh20:6:3);
         writeln(lst,'     The mixing ratio [ kg h20 / kg dryl air] is ',mix_ratio:10:8);
         writeln(lst,'     The relative humidity is ',rh:6:2);
         writeln(lst,'     Water capacity of the chamber is ',((cmdry*1.804)-cm):6:3);
         writeln(con);
         writeln(con,'For wetbulb=',wett:6:2,' and drybulb= ',dryt:6:2);
         writeln(con,'Saturated vapor pressure [mb] at the wetbulb is ',satpress:6:3);
         writeln(con,'Saturated vapor pressure [mb] at the drybulb is ',dry_satpress:6:3);
         writeln(con,'The vapor pressure [ mb] is ',ambpress:6:3);
         writeln(con,'The equivalent volume of water [cu cm] in cubic m is ',cmh20:6:3);
         writeln(con,'The mixing ratio [ kg h20 / kg dryl air] is ',mix_ratio:10:8);
         writeln(con,'The relative humidity is ',rh:6:2);

         writeln(con,'Water capacity of the chamber is ',((cmdry*1.804)-cm):6:3);
```

```
end;


Begin
  barpress:=1013;
  clrscr;
  gotoxy(1,4);
  Write('Enter the actual water volume evaporated ');
  readln(volmn);
  a:=1;
  page:=0;
  while a=1 do
     begin
         clrscr;
         gotoxy(1,4);
         write('Enter the drybulb temperature [0.0 to 40.0 degrees C] ');
         readln(DRY);
         write('Enter the wetbulb temperature [0.0 to 40.0 degree C] ');
         readln(WET );
         write('Enter the final drybulb temperature [0.0 to 40.0 degrees C] ');
         readln(dry2);
         write('Enter the final wetbulb temperature [0.0 to 40.0 degrees C] ');
         readln(wet2);
         calc(wet,dry,cmstart);
         calc(wet2,dry2,cmstop);
         writeln(con,'Equivalent cubic cm for chamber is ',(cmstop-cmstart):6:3);
         writeln(lst,'     Equivalent cubic cm for chamber is ',(cmstop-cmstart):6:3);
         dry:=dry2;
         cmh20:=cmstart;

         repeat
         SATPRESS:=6.1078*EXP((17.2693882*WET)/(WET+237.30));
         DRY_SATPRESS:=6.1078*EXP((17.2693882*DRY)/(DRY+237.30));
         AMBPRESS:=SATPRESS-0.000657*BARPRESS*((DRY-WET)*(1+0.00115*WET));
         CMM:=((AMBPRESS/1013.0*18.0)/(82.05*(273.15+DRY)))*1000000.0;
         RH:=ambpress/DRY_SATPRESS*100.0;
         mix_ratio:= 0.622*(ambpress*0.1)/(101.35-(ambpress*0.1));
         cmm:=cmm*1.804;
         wet:=wet+0.005;
         until cmm(cmh20+volmn);

         writeln(lst);
         writeln(lst,'     The actual wetbulb should be ',(wet-0.1):6:3,' RH= ',rh:6:3);
         writeln(lst);
         writeln(lst,'     Cm H2O at start= ',cmh20:6:3,' Cm H2O at stop= ',cmm:6:3,' dif-
ference= ',(cmm-cmh20):6:3);
         writeln(lst);
         writeln(con);
         writeln(con,'The actual wetbulb should be ',(wet):6:2,' RH= ',rh:6:2);
         writeln(con);
         writeln(con,'Cm H2O at start= ',cmh20:6:3,' Cm H2O at stop= ',cmm:6:2,' dif-
ference= ',(cmm-cmh20):6:3);
         writeln(con);
      page :=page +1;
      if (page 1) then
         begin
         page:=0;
         writeln(lst,chr(12));
         end;
      read(kbd,ch);
      end;

END.
```

```
PROGRAM TMPBIN
{
You must have Turbo Pascal 3.0 or greater to compile this program.
}
type CHARACTER       =ARRAY[1..34]OF CHaR;
     strg80          =string[80];

const
   readfile : integer =0;
   writefile: integer =1;
   IOVal              : Integer = 0;
   IOErr              : Boolean = False;

VAR
      hour,day,month,error        :integer;
      YY,junk_dt_pts,DATAPTS      :integer;
      blkct,select,FLAG,argcnt    :integer;
      infile                      :file of byte;
      inputfile,outputfile        :CHARACTER;
      dt                          :array[1..250,1..38] of integer;
      outfile                     :TEXT;
      argstrg                     :strg80;

(********************** WRITE PROGRAM NAME AND REVISION NUMBER**********)

procedure HEADER;
var ch     :char;

  BEGIN(*PROCEDURE*)
    clrscr;
    writeln;
    writeln;
    writeln;
    writeln;
    WRITELN;
    WRITELN('                    PSYCHROMETER DATA BINARY TO ASCII');
    WRITELN('                       CONVERSION PROGRAM');
    WRITELN('                              BY');
    WRITELN('                         GARY A. PETERSON');
    WRITELN('                           REV. 7/27/84');
    WRITELN('                           rev. 4/15/87');
    writeln;
    WRITELN;
    writeln('       Use this program only for data collected after July 19, 1984.');
    writeln('       No data was collected in 1985 or thereafter.');
    gotoxy(1,21);
    writeln('       Strike any key to continue.');
    read(kbd,ch);
  END;(*PROCEDURE*)

(**************************PRINTLINE*****************************************)

PROCEDURE printline(x,y:integer;chrstr:strg80);

begin
gotoxy(x,y);
clreol;
write(chrstr);
end;

(****************************NextScrn*****************************************)

procedure NextScrn;
var ch :char;

begin
     printline( 5,24,' press any key to continue');
```

```
    read(kbd,ch);
    gotoxy(5,24);
    clreol;
end;

(************************GetReal*************************************************)

procedure getreal(prompt:strg80;var r:real;var error:integer);

var s    :strg80;

begin
error:=1;
clreol;
write(prompt);
readln(s);
val(s,r,error);
if error  0 then
  begin
  sound(440);
  delay(250);
  nosound;
  gotoxy(1,24); clreol;
  write('     Enter a real number please.');
  delay(2000);
  gotoxy(1,24); clreol;
  end;
  end;

(************************GetInteger**********************************************)

procedure getinteger(prompt:strg80; var i,error:integer);

var s    :strg80;

begin
error:=1;
clreol;
write(prompt);
readln(s);
val(s,i,error);
if error  0 then
  begin
  sound(440);
  delay(250);
  nosound;
  gotoxy(1,24); clreol;
  write('     Enter an integer number please.');
  delay(2000);
  gotoxy(1,24); clreol;
  end;
end;


{********************** check for disk file problems *****************}

procedure IOCheck;
{
       This routine sets IOErr equal to IOresult, then sets
       IOFlag accordingly.  It also prints out a message on
       the 24th line of the screen, then waits for the user
       to hit any character before proceeding.
}
var
  Ch                   : Char;
begin
  IOVal := IOresult;
```

```
  IOErr := (IOVal  0);
  GotoXY(1,24); ClrEol;        { Clear error line in any case }
  if IOErr then begin
    Write(Chr(7));
    case IOVal of
      $01  :  Write('File does not exist.');
      $02  :  Write('File not open for input.');
      $03  :  Write('File not open for output.');
      $04  :  Write('File not open.');
      $05  :  Write('Can''t read from this file.');
      $06  :  Write('Can''t write to this file.');
      $10  :  Write('Error in numeric format.');
      $20  :  Write('Operation not allowed on a logical device.');
      $21  :  Write('Not allowed in direct mode.');
      $22  :  Write('Assign to standard files not allowed.');
      $90  :  Write('Record length mismatch.');
      $91  :  Write('Seek beyond end of file.');
      $99  :  Write('Unexpected end of file.');
      $F0  :  Write('Disk write error.');
      $F1  :  Write('Directory is full.');
      $F2  :  Write('File size overflow.');
      $FF  :  Write('File disappeared.')
    else      Write('Unknown I/O error:  ',IOVal:3)
    end;
    gotoxy(1,24);
    clreol;
    end;
end; { of proc IOCheck }



PROCEDURE OPEN_FILE(b:integer);
var
   OK:BOOLEAN;
   answer:char;

begin(*PROCEDURE*)
clrscr;
repeat
   case b of
        0:begin
           {$I-}
           gotoxy(1,8);clreol;
           write('The name of the file to read is? ');
           readln(inputfile);
           assign(infile,inputfile);
           reset(infile);
           iocheck;
           if not IOerr then
              begin
              gotoxy(1,8); clreol;
              writeln('Read file opened is ',inputfile);
              end;
           {$I+}
           end;(* case 0 *)

        1:begin
            repeat
               gotoxy(1,8); clreol;
               write('The name of the  output file  to write is? ');
               readln(outputfile);
               ASSIGN(outfile,outputfile);
               {$I-}
               reset(outfile);
               {$I+};
               if (IOresult =0 )then
                  begin
```

```
                gotoxy(1,10); clreol;
                writeln('The file already exsists. Overwrite ? [ y,n]');
                read(kbd,answer);
                if ( answer= 'y') or ( answer='Y') then OK :=true
                else OK:= false;
                end
              else ok:=true;

          until ok;
        REWRITE(outfile);
        iocheck;
        if not IOerr then
           begin
           gotoxy(1,8); clreol;
           writeln('File opened for writing is ',outputfile);
           end;
        end;(* case 1 *)

      end;(* case statement *)
nextscrn;
until not IOerr;
end;(*PROCEDURE*)

{**********************DEFINE  PARAMETERS ****************************}

procedure INPUT;
     begin(*PROCEDURE*)
      clrscr;
      gotoxy(1,5);
      writeln('               DEFINITION OF ANALYSIS PARAMETERS');
      repeat
        gotoxy(5,8);
        getinteger('NUMBER OF DATA POINTS                    ',datapts,error);
      until error=0;
      repeat
        gotoxy(5,10);
        getinteger('NUMBER OF RUNS READ FROM THIS FILE?      ',blkct,error);
      until error=0;

      repeat
        gotoxy(5,12);
        getinteger('NUMBER OF POINTS AT THE START OF FILE IS ',junk_dt_pts,error);
      until error=0;
      gotoxy(5,16);
      write('Input parameters defined. Thank You.');
      nextscrn;
    end;

{********************** display the main menu ************************}

procedure menu;
begin
   clrscr;
   printline(15,3,'Main Selection Menu');
   gotoxy(1,5);
   WRITELN(' 1     GET THE NAME OF THE FILE TO BE READ');
   WRITELN;
   WRITELN(' 2     Open a file for output.');
   writeln;
   writeln(' 3     Define temperature conversion parameters');
   writeln;
   writeln(' 4     Convert a count file to temperatures.');
   writeln;
   writeln(' 5     Input file utility routines menu');
   writeln;
   writeln(' 6     Close the output file');
   writeln;
```

```
   writeln(' 7     EXIT THE PROGRAM')
END;

{********************** convert decimal to hex numbers ***************}

function hex(k:integer):integer;
var b,c,d:integer;

  begin
   b:=k div 256;
   c:=(k-b*256) div 16;
   d:=k-b*256-c*16;
   hex:=b*100+c*10+d;
  end;

{********************** display 256 hex numbers **********************}
procedure hex_display;

var i,B:integer;
    a ,junk :byte;
begin(*procedure*)
for i:=1 to 256 do if not eof(infile) then
  begin
  read(infile,junk,a);
  B:=hex(A);
  write(B:4);
  if (i15)and (i mod 16=0)then writeln
  end (*if*)
      else
      begin
      writeln;
      writeln('can not complete this request. stopped at ',i:3);
      i:=256;
      end(*else*)
end(*procedure*);

{********************** forward input file in 256 integer blocks *****}

procedure r_data;
var a,j,c:integer;
    junk,b:byte;

begin
  writeln('read ? blocks of integers');
  readln(c);
  for a:=1 to c do for j:=1 to 256 do read(infile,junk,b)
 end;

{********************** forward input file "x" integers forward*******}

procedure r2_data;
var c,i:integer;
    junk,a:byte;

begin
  writeln('read ? integers from file');
  readln(c);
  for i:=1 to c do read(infile,junk,a)
end;

{********************** set file pointer to start of input file ******}

procedure reset_file;
begin
reset(infile);
end;
```

```
{********************** display utility menu *************************}

procedure menu_2;
begin
clrscr;
gotoxy(1,5);
writeln('                Input File Utility Menu');
writeln;
writeln(' 0 menu');
writeln;
writeln(' 1 read ? block(s) of 256 integers from ',inputfile);
writeln;
writeln(' 2 read ? integers from ',inputfile);
writeln;
WRITELN(' 3 reset the ',inputfile);
writeln;
writeln(' 4 display the next 256 integers');
writeln;
writeln(' 5 exit to main menu');
writeln;
end;

{********************** put up menu_2 and get new job ****************}

procedure file_utility_main;
var b:integer;
    ch: string[1];
begin
  b:=0;
  while bc do
  begin
    menu_2;
    repeat
       gotoxy(5,21);
       getinteger(' enter your menu selection [menu=0] ',b,error);
    until error=0;
  case b of
   0:menu_2;
   1:r_data;
   2:r2_data;
   3:reset_file;
   4:begin
       hex_display;
       readln(kbd,ch);
     end;
    5:b:=100;
   end;
  end
end;

{********************** get rid of unused data at end of a run *******}

PROCEDURE JUNK_DAT(junk_dt_pts:INTEGER);

VAR
  A,B,C,D       :INTEGER;
  junk,e        :byte;

   BEGIN(*PROCEDURE*)
     A:=junk_dt_pts+(DATAPTS*38);
     B:=A MOD 256;
     C:=256-B;
     FOR D:= 1 TO C DO READ(infile,junk,e)
   END;


{********************** calculate time and date **********************}
```

```
procedure TIME_GET(J:INTEGER);

VAR
  TIME      :REAL;
  temp      :integer;

BEGIN(*PROCEDURE*)
  time:=(((hex(dt[j,2]) + hex(dt[j,1])/100.0)/60.0 + hex(dt[j,3]))/60.0)*10000;
  dt[j,3]:=hex(dt[j,4]);
  dt[j,2]:=hex(dt[j,5]);
  dt[j,1]:=hex(dt[j,6]);
  temp:=ROUND(TIME);
  if temp=10000 then temp:=9999;
  DT[J,4]:=temp;
END;(*PROCEDURE*)

{********************** convert integers to temps ********************}

procedure DATA_CONVERT(J:integer; var error:INTEGER);

VAR
   a,B,C,D :INTEGER;

BEGIN(*PROCEDURE*)

error:=0;
d:=2;
repeat
   a:=dt[j,d+5]+dt[j,d+6]*256;
   if a4095 then
      begin
      error:=1;
      gotoxy(5,23);
      writeln('bad data at',j:4,d:4,' value was ',a);
      delay(2000);
      gotoxy(5,23);
      clreol;
      dt[j,(d div 2)+4]:=0;
      end

   else dt[j,(d div 2)+4]:=a;
d:=d+2;
until (d32);
end;(*PROCEDURE*)

(************THROW AWAY UNUSED BYTES AT START OF A RUN**********************)

PROCEDURE START;

VAR
   B:INTEGER;
   junk,a :byte;
BEGIN
 FOR B:=1 TO junk_dt_pts DO READ(infile,junk,a)
END;

{********************** read in the data ******************************}

procedure read_data(var points:integer);

var i,j     :integer;
    a, junk :byte;
begin
   points:=datapts;
   i:=1;
   repeat
```

```
      j:=1;
      repeat
         if not eof(infile) then
            begin
            read(infile,junk,a);
            dt[i,j]:=ord(a);
            end
         else begin
              points:=i-1;
              gotoxy(5,23);
              writeln('Eof at ',i:4,' byte ',j:3,' of 38');
              writeln('Data points reset to ',points:4);
              delay(3000);
              gotoxy(5,23);clreol;
              gotoxy(5,24);clreol;
              i:=datapts;
              j:=38;
              end;(*else*)
        j:=J+1;
       until j38;
       i:=i+1;
    until idatapts;
if not eof(infile) then JUNK_DAT(junk_dt_pts);
end;(* procedure *)

{********************** save the data to disk*************************}

procedure save_data(points:integer);

var l,j    :integer;

begin
writeln(outfile,points:6);
FOR l:=1 to points do
    begin
    write(outfile,dt[l,1]:3,' ',dt[l,2]:3,' ',dt[l,3]:3,' ');
    for j:= 4 to 12 do
       write(outfile,dt[l,j]:5,' ');
    WRITELN(outfile);
    end;
end;(* procedure *)

{********************** convert and save temps************************}

procedure process_file(var points,error:integer);
label finish;
var
  j:integer;

begin
  printline(5,9,'Doing binary to ASCII conversion.');
  gotoxy(1,11);
  for j:=1 to 12 do
    begin
    gotoxy(1,j+10);
    clreol;
    end;
  gotoxy(1,11);
  FOR J:=1 TO points DO
     BEGIN(*FOR J LOOP*)
     write(j:4);
     if (j15)and(j mod 16=0)then writeln;
     TIME_GET(J);
     DATA_CONVERT(J,error);
     if error = 1 then goto finish;
     END;(*FOR J LOOP*)
  WRITELN;
```

```
printline(5,20,'Saving the converted data to disk.');
  save_data(points);
finish:end;

{********************** calculate the temps ***************************}

PROCEDURE calculate;

VAR points, error,K:INTEGER;

  BEGIN(*PROCEDURE*)
  k:=1;
  error:=0;
  clrscr;
  repeat
     clrscr;
     printline(15,3,'Binary to ASCII Conversion Module');
   START;
     gotoxy(5,5);
     write('The current block being processed is ',k:3);
     printline(5,7,'Reading Data ');
     if not eof(infile) then
     begin
       read_data(points);
       gotoxy(46,5);
       writeln(' at
',hex(dt[1,6]):2,'/',hex(dt[1,5]):2,hex(dt[1,4]):3,':',hex(dt[1,3]):2);
       if points0 then
          process_file(points,error)
       else
          begin
          points:=-1;
          k:=k-1;
          end;
       k:=K+1;
     end
     else
       points:=-1;
   until ((kblkct) or (points = 0) or (error =1));
   printline(5,21,'Converted ');
   write((k-1):3,' runs');
   nextscrn;
   END;(*PROCEDURE*)

{************************MAIN PROGRAM*****************************************}

begin
argcnt:=paramCount;
if argcnt 0 then
   begin
   argstrg:=paramstr(1);
   writeln(argstrg);
   halt;
   end;
header;
SELECT:=98;
while selectc do
 begin
       menu;
       repeat
       gotoxy(5,21);
       getinteger('PLEASE ENTER YOUR MENU SELECTION. ',select,error);
       until error=0;
       WRITELN;

      case select of
        1:open_file(readfile);
```

```
        2:open_file(writefile);
        3:input;
        4:CALCULATE;
        5:file_utility_main;
        6:{$I-}
          close(outfile);
          {$I+}
        7:begin
          {$I-}
          close(infile);
          close(outfile);
          {$I+}
          SELECT:=100
          end;
      end(*CASE*)
  END(*WHILE*)
end.(*PROGRAM*)
```

```
PROGRAM ET;
{Program to calculate maximum ET value for data collected in 1984
with the portable ET chamber. Be sure to use TMPBIN.pas to convert
the binary file output by the tape deck to ASCII.

You must have Turbo Pascal 3.0 and Turbo Graphix toolbox to compile this
program.
}
 CONST MAXX = 14  (* MAX # DATA VALUES PER SAMPLE *);
       MAXY = 230 (* MAX NUMBER OF SAMPLES *);
       readfile             : integer =0;
       writefile            : integer =1;
       IOVal                : Integer = 0;
       IOErr                : Boolean = False;

(*********************************DECLARATIONS*************************)

{$I typedef.sys}                      {these files must be}
{$I graphix.sys}                      {included and in this order}
{$I kernel.sys}
{$I windows.sys}
{$I FINDWRLD.HGH}
{$I axis.hgh}
{$I POLYGON.HGH}
 TYPE  INDEXX = 1..MAXX;
       INDEXY = 1..MAXY;
       STAT   = ARRAY[1..8]OF REAL;
       LIST   =ARRAY[INDEXY] OF REAL;
       strg80 = string[80];
(*
       plotarray=array[1..200,1..2]of real;
*)

 VAR   DATA                            : ARRAY[INDEXY,INDEXX] OF INTEGER;

       statslope,statint,statsee,
       statsslope,statrsque,
       statcorr,statstart,statspan     :array[1..50,1..8] of real;

       inputfile,outputfile            : STRING[34];

       TIME,mmH20,RH                   : LIST;


       infile,outfile                 : TEXT;

       NUM_INC,incrmnt,SOLAR_INDEX,
       start, span,regstart,
       REGSTOP,FILECOUNT,
       points,NSAMPLES,SELECT,
       CHAN1,CHAN2,no_runs,
       maxspan,maxstart, year,
       RunNumber,returnerror,
       ConvertIndicator, InputCounter,
       StartIncrt, inp, doplot         :INTEGER;

       BARPRESS,ADJ_HGHT,START_TIME,
       maxslope,MAXINT,MAXRSQUE,
       MAXCORR,MAXSSLOPE,maxsee,
       min,max,mean,stddev,cv,
       timemax,cmmax,cmmin, volume          :real;

       SLOPE,INT,SSLOPE,RSQUE,RSS,SEE,
       REGSLOPE,CORR_COF,solar        : STAT;
```

```
        timestrg                        :strg80;
        plotdata                        :plotarray;

        DEBUG                           : BOOLEAN;

(*************************PRINTLINE*************************************)

PROCEDURE printline(x,y:integer;chrstr:strg80);

begin
gotoxy(x,y);
clreol;
write(chrstr);
end;

(*****************************NextScrn*************************************)

procedure NextScrn;
var ch :char;

begin
     printline( 5,24,' press any key to continue');
     read(kbd,ch);
     gotoxy(5,24);
     clreol;
end;

(************************GetReal*************************************)

procedure getreal(prompt:strg80;var r:real;var error:integer);

var s, st     :strg80;
    j         :integer;

begin
error:=1;
clreol;
str(r:12:5,st);
repeat
  j:=pos(' ',st);
  if j0 then  delete(st,j,1)
until j=0;
prompt:=concat(prompt,'',st,' ');
write(prompt);
readln(s);
val(s,r,error);
if (length(s)0) then
   begin
   if error  0 then
      begin
      sound(440);
      delay(250);
      nosound;
      gotoxy(1,24); clreol;
      write('     Enter a real number please.');
      delay(2000);
      gotoxy(1,24); clreol;
      end
    else
      error:=0;
    end;
  end;

(************************GetInteger*************************************)

procedure getinteger(prompt:strg80; var i,error:integer);
```

```
var s, st     :strg80;
    j         :integer;

begin
error:=1;
clreol;
str(i:8,st);
repeat
  j:=pos(' ',st);
  if j0 then  delete(st,j,1)
until j=0;
prompt:=concat(prompt,'',st,' ');
write(prompt);
readln(s);
if (length(s)0) then
   begin
   val(s,i,error);
   if error  0 then
       begin
       sound(440);
       delay(250);
       nosound;
       gotoxy(1,24); clreol;
       write('     Enter an integer number please.');
       delay(2000);
       gotoxy(1,24); clreol;
       end;
   end
 else
   error:=0;
end;

 (******************** PRINT HEADER ************************************)
 PROCEDURE HEADER;

var ch           :char;

   BEGIN (* HEADER *)
     clrscr;
     gotoxy(1,5);
     WRITELN('                                ET RATE');
     WRITELN;
     WRITELN(' THIS IS A PROGRAM TO CONVERT TEMPERATURE AND TIME DATA TO');
     WRITELN(' AN ESTIMATED EVAPOTRANSPIRATION RATE IN INCHES OF H20 PER HOUR.');
     WRITELN(' The program uses a maximum slope fitting technique that may require');
     writeln(' several seconds to complete.');
     writeln;
     WRITELN('                    WRITTEN BY GARY PETERSON ');
     WRITELN('                  ON 9/10/83. REVISED ON 8/20/84');
     WRITELN('                        REVISED 9/2/85 ');
     writeln('                        revised 7/30/85.');
     writeln;
     gotoxy(5,20);
     write('Press any key to continue.') ;
     read(kbd,ch);
END (* HEADER *);

 (********************** INPUT DEFINITION ************************************)
 PROCEDURE INPUTDEF;
   VAR error,I,J : INTEGER;
   BEGIN (* INPUT DEFINITION *)
     clrscr;
      gotoxy(15,3);
      write(' Input Definition Screen');
     repeat
       gotoxy(5,5);
       getinteger(' DRY BULB TEMPERATURE IS ON CHANNEL?(1-16) ',chan1,error);
```

```
      until error=0;
      repeat
        gotoxy(5,7);
        getinteger(' WET BULB TEMPERATURE IS ON CHANNEL?(1-16) ',chan2,error);
      until error=0;
      repeat
        gotoxy(5,9);
        getinteger(' START THE LINEAR REGRESSION at? ',START,error);
      until error=0;
      IF START  0 THEN START:=0;
      repeat
        gotoxy(43,9);
        getinteger(' By ',StartIncrt,error);
      until error=0;
      repeat
        gotoxy(5,11);
        getreal(' Enter THE BAROMETRIC PRESSURE, IN MILLBARS. ',BARPRESS,error);
      until error=0;
      repeat
        gotoxy(5,13);
        WRITEln(' WHAT IS THE chamber volume in cubic meters? ');
        writeln('              1 =  36 inch= 1.836 ');
        writeln('              2 =  60 inch= 2.842 ');
        writeln('              3 = 101 inch= 4.416 ');
        Writeln('              4 = 140 inch= 6.121' );
        getinteger('        Volume is ? ',inp,error);
        if inp= 1 then begin volume := 1.836261;gotoxy(28,18);Write(' Volume is
',volume:5:3);end;
        if inp=2 then begin volume := 2.841833;gotoxy(28,18);Write(' Volume is
',volume:5:3);end;
        if inp=3 then begin volume := 4.41577;gotoxy(28,18);Write(' Volume is
',volume:5:3);end;
        if inp=4 then begin volume := 6.12087;gotoxy(28,18);Write(' Volume is
',volume:5:3);end;
        if ((inp  ) or (inp 4)) then error :=1;
      until error=0;
      repeat
        gotoxy(5,19);
        getinteger(' Convert the data to temperatures? [Y=1,N=0] ',ConvertIndicator,error);
        if ConvertIndicator=0 then InputCounter:=14;
        if ConvertIndicator 1 then error :=1;
      until error=0;
      repeat
        gotoxy(5,20);
        getinteger(' Plot the data to the screen? [Y=1,N=0] ',doplot,error);
        if ((doplot 1) or (doplot  0)) then error :=1;
      until error=0;
      adj_hght:=volume/17294.28;
      year:=84;
      writeln;
      WRITELN(' INPUT PARAMETERS DEFINED - THANK YOU');
      NextScrn;
  END;

{********************** check for disk file problems *****************}

procedure IOCheck;
{
       This routine sets IOErr equal to IOresult, then sets
       IOFlag accordingly.  It also prints out a message on
       the 24th line of the screen, then waits for the user
       to hit any character before proceeding.
}
var
  Ch                    : Char;
begin
  IOVal := IOresult;
```

```
  IOErr := (IOVal  0);
  GotoXY(1,24); ClrEol;        { Clear error line in any case }
  if IOErr then begin
    Write(Chr(7));
    case IOVal of
      $01  :  Write('File does not exist.');
      $02  :  Write('File not open for input.');
      $03  :  Write('File not open for output.');
      $04  :  Write('File not open.');
      $05  :  Write('Can''t read from this file.');
      $06  :  Write('Can''t write to this file.');
      $10  :  Write('Error in numeric format.');
      $20  :  Write('Operation not allowed on a logical device.');
      $21  :  Write('Not allowed in direct mode.');
      $22  :  Write('Assign to standard files not allowed.');
      $90  :  Write('Record length mismatch.');
      $91  :  Write('Seek beyond end of file.');
      $99  :  Write('Unexpected end of file.');
      $F0  :  Write('Disk write error.');
      $F1  :  Write('Directory is full.');
      $F2  :  Write('File size overflow.');
      $FF  :  Write('File disappeared.')
    else      Write('Unknown I/O error:  ',IOVal:3)
    end;
    gotoxy(1,24);
    clreol;
    end;
end; { of proc IOCheck }



PROCEDURE OPEN_FILE(b:integer);
var
   OK:BOOLEAN;
   answer:char;

begin(*PROCEDURE*)
clrscr;
repeat
   case b of
        0:begin
           {$I-}
           gotoxy(1,8);clreol;
           write('The name of the file to read is? ');
           readln(inputfile);
           assign(infile,inputfile);
           reset(infile);
           iocheck;
           if not IOerr then
              begin
              gotoxy(1,8); clreol;
              writeln('Read file opened is ',inputfile);
              end;
           {$I+}
           end;(* case 0 *)

        1:begin
            repeat
                gotoxy(1,8); clreol;
                write('The name of the  output file  to write is? ');
                readln(outputfile);
                ASSIGN(outfile,outputfile);
                {$I-}
                reset(outfile);
                {$I+};
                if (IOresult =0 )then
                   begin
```

```
                gotoxy(1,10); clreol;
                writeln('The file already exsists. Overwrite ? [ y,n]');
                read(kbd,answer);
                if ( answer= 'y') or ( answer='Y') then OK :=true
                else OK:= false;
                end
              else ok:=true;

          until ok;
        REWRITE(outfile);
        iocheck;
        if not IOerr then
           begin
           gotoxy(1,8); clreol;
           writeln('File opened for writing is ',outputfile);
           end;
        end;(* case 1 *)

     end;(* case statement *)
nextscrn;
until not IOerr;
end;(*PROCEDURE*)

(*************************SetPlotData*********************************)
procedure setplotdata(var timemax,cmmax,cmmin:real);

var i,j:integer;
    divisor:real;

begin
clrscr;
for I:=1 to nsamples do                    { Put the X and Y values in the   }
                                           { plot array.                     }
   begin
   plotdata[i,2]:=mmh20[i];                { Store  water data in X array    }

   plotdata[i,1]:=time[i]*3600;            { Store  time in seconds in the X  }
                                           { array.                          }
   end;

timemax:=trunc(plotdata[nsamples,1]/10);    { Adjust the time base to the     }
                                           { nearest evenly divisible number }
                                           { by 10.                          }

timemax:=(timemax+1)*10;                    { Set the value of max time to    }
                                           { nearest number greater than time}
                                           { divisible evenly by 10.         }

cmmax:=trunc(mmh20[nsamples]/0.001);        { Adjust the water max to the     }
                                           { nearest number evenly divisible }
                                           { by 10.                          }

cmmax:=(cmmax+1)*0.001;                    { Set the value of max cm to      }
                                           { nearest number  the cm divided  }
                                           { by 10.                          }

divisor:=1;
repeat                                     { Adjust the water base max to the}
                                           { nearest number evenly divisible }
                                           { by 10.                          }
   divisor:=divisor*0.1;
   cmmin:=mmh20[1]/divisor;
   until cmmin1;
cmmin:=trunc(cmmin);
cmmin:=(cmmin-1)*divisor;                  { Set the value of min cm to the  }
                                           { nearest number  the cm divided  }
                                           { by 10.                          }
```

```
end;                                        { End procedure                    }

(*************************PLOT TO PRINTER*******************************)

(*---------------------------SETUP FOR PLOT--------------------------*)
procedure PLOT;

var graphhead:strg80;
    i,j :integer;

begin

  ClearScreen;                          {init screen}
  setcolorwhite;
  graphHead:=concat(inputfile,' ','Cm Water Vs. Time ',timestrg);
  definewindow(1,0,0,xmaxglb,ymaxglb);
  defineHeader(1,graphHead);
  DEFINEWORLD(1,0,cmmax,timemax,cmmin);
  SELECTWORLD(1);
  SelectWindow(1);
  SETCOLORWHITE;
  setheaderon;
  DrawBorder;                           {draw it}
  DrawAxis(8,-7,0,0,0,0,0,0,false);      {draw coordinate axis}
  SETLINESTYLE(0);
  DRAWPOLYGON(PLOTdata,1,NSAMPLES,-9,1,0);
  delay(4000);
  end;

PROCEDURE PLOTIT;
var divisor:real;

(*---------------------------PLOTIT MAIN PROGRAM--------------------*)

begin                                   {START OF PLOTIT BODY}

setplotdata(timemax,cmmax,cmmin);
ENTERGraphic;                           {initialize the graphics system}

PLOT;                                   {do the demo}


LeaveGraphic;                           {leave the graphics system}

end;                                    {END OF PLOTIT PROCEDURE}


{*************************ReadError*****************************************)

procedure ReadError(number,count:integer);

var i       :integer;
    ch      :char;

begin                                       { Begin the Procedure          }
                                            { Display the message          }
gotoxy(40,21);
write('Error reading the disk file ');
gotoxy(40,22);
write('Nsamples is being reset to ',(number-1):4);clreol;
nsamples:=number-1;
gotoxy(40,23);
write('Error occurred at count ',count:3);clreol;
```

```
gotoxy(40,24);
write('Press any key to continue.');clreol;
read(kbd,ch);

for i:=21 to 24 do                          { Clear the message.              }
   begin
   gotoxy(40,I);
   clreol;
   end;
end;                                        { End of the Procedure            }

 (********************* READ DATA ***********************************************)
procedure READDATA;

   label     error;
   VAR I,J : INTEGER;

     BEGIN (* READDATA *)
       FOR I:=1 TO nsamples DO
            FOR J:=1 TO InputCounter DO
               begin
               if not eof(infile) then
                  READ(infile,DATA[I,J])
               else begin(*else *)
                  begin
                  readError(i,j);           {Report the error to the operator  }
                                            {at the bottom right of the screen.}

                  goto error;               {Break out if problem reading the  }
                                            {input file. Jump to the end of the}
                                            {procedure.                        }
                  end; {else}
               if not eof(infile) then
                  readln(infile);
               end;
            end;                            {End of I,J loop                   }
     Error:END;                             {End of procedure. May exit early  }
                                            {if an error is found. On error    }
                                            {nsamples is reset by ReadError.   }

(*********************************Convert*****************************************)

procedure convert(index:integer;var temp:integer;ct:integer);
begin
case index of
   1:temp:=round((0.43381e2 -0.2162e-1*ct +0.78096e-5*ct*ct
                -0.194007e-8*ct*ct*ct +0.20549e-12*ct*ct*ct*ct)*100.0);

   2:temp:=round((0.560699e2 -0.350497e-1*ct +0.16898e-4*ct*ct
                 -0.57919e-8*ct*ct*ct +0.11067e-11*ct*ct*ct*ct
                 -0.87168e-16*ct*ct*ct*ct*ct)*100.0);

   3:temp:=round((-0.24546e2 +0.2739e-1*ct)*100.0);

   4:temp:=round((0.52573e2 -0.3071e-1*ct +0.14217e-4*ct*ct
                -0.48256e-8*ct*ct*ct +0.92116e-12*ct*ct*ct*ct
                -0.72579e-16*ct*ct*ct*ct*ct)*100.0);

   5:temp:=round((-0.23949e2 +17.4268e-3*ct +39.2697e-7*ct*ct
                -66.15e-11*ct*ct*ct)*100.0);

   6:temp:=round((0.53658e2 -0.256719e-1*ct +0.641828e-5*ct*ct
                -0.68753e-9*ct*ct*ct)*100.0);

   7:temp:=round((-0.26226e2 +0.2435e-1*ct)*100.0);

   8:temp:=round(((ct/2.75)*10.0))
```

```
else
   temp:=ct;
end;                                        {End of the Case Statement        }

end;                                        { End of Procedure                }

(*************************CalculateTemps*************************************)

Procedure CalculateTemps;

var a, i, j     :integer;

begin
for i:=1 to nsamples do
   begin
{
   writeln(outfile,nsamples:3);
}
   for j:= 1 to 8 do
   begin
   a:=data[i,j+4];
   if ConvertIndicator = 1 then convert(j,data[i,j+4],a);
{
   write(outfile,data[i,j+4]:5);
}
   end;
{
   writeln(outfile);
}
   end;
end;

 (***************************TEST DATA*****************************************)

 PROCEDURE TESTDATA(var return:integer);

VAR I,A,B : INTEGER;

BEGIN
 a:=chan1+4;
 b:=chan2+4;
 FOR I:=1 TO NSAMPLES DO
  if data[i,a]-data[i,b] then
    begin
    printline(40,22,'dry bulb  wet bulb at ');
    write (i:3);
    printline(40,23,'dry bulb = ');
    write(data[i,a]:5,' wet bulb = ',data[i,b]);
    delay(1000);
    return:=-1;
    end;(* if data *)
return:=0;
end;

 (*************************WET-DRY TEMP*************************************)

procedure WETDRYTEMP;

VAR J,K,L:INTEGER;
    WET,DRY:REAL;
    c:boolean;

BEGIN
  {$I-}                                     { Check to see if file is open    }
  WRITELN(outfile,'OUTPUT FROM WET-DRY TEMPERATURE FUNCTION');
  IOcheck;
  {$I+}
```

```
 if not IOerr then
    begin
    WRITELN(outfile,'OUTPUT FROM WET-DRY TEMPERATURE FUNCTION');
    WRITELN(outfile);
    WRITELN(outfile,'INPUT FILE IS ',inputfile);
    WRITELN(outfile,'OUTPUT FILE IS ',outputfile);
    WRITELN(outfile);
    FOR J:= 1 TO FILECOUNT DO
       BEGIN
       WRITELN(outfile);
       WRITELN('RUN BEING PROCESSED IS ',J:4);
       READ(infile,NSAMPLES);
       READDATA;
       dry:=DATA[1,CHAN1+4]/100.0;
       wet:=DATA[1,CHAN2+4]/100.0;
       K:=TRUNC(DATA[1,4]/10000.0*60.0);
       WRITELN(outfile,'TIME IS ',data[1,1]:2,' ',data[1,2]:2,' ',
            DATA[1,3]:2,':',K:2);
       WRITELN(outfile);
       WRITELN(outfile,'DRYBULB TEMP IS ',DRY:5:2);
       WRITELN(outfile,'WETBULB TEMP IS ',WET:5:2);
       WRITELN(outfile);
       END;
    end
   end;

(********************* COMPUTE TIME ***************************************)
PROCEDURE COMPUTETIME;
  VAR I,J : INTEGER;

    BEGIN (* COMPUTETIME *)
      START_TIME:=data[1,3]+DATA[1,4]/10000.0;
      FOR I:=1 TO NSAMPLES DO
          BEGIN
          TIME[I]:=(DATA[I,3]+DATA[I,4]/10000.0)-START_TIME;
          END
    END (* COMPUTETIME *);


(********************* DISPLAY DATA ***************************************)
PROCEDURE DISPLAYDATA;
  VAR I,J : INTEGER;

    BEGIN (* DISPLAYDATA *)
      FOR I:=1 TO NSAMPLES DO
        BEGIN
          WRITELN(I:4,DATA[I,1]:3,DATA[I,2]:3,TIME[I]:8:6);
          FOR J := 5 TO InputCounter DO WRITE(DATA[I,J]:5);
          WRITELN;
        END (* FOR I *);
    END (* DISPLAYDATA *);

(********************* H20 DEPTH EQUIV ************************************)
PROCEDURE WATERDEPTH(INDEXDRY,INDEXWET : INTEGER);
  VAR I,J : INTEGER;
    SATPRESS,DRY_SATPRESS,AMBPRESS,WET,DRY : REAL;

  BEGIN (* CALCULATE WATER DEPTH *)
    FOR I := 1 TO NSAMPLES DO
      BEGIN
        WET := DATA[I,INDEXWET]/100.0;
        DRY := DATA[I,INDEXDRY]/100.0;
        SATPRESS:=6.1078*EXP((17.2693882*WET)/(WET+237.30));
        DRY_SATPRESS:=6.1078*EXP((17.2693882*DRY)/(DRY+237.30));
        AMBPRESS:=SATPRESS-0.000657*BARPRESS*((DRY-WET)*(1+0.00115*WET));
        mmh20[I]:=((AMBPRESS/1013.0*18.0)/(82.05*(273.15+DRY)))*ADJ_HGHT*
                    1000000.0;
```

```
          mmh20[i]:=mmh20[I]*10.0;
          RH[I]:=ambpress/DRY_SATPRESS*100.0;
          IF DEBUG THEN WRITELN('WD PROC-DRY ',DRY:6:3,' WET ',WET:6:3,
                                'mmh20 ',mmh20[I]:10:9,'TIME ',TIME[I]:10:9);
        END
    END;

(************************SPOOL_FILE*****************************************)
procedure SPOOL_FILE;
VAR I,J,K,A,B:INTEGER;
    ANSWER:BOOLEAN;
    ANSWR:STRING[1];

BEGIN(*PROC*)
ANSWER:=FALSE;

WHILE NOT ANSWER DO
  BEGIN
  WRITE('READ ? RUNS');
  READLN(J);
  NO_RUNS:=J;
  WRITE('READ',J:4,' RUNS? ]T/F]');
  READLN(ANSWR);
  IF ((ANSWR='T') or (answr='t')) THEN ANSWER:=TRUE;
  END(*WHILE*);

FOR I:=1 TO J DO IF NOT EOF(infile) THEN readdata;
J:=0;
END(*PROC*);

(*********************************RESET FILE*********************************)

PROCEDURE FILE_RESET;
BEGIN
{$I-}
RESET(infile);
IOcheck;
{$I+}
END;


 (********************** BEGIN END RATE ***************************************)
 PROCEDURE BEGENDRATE(VAR K:INTEGER);
   VAR I,J : INTEGER;
       SUM,AVE : REAL;

   BEGIN
   BESLOPE[K]:=(mmh20[REGSTOP]-mmh20[REGSTART])
               /abs(TIME[REGSTOP]-TIME[regstart]);
   END;

 (********************** SOLAR AVERAGE ****************************************)
 PROCEDURE SOLAVE(j:integer);
   VAR I,points : INTEGER;
       SUM,value,stddev,sumsqr : REAL;

   BEGIN
     SUM := 0.0;sumsqr:=0;
     points:=abs(regstart-regstop)+1;
     FOR I:=regstart TO regstop DO
       begin
       value:=DATA[I,SOLAR_INDEX]/10.0;
       SUM:=SUM+value;
       sumsqr:=sumsqr+value*value;
       end;
     SOLAR[j]:=SUM/points;
     stddev:=sqrt((sumsqr-((sum*sum)/points))/(points-1));
```

```
  END;

(*****************************MINMAXAVESTD*******************************)

PROCEDURE MinMaxAveStd(dtapts:list;
                       size:integer;
                       var min,
                       max,
                       mean,
                       stddev,
                       cv       :real);

VAR I             :INTEGER;
    TEMP,sum,
    sumsqr        :REAL;

BEGIN{PROCEDURE}
MIN:=32000;
MAX:=0.0;
MEAN:=0.0;
stddev:=0.0;
SUM:=0.0;
SUMSQR:=0.0;
CV:=0.0;
FOR I:=1 TO size DO
   begin
   TEMP:=dtapts[I];
   IF TEMP   THEN MIN:=TEMP;
   IF TEMPMAX THEN MAX:=TEMP;
   SUM:=TEMP+SUM;
   SUMSQR:=TEMP*TEMP+SUMSQR;
   MEAN:=SUM/size;
   stddev:=SQRT((SUMSQR-((SUM*SUM)/size))/(size-1));
   if (mean0.0)then CV:=stddev*100/MEAN;
   END;
END;{PROCEDURE}

(*****************************WriteFileStat*************************************)
procedure writefilestat(runs:integer);

var temp:list;
    i,j:integer;

begin
writeln(outfile,'Runs = ',runs);
for j:=1 to 7 do
   begin
   for i:=1 to runs do
       temp[i]:=statstart[i,j];
   {
   writeln('passing starting  number to minmax ', j:4,i:4);
   }
   minmaxavestd(temp,runs,min,max,mean,stddev,cv);
   writeln(outfile,mean:10:6,
                   stddev:10:6,
                   max:10:6,
                   min:10:6,
                   cv:12:4);
      for i:=1 to runs do
       temp[i]:=statslope[i,j];
   {
   writeln('passing slope to minmax ', j:4,i:4);
   }
   minmaxavestd(temp,runs,min,max,mean,stddev,cv);
   writeln(outfile,mean:10:6,
                   stddev:10:6,
                   max:10:6,
```

```
                min:10:6,
                cv:12:4);
for i:=1 to runs do
    temp[i]:=statint[i,j];
{
writeln('passing int to minmax ', j:4,i:4);
}
minmaxavestd(temp,runs,min,max,mean,stddev,cv);
writeln(outfile,mean:10:6,
                stddev:10:6,
                max:10:6,
                min:10:6,
                cv:12:4);
for i:=1 to runs do
    temp[i]:=statsee[i,j];
{
writeln('passing SEE to minmax ', j:4,i:4);
}
minmaxavestd(temp,runs,min,max,mean,stddev,cv);
writeln(outfile,mean:10:6,
                stddev:10:6,
                max:10:6,
                min:10:6,
                cv:12:4);
for i:=1 to runs do
     temp[i]:=statsslope[i,j];
{
writeln('passing Sslope to minmax ', j:4,i:4);
}
minmaxavestd(temp,runs,min,max,mean,stddev,cv);
writeln(outfile,mean:10:6,
                stddev:10:6,
                max:10:6,
                min:10:6,
                cv:12:4);
for i:=1 to runs do
    temp[i]:=statrsque[i,j];
{
writeln('passing rsque to minmax ', j:4,i:4);
}
minmaxavestd(temp,runs,min,max,mean,stddev,cv);
writeln(outfile,mean:10:6,
                stddev:10:6,
                max:10:6,
                min:10:6,
                cv:12:4);
for i:=1 to runs do
    temp[i]:=statcorr[i,j];
{
writeln('passing corr to minmax ', j:4,i:4);
}
minmaxavestd(temp,runs,min,max,mean,stddev,cv);
writeln(outfile,mean:10:6,
                stddev:10:6,
                max:10:6,
                min:10:6,
                cv:12:4);
for i:=1 to runs do
begin
mean:=statspan[i,j];
stddev:=0;
max:=statspan[i,j];
min:=statspan[i,j];
cv:=0;
end;
writeln(outfile,mean:10:6,
                stddev:10:6,
```

```
                    max:10:6,
                    min:10:6,
                    cv:12:4);
   writeln('Leaving minmax  ', j:4,i:4);
   writeln(outfile);
   end;
end;
(*****************************Y_Statistics************************************)

procedure Y_Statistics;

var
   y_diff:list;
   i:integer;

begin
for i:=11 to (nsamples-10) do
   y_diff[i-10]:=(mmb20[i+1]-mmb20[i]);
MinMaxAveStd(Y_diff,nsamples-20,min,max,mean,stddev,cv);
gotoxy(45,10);write('Mean y difference      ',mean:10:8);
gotoxy(45,11);write('Std. deviation         ',stddev:10:8);
gotoxy(45,12);write('Coeffient of Var       ',cv:10:8);
gotoxy(45,13);write('Max y difference       ',max:10:8);
gotoxy(45,14);write('Min y difference       ',min:10:8);
writeln(outfile,'Mean, Std. Dev., Cv, Max Ydev, Min Ydev');
writeln(outfile,mean:10:8,' '
                ,stddev:10:8,' '
                ,cv:10:3,' '
                ,max:10:8,' '
                ,min:10:8);
end;
(*************************X_Statistics*************************************)

procedure X_Statistics;

var
   X_diff:list;
   i:integer;

begin
for i:=11 to (nsamples-10) do
   x_diff[i-10]:=(time[i+1]-time[i]);
MinMaxAveStd(x_diff,nsamples-20,min,max,mean,stddev,cv);
gotoxy(45,16);write('Mean X difference      ',mean:10:8);
gotoxy(45,17);write('Std. deviation         ',stddev:10:8);
gotoxy(45,18);write('Coeffient of Var       ',cv:10:8);
gotoxy(45,19);write('Max X difference       ',max:10:8);
gotoxy(45,20);write('Min X difference       ',min:10:8);
writeln(outfile,'Mean, Std. Dev., Cv, Max Xdev, Min Xdev');
writeln(outfile,mean:10:8,' '
                ,stddev:10:8,' '
                ,cv:10:3,' '
                ,max:10:8,' '
                ,min:10:8);
end;
  (*********************LINEAR REGRESSION*************************************)
PROCEDURE LINREG( Y,C_TIME:LIST; M:INTEGER);

VAR K,j:INTEGER;
    SUM_Y,SUM_X,SUM_XY,SUM_X2,SUM_Y2,STDT:REAL;
    SUM_YD2,Y_HAT,Y_DIFF,NUMBER,X1,Y1,SXY,SXX,SYY:REAL;

     BEGIN
        Stdt:=2.00;
        SUM_X:=0.0;
        SUM_Y:=0.0;
        SUM_XY:=0.0;
```

```
        SUM_X2:=0.0;
        SUM_Y2:=0.0;
        Y_DIFF:=0.0;
        SUM_YD2:=0;
        NUMBER:=REGSTOP-REGSTART+1;
        FOR J:=REGSTART TO REGSTOP DO
              BEGIN
              X1:=C_TIME[J];Y1:=Y[J];
              SUM_X:=SUM_X+X1;
              SUM_Y:=SUM_Y+Y1;
              SUM_XY:=SUM_XY+Y1*X1;
              SUM_X2:=SUM_X2+X1*X1;
              SUM_Y2:=SUM_Y2+Y1*Y1;
              end;

        SXX:=SUM_X2-SUM_X*SUM_X/NUMBER;
        SXY:=SUM_XY-SUM_X*SUM_Y/NUMBER;
        SYY:=SUM_Y2-SUM_Y*SUM_Y/NUMBER;
        SLOPE[M]:=SXY/SXX;
        INT[M]:=((SUM_X2*SUM_Y-SUM_X*SUM_XY)/NUMBER)/SXX;
        FOR K:=REGSTART TO REGSTOP DO
            BEGIN(*FOR K LOOP*)
            Y_HAT:=INT[M]+SLOPE[M]*C_TIME[K];
            Y_DIFF:=y_diff+Y[K]-Y_HAT;
            SUM_YD2:=SUM_YD2+(Y_DIFF*Y_DIFF);
            END;(*FOR K LOOP*)
        RSS[M]:=SUM_YD2;
        SEE[M]:=SQRT((SUM_Y2-INT[M]*SUM_Y-SLOPE[M]*SUM_XY)/(NUMBER-2));
        SSLOPE[M]:=SEE[M]/SQRT(SXX);
        RSQUE[M]:=(SUM_XY*SUM_XY)/(SUM_X2*SUM_Y2);
        CORR_COF[M]:=SXY/SQRT(SXX*SYY);
END;(*PROCEDURE*)

(*****************************MAXLINREG************************************)
procedure maxlinreg(start,span:integer);

begin
   Regstart:=start;
   regstop:=start+span;
   incrmnt:=incrmnt+1;
   linreg(mmb20,time,1);
   if (MAXSlope  slope[1]) and (corr_cof[1]  0.80) and (slope[1] 0) then
       begin
       maxslope:= slope[1];
       maxstart:=regstart;
       maxspan:=span;
       maxint:=int[1];
       maxrsque:=rsque[1];
       maxsslope:=sslope[1];
       maxcorr:=corr_cof[1];
       maxsee:=see[1];
       end;
end;

(*****************************FINDMAXSLOPE*********************************)

procedure FindMaxSlope(start,span:integer);

var   slope          :real;

begin
maxsee:=0.0;
maxslope := 0.0;
maxstart := 0;
maxspan  := 0;
maxcorr:=0.0;
maxrsque:=0.0;
```

```
maxint:=0.0;
maxsslope:=0.0;
repeat
   gotoxy(17,23);write(span:4);
   gotoxy(22,24);write(incrmnt:4);
   maxlinreg(start,span);
   gotoxy(17,20);WRITE(MAXSLOPE:6:5);
   gotoxy(17,21);WRITE(MAXSTART:7);
   gotoxy(17,22);;WRITE(MAXSPAN:7);
   start:=start+StartIncrt;
until (start+span)nsamples;
end;


(**********************NORMALLINREGS*****************************************)

procedure NormalLinReg;

begin
regstart:=10;
regstop:=50;
linreg(mmh20,time,1);
writeln(outfile,'Normal Slope, Int, See, Sslope, Rsque, Cor, Start, Stop');
wRITEln(outfile,SLOPE[1]:10:6
                ,INT[1]:10:6
                ,see[1]:14:10
                ,SSLOPE[1]:10:6
                ,RSQUE[1]:6:3
                ,CORR_cof[1]:6:3
                ,regstart:4
                ,regstop:4);
end;
(**************************PRINTHEADER*****************************************)

PROCEDURE printheader(var return:integer);

BEGIN
{$I-}
WRITELN(outfile,'                      ET ');
IOcheck;
{$I+}
if not IOerr then
   begin
   WRITELN(outfile);
   WRITELN(outfile,'INPUT FILE ',inputfile
                  ,' OUTPUT FILE '
                  ,outputfile
                  ,' VOLUME '
                  ,(ADJ_HGHT*17294.28):10:4
                  ,' BAR PRESS '
                  ,BARPRESS:8:4);
   WRITELN(outfile);
   return:=0;
   end
else return:=-1;
end;

(****************************PrintRunNumber*************************************)

procedure PrintRunNumber;

var c:integer;
    temp:strg80;

begin
C:=ROUND(DATA[1,4]/10000.0*60.0);
writeln(outfile,'RunNumber, Datapoints, Date, Time, Drybulb, Wetbulb');
```

```
WRITELN(outfile,RunNumber:3,' '
                ,nsamples:3,' '
                ,DATA[1,1]:2
                ,'/'
                ,DATA[1,2]:2
                ,'/'
                ,YEAR:2,' '
                ,' '
                ,DATA[1,3]:4
                ,':'
                ,C:3,' '
                ,CHAN1:2,' '
                ,CHAN2:2,' '
                ,start_time:12:8);
str(Data[1,1]:2,timestrg);
str(data[1,2]:2,temp);
timestrg:=concat(timestrg,'/',temp,'/');
str(year:2,temp);
timestrg:=concat(timestrg,temp,' ');
str(data[1,3]:2,temp);
timestrg:=concat(timestrg,temp,':');
str(c:2,temp);
timestrg:=concat(timestrg,temp);
END;


(**************************PRINTFILESTATISTICS*****************************)

     PROCEDURE printfilestatistics(runs,no:integer);

     BEGIN
     WRITEln(outfile,MAXSLOPE:10:6,' ',
                     MAXINT:10:6,' ',
                     MAXSEE,' ',
                     MAXSSLOPE,' ',
                     MAXRSQUE:6:3,' ',
                     MAXCORR:6:3,' ',
                     MAXSTART:4,' ',
                     MAXSPAN:4);

statslope[runs,no]:=maxslope;
statint[runs,no]  :=maxint;
statsee[runs,no]  :=maxsee;
statsslope[runs,no]:=maxsslope;
statrsque[runs,no]:=maxrsque;
statcorr[runs,no]:=maxcorr;
statstart[runs,no]:=maxstart;
statspan[runs,no]:=maxspan;
end;

(******************** ANALYSIS *********************************************)
 PROCEDURE ANALYSIS;
   label nextRun, exit;

   VAR A,B,C,I,J,K,M,L,inc,
       minute              :integer;

       timemax,cmmin,cmmax, x_incrt:real;
   (*-----------------------------------------------------------------*)
   BEGIN(*analysis*)
     RunNumber:=0;
     returnerror:=0;
     clrscr;
     gotoxy(20,2);
     write('ET ANALYSIS PROCEDURE');
     printheader(returnerror);
     if returnerror= -1 then goto exit;
```

```
WHILE NOT EOF(infile) DO
  BEGIN
  READln(infile,points);
  if not eof(infile) then
     begin
     RunNumber:=RunNumber+NO_RUNS;RunNumber:=RunNumber+1;
     nsamples:=points;
     gotoxy(5,6);
     write('DATA ANALYSIS PROCEDURE');
     write (' Drybulb is ',chan1:2,' Wetbulb is ',chan2:2);
     gotoxy(5,8);
     clreol;
     writeln('Processing data run ',RunNumber:2,' It has ',points:3,' datapoints.');
     printline(5,10,'Reading in data');
     READDATA;
     printline(5,12,'Converting counts to temperatures.');
     CalculateTemps;
     printline(5,14,'Testing for data errors.');
     TESTDATA(returnerror);
     if returnerror = -1 then goto nextrun;
     printline(5,16,'Computing time and water depth.');
     COMPUTETIME;
     gotoxy(5,18);
     minute:=Round(data[1,4]/10000.0*60.0);
     write('Date is ',data[1,1]:2,'/',data[1,2]:2,'/',year:2,' Time is ',
           data[1,3]:2,':',minute:2);
     IF DEBUG THEN DISPLAYDATA;
     A:=CHAN1+4;
     B:=CHAN2+4;
     WATERDEPTH(A,B);
     printRunNumber;
     y_statistics;
     X_Statistics;
     x_incrt:=mean*3600;
     gotoxy(5,19);
     write('Computing Max slope. BE PATIENT.');
        begin
        incrmnt:=0;
         gotoxy(5,23);clreol;write('Span is now ');
        gotoxy(5,24);clreol;write('Regression number ');
        gotoxy(5,20);WRITE(' MAXSLOPE = ');
        gotoxy(5,21);WRITE(' MAXSTART = ');
        gotoxy(5,22);WRITE(' MAXSPAN  = ');
        span:=round(10/X_incrt);
        FindMaxSlope(start,span);
        printfilestatistics(runNumber,1);
        span:=round(15/x_incrt);
        FindMaxSlope(start,span);
        printfilestatistics(runNumber,2);
        span:=round(20/x_incrt);
        FindMaxSlope(start,span);
        printfilestatistics(RunNumber,3);
        span:=round(30/x_incrt);
        FindMaxSlope(start,span);
        printfilestatistics(RunNumber,4);
        span:=round(40/X_incrt);
        FindMaxSlope(start,span);
        printfilestatistics(RunNumber,5);
        span:=round(60/x_incrt);
        FindMaxSlope(start,span);
        printfilestatistics(RunNumber,6);
        span:=round(80/x_incrt);
        FindMaxSlope(start,span);
        printfilestatistics(RunNumber,7);
        normallinreg;
        writeln(outfile);
        if doplot = 1 then plotit;
```

```
            end;
          end;
          NextRun:END;
  writefilestat(runnumber);
  exit:write(chr(7));delay(500);write(chr(7));
END;

(********************* MENU ************************************************)

PROCEDURE MENU;
  BEGIN (* MENU *)
    GOTOXY(15,2);
    Writeln(' ET Analysis Menu');
    gotoxy(1,5);
    WRITELN(' 1:NAME THE INPUT FILE                    ');
    WRITELN(' 2:NAME THE TEXT OUTPUT FILE              ');
    WRITELN(' 3:DEFINE THE ANALYSIS PARAMETERS         ');
    WRITELN(' 4:DO ANALYSIS                            ');
    WRITELN(' 5:SPOOL THE INPUT FILE FORWARD ? RUNS    ');
    WRITELN(' 6:RESET INPUT FILE                       ');
    WRITELN(' 7:GET THE STARTING WET AND DRY TEMP FROM ? RUNS');
    WRITELN(' 8:ANALYZE ALL PSYCHROMETERS              ');
    WRITELN(' 9: STOP                                   ');
  END (* MENU *);

(*************************DOALL************************************************)

procedure doall;
begin
chan1:=1;
chan2:=6;
analysis;
file_reset;
chan1:=2;
chan2:=4;
writeln(outfile,chr(12));
analysis;
file_reset;
chan1:=7;
chan2:=3;
writeln(outfile,chr(12));
analysis;
{$I-}
close(outfile);
{$I+}
select:=9;
end;

(*****************************MAIN PROGRAM***********************************)

BEGIN
initgraphic;
leavegraphic;
chan1:=1;
chan2:=6;
barpress:=1013.0;
volume:=1.80433;
adj_bght:=volume/17294.28;
year:=84;
start:=5;
StartIncrt:=1;
InputCounter:=12;
ConvertIndicator:=1;
inp:=4;
inputfile:='linfit.asc';
outputfile:='linfit.out';
doplot:=0;
```

```
FILECOUNT:=0;
SELECT:=0;
NO_RUNS:=0;
DEBUG:=FALSE;
if paramcount  0 then
   begin
   Assign(infile,inputfile);
   assign(outfile,outputfile);
   rewrite(outfile);
   reset(infile);
   doall;
   halt;
   end;
HEADER;
clrscr;
WHILE SELECT  DO
BEGIN
returnerror:=0;
clrscr;
gotoxy(1,5);
menu;
repeat
  gotoxy(5,20);
  getinteger('PLEASE ENTER YOUR MENU SELECTION.',select,returnerror);
until returnerror=0;
  CASE SELECT OF
        1:OPEN_File(readfile);
        2:OPEN_File(writefile);
        3:INPUTDEF;
        4:BEGIN
            ANALYSIS;
            END;
        5:SPOOL_FILE;
        6:FILE_RESET;
        7:WETDRYTEMP;
        8:Doall;
        9:BEGIN
          SELECT:=20;
          {$I-}
          CLOSE(outfile);
          {$I+}
          END;
        10:debug:=NOT DEBUG;
  END
 END
END.
```