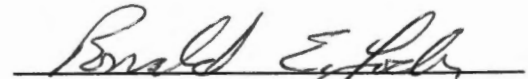
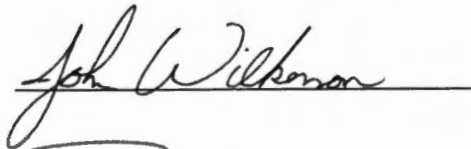


To the Graduate Council:

I am submitting herewith a thesis written by Joseph C. Zimmerman entitled "Design and Evaluation of a Small Weighing Lysimeter." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Engineering.


Ronald E. Yoder, Major Professor

We have read this thesis
and recommend its acceptance:







Accepted for the Council:


Associate Vice Chancellor and
Dean of The Graduate School

DESIGN AND EVALUATION OF A SMALL WEIGHING LYSIMETER

A Thesis
Presented for the
Master of Science Degree
The University of Tennessee, Knoxville

Joseph Christopher Zimmerman
May 1996

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Thesis
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DEDICATION

This thesis is dedicated to my parents

Mr. William Adrian Zimmerman

and

Mrs. Emma Ruth Zimmerman

for all their love, support and encouragement

for all these years.

ACKNOWLEDGMENTS

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ABSTRACT

The purpose of this project was to design and test a small, 12 inch in diameter, lysimeter to measure evapotranspiration (ET) in the field. An initial lysimeter design using load cells was constructed and tested in a laboratory setting. Temperature tests indicated that this design lacked the sensitivity desired for accurate ET measurement in the field. A second design was developed that incorporated the use of a counterbalance system to remove non-water weight from the system. This allowed an increased sensitivity and, when tested in the laboratory, met desired requirements for a field scale test. This lysimeter was installed in the field and tested over several weeks. ET measurements from the small lysimeter were compared to ET measurements taken from a large monolithic lysimeter installed at the test site and against ET values calculated from on site weather data. These field tests indicated that the small lysimeter tracked the large lysimeter to within 0.5 mm of water for daily ET readings. These field tests demonstrated that it is feasible to design a small lysimeter of less than one meter square that can overcome thermal and surface area effects and effectively measure ET rates in a humid climate.

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NOMENCLATURE

c	Penman equation calibration coefficient
cm	centimeter
°C	degrees Celsius
delta	slope of saturation pressure (change in mb/°C)
e:a	mean actual vapor pressure of air, mb
epsilon	ratio of mass of water vapor to mass of dry air
e:s	saturated vapor pressure of air, mb
ET	evapotranspiration
g	grams
gamma	psychrometric constant
hr	hour
hrs	hours
in.	inches
in ²	square inches
km	kilometers
kPa	kilopascals
L	latent heat of evaporation
lb	pound
lbs	pounds
m	meters

m^2	square meters
mb	millibars
mm	millimeters
mV/V	millivolts per volt
m/s	meters per second
P	atmospheric pressure
psi	pounds per square inch
r^2	correlation coefficient
Rbo	net outgoing clear sky long-wave radiation, kJ/m^2
R:b	net outgoing long-wave (terrestrial) radiation
R:n	net radiation, mm/d
R:s	incoming short-wave (solar) radiation
Temp	temperature
T	temperature
Ud/Un	day - night wind run ratio (daytime arbitrarily chosen as 0700-1900)
yd	yards
yd^2	square yards

LIST OF ABBREVIATIONS

ASAE	American Society of Agricultural Engineers
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing and Materials
BLH _®	BLH _® Electronics
deg. C	degrees Celsius
ea	each
FAO	Food and Agriculture Organization of the United Nations
H ₂ O	water
LC	load cell
LC#3	load cell, third design
PVC	polyvinyl chloride
RH	relative humidity
TC	type-T thermocouple (copper-constantan)
WR	wind run
WS	wind speed
vs	versus

CHAPTER 1

INTRODUCTION

Growing demands on the American agricultural community for increased production and land and water use efficiency have created economic pressures for new applications of technology to the field of lysimetry. Mounting demands on water supplies and the rising cost of irrigation have led to a new interest in efficient irrigation scheduling that requires accurately determined evapotranspiration (ET). To date, most lysimeters used to measure ET have had a surface area greater than one meter square to enhance accuracy. These large lysimeters can produce accurate ET measurements but are expensive to build and maintain, making them economically unfeasible for use except by research facilities (Gebet and Cuenca, 1991; Howell et al., 1991)

In the past, it has been considered impractical to use lysimeters with small surface areas to measure ET because of temperature and surface area effects on the lysimeter system. With large lysimeters, these effects may cause some inaccuracies, but with the reduced surface area to ET ratio for small lysimeters, these errors are often substantial. However, new load cell and data collection techniques have led to the development of smaller lysimeters (Allen and Fisher, 1990).

Historically, most lysimeter research has been conducted in arid regions where a large vapor pressure differential exists between the crop canopy and the air. This large differential causes a higher rate of evaporation from any system which could lead to a

marked drying effect on a small lysimeter, leaving less water within the system for plants to use and leading to a possible reduction in ET readings. However, in a humid climate such as the Southeast, this vapor pressure differential is not as large. This leads to the possibility of effective lysimeters that are smaller than one meter square.

With the increase in irrigation for high value crops in humid climates, the estimation of ET takes on monetary significance. The cost to install large weighing lysimeters ranges from \$50,000 (Aboukhaled et al., 1982) to \$100,000 (Allen and Fisher, 1990). To decrease the cost of lysimeters, the recent trend has been towards a reduction in size and complexity of weighing systems, as reflected in lysimeter designs such as those installed by Fisher and Elliott (1994) in Oklahoma for \$2,999, and a pair installed by Allen and Fisher (1990) in Utah for \$9,200, excluding labor.

The purpose of this project was to address the previously mentioned concerns by designing a small monolithic weighing lysimeter and subjecting it to testing under field conditions in order to determine the validity of a small lysimeter design for accurate measurement of ET. A small monolithic lysimeter was assembled and laboratory tested for system accuracy and reliability. Upon successful completion of laboratory tests, this lysimeter was placed in field operation at the Plateau Experiment Station, Crossville near a large monolithic weighing lysimeter, surface area of 4 m² (6,200 in²), of the Bushland type (von Bernuth, 1988). Evapotranspiration values collected from the large lysimeter were used as comparison values for evaluation of the small lysimeter design. Estimated ET values calculated using the Penman equation were also used to assist with design evaluation.

CHAPTER 2

LITERATURE REVIEW

In order to properly appreciate lysimeters and their use, one must first have some understanding of their history. A lysimeter is a device used to measure movement of water through the soil matrix. The word lysimeter has Greek origins and means "movement and measurement". The first recorded use of a lysimeter was in France in 1688 (Howell et al., 1991). Since their inception, continuous improvements have been made in the design and operation of lysimeters to enhance their accuracy and reliability. In 1906, the first lysimeter equipped with a mechanical weighing device was developed in Germany (Aboukhaled et al., 1982). Beginning in 1937, the Coshocton experiments, conducted in Coshocton, Ohio, were the first lysimeter experiments in the United States and incorporated a continuous weighing device (Harrold and Dreibelbis, 1958).

Aboukhaled et al. (1982) describe two categories of lysimeters, weighing and non-weighing. Non-weighing lysimeters are mainly used for the study of water infiltration and transport effects but have also been used to measure ET for time periods greater than one week. Weighing lysimeters are used to measure evapotranspiration (ET) and soil moisture accumulation through dew, rainfall, and irrigation. The category of weighing lysimeters can be further delineated by methods of monitoring ET through weight change and by construction type.

Method of construction divides weighing lysimeters into two groups; monolithic

and disturbed. With monolithic lysimeters, the soil column is taken in an undisturbed condition (Aboukhaled et al., 1982) to approximate actual field conditions. Disturbed lysimeters contain a soil column of disturbed soils which may not accurately depict field drainage or crop cover growth conditions. Exact soil physical and chemical properties and vegetation characteristics are best preserved with soil monoliths. Disturbed soil lysimeters can destroy both vertical and horizontal naturally occurring soil differences, particularly hydraulic conductivity (Howell et al., 1991). The method of weight measurement further divides lysimeters into several categories; mechanical, electro-mechanical, and hydraulic.

Mechanical Lysimeters

Mechanical lysimeters use a mechanical counterbalance and recording device to indicate change in weight. These lysimeters are often quite large, with a surface area frequently greater than 1 m² (1.2 yd²). Examples of this lysimeter type are the Coshocton lysimeters in Ohio (Harrold and Dreibelbis, 1958).

Electromechanical Lysimeters

Electromechanical lysimeters are an improvement upon the design of the mechanical lysimeters. They incorporate the addition of electrical devices to aid in monitoring the weight change of the lysimeter. Such devices include strain gauges, strain gauge load cells, and electronic data monitoring devices such as dataloggers and computer

systems. Some of these lysimeters use load cells in conjunction with counterbalance systems to monitor ET, as in the Bushland lysimeters (Marek et al., 1988). Another design supports the entire weight of the lysimeter on load cells, such as the designs by Fisher and Elliott (1994) in Oklahoma and Allen and Fisher (1990) in Utah. These lysimeter designs make use of the increasing precision of the modern electronic and monitoring equipment that has become more prevalent in the past twenty-five years.

Hydraulic Lysimeters

Hydraulic lysimeters measure change in weight through hydrostatic pressure change. These lysimeters include the use of hydraulic load cells (Aboukhaled et al., 1982) and designs like those of Kincaid et al. (1979) that "float" the entire weight of the lysimeter on hydraulic pillows. Many experiments have been done and field units constructed using these techniques. However, these systems are prone to great temperature effects due to the expansive nature of the fluids involved (Howell et al., 1991; Kruse and Neale, 1991)

Problems in Monitoring ET with Lysimeters

There are a number of inherent problems in measuring ET with a lysimeter. Most of these problems are associated with the size of the system, i.e., using a small, isolated segment to model a larger dynamic system. The smaller the lysimeter, the lower its mass

and therefore the quicker its response to atmospheric changes. Size also dictates surface area which controls the ratio of ET to total system weight. As this ratio increases, the weight change due to ET becomes a progressively smaller percentage of the system's total weight, making accurate isolation and measurement of this weight change difficult.

Another effect of size is seen in the ability to match surrounding crop vegetation. Small lysimeters can not accurately support a representative cover of a large spacing row crop such as corn. Further, difficulties in attaining accurate measurements rest in the effects seen due to the ratio of surface area to area of exposed lysimeter assembly walls. The larger the ratio of surface area to area of exposed assembly walls, the less likely thermal effects are to influence accurate measurement.

Other problems include the difference of soil composition between the lysimeter and the surrounding area. Lysimeter effects in general can be caused by the type of construction materials used as well as maintenance practices. These include vegetative growth over the rim of the lysimeter which artificially increases ET surface area, and installation depth that can effect both crop root growth and drainage.

Comparison of Disturbed and Monolithic Lysimeters

Traditional research over the last fifty years has encouraged the use of monolithic lysimeters as opposed to disturbed lysimeters. However, Allen and Fisher (1990) and Fisher and Elliot (1994) report good results with disturbed lysimeters. Monolithic systems are more representative of actual field conditions than are disturbed systems. If the soil

matrix is disturbed, natural soil structure is destroyed and water holding capacity, infiltration, and drainage pathways may no longer be similar to the surrounding soil. For a weighing lysimeter, this can mean different rooting depths for plants and a change in the amount of available soil water to those crops as compared to the surrounding natural systems. From a financial standpoint, the use of disturbed soil columns in lysimeters is attractive. It is an expensive proposition to take an undisturbed soil column in the field when the soil column is one square meter or greater (Marek et al., 1988). This cost makes the use of undisturbed lysimeters prohibitive for most research. The large scale construction required for monolithic lysimeters has been reported from \$50,000 to \$100,000 depending on the design and number of lysimeters installed. A typical example of cost for the installation of a one meter square monolithic lysimeter is \$50,000 (Aboukhaled et al., 1982)

Lysimeter Area and Depth

Aboukhaled et al. (1982) suggested that a lysimeter of one meter square surface area was the minimum needed for accurate ET measurements. Surface area is a primary concern in lysimeter design and construction. The larger surface area provides a better approximation of field conditions and allows for a wider variety of crops and agricultural practices. Larger lysimeter surface areas and depths decrease thermal effects in the system by increasing mass. The increased system mass slows response to diurnal temperature fluctuations and sudden alterations in weather conditions as well as providing greater

stability against wind effects. To insure a healthy crop, free growth of roots must be permitted, which requires a minimum soil column depth, dependent upon the crop. As the depth, area, and mass of the lysimeter increases, the soil column becomes more representative of the surrounding soil system, but the system becomes more expensive to install and maintain.

Design and Installation

Careful design and installation of the lysimeter is important to insure accurate readings in the field. The lysimeter must permit some type of drainage. Damage to the cover crop caused by the saturated conditions resulting from a sealed bottom produces poor ET readings not representative of the surrounding system. Likewise, over-drainage, such as that provided in a vacuum assisted system, can reduce the amount of soil moisture in the system as compared to the surrounding naturally drained soils.

A large gap between the soil column support and the outer frame of the lysimeter allows circulation of air around the lysimeter. This gap can potentially cause heating and cooling of the lysimeter soil column as well as drying effects, depending on design. This gap should be kept to a minimum, but must remain open since sealing of this gap even with materials such as grease causes binding which can affect weight measurements (Howell et al., 1991).

An above ground lysimeter assembly can potentially create several problems due to construction materials. For example, metal lysimeter walls extending above the

ground's surface become heat conductors, thereby warming the soil column to temperatures greater than in the surrounding soil. Exposure of the lysimeter assembly materials can also result in reflection and magnification of solar radiation received by plants on the lysimeter. Additionally, crops or grass cover on the lysimeter higher than the surrounding field allows greater loss of moisture due to wind. This combination of factors is known as an "oasis effect" (Allen et al., 1991).

Lysimeter Placement and Maintenance in the Field

Proper placement and maintenance of the lysimeter in the field is vital to achieve accuracy in data collection (Aboukhaled et al., 1982). It is necessary to maintain a representative wind reach to the lysimeter, and it has been suggested that at least 100 m is necessary (Aboukhaled et al., 1982). It has been noted that placing lysimeters in proximity to different, nonrepresentative crop cover produces deviations of expected ET readings (Allen and Fisher, 1990). Maintenance of the lysimeter and its cover crop is of vital importance. Vegetation allowed to grow over the rim of the lysimeter, either from the field or from the lysimeter itself, effectively creates a different surface area for ET than the actual surface area of the lysimeter (Allen and Fisher, 1991).

Small Lysimeters

Small lysimeters of less than 1 m² surface area have not been considered practical because of their difficulty in handling some of the aforementioned phenomena. One further concern is that their small surface area means that the weight change due to ET can be a very small portion of the actual weight of the system. However, with the growing demand on water supplies and the increasing use of irrigated agriculture in humid climates, it is economically attractive to develop small lysimeters which can be made and installed relatively inexpensively to provide accurate ET measurements. It is now considered possible to design a small lysimeter that could overcome each of the adverse effects associated with small mass and surface area by using materials, equipment, design, and installation practices that focus on surmounting these obstacles. This will allow installation of accurate lysimeters at irrigated areas to assist with irrigation scheduling and cost effective use of water resources. These small lysimeters will also enable researchers to place several lysimeters over a large area to study ET variability over an extended region for the cost of a single large lysimeter.

CHAPTER 3

CONSTRUCTION AND TESTING OF INITIAL DESIGN

Design Procedure

A monolithic design was chosen to maintain consistency with the surrounding soil and the larger lysimeter. The lysimeter was designed utilizing readily available commercial materials to permit ease of construction and equipment procurement. To overcome problems with thermal effects on the system, plastic materials were used since PVC materials transmit and store less heat than metal or concrete. The lysimeter was designed to be installed flush with the ground's surface to prevent oasis effects. The lysimeter was 30.6 cm (12 in.) in diameter, with a surface area of 0.07 m² (113 in²). The lysimeter was assembled and laboratory tested for system accuracy and reliability. The following sections detail the construction and testing of the initial design.

Lysimeter Assembly

The lysimeter was designed to be inexpensive and easy to fabricate with readily available commercial materials. The inner bucket assembly that holds the soil column was constructed of a 76 cm (30 in.) length of 30.6 cm (12 in.) nominal diameter PVC sewer pipe. The inner assembly (inner bucket) was divided into two compartments-- a soil

column and a water reservoir. The soil column is 61 cm (24 in.) in length and is supported by a 1.3 cm (0.5 in.) thick PVC plate with reinforcing brace (Figure 1). All PVC and other construction materials used in the assembly were purchased "off-the-shelf". A 1.3 cm (0.5 in.) diameter hole was cut into the bottom of the support plate for insertion of a nylon wicking assembly similar to the type used by Boll et al. (1990). The purpose of the wick assembly is to encourage drainage of infiltrating water from the soil column into the water reservoir thereby preventing saturated conditions in the column. The remaining 15 cm (6 in.) formed a reservoir to collect excess water in the system. This reservoir is accessible by two tubes, one for evacuation of water and one for use as a vent. Three anchoring points were installed in the top 2 cm of the inner bucket to grant easy handling and installation of the inner assembly into the outer assembly. A 1.3 cm (0.5 in.) thick support ring was attached to the inner bucket assembly, 15 cm (6 in.) down from the top of the column. This functions as the support for the inner assembly, and includes four threaded stainless steel screws with polished ends to allow contact adjustment.

The outer assembly was constructed of a 91 cm (36 in.) length of PVC duct with a 35 cm (14 in.) nominal diameter. A 1.3 cm (0.5 in.) thick, 15 cm (6 in.) wide circular support plate was attached 20.3 cm (8 in.) from the top. This plate had drainage holes to prevent water ponding and contained four 15 x 7.6 cm (6 x 3 in.) PVC boxes to house the load cells (Figure 2). To prevent compaction or settling of the assembly the outer assembly was designed so the weight of the assembly was borne by the support plate with approximately 6.9 kPa (1 psi) of pressure bearing on the soil under the support plate.

To minimize height effects, the entire lysimeter assembly was designed to be

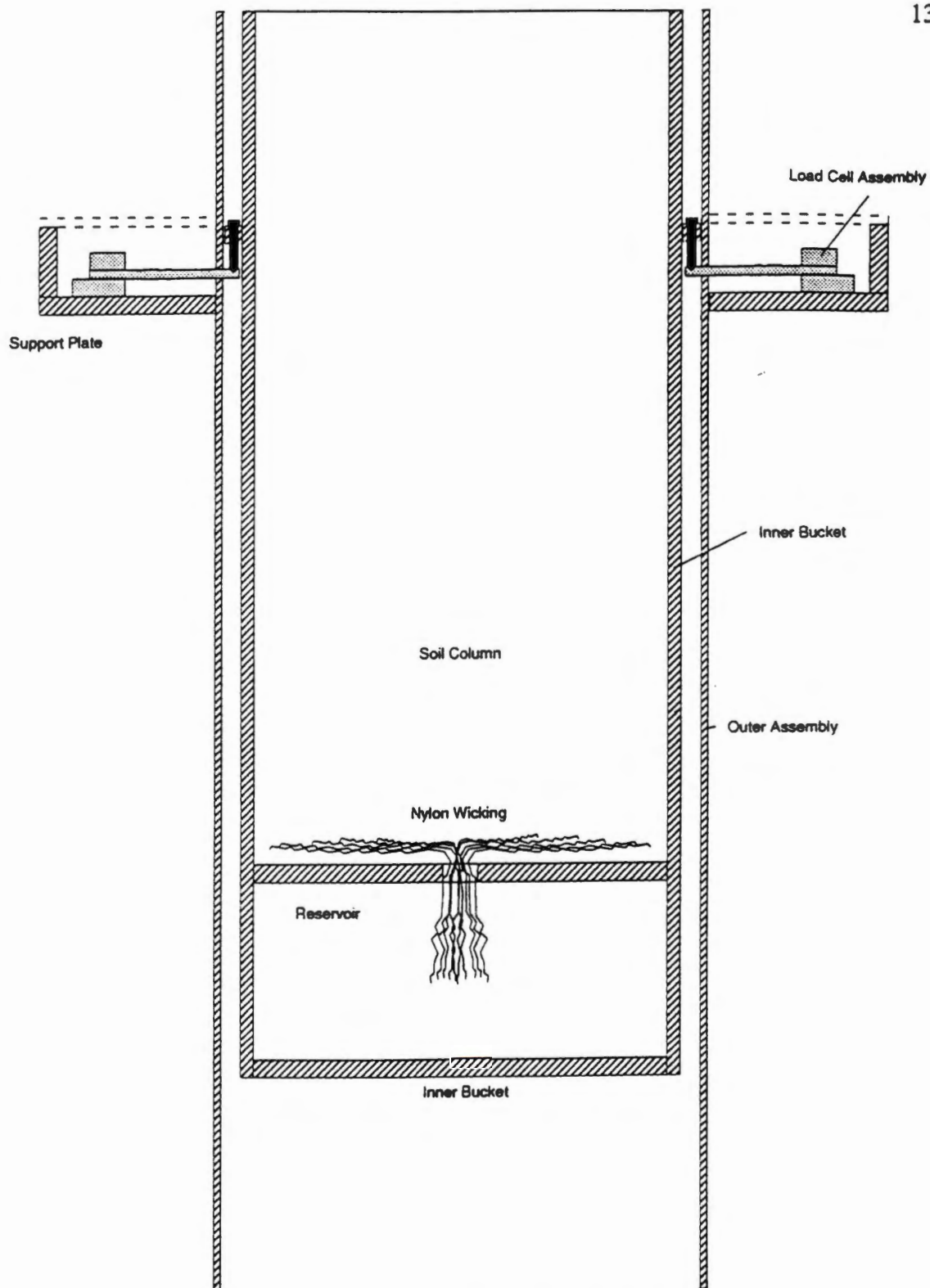


Figure 1. The cutaway view of the small lysimeter design showing inner and outer bucket assembly, including load cell assembly, nylon wicking, and water reservoir.

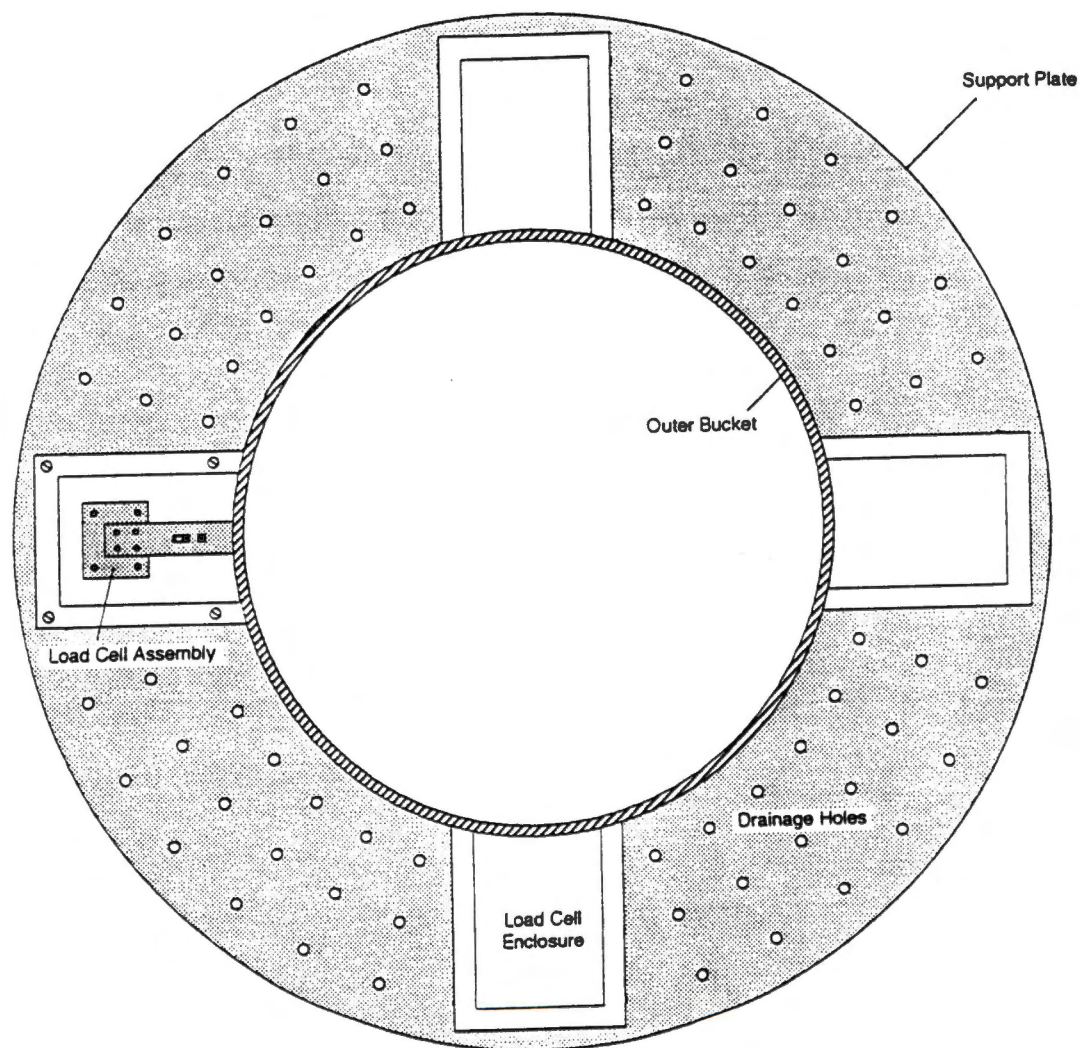


Figure 2. Top view of outer assembly support plate, showing load cell enclosures and drainage holes.

mounted flush with the surface of the ground. The PVC materials used blend well with the surrounding soil and grass, thereby reducing the chance of problems due to reflectance of incoming solar radiation. The gap between the inner and outer assemblies was approximately two cm (0.75 in.). This was the minimum gap possible to accommodate the support ring and allow free movement of the inner assembly within the outer one.

Design and Testing of First Load Cell

The first load cell design was a simple beam load cell with two strain gauges mounted in tension on the top of the beam and two strain gauges in compression mounted on the bottom. This allowed the gauges to be connected in a full Wheatstone bridge configuration, allowing greater accuracy and signal stability. The load cell was made of ASTM 2024-T4 aluminum, was 7.6 cm (3 in.) long, 1.9 cm (0.75 in.) wide, and approximately 0.64 cm (0.25 in.) thick (Figure 3). Equations for mechanics of materials

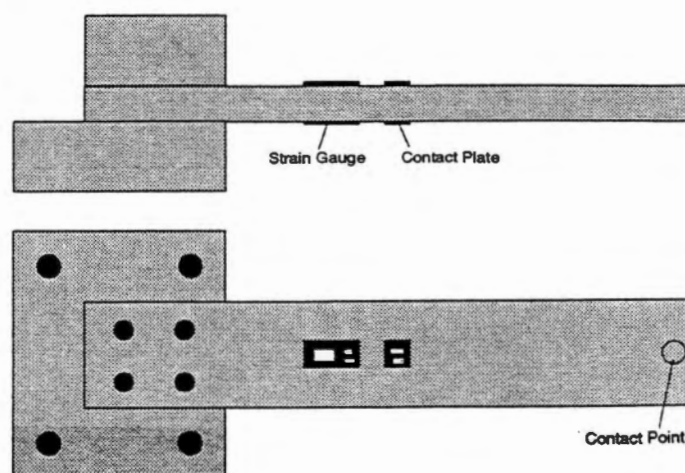


Figure 3. Top and side view of first load cell design.

were used to calculate the optimum material thickness for a given width and length. The beams were sized to maximize surface stress without the material yielding. Four load cells were placed around the support plate of the outer assembly that supported the weight of the inner assembly. Inner assembly weight was estimated based on the known weight of the inner assembly and the calculated weight of the soil column and a typical soil moisture content. Each load cell was designed to support one fourth of the weight of the inner assembly. A Campbell Scientific 21X* datalogger was used to record load cell output and monitor ambient and assembly temperature with two type-T thermocouples. The assembly was tested in the laboratory using known weights. Weight equivalent to 0.5 mm water, approximately 35 grams, was placed upon the inner assembly. The system registered this 35 gram weight change. However, testing of the system over several days showed a signal variation attributed to temperature effects that was four times greater than the signal change due to the weight of 0.5 mm of water (Figure 4).

An additional set of tests was conducted with this load cell assembly using a new set of strain gauges. The same series of tests was conducted. Again, these tests demonstrated unacceptable temperature effects for this load cell configuration (Figure 5). From these tests, it was determined that this load cell configuration was not capable of producing the desired results because the load cell did not have the sensitivity required to accurately measure ET in the desired increments.

* Product names are provided as a reference for the reader but do not in any way indicate endorsement of these products by either the author or The University of Tennessee.

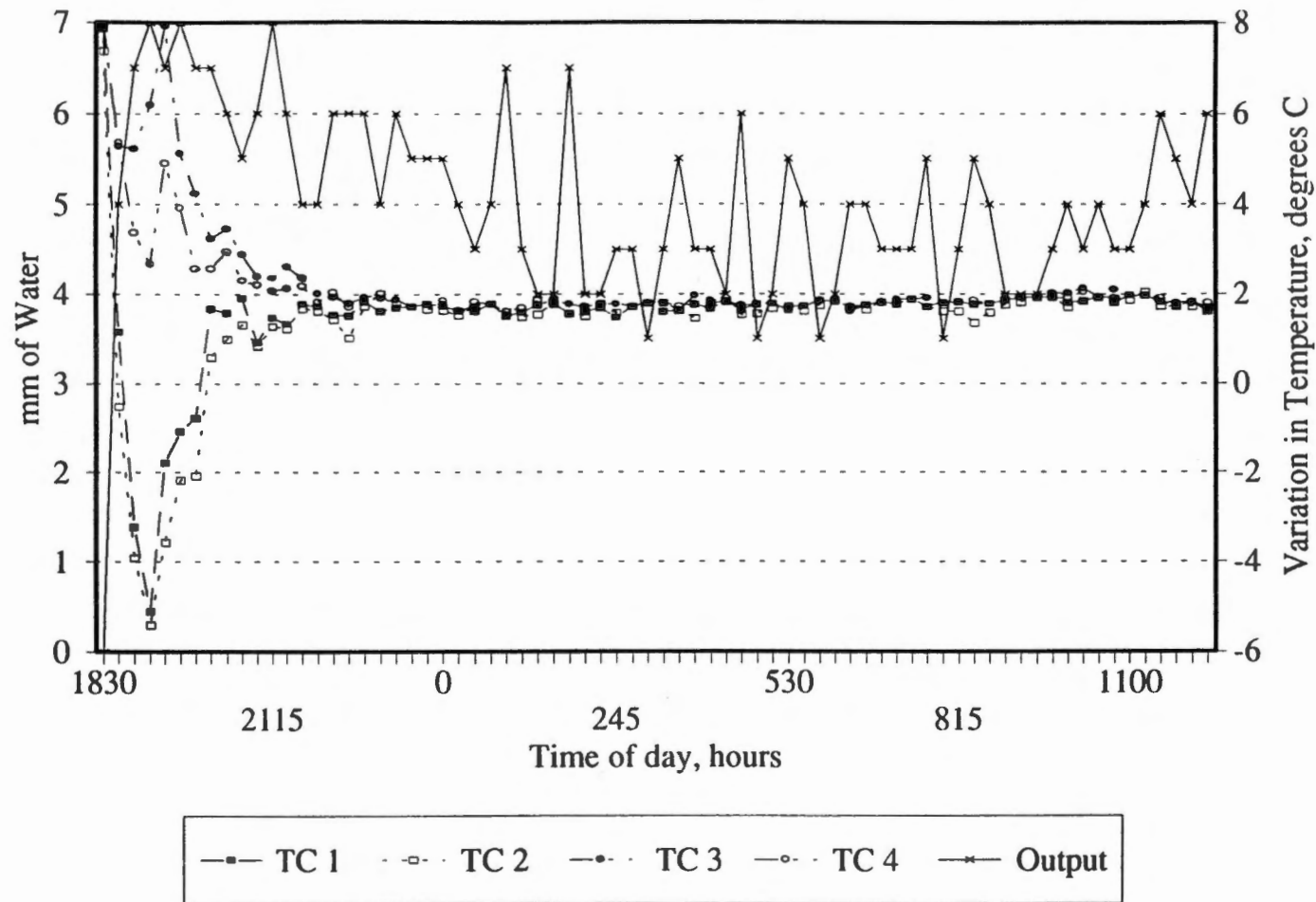
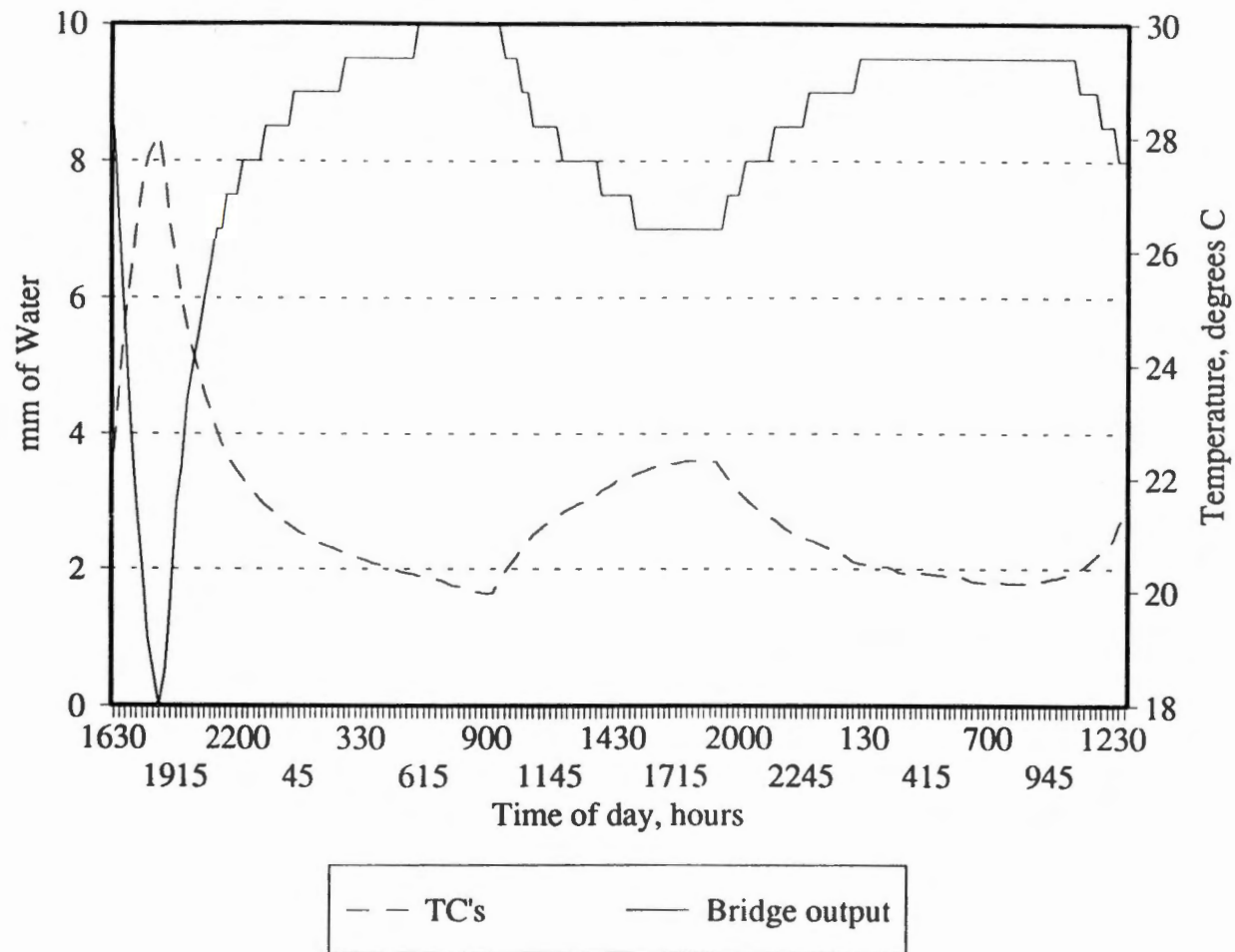


Figure 4. Testing of the first load cell design and initial strain gauges, November 5, 1993. TC1 through TC4 are temperature outputs from the thermocouples located at each load cell assembly. Output is electronic bridge output from the load cells.



Second Load Cell Design

A second load cell design was constructed (Figure 6). This design used the same load cell bar as the first design with the addition of a thinner, more sensitive bar below the first bar. After placing a known weight on this load cell, a series of tests showed that it was unable to detect the 35 g weight change necessary for the project. This load cell also exhibited similar temperature effects to those for the first design, (Figure 7) and was therefore discarded before being placed on the assembly for a full four load cell test.

Third Load Cell Design

The third load cell design was also a bar type load cell made of ASTM 2014-T6 aluminum. This material has a higher yield stress than the material used in the original design. A stress intensifier was incorporated into this design as well as the use of a different type of strain gauge (Figure 8). Four of these load cells were installed on

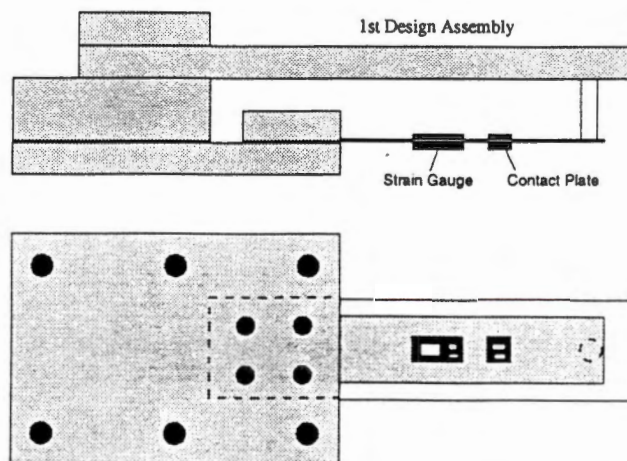


Figure 6. Top and side view of second load cell design.

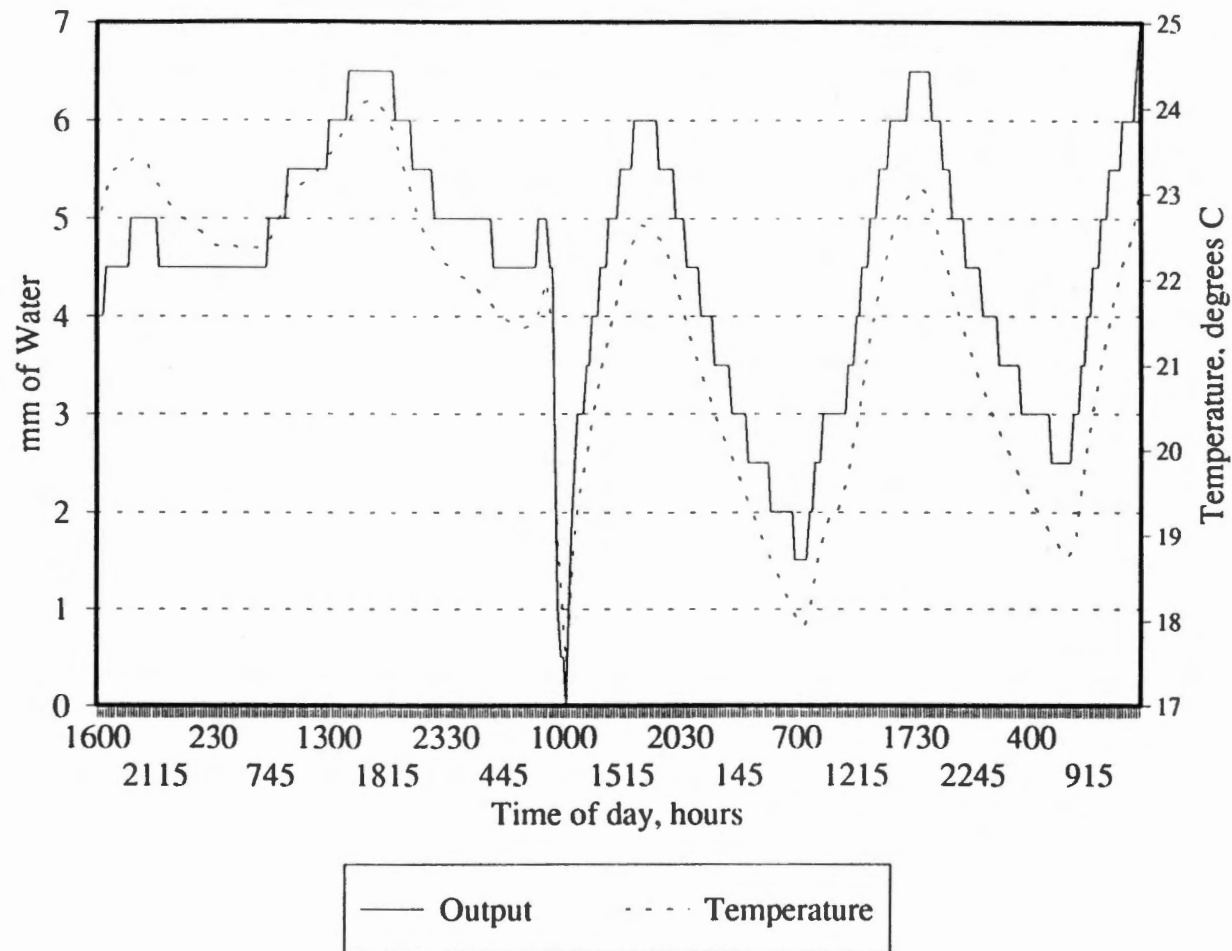


Figure 7. Temperature test of the second load cell design, completed March 7, 1994. Temperature is the ambient air temperature read by the thermocouples. Output is electronic bridge output from the load cell assembly in terms of mm of water.

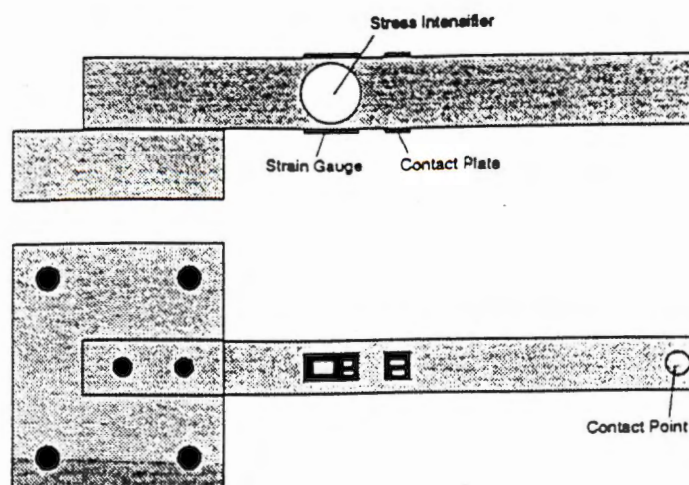
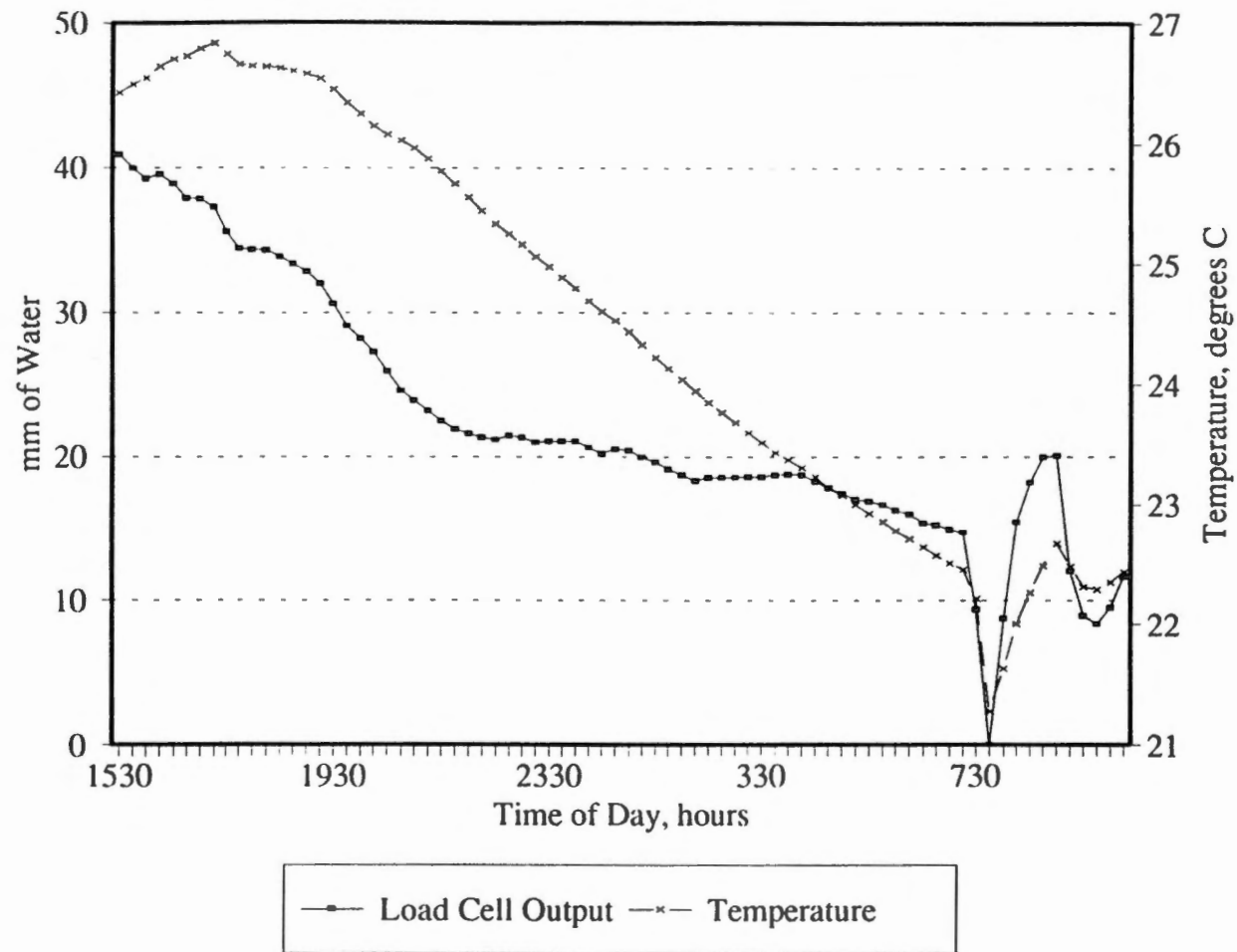


Figure 8. Top and side view of third load cell design.

the outer support ring. It was hoped that this improved design would allow for a greater accuracy and sensitivity which could overcome the temperature effects seen in the previous two designs. As in the first test, the inner bucket was placed in the outer assembly and a known weight was added. Once more, a 35-g weight was added to the known weight on the assembly. This load cell assembly had the sensitivity to easily recognize the change. A series of temperature tests was conducted over a several day period. Again, as in previous tests, this assembly showed greater variation due to temperature than its ability to measure the 35-g weight change, (Figure 9).

At this point, it was decided to subject both this load cell design and the datalogger to a set of controlled temperature experiments to see if the temperature variation was due to the effect of temperature on the electronics of the system as seen in experiments by Allen and Fisher (1990). An environmental chamber was used to subject each individual component of the system to fixed temperature and humidity. First, the load cell was placed in the temperature chamber and the datalogger remained at ambient room



temperature to experience diurnal temperature fluctuations, (Figure 10). Secondly, the process was reversed -- the datalogger was held at constant temp and the load cell was allowed to experience variation in temperatures, (Figure 11). Analysis of this data indicated that the temperature did have an effect on both the datalogger and the load cell, although the datalogger proved to be more severely affected. However, even with the datalogger stabilized, variation due to temperature effects exceeded the load cell's ability to detect the desired weight change. It was then decided to ascertain whether a commercially available temperature-compensated load cell could overcome these effects. An Alphasatronics Model L5 was placed outside the chamber. The datalogger was placed in the chamber and held at a constant temperature. While the commercial load cell showed some signal drift, this variation was not attributable to temperature. Additionally, this small variation in signal change was not of a sufficient strength to mask the signal change due to ET-related weight change, allowing accurate ET measurements. Therefore, it was determined that the commercial load cell was far more capable of compensating for the temperature fluctuations than the shop fabricated load cell (Figure 12).

At this point, it was concluded that to measure the desired weight change in water of the inner bucket a means was required to remove the weight of soil and the assembly from the system. This was necessary because the weight of water being measured, 0.035 kg (0.07 lb) proved to be insignificant when compared to the overall mass of 114 kg (250 lbs) of the inner assembly. A counterbalance system would augment the sensitivity of the load cell by placing only the weight of water over the full active range of the load cell.

From analysis of data from the large lysimeter at Crossville, it was determined that

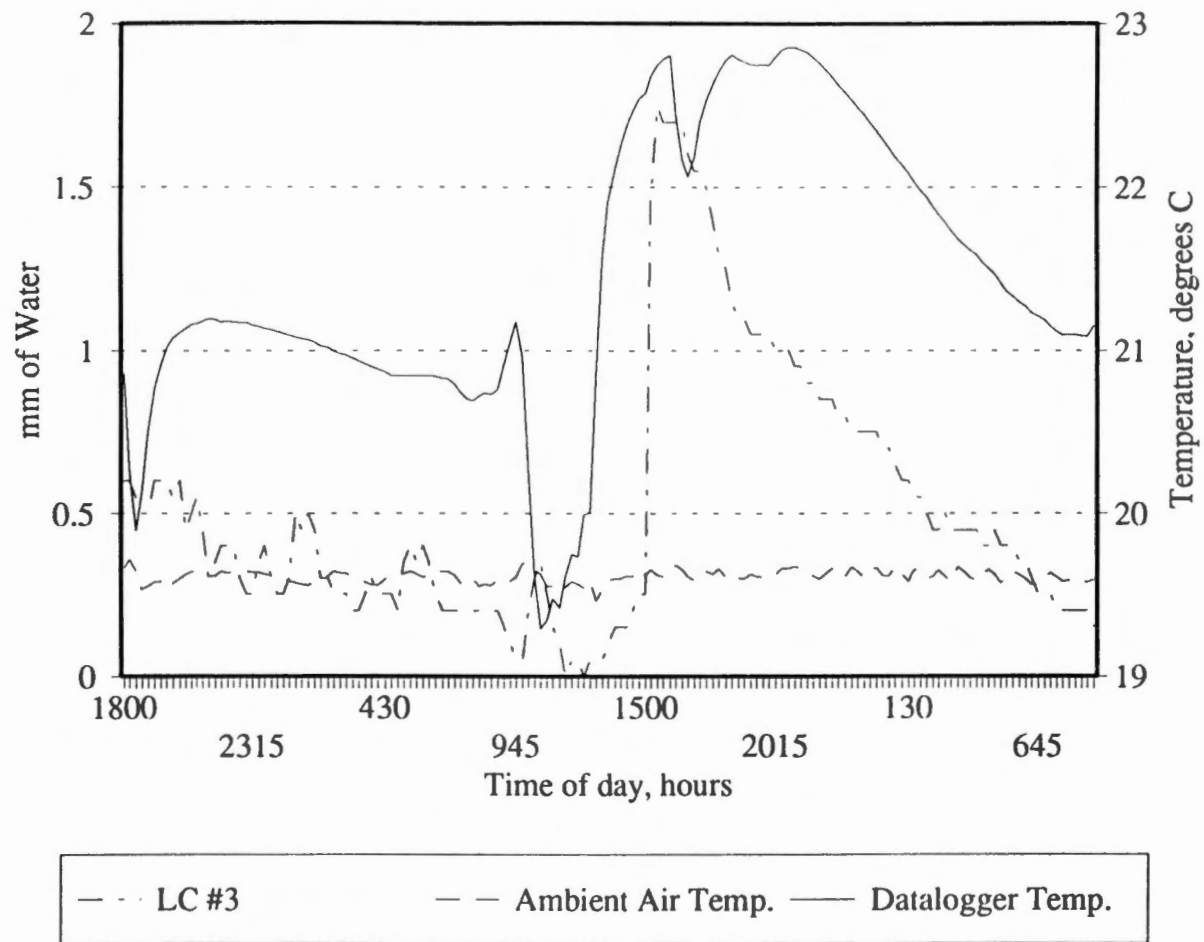


Figure 10. Environmental chamber test of the third load cell design, completed May 6, 1994. The load cell was held at a constant temperature

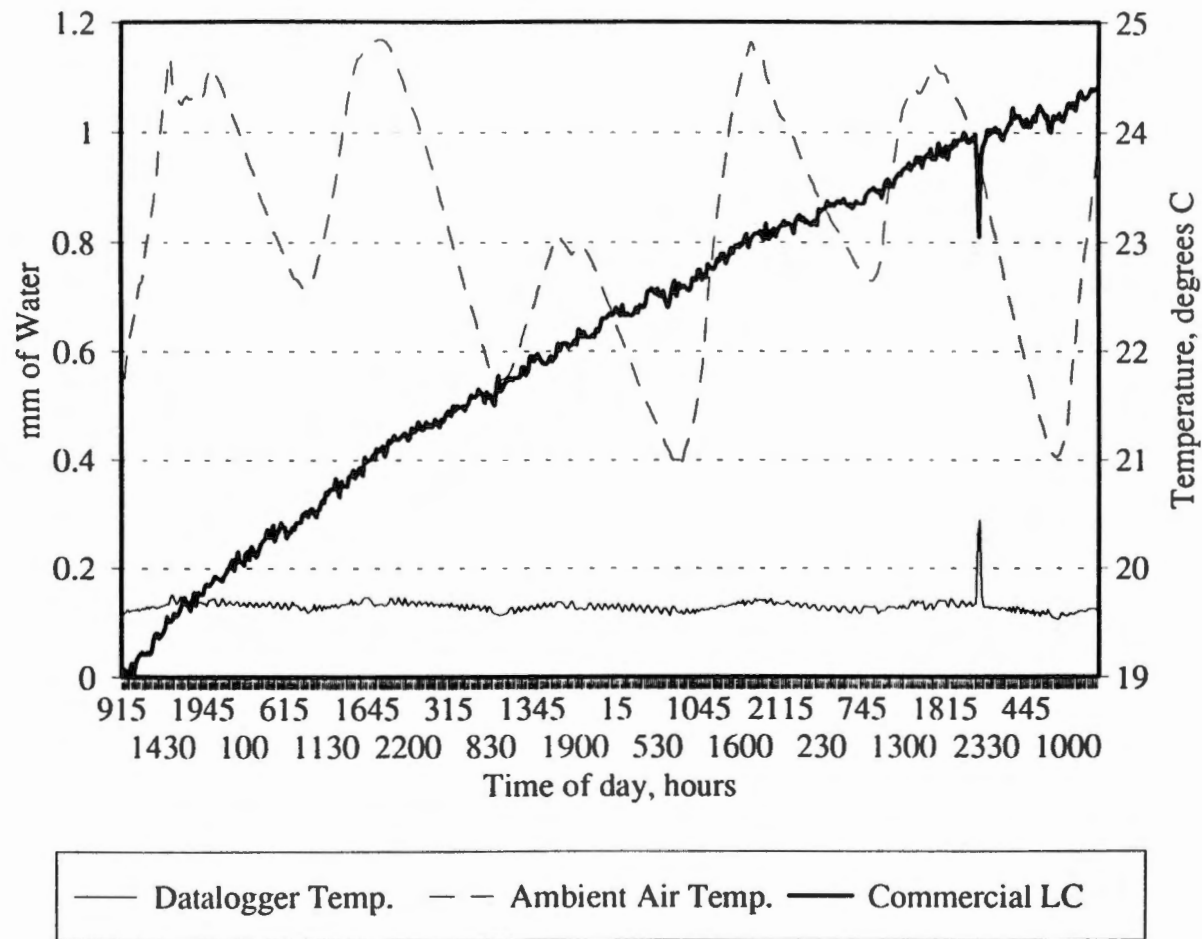


Figure 12. Environmental chamber test of the commercial load cell, completed May 11, 1994. The datalogger was held at a constant temperature.

on a day to day basis the temperature of the 21X datalogger was relatively constant because it is housed in the lysimeter pit several feet underground minimizing the temperature effects seen in the environmental chamber test. Therefore, a counterbalance system for the inner bucket was designed to remove the non-water weight from the system. This design utilized a single commercial load cell to determine the mass of the small lysimeter.

Design and Testing of the Counterbalance System

To maintain ease of assembly and low cost, a small counterbalance assembly was developed that incorporated as much of the original design of the inner and outer bucket as possible. The inner bucket assembly was not modified. The outer bucket assembly was modified by removing the four load cell housing boxes from the outer ring. An enclosed box approximately 30 cm (12 in.) deep by 60 cm (24 in.) long was built of 1.3 cm (0.5 in.) PVC and 3.8 x 3.8 x 0.64 cm (1.5 x 1.5 x 0.25 in.) steel angle frame and attached to the outer assembly on a section of the outer support plate (Figures 13 and 14)

The counterbalance assembly consisted of two, double bar lever-arms. The top arm was 97 cm (3 ft) in length and stretched from a fixed pivot point on one side of the outer assembly support plate through the outer assembly to a point inside the main housing box. The inner assembly rested on two load points, one on each arm, where the outer lever-arm ran through the outer assembly. The second lever arm was inside and slightly beneath the first lever-arm and was attached to the upper lever-arm at a single pivot point. This was

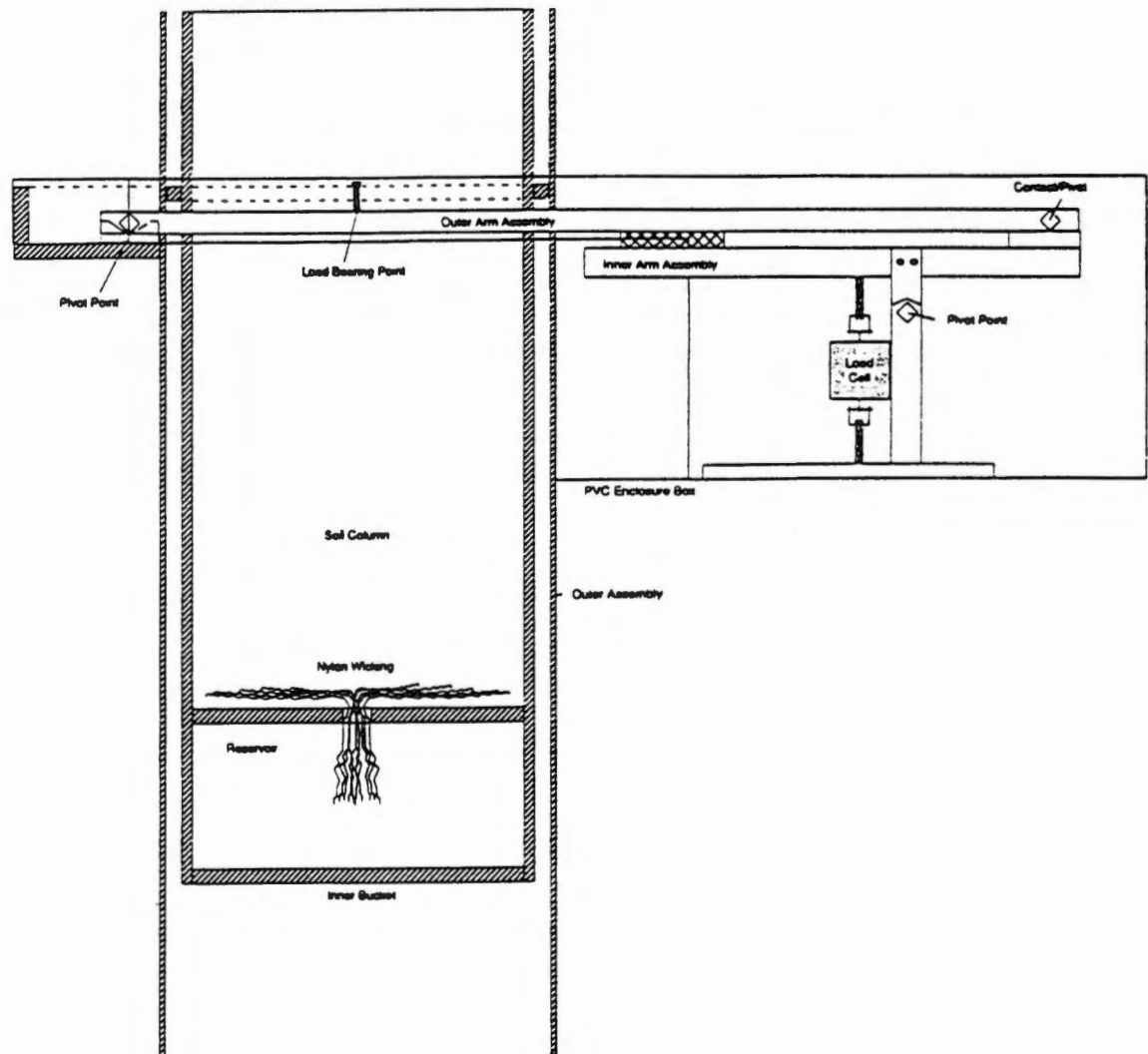


Figure 13. Cutaway side view of the counterbalance lysimeter assembly, showing positioning of pivot points and load cell attachment .

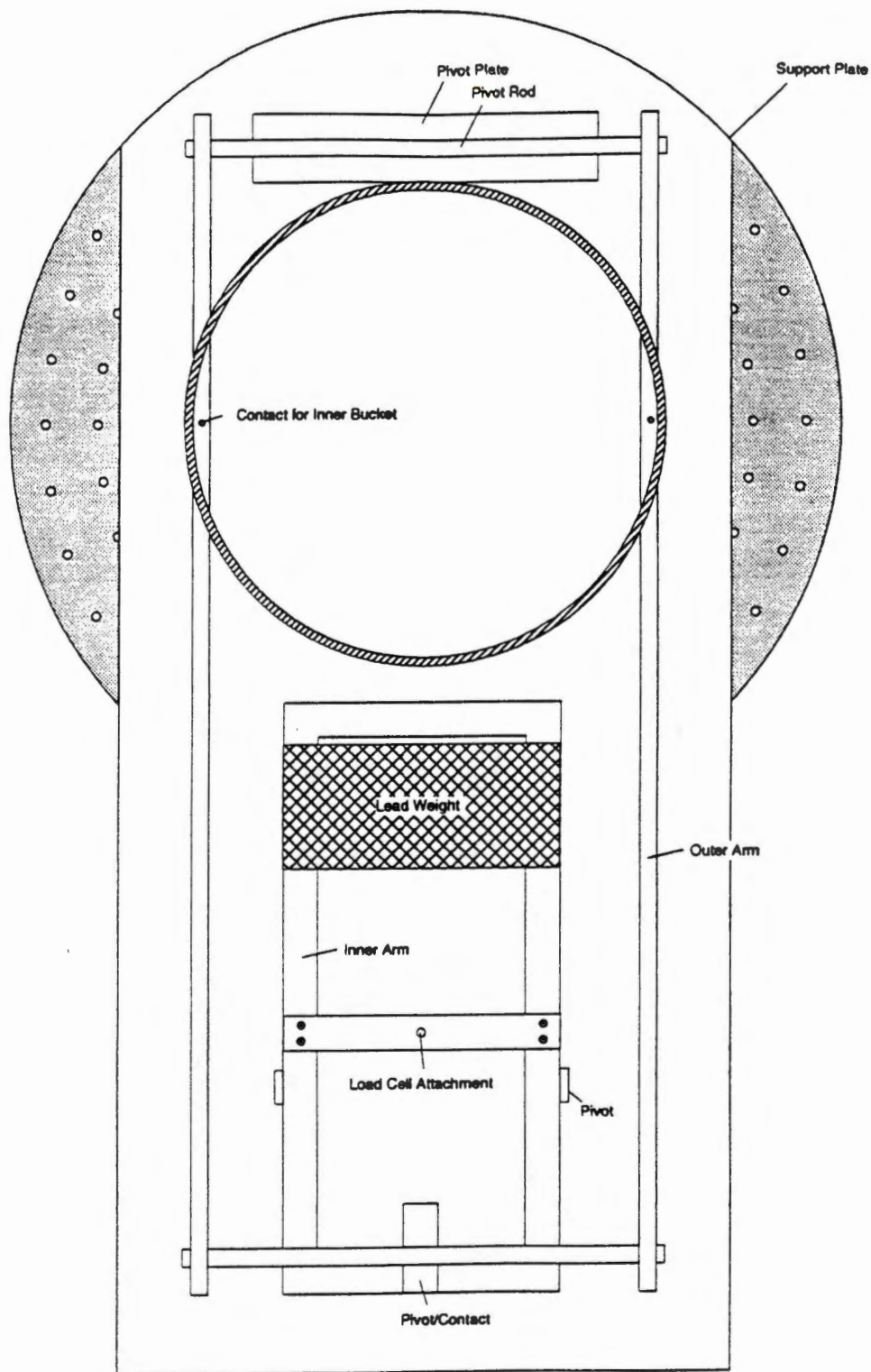


Figure 14. Top view of the counterbalance lysimeter assembly showing position of pivot points, load cell attachments and counterweight positioning.

to prevent binding of the two arms. This inner lever arm was mounted on a support plate and held the load cell attachment point (Plate 1). The counterbalance system was designed such that the counterbalance maintained all but approximately 15 kg (35 lb) of the total weight of the inner assembly. This remaining weight, the weight of water in the system, was supported by a single BLH® Alpha series 150 load cell at a mechanical advantage point such that the weight change in water was directly read by the load cell. The mechanical advantage of the outer (first assembly) arm is 3:1. The mechanical advantage of the inner arm is 2:1 to the counter weight and 1:0.25 for the load cell placement. The counter weight removes the static weight of the lysimeter bucket assembly and soil column, transferring only the weight of water in the system. The less than 1:1 ratio of mechanical advantage serves as a mechanical multiplier which spreads the active weight of water over the full range of the load cell. Cost estimates for construction of this design are given in Table 1.

This assembly was made in the shop and tested in an environmental chamber. It was not possible to control humidity or fully control temperature in this larger facility, but the range of temperature change was within the range of change expected on a daily basis for the buried equipment in the field. This system easily recognized the 0.5 mm water weight change, and while temperature effects were noted, they were greatly reduced from those seen in the original design (Figure 15). Analysis of this data indicated that over a 24-hour monitoring period, the anticipated temperature effects were not expected to be problematic since the datalogger was at a relatively constant temperature and soil temperature changes were expected to be slow at a depth of 15 - 20 cm (6-8 in.).



Plate 1. Photograph taken during temperature chamber test showing counterbalance lysimeter assembly prior to installation in the field.

Table 1. Cost estimate for construction of counterbalance lysimeter.

Item	Unit Price	Quantity	Total
½" PVC Sheet	\$132.00/sheet	1 sheet	\$132.00
12" PVC Sewer Pipe	\$6.20/ft	3 ft	\$18.60
14" PVC Duct	\$16.65/ft	3 ft	\$49.95
Steel (flat and angle)	-----	-----	\$40.00
Stainless Steel Fasteners	-----	-----	\$50.00
Wiring and Construction Material	-----	-----	\$50.00
Load Cell	\$500.00/ea	1	\$500.00
Labor	\$30.00/hr	8 hrs	\$240.00
Total			\$1080.55

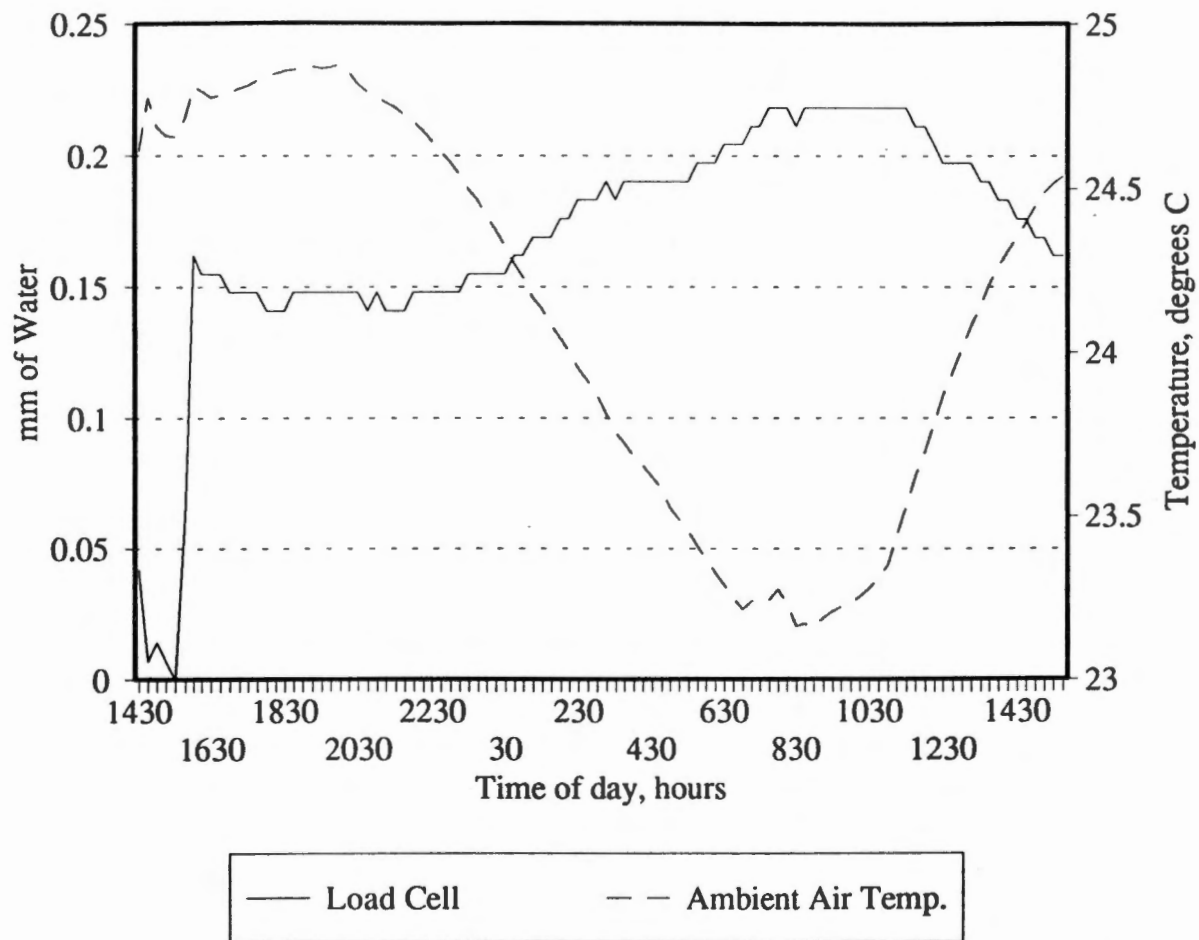


Figure 15. Temperature chamber test of the counterbalance lysimeter design, completed June 28, 1994.

CHAPTER 4

FIELD INSTALLATION AND TESTING

The Crossville lysimeter station, located at the Tillage Tract of the Plateau Experiment Station, consists of a full agricultural meteorological weather station and the Crossville lysimeter test plot. The weather station is equipped with a tipping bucket rain gauge, temperature and relative humidity probe, wind velocity and direction gauge pyranometer, and a Class A evaporation pan. Located on the Cumberland Plateau, approximately eight miles southwest of the city of Crossville TN, at an elevation of 573 m (1881 ft) at 35°57' N by 85°05'W, the area consists mainly of rolling pasture lands interspersed with areas of deciduous forest and fence rows. The lysimeter test plot is a 36 x 36 m (120 x 120 ft) irrigated section of a field planted in fescue. Irrigation is scheduled every third day, and water application is adjusted to keep the cover crop growing and healthy. The Tillage Tract Plot and the surrounding area are representative of this region of the Plateau and its agricultural practices. A Campbell Scientific 21X datalogger is housed in the large lysimeter control pit in the center of the irrigated section. This datalogger and a Campbell Scientific CR10 datalogger in the weather station are accessible 24 hours a day by cellular phone modem and telecommunications equipment (Yoder et al., 1992), and data is downloaded twice weekly.

The small lysimeter assembly was installed at the lysimeter test plot 18 m (60 ft) from the large lysimeter. A hole approximately 36 cm (14 in.) in diameter and 1.06 m (3.5

ft) deep was dug by hand. The soil was placed on plastic sheeting and a plywood board was used while digging to prevent disturbance of soil and grass around the site. Once the hole was completed, the outer assembly was lowered into the hole and an outline was made of the box and support plate portions of the assembly. Using this outline, the turf was carefully removed to a depth of 15 cm (6 in.). The entirety of this excavation was performed by hand (Plate 2).

The outer assembly was then lowered into the ground and leveled. A PVC access line was laid at a depth of 15 cm (6 in.) in a narrow trench to allow wiring to run from the small lysimeter to the main lysimeter control pit approximately 18 m (60 ft) away.

An undisturbed soil core was taken from a different location at the site with the same Lily loam soil type. This core was taken by excavating an area around the monolithic block and slowly forcing the inner assembly down over this block, trimming away the edges with a hand trowel to ensure a good fit between the block and the inner assembly. A temporary top was placed on the outer assembly and it was inverted, allowing the soil column to be made level with the top of the inner assembly. Once this was completed a 2.5 cm (1 in.) layer of sand was placed along the bottom of the core to provide good hydraulic contact between the soil and the nylon wicking assembly. The support plate and a nylon wicking assembly was then PVC welded into place. The lower plate of the water retention reservoir was PVC welded into place and the access tubes were inserted and sealed to the side of the inner assembly. A nylon wick was used to draw water away from the bottom of the lysimeter to prevent soil saturation without placing substantial tension on the system that would reduce the soil water content (Boll et

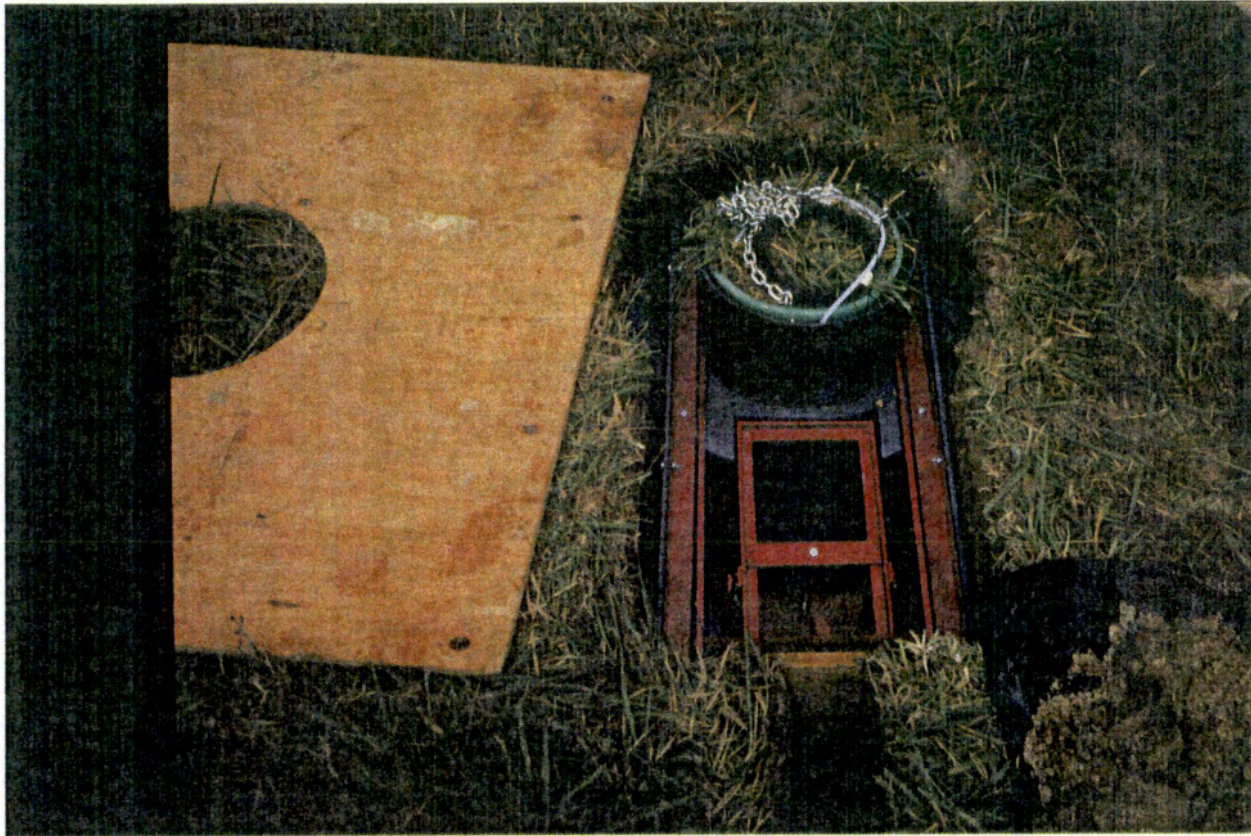


Plate 2. Photograph of small lysimeter installation excavation prior to installment on June 30, 1994, showing undisturbed surrounding soil conditions.

al., 1990; Holder et al., 1991). Wicks of this type have been used in soil water sampling in non-weighing lysimeters. Excess water was collected in a reservoir where it could be removed and measured.

The inner assembly was then carefully lowered into the outer assembly and set on the load points of the counterbalance. A 23 kg (50 lb) weight was placed in the counterbalance and adjusted to balance the dead weight of the system. The BLH₆ load cell was installed to carry the remainder of the weight. Once it was determined the assembly was stable and operating, three type-T thermocouples were inserted into the system. The thermocouples were used to take temperature readings to assess temperature effects on the operation of the small lysimeter. The first was inserted through a small hole in the inner assembly into the soil column at a 15-cm (6-in.) depth. The second was placed in the box to monitor ambient temperature at the load cell. The third thermocouple was inserted through a small hole in the outer assembly into the surrounding soil at a depth of 15 cm (6 in.). The assembly box was then closed and sealed to prevent entry of moisture and the area of cut away turf was placed back over the buried assembly to approximate undisturbed conditions as closely as possible.

All the thermocouples and the load cells were then attached to the Campbell 21X datalogger located in the lysimeter pit. Dataloggers of this type have frequently been used in lysimeter and agricultural applications (Allen and Fisher, 1991; Fisher and Allen, 1991). In combination with the load cells, they are expected to perform very well. The accuracy of the datalogger system is generally greater than that of the load cell, making the load cell the limiting factor in attaining data accuracy. However, during laboratory tests on the

small lysimeter, problems were revealed with both the datalogger and the load cell. The load cells used for the experiment were BLH_® Alpha series 150 and an Alpatronix model SL50lb-T. At 5,000 mV excitation from the datalogger, the sensitivity of the BLH_® was calculated at 71.11 mm H₂O/mV/V and the Alpatronix at 312 mm H₂O/mV/V. The small lysimeter load cell and the three thermocouples were attached to this datalogger. The datalogger was set to sample the two lysimeters and the thermocouple every minute, averaging every 15 minutes. The datalogger was set to read the small lysimeter as a full bridge input.

The system was allowed to settle and stabilize for four days. The small lysimeter was field calibrated using a set of known weights. Lead weights of approximately 1200 g (2.6 lb) were sequentially placed on the lysimeter until a maximum weight of 7000 g (15.4 lb) was attained. The lysimeter was loaded incrementally with six weights, then unloaded incrementally, with readings taken after each change of weight. A two minute interval was utilized between readings to allow the load cell to reach a steady state. A regression of output signal to weight on lysimeter was performed to calibrate the weight to the signal. The large monolithic lysimeter is field calibrated yearly. All calibrations are included in Appendix A. The field calibration determined the conversion coefficient to equate mV/V output to mm of water, resulting in the following equation:

$$ET \text{ (mm)} = (71.11 \text{ mm/mV/V}) (mV/V)$$

Data collected from the small lysimeter was compared to two references. The first was a large monolithic weighing lysimeter of the Bushland type (von Bernuth, 1988). Installed in 1989, this lysimeter is calibrated annually according to the procedure by

established by The University of Tennessee Agricultural Engineering Department (data shown in Appendix A). The second reference was a derived ET value calculated using the FAO Penman and unmodified Penman equations (Cuenca, 1989).

The Penman method of estimating evapotranspiration uses a radiation balance to indicate the amount of energy available for evaporation and an aerodynamic term to quantify advective conditions that remove water vapor from the field. The FAO modified Penman equation adds a calibration coefficient to adjust for a wide range of climatic conditions that is statistically determined by analysis of meteorological parameters, including maximum relative humidity, solar radiation, mean daytime wind velocity, and the ratio of day to night wind run (Jensen et al., 1990). Meteorological information used in these calculations was gathered from the on-site weather station set up and operated along standards established by The University of Tennessee Department of Agricultural Engineering. Information at the weather station is read every minute then averaged on an hourly basis. This weather information was downloaded to a spread sheet computer program and used to calculate ET data using the two forms of the Penman equation previously mentioned.

Differences between estimated and measured values of the two lysimeters were compared to climatic conditions to determine if there was a correlation between individual meteorological parameters, combinations of meteorological factors, and measured ET variances.

Data were collected from both lysimeters for 2 weeks through the month of July, 1995. Data were not collected after July 16 due to electrical damage received by the

datalogger and load cell during a thunderstorm. On July 29, repairs were made to the 21X system and a new load cell was installed in the small lysimeter, again maintaining undisturbed conditions by rolling back the turf. The new load cell was an Alphasatronix model SL 50LB-T. A new field calibration was done at this time. Data were taken continuously from August 8 through September 13. Values collected after September 2 were not used because the grass had been treated on that date with a herbicide in preparation for replanting of a new stock grass. Data were also not available for one week in the middle of August due to loss of a data storage module.

CHAPTER 5

ANALYSIS

Analysis of the July data showed that the small lysimeter tracked within 0.5 mm ET of the large lysimeter (Figure 16) and within less than 1 mm ET from the unmodified Penman equation (Figure 17). The modified FAO Penman was not used in comparison because analysis of on-site weather data showed none of the extremes of conditions for which this modification was calculated. On-site weather data and information used for calculation of Penman values is included in Appendix B. Temperature in the lysimeter pit was recorded every 15 minutes and remained constant with the exception of 4 hours on day 186 during which the pit door was open while the lysimeter was calibrated.

Temperature differences between the surrounding soil, the load cell in the counter balance box, and the small lysimeter soil column were never greater than 1.5°C, with a diurnal fluctuation of less than 4°C. Diurnal temperature variation for days 188 and 189 are presented in Figure 18 and are representative of all days measured.

Analysis of the temperature data and the small lysimeter ET data indicated that the greatest diurnal temperature difference occurred in the small lysimeter soil column. This temperature difference was less than 4°C and was on average, approximately 0.5 degree greater than the diurnal temperature flux seen in either the surrounding soil or the lysimeter assembly box. Based on data collected in the chamber temperature tests, a variance of approximately 3°C at the load cell was not considered a detrimental factor to

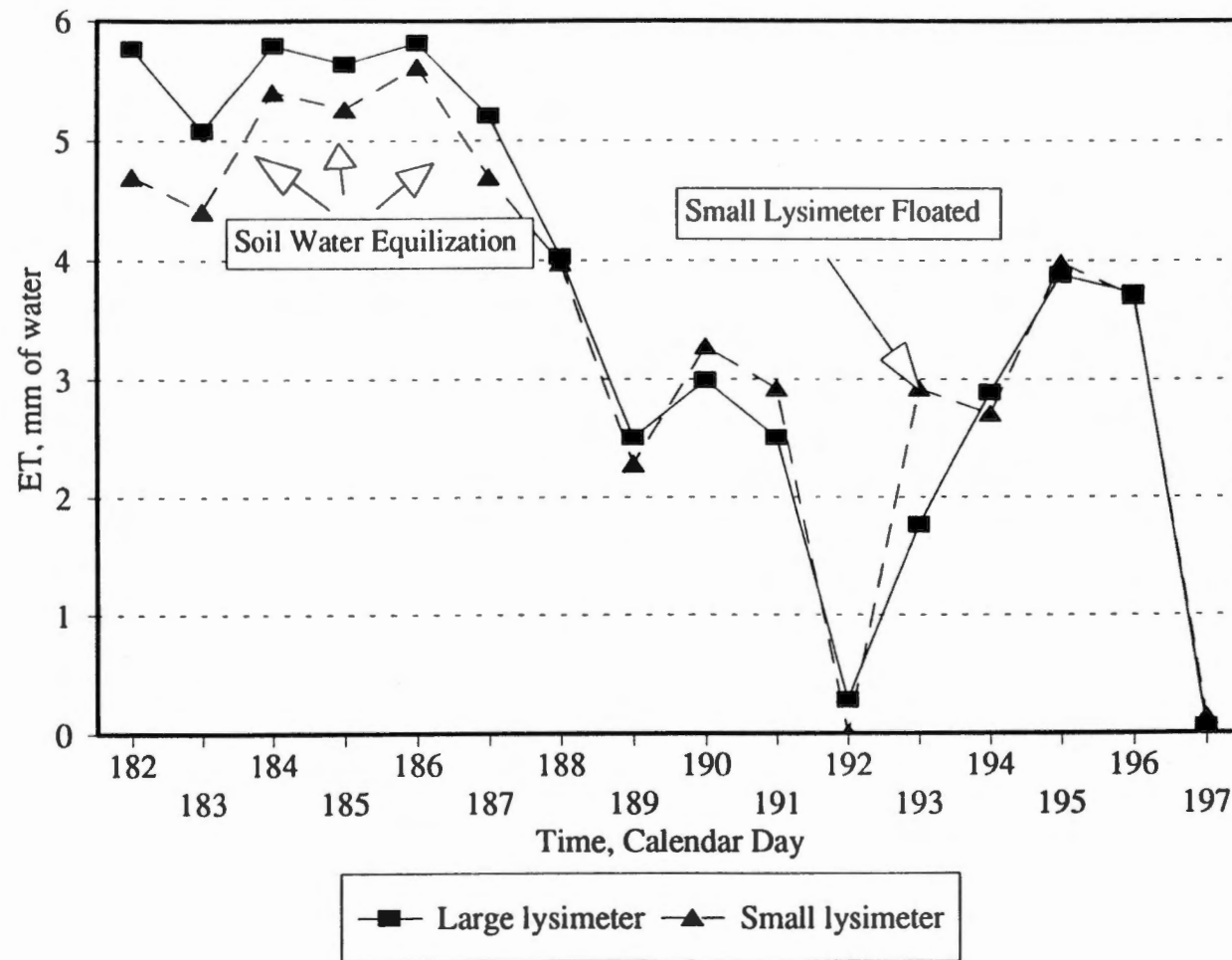


Figure 16. ET comparison between the large and the small lysimeter from July 1-16, 1994.

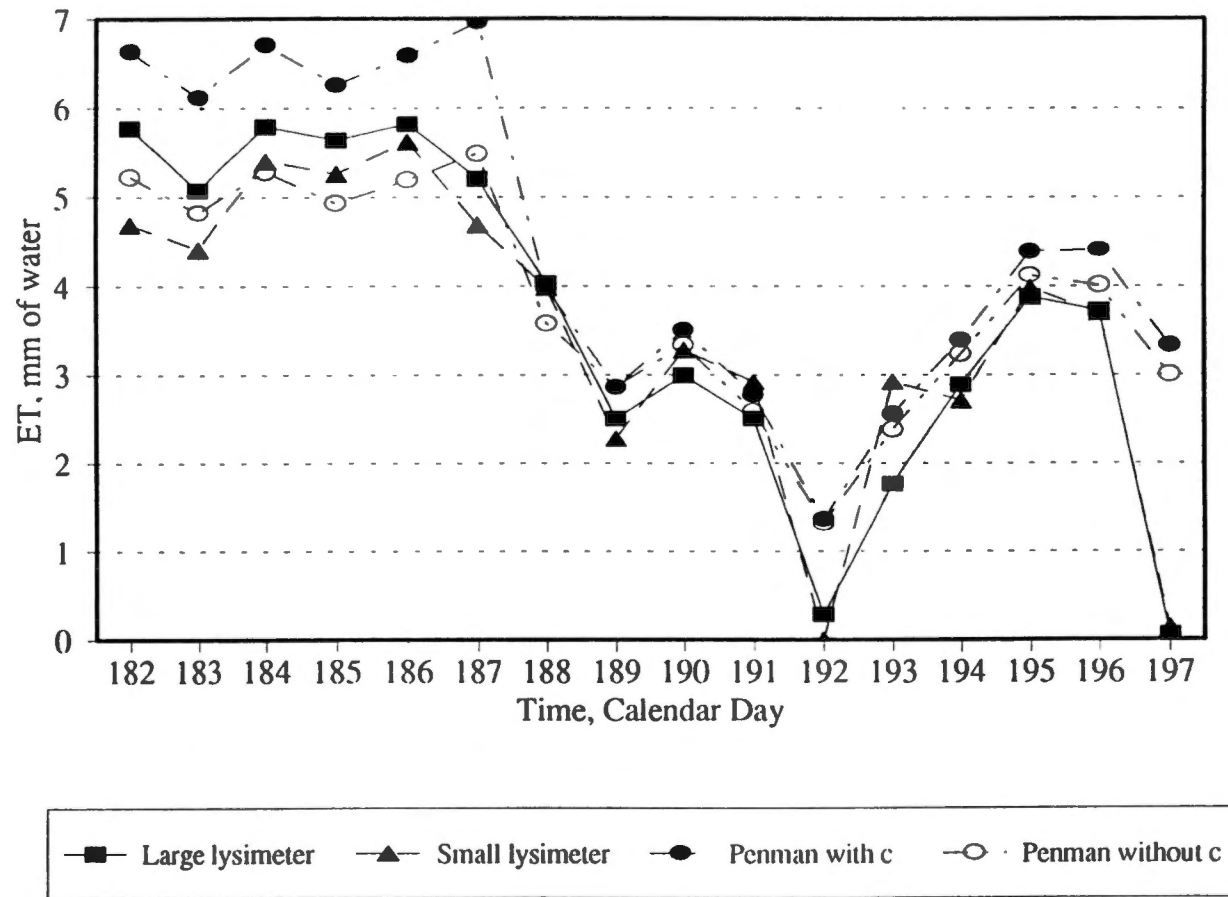


Figure 17. ET comparison between the large and small lysimeters and the Penman equations from July 1-16, 1994. Penman without c is the unmodified Penman equation. The Penman with c is the modified Penman equation which is not used in the statistical comparison.

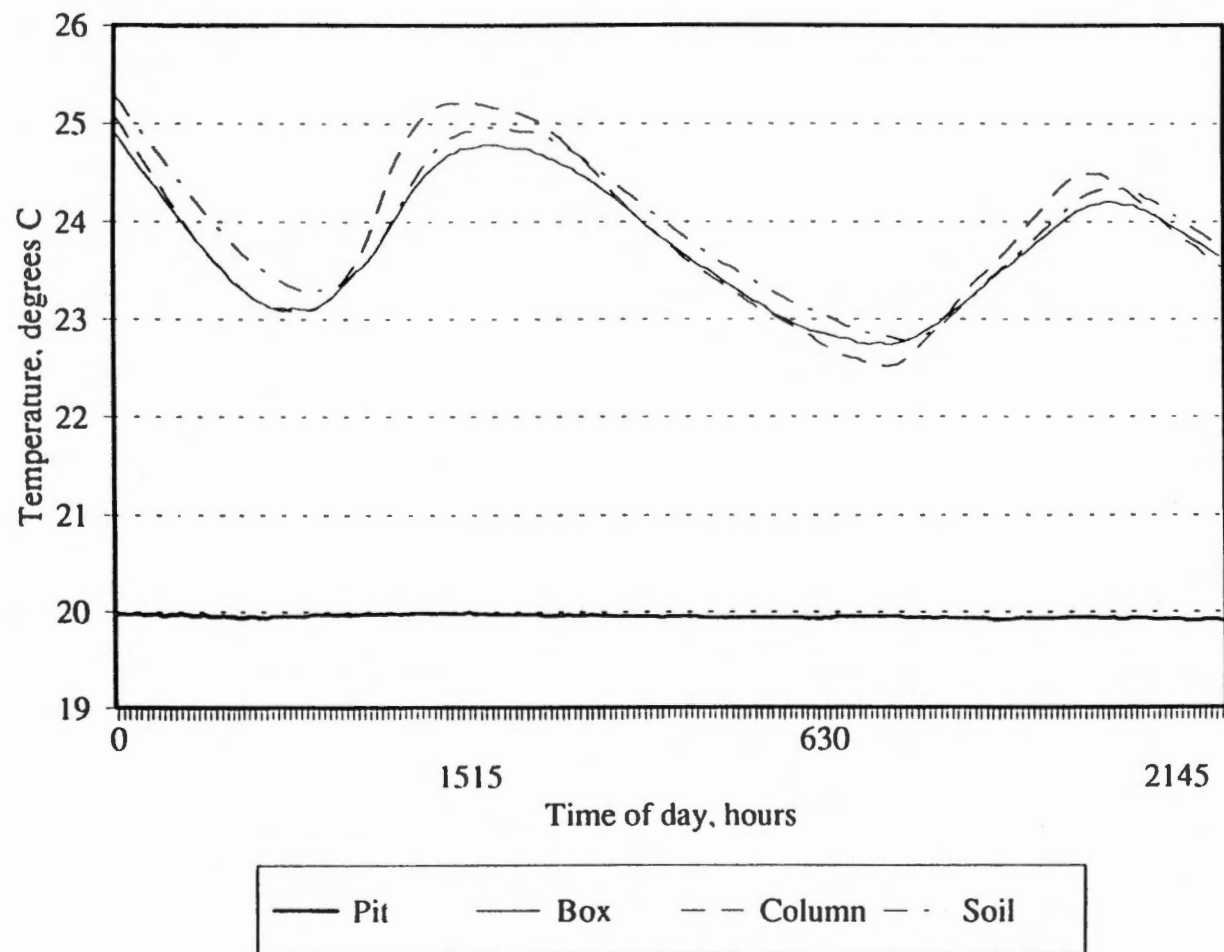


Figure 18. Temperature comparison of the surrounding soil, soil column, control pit temperature, and small lysimeter assembly, using July 7-8, 1994 as representative days.

accurate ET determination.

Examination of the ET data indicated that the greatest difference between the small and large lysimeter occurred within the first five days after installation and during days 190-194 (Figure 16). Statistical regression of ET values of the small lysimeter against those measured with the large lysimeter generated a correlation r^2 value of 0.94 indicating a definite relationship between the two. Removal of the data values for the first four days did not statistically alter the correlation. Regression calculations of ET data from both the small and large lysimeters against the Penman equation revealed respective r^2 values of 0.76 and 0.85. Upon visual inspection of the data to seek a reason for the variation of r^2 square values, it was discovered that the small lysimeter has a more pronounced reaction to rainfall than the large lysimeter. Day 193 is an aberrant data point and was not considered in any comparisons. Heavy rainfall on the evening of day 192 and early morning of day 193 caused the inner bucket to float as the outer bucket filled with water, thereby distorting the data. Variations in ET between the two lysimeters were seen throughout a four-day rainfall period from 190-194, suggesting that rainfall can hinder the acquisition of closely correlated data. During this period, the large lysimeter more closely tracked the Penman equation than did the small lysimeter (Figure 17).

Compared to the Penman equation, the small lysimeter was inconsistent in predicting ET during the first five days after installation (Figure 17). This settling period coincided with the greatest diurnal atmospheric temperature difference. This theoretically should have caused a greater amount of ET from the small lysimeter. However, the small lysimeter soil column was taken from a non-irrigated section of the site. The ET data

from the two lysimeters steadily converged through three irrigation cycles before matching for the first time on day 188. This variation was probably due to the lower soil moisture content in the transplanted soil column. Another possibility was that this was merely a settling time for the system. However, this phenomenon led to a statistical investigation of the effects of atmospheric and temperature conditions on ET.

Statistical regression analysis was done comparing the ET values from the large and small lysimeter using various measured, calculated climatic, and combination variables. Three linear regression trials were performed using data for days 182-197, days 182-187, and days 187-197, with day 193 excluded (Table 2). These calculations indicated no definitive correlation between ET and any single variable in any of the trials. Four combinations of variables were also investigated for the entire period. All four combinations suggested correlation with an r^2 value of approximately 0.8 with an adjusted r^2 value of 0.76. This indicates that the variance between the lysimeters is a multifactorial problem. Days 182, 188 and 195 were selected for individual statistical analysis on an hourly basis because these days represented respectively the settling period, the least variation from the large lysimeter in ET estimation, and a rain day (Table 3). It was hoped that this investigation might allow further identification of the most relevant factors. Analysis of these data showed no relevant statistical impact for any variable on days 188 and 195. However, definitive correlation was seen for the variables of box, surrounding soil, and soil column temperatures on day 182.

Data collected in August were not used in the performance analysis for the small lysimeter. There were some undetermined difficulties with the data collection following

Table 2. Regression analysis of correlation r^2 for July ET and Weather Data.

Delta Water Small - Large Lysimeter Comparison Property	Days 182-197	Days 182-187	Days 187-197 (day 193 excluded)
Maximum Pit Temperature	0.00029	0.06857	0.06062
Maximum Box Temperature	0.28422	0.2175	0.09744
Maximum Soil Column Temperature	0.36801	0.47087	0.12285
Maximum Surrounding Soil Temperature	0.2913	0.20371	0.09446
Delta Pit Temperature	0.04653	0.09781	0.02631
Delta Box Temperature	0.45114	0.15647	0.3015
Delta Column Temperature	0.44777	0.00304	0.27196
Delta Surrounding Soil Temperature	0.44032	0.17869	0.25123
Maximum Ambient Air Temperature	0.31686	0.09695	0.11619
Minimum Ambient Air Temperature	0.4001	0.25315	0.05686
Maximum Relative Humidity	4.2E-07	0.00527	0.27099
Minimum Relative Humidity	0.46243	0.21513	0.23164
Delta Column vs Soil Maximum Temperature	0.39095	0.64484	0.01683
Delta Column vs. Soil Minimum Temperature	0.32494	0.07397	0.09286
Solar Radiation	0.3715	0.00782	0.10767
Rain	0.00815	-----	0.10423
Wind Run	0.04691	0.39804	0.01554
Day/Night Wind Run Ratio	0.34347	0.10542	0.0007
Average Wind Speed	0.04693	0.39816	0.01553
Day Wind Run	0.01233	0.41968	0.01688
Average Day Wind Speed	0.01234	0.41981	0.01686
Delta Ambient Air Temperature	0.47768	0.21794	0.30264
Delta Air Temp + Min RH + Delta Pit Temp	0.80845		
Delta Air Temp + Min RH	0.79386		
Min RH + Delta Pit Temp	0.80834		
Solar Radiation + Delta Air Temp + Min RH	0.79618		

Table 3. Regression analysis of small lysimeter vs. weather data, days 182, 188, 195.

Delta Water Small vs. Large Lysimeter Comparison Property	Correlation r^2 Day 182	Correlation r^2 Day 188	Correlation r^2 Day 195
Solar radiation	0.003151	0.376374	0.03122
Relative Humidity	0.069386	0.037401	0.008985
Ambient Air Temp.	0.195012	0.021001	0.008825
Wind Velocity	0.01222	0.034435	0.108624
Wind Run	0.01218	0.034435	0.108935
Pit Temp.	0.459186	0.288788	0.086926
Box Temp.	0.796451	0.011684	0.020979
Column Temp.	0.828722	0.00038	0.01368
Soil Temp.	0.787465	0.016968	0.025671

the installation and calibration of the new Alphasatronics load cell. The measured values for ET using the new load cell were four times greater than that predicted by both the large lysimeter and the Penman equation (Figure 19). Regression of this data from the first 12 days against that of the large lysimeter produced a correlation r^2 value of 0.59. The exact nature of the problem has not yet been determined but it is assumed to be electronic. Until the small lysimeter can be repaired with equipment that matches that used prior to destruction by lightning on July 29, this data is not valid for use in performance analysis.

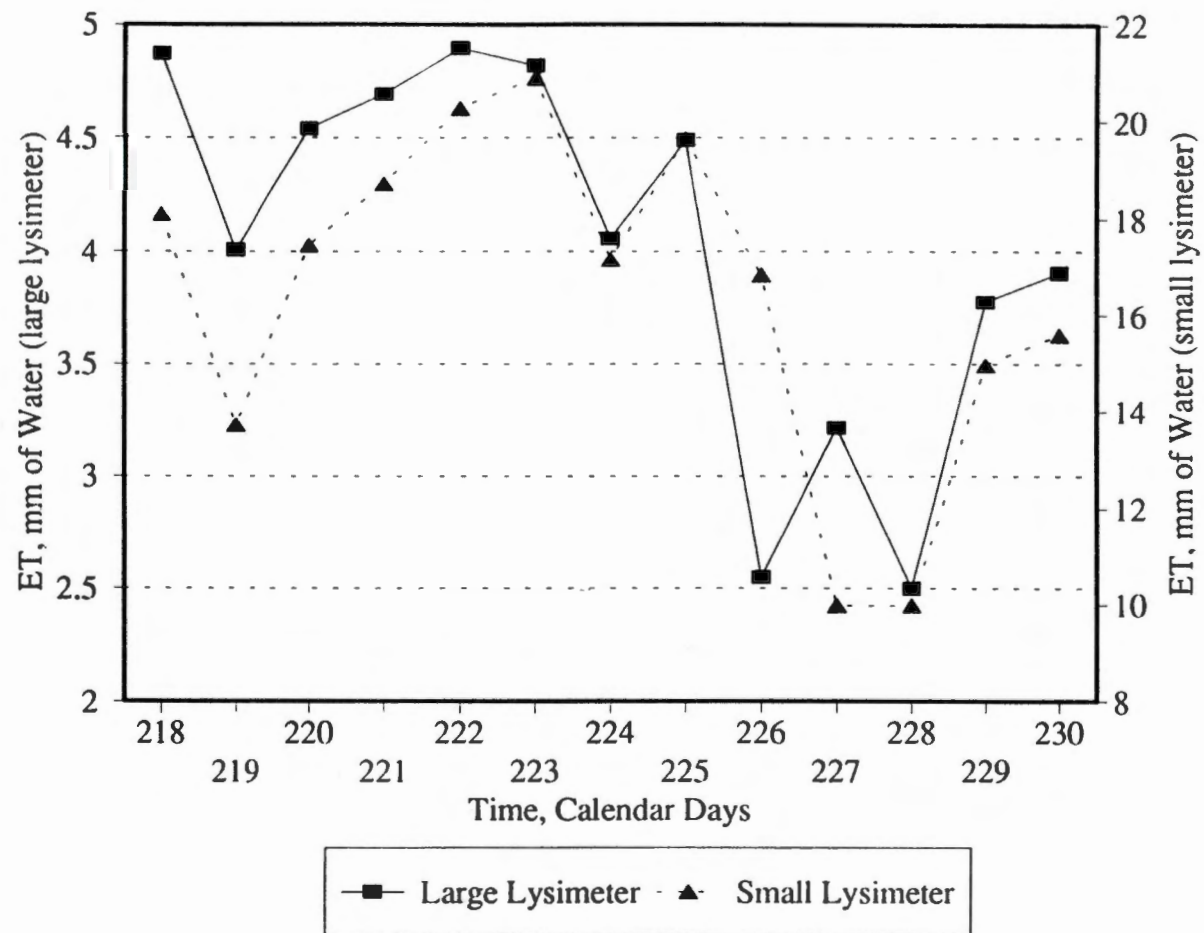


Figure 19. ET comparison between the large and small lysimeter for the first two weeks of August, 1994. These data were not used in analysis of the small lysimeter design due to technical problems.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Summary

The removal of the first four days from statistical analysis did not greatly alter the correlation between the small and large lysimeter. Although the two did not track during these four days, they maintained the same pattern and slowly converged by day 188. It is suspected that this slow convergence was due to the equilibration of soil moisture content between the irrigated plot and the non-irrigated soil column sample during the first three irrigation cycles. The high correlation on day 182 between small lysimeter error in ET readings and the temperatures of the surrounding soil, load cell assembly box, and soil column can also be attributed to this equilibration phase. Days 182-187 had the highest ambient air temperature fluctuations, which corresponds to the greatest diurnal fluctuation in soil column temperatures. These first 6 days experienced approximately 10°C fluctuations in atmospheric temperature and 4°C fluctuations in assembly temperatures. Throughout the remaining period, diurnal temperature change was less than 10°C. This greater temperature change could have resulted in variation on the ET which is attributed to the previously mentioned settling phenomenon from installation. It is suggested that further investigation be initiated to examine days experiencing greater than 10°C change in ambient air temperatures and greater than 4°C change in temperature of the assembly, to

determine whether this was actually a settling phenomena or was due to the greater temperature shift.

The problems with attaining accurate data in conjunction with rainfall is attributed to system design. The issue of the floating bucket due to flooding of the outer bucket can be rectified by increasing the area under the inner assembly or by providing improved drainage to prevent ponding of water within the outer assembly bucket. The increased ET noted on other days where rainfall occurred is attributed to no cover over the gap between the inner and outer assemblies. This gap allows rainfall to wet the outside of the inner assembly and to collect on the support ring. This large wet surface therefore provides greater evaporation than would be seen from the surrounding natural system. Alleviation of this problem could be attained by installing a cover for the gap between the inner and outer bucket assembly.

Conclusions

Design and evaluation of the small weighing lysimeter has produced a 30 cm (12 in.) easy-to-manufacture lysimeter costing \$1080 that is capable of estimating ET in the field within 0.5 mm of an existing large monolithic weighing lysimeter. Several days tracked almost identically with the large lysimeter and only one day showed a variance greater than 1.01 mm of water. Excluding the first 5 days of the settling period and day 193, the maximum difference between large and small lysimeter was 0.4 mm, with a maximum difference of 17%. The remainder of the days had a differences of less than 0.3

mm of water and percentage differences of less than 10%. The small lysimeter experiences difficulty in dealing with rainfall events. However, this problem can possibly be overcome if some method was employed that could prevent water from collecting on the outside surface of the inner assembly and its support ring such as a cover or rain shield. Further investigation needs to be implemented to determine whether the increased variation during the first 5 days was due to a settling phenomena. If this is a settling phenomena, then it provides no impediment to small lysimeter use.

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APPENDICES

APPENDIX A

LYSIMETER CALIBRATION DATA

(Large lysimeter identified as “Crossville Lysimeter”)

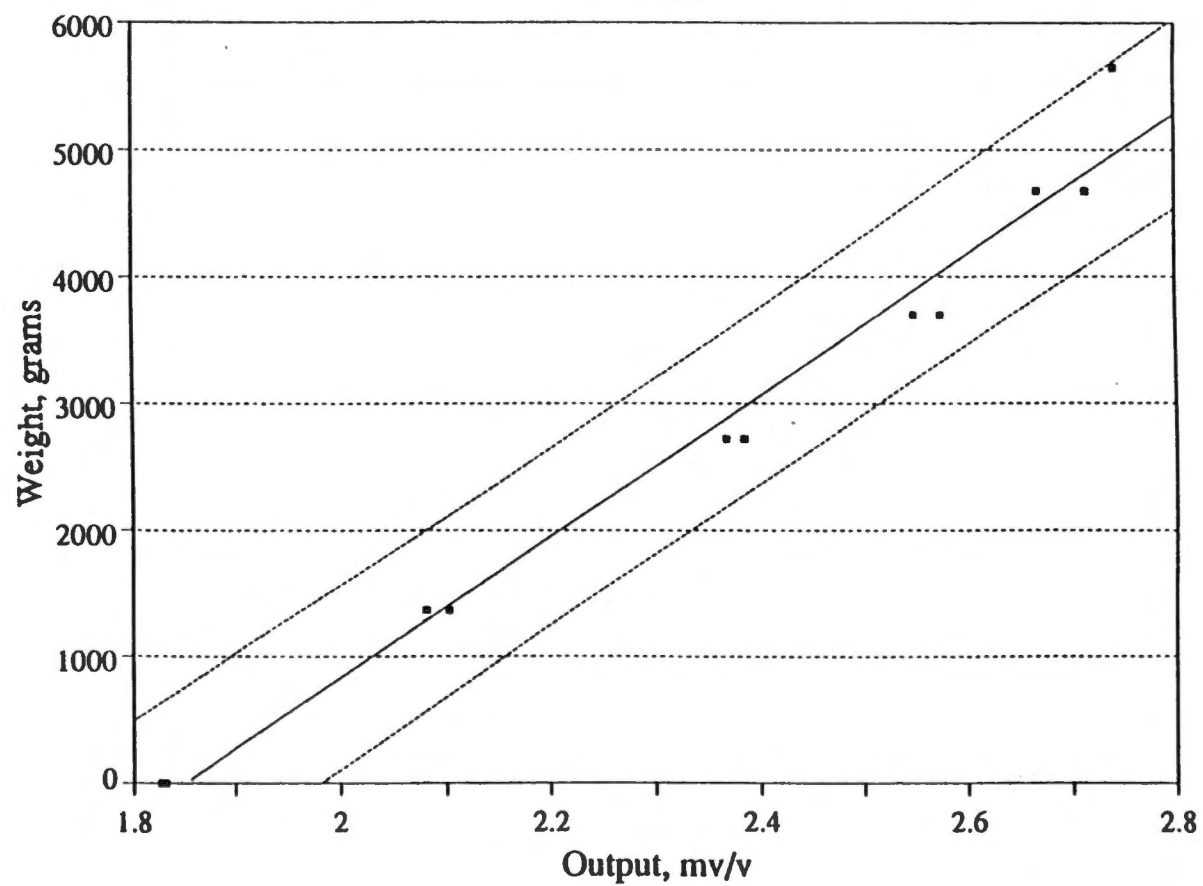
Small Lysimeter calibration Test #1

$r^2=0.978961003$ FitStdErr=292.194439 Fstat=418.777041

Rank 1558 Eqn 1 $y=a+bx$

$a=-10282.518$

$b=5557.875$



TableCurve Numerical Summary Jul 8, 1994 10:49 AM
 Description: Small Lysimeter calibration Test #1
 X-Y Table Size: 11 Active Points: 11
 X Variable: Output, mv/v
 Y Variable: Weight, grams
 File Source: CALIBRAT.PRN

Rank 1558 Eqn 1 $y=a+bx$

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.9789610027	0.9737012534	292.19443862	418.77704117

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	-10282.518	644.1956787	-15.961793	-11744.158	-8820.8781
b	5557.875049	271.5922336	20.46404264	4941.649156	6174.100942

Area Xmin-Xmax
2214.179419

Function min	X-Value	Function max	X-Value
-128.2615772	1.8270033746	4962.7332126	2.743
1st Deriv min	X-Value	1st Deriv max	X-Value
5557.8750482	2.6432120124	5557.8750487	2.6250862228
2nd Deriv min	X-Value	2nd Deriv max	X-Value
-0.135493743	2.393149421	0.0677468712	2.1272607409

Soln Vector Covar Matrix
Direct LUDecomp

r2 Coef Det	DF Adj r2	Fit Std Err	
0.9789610027	0.9737012534	292.19443862	
Source	Sum of Squares	DF	Mean Square
Regr	35754175	1	35754175
Error	768398.31	9	85377.59
Total	36522573	10	

F
418.777

X Variable: Output, mv/v

Xmin: 1.827	Xmax: 2.743	Xrange: 0.916
Xmean: 2.3496363636	Xstd: 0.340215894	Xmedian: 2.385
X@Ymin: 1.827	X@Ymax: 2.743	X@Yrange: 0.916

Y Variable: Weight, grams

Ymin: 0	Ymax: 5644.76	Yrange: 5644.76
Ymean: 2776.4672727	Ystd: 1911.0879837	Ymedian: 2721.36
Y@Xmin: 0	Y@Xmax: 5644.76	Y@Xrange: 5644.76

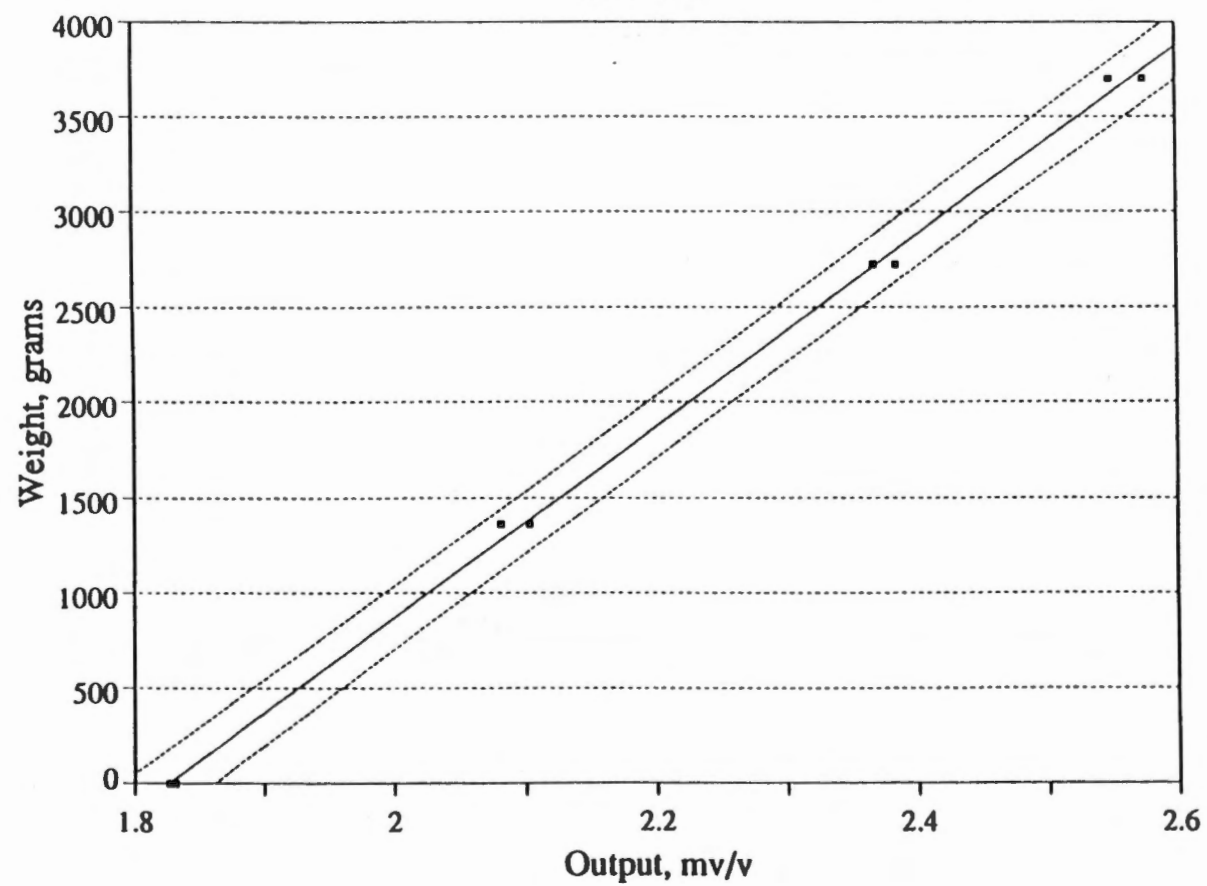
Small Lys cal Test #1 (less 2 weights)

$r^2=0.998518433$ FitStdErr=62.0345389 Fstat=4043.76644

Rank 1464 Eqn 1 $y=a+bx$

$a=-9134.3291$

$b=5001.9997$



TableCurve Numerical Summary Jul 8, 1994 10:59 AM
 Description: Small Lys cal Test #1 (less 2 weights)
 X-Y Table Size: 11 Active Points: 8
 X Variable: Output, mv/v
 Y Variable: Weight, grams
 File Source: CALIBRAT.PRN

Rank 1464 Eqn 1 $y=a+bx$

r2	Coef Det	DF	Adj r2	Fit Std Err	F-value
0.9985184331			0.9979258063	62.0345389	4043.7664411

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	-9134.32907	175.5958462	-52.0190498	-9565.78586	-8702.87229
b	5001.999695	78.65939994	63.59061598	4808.725581	5195.273809

Area Xmin-Xmax

1402.5540462

Function min	X-Value	Function max	X-Value
4.3375317039	1.8270026316	3745.8201401	2.575
1st Deriv min	X-Value	1st Deriv max	X-Value
5001.999696	2.4677262716	5001.9996963	2.289289432
2nd Deriv min	X-Value	2nd Deriv max	X-Value
-0.10159609	2.1145004838	0.2031921806	2.5164536092

Soln Vector Covar Matrix

Direct

LUDecomp

r2	Coef Det	DF	Adj r2	Fit Std Err
0.9985184331			0.9979258063	62.0345389

Source	Sum of Squares	DF	Mean Square	F
Regr	15561562	1	15561562	4043.77
Error	23089.704	6	3848.284	
Total	15584651	7		

X Variable: Output, mv/v

Xmin: 1.827	Xmax: 2.575	Xrange: 0.748
Xmean: 2.214875	Xstd: 0.2980807357	Xmedian: 2.2355
X@Ymin: 1.831	X@Ymax: 2.575	X@Yrange: 0.744

Y Variable: Weight, grams

Ymin: 0	Ymax: 3695.78	Yrange: 3695.78
Ymean: 1944.475	Ystd: 1492.1054858	Ymedian: 2041.06
Y@Xmin: 0	Y@Xmax: 3695.78	Y@Xrange: 3695.78

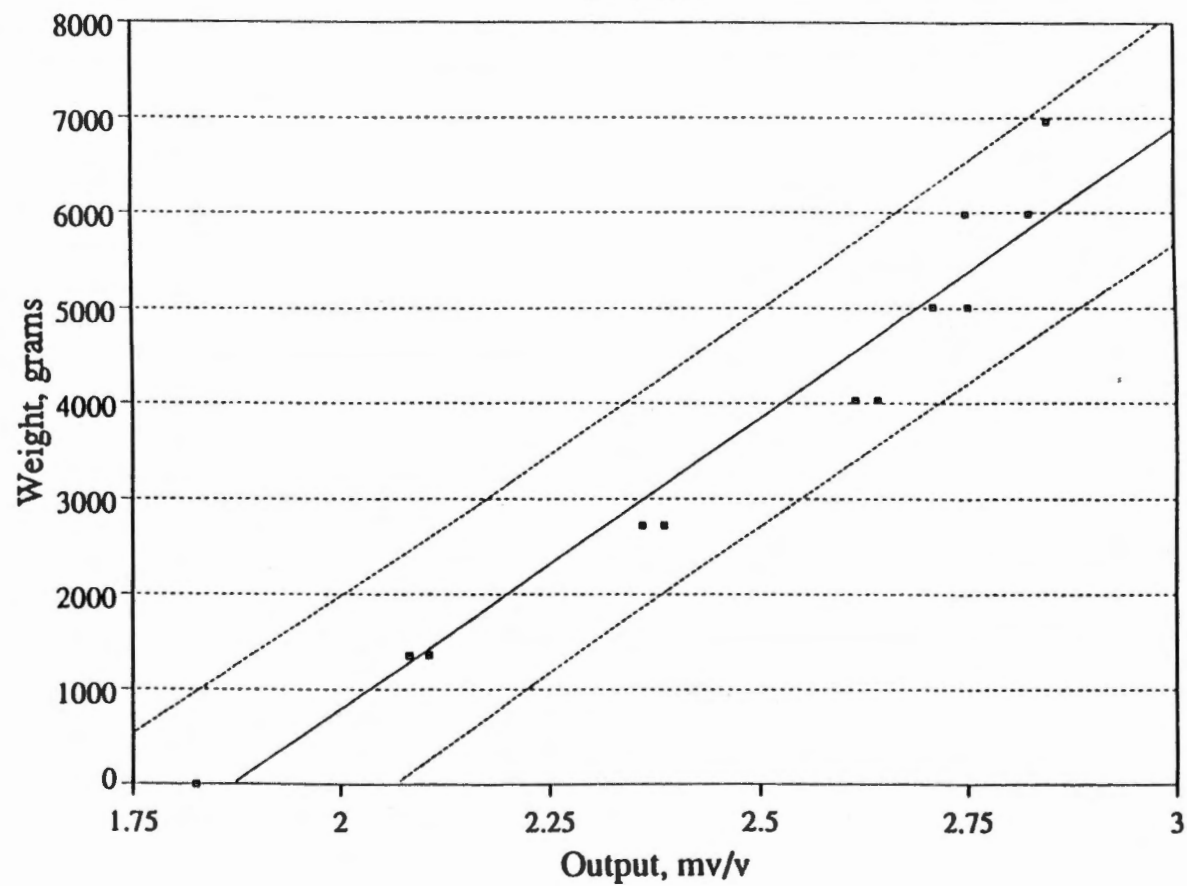
Small Lysimeter calibration Test #2

$r^2=0.958465376$ FitStdErr=492.41527 Fstat=253.839284

Rank 216 Eqn 1 $y=a+bx$

$a=-11396.193$

$b=6092.738$



TableCurve Numerical Summary Jul 8,1994 10:23 AM
 Description: Small Lysimeter calibration Test #2
 X-Y Table Size: 13 Active Points: 13
 X Variable: Output, mv/v
 Y Variable: Weight, grams
 File Source: CALIBR2.PRN

Rank 216 Eqn 1 $y=a+bx$

r2	Coef Det	DF	Adj r2	Fit Std Err	F-value
0.9584653763		0.9501584515		492.4152698	253.83928375

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	-11396.1931	943.2631761	-12.0816686	-13476.611	-9315.77516
b	6092.73796	382.4133837	15.93233454	5249.304573	6936.171346

Area Xmin-Xmax

Function min	X-Value	Function max	X-Value
-270.8417478	1.826001939	5955.9246334	2.848
1st Deriv min	X-Value	1st Deriv max	X-Value
6092.7379595	1.9817865846	6092.7379609	2.162781938
2nd Deriv min	X-Value	2nd Deriv max	X-Value
-0.027211244	1.9834261094	0.0136056222	1.922971147

Soln Vector Covar Matrix

Direct	LUDecomp	r2	Coef Det	DF	Adj r2	Fit Std Err	Mean Square	F
0.9584653763	0.9501584515	492.4152698						
Source	Sum of Squares	DF						
Regr	61549121	1						253.839
Error	2667200.8	11						
Total	64216322	12						

X Variable: Output, mv/v

Xmin	Xmax	Xrange
1.826	2.848	1.022
Xmean	Xstd	Xmedian
2.4406153846	0.3717130476	2.615
X@Ymin	X@Ymax	X@Yrange
1.826	2.848	1.022

Y Variable: Weight, grams

Ymin	Ymax	Yrange
0	6955.62	6955.62
Ymean	Ystd	Ymedian
3473.8369231	2313.3007106	4032.22
Y@Xmin	Y@Xmax	Y@Xrange
0	6955.62	6955.62

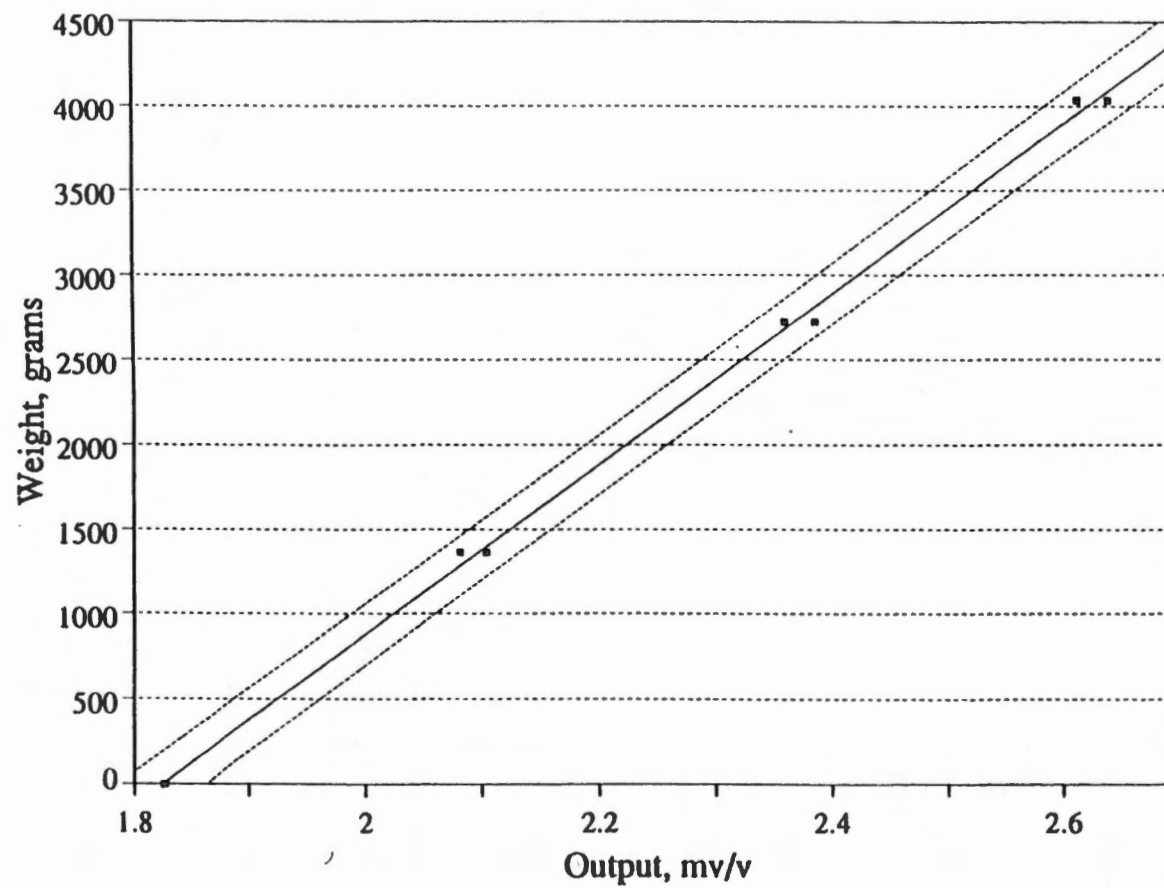
Small Lys. cal. Test #2 (less 3 weights)

$r^2=0.998519852$ FitStdErr=66.8423049 Fstat=4047.64958

Rank 1435 Eqn 1 $y=a+bx$

$a=-9115.667$

$b=4996.8622$



TableCurve Numerical Summary

Jul 8, 1994 10:40 AM

Description: Small Lys. cal. Test #2 (less 3 weights)

X-Y Table Size: 8 Active Points: 8

X Variable: Output, mv/v

Y Variable: Weight, grams

File Source: CALIBR2A.PRN

Rank 1435 Eqn 1 $y=a+bx$

r2	Coef Det	DF	Adj r2	Fit Std Err	F-value
0.9985198523		0.9979277933		66.842304892	4047.6495752

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	-9115.66698	176.7528383	-51.5729596	-9549.96661	-8681.36735
b	4996.862227	78.54090877	63.62114095	4803.879258	5189.845196

Area Xmin-Xmax

1670.6157584

Function min	X-Value	Function max	X-Value
8.6184662226	1.8260030062	4086.0430218	2.642
1st Deriv min	X-Value	1st Deriv max	X-Value
4996.8622268	2.5229510556	4996.862227	2.3303017842
2nd Deriv min	X-Value	2nd Deriv max	X-Value
-0.170737874	2.330315744	0	2.5456804503

Soln Vector Covar Matrix

Direct

LUDecomp

r2	Coef Det	DF	Adj r2	Fit Std Err
0.9985198523		0.9979277933		66.842304892

Source	Sum of Squares	DF	Mean Square	F
Regr	18084468	1	18084468	4047.65
Error	26807.362	6	4467.8937	
Total	18111275	7		

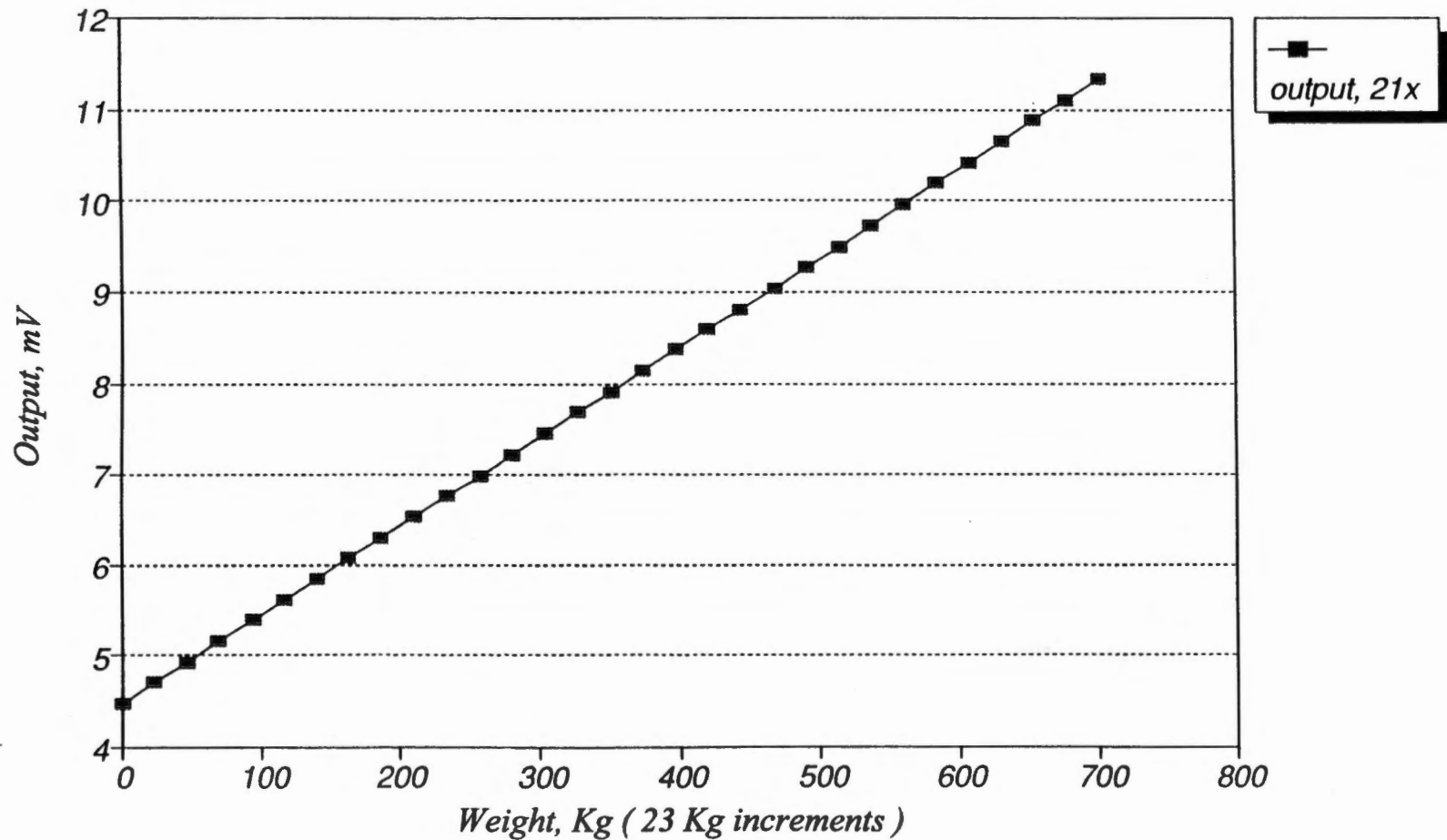
X Variable: Output, mv/v

Xmin: 1.826	Xmax: 2.642	Xrange: 0.816
Xmean: 2.23025	Xstd: 0.3216669751	Xmedian: 2.2325
X@Ymin: 1.826	X@Ymax: 2.642	X@Yrange: 0.816

Y Variable: Weight, grams

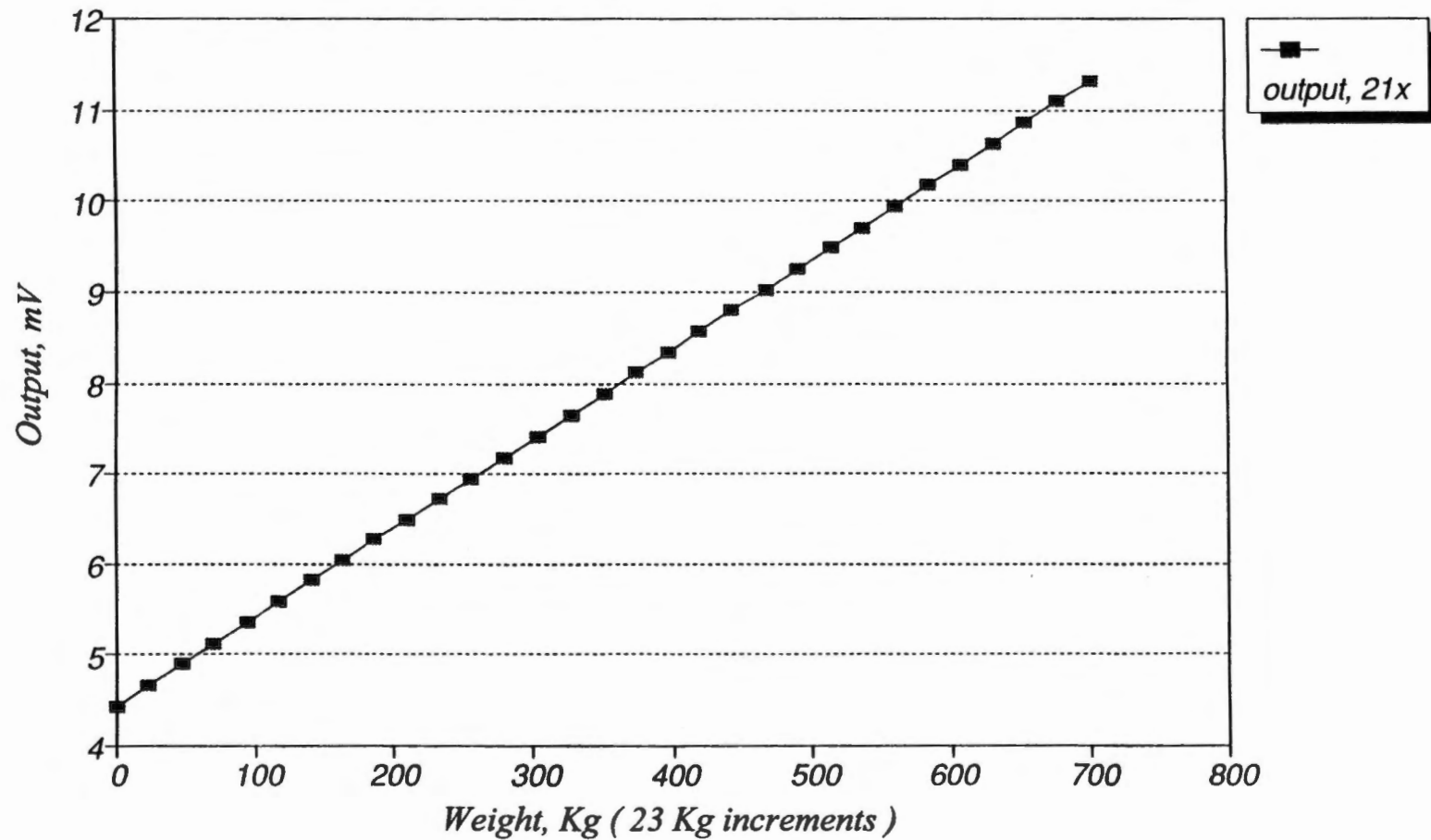
Ymin: 0	Ymax: 4032.22	Yrange: 4032.22
Ymean: 2028.585	Ystd: 1608.5164191	Ymedian: 2041.06
Y@Xmin: 0	Y@Xmax: 4032.22	Y@Xrange: 4032.22

Calibration, Crossville Lysimeter Loading, April 29, 1994

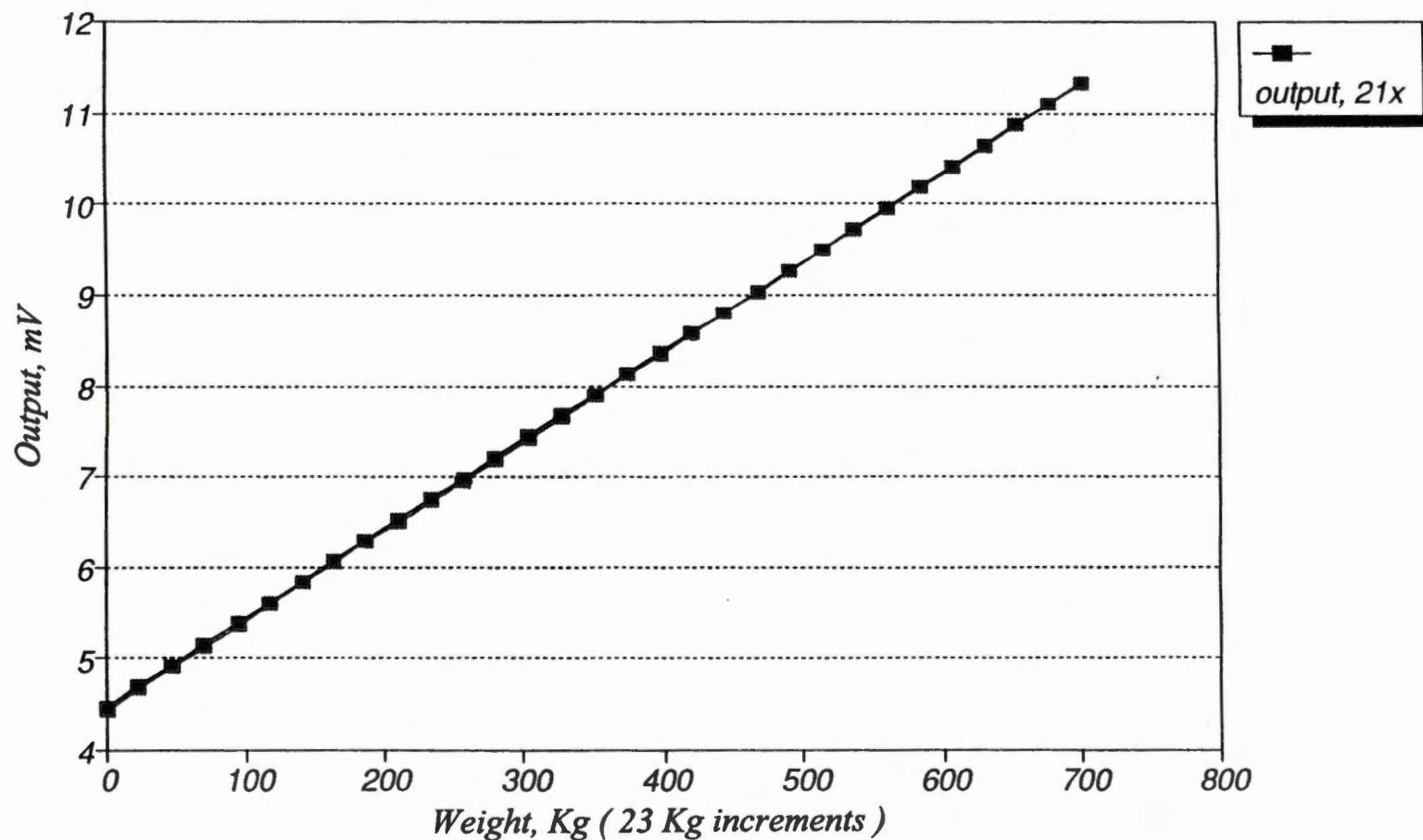


Calibration, Crossville Lysimeter

Unloading, April 29, 1994



Calibration, Crossville Lysimeter Combined, April 29, 1994



Loading

Regression Output:

Constant	4.467873
Std Err of Y Est	0.003392
R Squared	0.999997
No. of Observations	31
Degrees of Freedom	29

X Coefficient(s)	0.009755
Std Err of Coef.	2.91E-06

Unloading

Regression Output:

Constant	4.425794
Std Err of Y Est	0.002465
R Squared	0.999999
No. of Observations	31
Degrees of Freedom	29

X Coefficient(s)	0.0098
Std Err of Coef.	2.11E-06

Combined

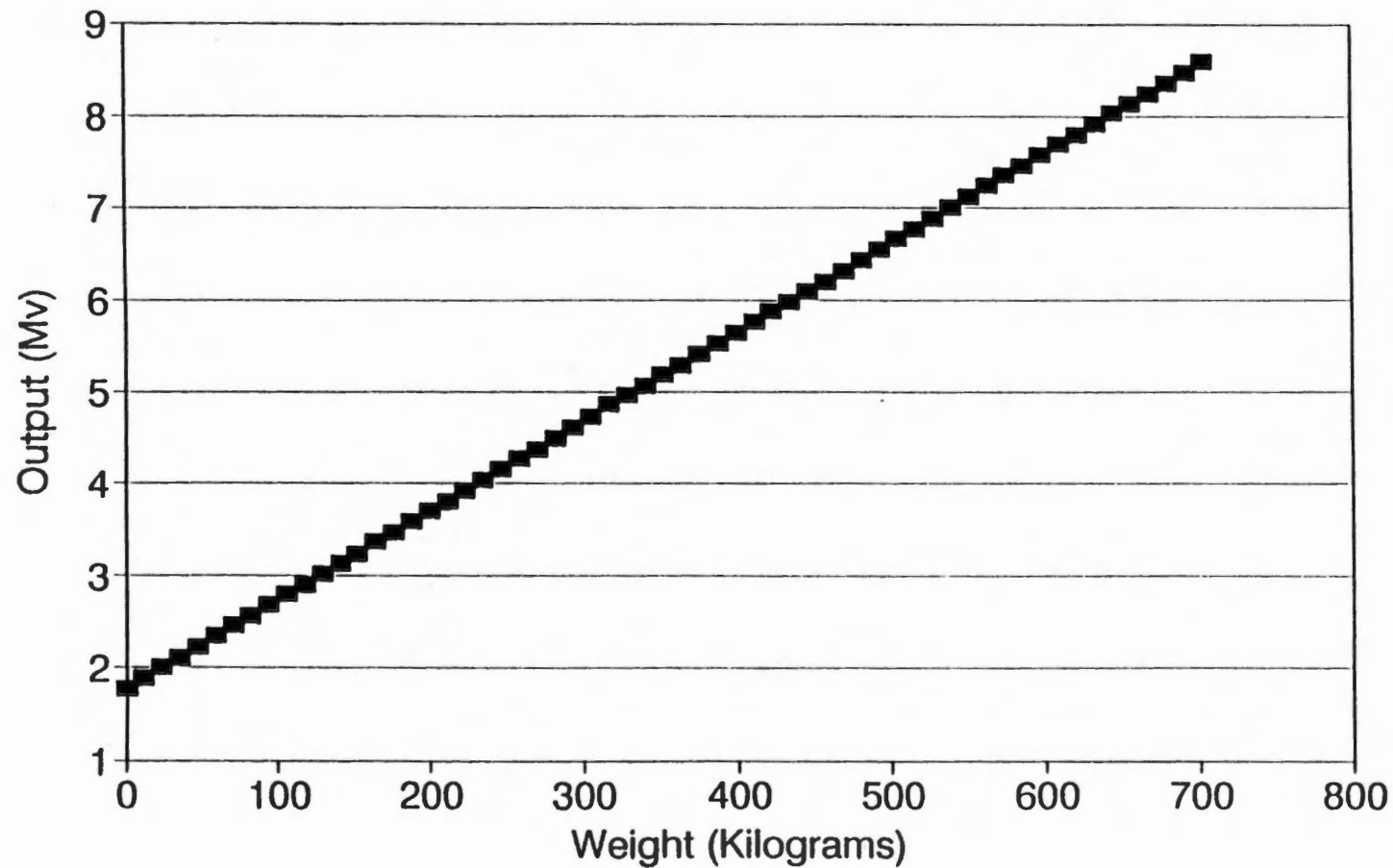
Regression Output:

Constant	4.446829
Std Err of Y Est	0.01443
R Squared	0.999952
No. of Observations	62
Degrees of Freedom	60

X Coefficient(s)	0.009777
Std Err of Coef.	8.74E-06

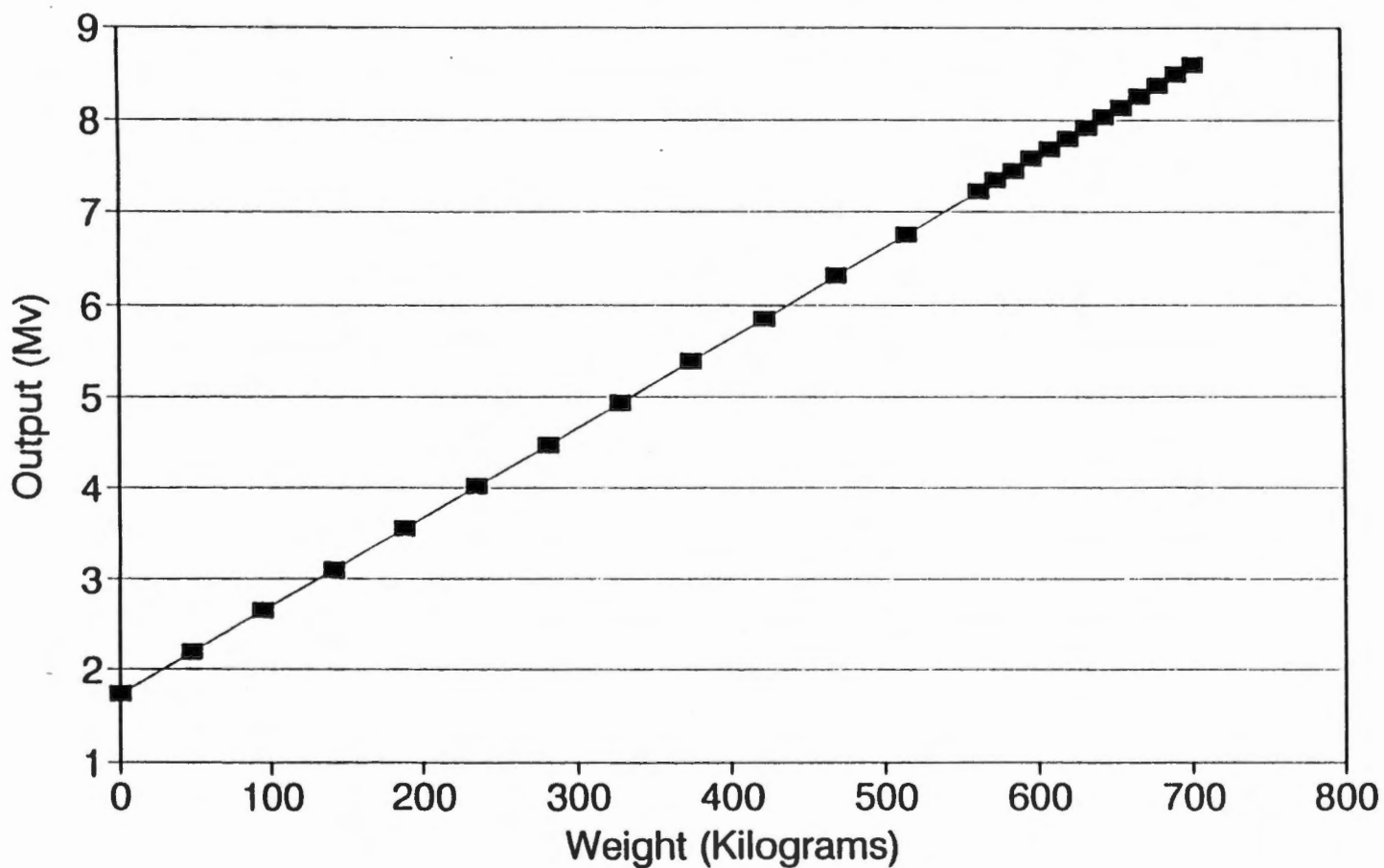
Lysimeter Calibration, June 1993

Load up 0 to 700 kg

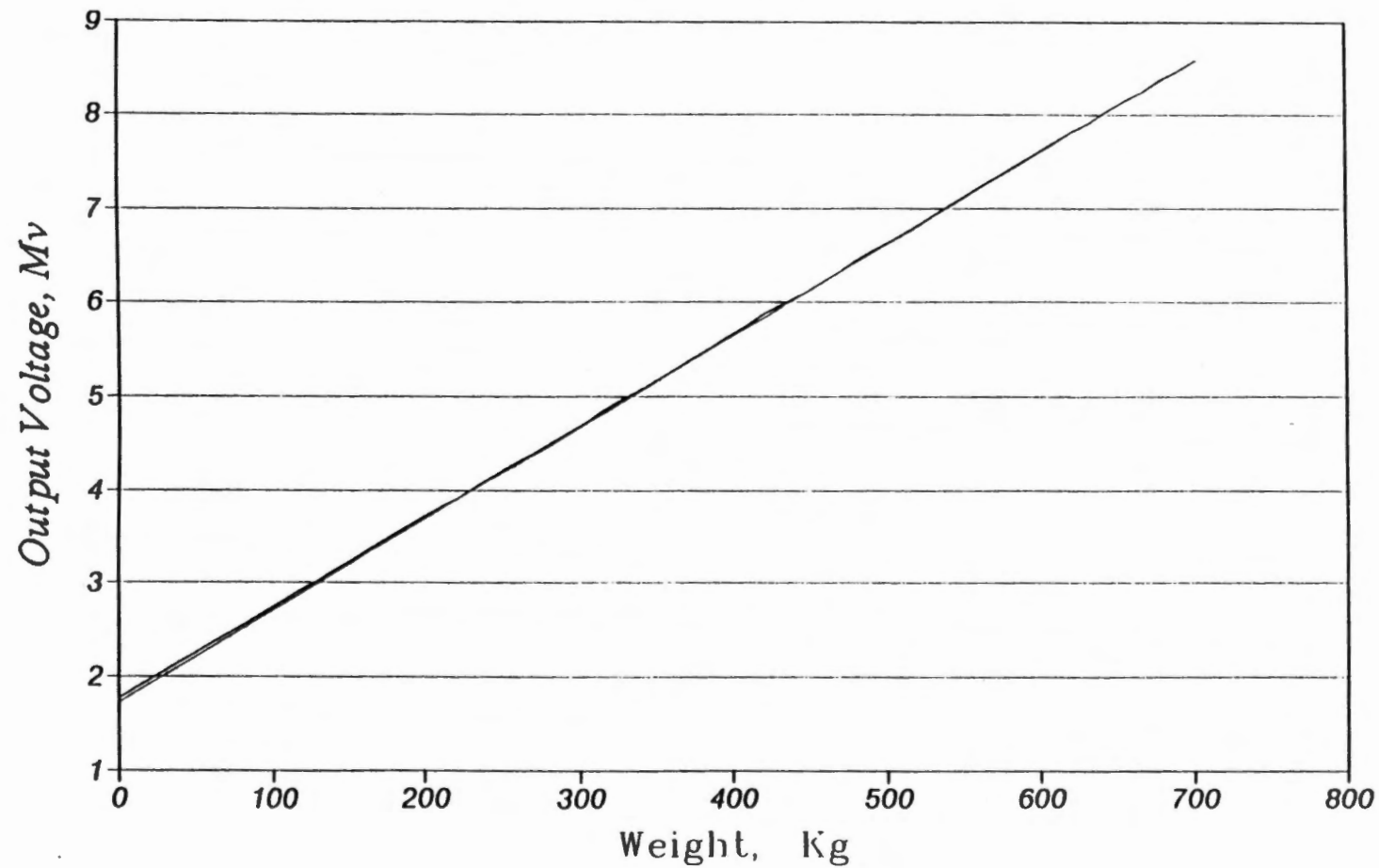


Lysimeter Calibration, June 1993

Load down 700 to 0 kg



*Lysimeter Calibration, June 1993
Loading and unloading (0 to 700 kg)*



APPENDIX B

WEATHER DATA

July 1994, ET Calculation and weather data

Day Julian	Max Temp deg.c	Min Temp deg.c	Max RH %	Min RH %	Solar w/m^2	Rain mm	Avg WS m/s	Wind Run km	Day WR km	Day Avg WS m/s
182	28.91	15.26	100	49.97	7501.79	0	0.48	41.07	40.68	0.94
183	28.86	17.79	99.3	61.43	6752.37	0	0.57	49.37	46.09	1.07
184	28.98	18.55	99.6	62.05	7426.59	0	0.66	56.93	52.40	1.21
185	28.61	18.87	99.7	65.05	6763.16	0	0.95	82.41	73.86	1.71
186	29.31	19.22	99.7	62.93	7004.75	0	0.99	85.72	80.38	1.86
187	29.07	19.13	99.9	60.85	7559.10	0	0.86	74.14	67.60	1.56
188	24.74	19.46	99	76.9	4887.82	0	1.33	115.24	87.28	2.02
189	25.99	20.81	98.7	81.3	3483.38	2.794	1.79	154.86	92.16	2.13
190	26.79	20.08	99.5	78.9	4300.14	13.97	1.53	132.44	87.48	2.03
191	25.35	19.9	100	76.9	3457.88	0	0.37	31.95	22.47	0.52
192	22.44	20.24	99.7	94.7	1704.58	27.94	0.27	23.23	17.26	0.40
193	24.15	20.18	99.7	86.8	3249.58	1.016	0.87	75.46	58.68	1.36
194	26.75	20.92	99.4	77	4054.45	5.334	1.41	122.24	81.58	1.89
195	27.9	21.42	99.4	75.9	5214.88	0.508	1.90	164.48	93.20	2.16
196	26.49	21.5	99.3	80.6	2810.89	0	1.35	63.36	35.84	0.83

July 1994, ET Calculation and weather data

P: 952.34									
delta/ gamma/									
Day Julian	Ud/Un	T:mean	RH:mean	delta	L	gamma	delta+gamma	delta+gamma/ gamma	e:s e:a
182	104.84	22.09	74.99	1.61	2448.66	0.63	0.72	0.28	26.57 19.92
183	14.06	23.33	80.37	1.72	2445.73	0.63	0.73	0.27	28.64 23.02
184	11.55	23.77	80.83	1.76	2444.69	0.63	0.74	0.26	29.41 23.77
185	8.64	23.74	82.38	1.76	2444.75	0.63	0.74	0.26	29.37 24.19
186	15.05	24.27	81.32	1.81	2443.51	0.63	0.74	0.26	30.31 24.64
187	10.34	24.10	80.38	1.80	2443.90	0.63	0.74	0.26	30.01 24.12
188	3.12	22.10	87.95	1.62	2448.62	0.63	0.72	0.28	26.59 23.39
189	1.47	23.40	90.00	1.73	2445.55	0.63	0.73	0.27	28.77 25.89
190	1.95	23.44	89.20	1.73	2445.47	0.63	0.73	0.27	28.83 25.72
191	2.37	22.63	88.45	1.66	2447.38	0.63	0.73	0.27	27.46 24.28
192	2.89	21.34	97.20	1.55	2450.42	0.63	0.71	0.29	25.39 24.68
193	3.50	22.17	93.25	1.62	2448.47	0.63	0.72	0.28	26.70 24.90
194	2.01	23.84	88.20	1.77	2444.53	0.63	0.74	0.26	29.53 26.05
195	1.31	24.66	87.65	1.85	2442.58	0.63	0.75	0.25	31.03 27.20
196	1.30	24.00	89.95	1.79	2444.15	0.63	0.74	0.26	29.82 26.82

July 1994, ET Calculation and weather data

Day Julian	e:s-e:a	epsilon	Rbo	R:s	R:b	R:n	c	corrected c	ET with c	ET without c
182	6.65	0.16	2.40	11.03	2.00	6.27	3.46	1.27	6.63	5.22
183	5.62	0.15	2.32	9.94	1.70	5.75	1.44	1.27	6.12	4.82
184	5.64	0.15	2.29	10.94	1.89	6.31	1.42	1.27	6.71	5.28
185	5.18	0.15	2.29	9.96	1.69	5.78	1.35	1.27	6.26	4.93
186	5.66	0.15	2.26	10.32	1.74	6.00	1.57	1.27	6.59	5.19
187	5.89	0.15	2.27	11.14	1.92	6.44	1.42	1.27	6.97	5.49
188	3.20	0.16	2.39	7.19	1.15	4.24	1.11	1.11	3.98	3.57
189	2.88	0.15	2.31	5.13	0.67	3.17	1.00	1.00	2.85	2.85
190	3.11	0.15	2.31	6.33	0.93	3.82	1.05	1.05	3.50	3.32
191	3.17	0.16	2.36	5.09	0.68	3.14	1.07	1.07	2.77	2.59
192	0.71	0.16	2.44	2.50	0.12	1.76	1.03	1.03	1.36	1.32
193	1.80	0.16	2.39	4.78	0.62	2.96	1.07	1.07	2.55	2.38
194	3.49	0.15	2.28	5.97	0.84	3.64	1.05	1.05	3.39	3.23
195	3.83	0.14	2.23	7.69	1.17	4.59	1.07	1.07	4.39	4.12
196	3.00	0.15	2.27	4.14	0.46	2.65	1.02	1.02	2.35	2.30

R:so

13.26

VITA

Joseph C. Zimmerman was born in Winchester, TN on February 27, 1967. He attended schools in the public school systems of Franklin County, TN and graduated from Franklin County High School in 1985. He entered The University of Tennessee in September of 1985 and graduated December, 1989 with a Bachelor's of Science in Engineering Mechanics. After working for a United States Air Force subcontractor as a piping and hazardous systems engineer for two years, he returned to The University of Tennessee in August, 1992 and was granted a research assistantship in the Master's program in Agricultural Engineering in June of 1993. In August, 1994, he began work at the Oak Ridge Reservation with the Environmental Restoration Program for the Jacob's Engineering Group. His master's degree was received in May, 1996.

He is presently working with the Cost Estimating Group of the Jacob's Engineering Group in Oak Ridge Tennessee and is employed by Geraghty and Miller, Inc.

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