Technical Report No. 165

DEVELOPMENT OF A LARGE, UNDISTURBED WEIGHING LYSIMETER FOR EVAPOTRANSPIRATION STUDIES ON GRASSLAND

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GRASSLAND BIOME

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ABSTRACT

ARMIJO, JOE D. Development of a Large, Undisturbed Weighing Lysimeter for Evapotranspiration Studies of Grassland, Ph. D., Civil Engineering, September, 1972.

For the Grassland Biome, United States International Biological Program for Analysis of Structure, Function, and Utilization of Grassland Ecosystems, a large weighing lysimeter was developed, 1969 to 1972.

This dissertation describes the research, planning, design, construction, calibration, operation, maintenance, and performance of the lysimeter. Special emphasis is given to the undisturbed features of the soil core and perimeter area of the lysimeter, features which make it unique in the field of lysimetry.

Preliminary analysis and evaluation of one year's data are given, paving the way for several years of study into evapotranspiration and its role in the energy-dependent biological processes of the grassland.

ACKNOWLEDGEMENTS

Brevity at this point is usually a virtue; however, a project of this size had many vital contributors and I would like to thank several of them. For those who are not documented, please know that I am appreciative. First to be commended is George Twitchell, who spent many hours in the hole with me (enough said). For his contributions and last minute marathon to provide data, I thank John Nunn.

No Grassland Biome paper should be published without a tribute to Ray Souther and his Pawnee staff. Ray always loaned me the tool I forgot and did not complain when I lost it in an inaccessible place. His humor made those long winter days enjoyable.

The Natural Resource Ecology Laboratory of Colorado State University and the Agricultural Engineering Division of the University of Wyoming provided me the opportunity to develop the lysimeter, and I am grateful. In particular, Dr. Donald Jameson gave encouragement and understood the numerous delays.

Guidance and support in writing this dissertation was willingly given by Dr. Freeman Smith. My thanks to Freeman, Larry Nell, Barbara Hendricks, and Betty Faust of the Natural Resource Ecology Laboratory for making the manuscript a reality. Larry also managed to shorten administrative tape and expedite purchase of materials during construction.

For overall planning of my doctoral program and continued guidance in my engineering and environmental profession, I thank Dr. Donald Lamb.

Finally, an appreciative note to Janet, who began and completed her Master's Degree during this period, and still managed to get supper on the table for Molly, Reed, and me.

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CHAPTER I

INTRODUCTION

The Grassland Biome project of the United States International Biological Program represents an extensive effort to quantitatively describe biological productivity and nutrient and energy cycling in a grassland ecosystem. Grassland areas are generally characterized by low to moderate annual precipitation amounts and high evaporative demands of the atmosphere. These two effects cause water to be an important, if not the most important, limiting factor regulating biological activity on the grasslands (1)[1].

With this concept in mind, it was apparent that a means of accurately determining evapotranspiration was necessary on the Grassland Biome project. Slatyer and McIlroy (2) have observed that "A properly designed lysimeter, undoubtedly, constitutes the most direct, accurate, and reliable means at present available for determining true evaporation from almost any type of land surface ... a well constructed lysimeter can provide an excellent means (possibly the only really satisfactory way) of calibrating other methods of evaporation measurement."

This thesis, then, deals with the development of the Grassland Biome lysimeter. Planning, design, construction, calibration, operation, and maintenance are treated in detail. In addition,

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[1] Numbers in parentheses refer to Selected References.

performance and data output are discussed. Finally, several possibilities for utilization are outlined and recommendations for future studies are given.

The primary investigative site for the Grassland Biome is the Pawnee Intensive Site in northeastern Colorado. The site is funded by the National Science Foundation and administered by the Natural Resource Ecology Laboratory of Colorado State University. The author, through the Agricultural Engineering Division of the University of Wyoming, was responsible for total development of the lysimeter.

Exact location of the Pawnee Site is 25 miles south of Cheyenne, Wyoming (E½ Sec. 27, T10N R66W, 6th P.M.) (see Fig. 1). Work on the lysimeter began with initial planning in June of 1969 and final calibration was completed two years later. To date the lysimeter has functioned for one year.

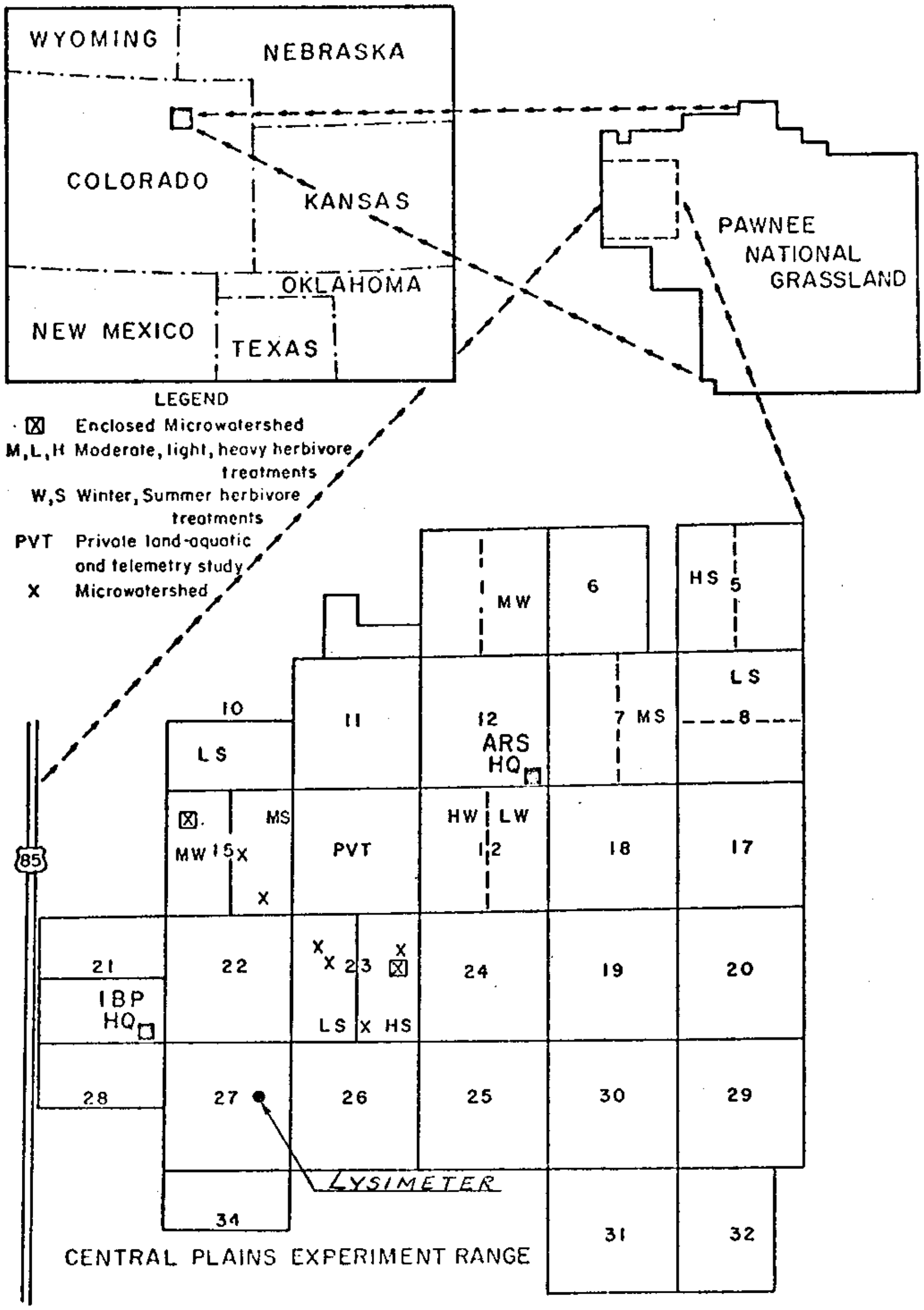

Fig. 1. Location of the Pawnee Site and the lysimeter.

CHAPTER II

BASIC LYSIMETRY

The author recalls his initial reaction to the word lysimetry and, therefore, believes a definition is in order. A lysimeter is a device in which a volume of soil is located in a container to isolate it hydrologically from the surrounding soil. The usual method used is to set the container freely within an outer retainer and monitor the container weight fluctuations due to evapotranspiration (ET) or precipitation. Fig. 2 gives a simple schematic of a weighing lysimeter. Several weight detection methods are available and will be discussed. Basic lysimetry requirements are summarized.

Representativeness

The lysimeter must represent in situ surface and subsurface conditions of the area to be studied. Representativeness is affected by the following:

1. Soil water conditions within the soil container must be comparable to those within the surrounding soil. In addition to causing variations in water available for evaporation, nonrepresentative soil water can alter the vegetative cover, root structure, and biomass. The cover and roots obviously affect respiration rates and soil water movement.

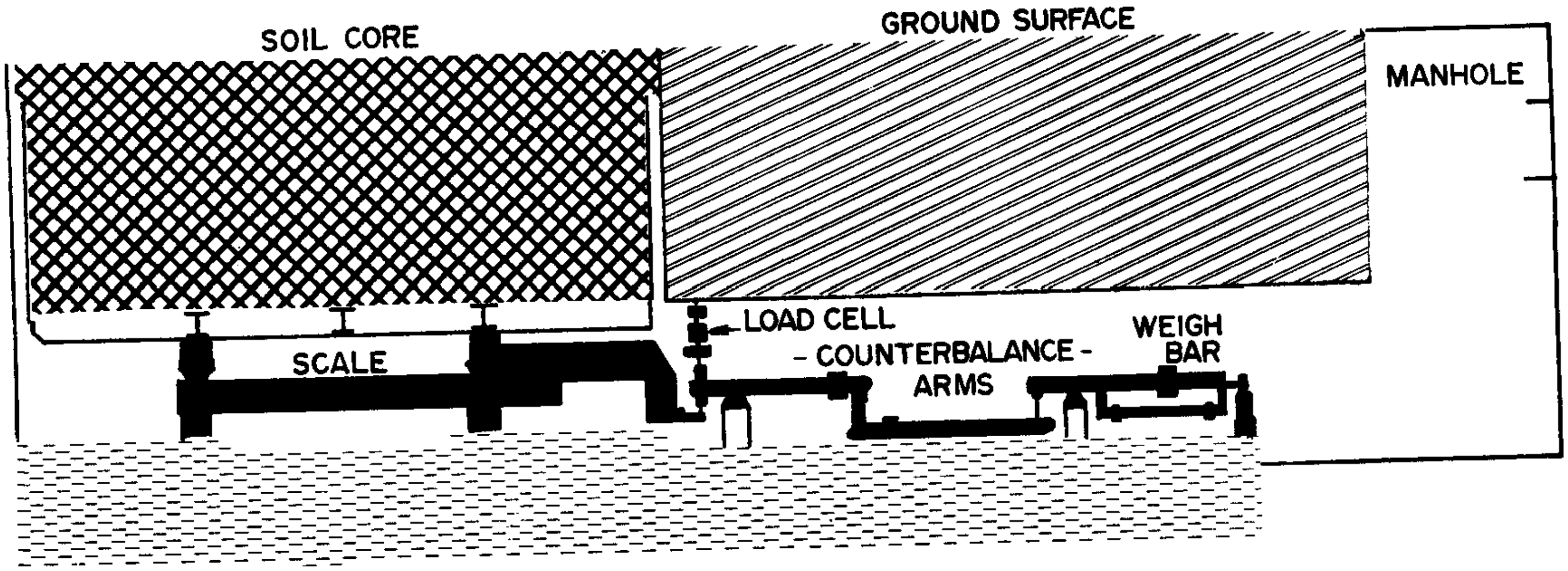

Fig. 2. Schematic of weighing lysimeter.

2. Thermal properties of the soil container should be in equilibrium with the surrounding soil. Variations in the energy budget affect heat available for evaporation and biological processes of the vegetation.
3. Depth of the soil container should be sufficient to include most of the root system to assure representative respiration and soil water movement.
4. Unnatural surface area of the lysimeter affects representativeness due to the nonviable exposures. Thermal influences are also introduced by unnatural materials such as steel or concrete. Minimization of unnatural area is therefore a necessity.
5. Total surface area of the lysimeter is a critical factor. The representativeness of the vegetation sample per unit area of the lysimeter as compared to that of the surrounding area is related to the scale of inhomogeneity of vegetation and the size of the lysimeter. The lysimeter area must be large compared to the scale of inhomogeneity in the vegetation. If the plant cover is relatively homogeneous spatially, such as with uniform grass or forages, the area of the lysimeter can be smaller than when the scale of inhomogeneity of the plant cover is large (e.g., that found with shrubbery, corn, shorter row crops, and with "patchy" surfaces such as nonuniform soils and poorly grazed pastures). The size of the lysimeter also must be large compared to the scale of inhomogeneities of soil surface and subsurface water properties (e.g., roughness, albedo, soil water retention) (3).

Sensitivity

The minimum increment of weight fluctuation that can be measured accurately and with repeatability is called the sensitivity. The desired sensitivity will, therefore, dictate the method of weight detection. The desired sensitivity depends on the time value of ET that is sought by the researcher (e.g., hourly, daily, or monthly values). In arid areas, in contrast to humid or irrigated conditions, hourly values of ET are very small, particularly in late summer and early fall. One can readily see the need for very high sensitivity for the Grassland Biome lysimeter.

Thus, sensitivity largely dictates the type of lysimeter. Basically, there are three types of lysimeters--weighing, manometer, and floating. Brief descriptions are as follows.

Weighing lysimeter. The weighing lysimeter is a type which directly measures the weight fluctuations of the soil container. The detection apparatus consists of mechanisms to counterbalance most of the soil container weight and more precise instruments, usually electronic transducers, to monitor the remaining small increment of weight. This type is necessary for the sensitivity required for hourly values of ET.

Manometer lysimeter. The manometer lysimeter is a simpler type which utilizes liquid-filled rubber bags connected to a manometer system. The soil container rests upon the bags, and weight variations are reflected in the height of the manometer fluid. Monthly ET values are usually attainable, and possibly daily values.

Floating lysimeter. The floating lysimeter is a complex type that is used primarily for wind drag studies. The soil container rests upon materials (e.g., styrofoam logs) which float in a liquid. Through buoyancy relationships horizontal and vertical forces can be determined.

With the basis of lysimetry outlined, the planning of the Grassland Biome lysimeter was the next step.

CHAPTER III

PLANNING

Planning of the lysimeter initially involved a review of literature of and visitations to existing lysimeters. Communications with scientists experienced in lysimetry occurred, culminating in a meeting with the eminent soil physicist, Cornelius H. M. van Bavel. This chapter summarizes these phases and concludes with the general requirements that were derived for design. But first, a description of the Pawnee Site is needed to set the scene for planning and later for design.

Description of the Pawnee Site

The Pawnee Grassland is typical of semiarid shortgrass prairie with vegetation basically blue grama and buffalo grass (a detailed plant list will be given later). Average annual precipitation varies from 10 to 15 inches, 80% of which falls during the summer months of May through September. Although most of the storms are light thundershowers, the greatest fluctuations are caused by storms greater than 1 inch (4). Temperature extremes do occur and heavy winds are not uncommon, conditions which have plagued lysimeters in the past. Snow and ice conditions with frequent free-thaw cycles also occur.

Soil conditions, at this phase, were viewed from an engineering standpoint. The soil is in the Ascalon series, which is formed predominantly by fluvial outwash materials. The texture of the Ascalon series is described by Franklin (5) in Table A-1. Exploratory bores at the lysimeter site confirmed Franklin and also revealed the existence of cobble material below a depth of 4 ft. While engineering soil tests indicated that the sandy clay loam was non-plastic, there appeared to be appreciable uniformity and cohesion. In situ moisture conditions on a dry weight basis and standard Proctor lab tests gave clues to the range of weight of soil that could be expected. Fig. A-1 and A-2 show typical curves of dry density and in situ water content.

Physically, the lysimeter site is on a level bench of the rolling prairie, a feature which offers considerable fetch. Though somewhat distant, the cities of Denver, Greeley, and Cheyenne offered markets for equipment and materials.

With this general information, the task of selecting the type of lysimeter appropriate for grassland conditions was begun.

Review of Existing Lysimeters

Initially, a review of literature was done to become familiar with the features, successes, and pitfalls of previously constructed lysimeters. Intermingled with these readings were inspections of lysimeters and personal discussions with experts in lysimetry. Perhaps it is convenient to summarize under the headings of manometer, floating, and weighing lysimeters.

Manometer Lysimeters

Hydraulic-manometer lysimeters have proven to be quite popular among scientists because of their simplicity and cheap cost. Hanks (6) (1965) has constructed several such lysimeters in eastern Colorado at Akron. These installations are small in surface area, 1 m^2, and are limited to daily measurements of ET. Hanks (7) (1969) also constructed hydraulic lysimeters at Logan, Utah, in sizes up to 6 ft^2 and 4 ft deep. Utilizing differential pressure transducers, he has been successful in improving the resolution to 0.01 cm equivalent ET, a sensitivity roughly 1/5 of that attainable by a weighing lysimeter. Temperature induced errors due to density changes in the hydraulic system have been a problem in manometer lysimeters. Also, long-time drift errors have occurred due to changes in the elastic properties of the rubber membranes. This condition has improved with the introduction of nylon-reinforced butyl rubber.

The author visited the Akron and Logan installations and discussed lysimetry with Dr. Hanks (8). It was generally agreed that a weighing type lysimeter would be more appropriate for the Grassland Biome. Features such as undisturbed installation and representativeness factors were also discussed. Since the gist of that discussion concurs with others, the conclusion of this chapter will serve to summarize the points that were made.

Floating Lysimeters

Several floating lysimeters are in existence. Although constructed primarily for wind studies, they are capable of precision ET measurements. Discussion here will be brief since floating lysimeters are not recommended for studies of strictly ET.

Perhaps one of the most successful floating lysimeters is the installation at Davis, California, reported by Brooks and Pruitt (9) (1966). The surface area is large (6 m in diameter) and shallow (1 m). The soil container is made of fiber glass and the retainer of concrete. The soil container rests on a flotation unit of styrofoam logs encapsulated by polyurethane foam and then fiber-glassed. Determination of evaporative flux rates is done with a stilling well system which utilizes a fluid level transducer. The water loss record between the floating lysimeter and a 20-ft weighing lysimeter in the same field varies ±20 lb. in 1500, or about 1.3%.

While the results of such floating lysimeters have been excellent, applicability to a cold, windy climate has obvious drawbacks due to freezing and wind-induced electronic noise. A telephone conversation with W. O. Pruitt (10) indicated that the characteristics of the semiarid grassland would be best served with a weighing type lysimeter. As with Hanks (8), general features of lysimetry were discussed and will be reflected in the conclusion of this chapter.

Other floating lysimeters were reviewed, notably King (11) (1956) and McMillan (12) (1961) with similar conclusions.

Weighing Lysimeters

The most common type of weighing lysimeter employs mechanical balances to measure the weight loss. In the simplest arrangement, the soil container is attached to a portable overhead balance and lifted free of its supports when weighed. Among recent, commonly cited arrangements of this type is the lysimeter described by Makkink (13) (1953). The exposure of such installations leaves much to be desired for representative measurements.

The large Coshocton lysimeters (Harold (14), 1958) were one of the first installations with large containers supported on a mechanical balance for continuous weighing. A monolith block of soil, 6 ft by 14 ft in area and 8 ft deep, is encased in a concrete container. The retaining tank also is concrete. (Note that while a monolith block of soil was isolated, considerable disturbance of surroundings occurred during construction.) The balance is recording and sensitive to 0.25 mm ET (0.025 mm is attainable by others). Three major sources of errors could be present: wall-gap-wall area is about 65% of the soil area, the seal of the air gap between the walls may cause condensation errors, and the large underground installation adjacent to the lysimeter may influence the thermal regime. The Coshocton lysimeters have recently been modified to avoid the grease seal and to minimize wall-gap error.

The lysimeter of Pruitt and Angus (15) (1960) is an excellent example of a large weighing lysimeter with minimal wall-gap area, water suction control, temperature control at the container bottom, and dehumidified air surrounding the container. The container is 20 ft in diameter and 3 ft deep, the unnatural surface area is 3% of the enclosed soil, and the balance has a continuous recording accuracy of 0.03 mm ET. The 20-ft soil sample was obtained by backfilling the container after the lysimeter was in place. This method has been used for most lysimeters and will be discussed in the conclusion of this chapter (discussions with W. O. Pruitt (10)).

A smaller continuous weighing lysimeter is the van Bavel (16) unit in Tempe, Arizona, completed in 1962. The lysimeter is square (1 m by 1 m area by 1.5 m deep) and has an unnatural surface area which is 5% of the soil area. The design is basically a balanced beam system with counterbalancing done by lowering or raising weights from the ground surface via a cylindrical access. An electronic strain cell is used to read out the minute weight changes. The author inspected van Bavel-type installations at the University of Nebraska Research Station at Scottsbluff and discussed weighing lysimeters with Hollis Shull (17). Maintenance of the Scottsbluff lysimeter requires lifting the soil container, a feature that was not considered desirable for a large lysimeter.

Included in all of the discussions with the aforementioned scientists was the subject of an undisturbed soil sample for the lysimeter container. Attention turned to the efforts of Mukammal in Toronto, Canada, who had made attempts at obtaining an undisturbed core. A discussion with Dr. Mukammal (18) indicated that his attempts were not successful and that he was trying an incremental building block method.

The lysimeter which most influenced the planning and design of the Grassland Biome lysimeter was the installation of Ritchie and Burnett (19) (1968). While many features of this lysimeter are similar to other weighing lysimeters (e.g., unnatural surface area of 4.5% of the lysimeter area, 0.025 mm equivalent water weight change, 6 ft^2 and 4 ft deep), a unique feature is the use of a commercial scale to counterbalance the weight of the soil container. The scale is used to tare (counterbalance) most of the weight of the soil, leaving a small portion which stresses a tension-type electronic load cell. The strain-dependent output voltage of the load cell is calibrated and offers continuous recording of changes in weight.

Discussion with Ritchie (20) revealed that a year of operation had passed with good, stable performance from the lysimeter. While possibilities of using a similar design for the Grassland Biome lysimeter seemed good, a larger lysimeter with undisturbed installation raised doubts.

A Ritchie-type lysimeter was observed at the Agriculture Research Service site in Twin Falls, Idaho, during discussions with James Wright (21). Dr. Wright indicated satisfaction with the lysimeter for row crop studies. The method of obtaining the soil container sample was, again, by backfilling the soil and planting a crop under irrigation practices.

While other weighing lysimeter publications were reviewed, discussion of their content would be similar to the summarizations already given.

Other Alternatives Investigated

Aware that the electronics industry is an innovative, rapidly changing field, an attempt was made to determine if it was possible to detect weight changes in a lysimeter utilizing transducers (load cells) exclusively. Instead of using a mechanical device to counterbalance most of the lysimeter weight and then monitor the remaining small portion with a load cell, it was thought that load cells could reflect the entire weight and fluctuations.

A system was envisaged whereby the soil container would, through a rigid platform, transfer its load directly to a series of three or four compression-type load cells. The load cells would rest on steel plates imbedded in concrete. In addition to simplifying construction, such a system would result in the air volume beneath the soil container being very small compared to the soil volume. Thus, air-induced thermal variations would be largely eliminated. A disadvantage would be the necessity of lifting the soil container for maintenance of the load cells or components. However, maintenance was thought to be infrequent.

Visits with electronic industries representatives (22) (23) and subsequent correspondence indicated that such a system was possible. Utilizing flexure shrouds at each load cell to prevent horizontal forces (wind) would insure minimum nonlinearity. After extensive study, it was determined that while 0.001% detection of full range (0.4 lb., 0.025 mm) was possible, only 0.01% was guaranteed (4 lb., 0.25 mm). The investigation ended since 0.25 mm is not acceptable.

Conclusions

Throughout the review of existing lysimeters, the author was aware of one overriding feature--the soil within the container of the lysimeter was obtained by filling after the lysimeter was installed. In addition, installation was done utilizing earth moving machinery which resulted in total alteration of in situ conditions of the surrounding area. All of the lysimeters are located in humid climates or irrigated fields and are used for crop studies. Thus, upon filling the container with soil, the crop is planted and a luxuriant cover is achieved in several weeks.

It is generally conceded that disturbance of soil will alter its structure and properties. This is especially true with clays where disturbance causes reorientation and shifting of the particles, resulting in changes in strength, permeability, and porosity. Although thought to be less sensitive to disturbance than clays, granular materials exhibit marked differences in hydraulic conductivity in laboratory experiments, despite meticulous attempts to achieve similarity when hand-packing soil columns. In short, the soil within a filled lysimeter container may have different soil-water movement characteristics than the natural surrounding soil, a phenomenon that would affect ET.

Planting of crops in a lysimeter seems appropriate since the entire field is subjected to the same treatment and subsequent plant and root development are likely similar, that is, assuming representativeness is achieved.

Semiarid grassland, an ecosystem that has evolved over time, is a complex system that the IBP study is trying to understand. If the conventional filling method is used, how long would it take to reestablish the prairie cover, if at all possible? If sodding methods did result in a viable cover in a few seasons, what about the intricate root systems? Would alteration of the clay-loam structure change soil water movement appreciably and thus affect ET? The effects could be due to changes in soil water available for evaporation or to water-induced changes in plant types or physiology.

These questions, though not answerable as yet, did cause sufficient concern that the decision was made to construct the Grassland Biome lysimeter with an undisturbed soil core set in undisturbed environs (recognizing that totally undisturbed is not possible). Along with undisturbed installation, lysimetric features comparable to the best yet achieved were planned. A sketch similar to Fig. 2 was prepared which included the following features:

1. Weighing-load cell type lysimeter
2. Sensitivity of 0.001 inch (0.025 mm) equivalent ET (detection of 1:100,000)
3. Large size (10 ft-5 inch) diameter of soil surface (85 ft^2)
4. Unnatural surface area of less than 2%
5. Depth of 4.0 ft
6. Air volume beneath soil container approximately 50% of that of soil to minimize thermal effects
7. Temperature and soil water monitoring devices

8. Drainage provisions for soil container
9. Continuous and integrated data recording
10. Climatic control, if necessary

Review with C. H. M. van Bavel

Although extensive study had gone into the lysimeter planning, it was felt that review of the proposed installation by van Bavel would be "good insurance" (estimated cost of $50,000). The author contacted Dr. van Bavel who proposed a meeting. Discussions with van Bavel (24) were held in Fort Collins, Colorado (October 1969).

Dr. van Bavel essentially endorsed the proposed lysimeter and made two important modifications.

1. The depth was increased 1 ft (to the concluded depth of 4 ft). The point was made that while very little root biomass exists below 1 or 2 ft, the capillary-like roots at greater depths may be critical during stressed soil water conditions. Soil water stresses can become great in the semiarid grassland. The author observed only a few capillary-like roots protruding from the tunnel ceiling (depth 4 ft) when excavating the tunnel.
2. The sketch (Fig. 2) of the proposed lysimeter contained provisions for an access manhole to the subsurface mechanisms. Initially, this manhole was planned at a distance of tunnel from the lysimeter sufficient to contain counterbalance mechanisms. Dr. van Bavel recommended a minimum of 15 ft, regardless. The sparse canopy of the grassland is conducive to radiative heating. The exposure

of a metal manhole near the lysimeter could create a heat sink, thereby affecting the thermal regime. Thus, the challenge of an undisturbed installation was furthered by the addition of a tunnel at least 15 ft in length (18 ft-6 inches was constructed).

CHAPTER IV

DESIGN AND CONSTRUCTION

Summarizations of design and construction of the components of the lysimeter are contained in separate discussions in this chapter. Believing the adage, "A picture is worth a thousand words," the author has generously sprinkled the story with construction photographs. In an effort to avoid verbosity, the discussions are given a terse treatment. It is hoped that the photos will serve to illustrate some of the frustrations, tedium, and humor that the author incurred during this satisfying 18-month period.

Before beginning D and C discussions, the reader may be interested in how the method used to obtain an undisturbed soil core (described later) came about. Several large construction firms in the Denver area were visited, with particular attention given to those firms doing construction of high-rise buildings. It was noted on a construction site that a large drilling rig was actually screwing a caisson tube, 6 ft in diameter, into the ground. Inquiry into this operation led to meetings with Mr. John Meredith (25), engineer and head of Meredith Drilling Co. Despite its relative low dollar value, the lysimeter captured the interest of Mr. Meredith. After several meetings of rough computations, head scratching, and inspection of several drilling rigs, it was decided that one rig had the power and physical characteristics (clearance, etc.) to screw a 10-ft cylinder into the ground.

Other methods were investigated, including a large digging machine used in uprooting and transplanting very large trees. Excavating a core by hand and allowing the cylinder to slide and envelope the core was also a consideration.

Decisions concerning design and acquisition of the counterbalance scale and structural steel also entailed several meetings with manufacturers' representatives. In the case of the scale, several letters and phone calls culminated in a trip to Cardinal Scale Co. (26) in Missouri. Problems in reducing the vertical dimension of the scale assembly were solved, resulting in minimizing the subsurface volume beneath the soil container to 50% of the soil volume. The diameter of the tunnel was also decreased.

Problems encountered with structural steel were primarily due to fabrication tolerances and avoidance of distortion of the cylinders. Using a cold roll method with a butt weld, the manufacturer[2] was able to achieve a tolerance of 1/4 inch out of round. Prevention of distortion during handling was aided by temporary bracing and personal delivery of the cylinders to the Pawnee Site.

Description and Installation of Components

The lysimeter system and layout are shown in Fig. 3 and 4. A cylindrical tub, containing the undisturbed soil core, fits concentrically and freely within an outer retaining silo. The tub container rests on a mechanical balance connected to an electronic

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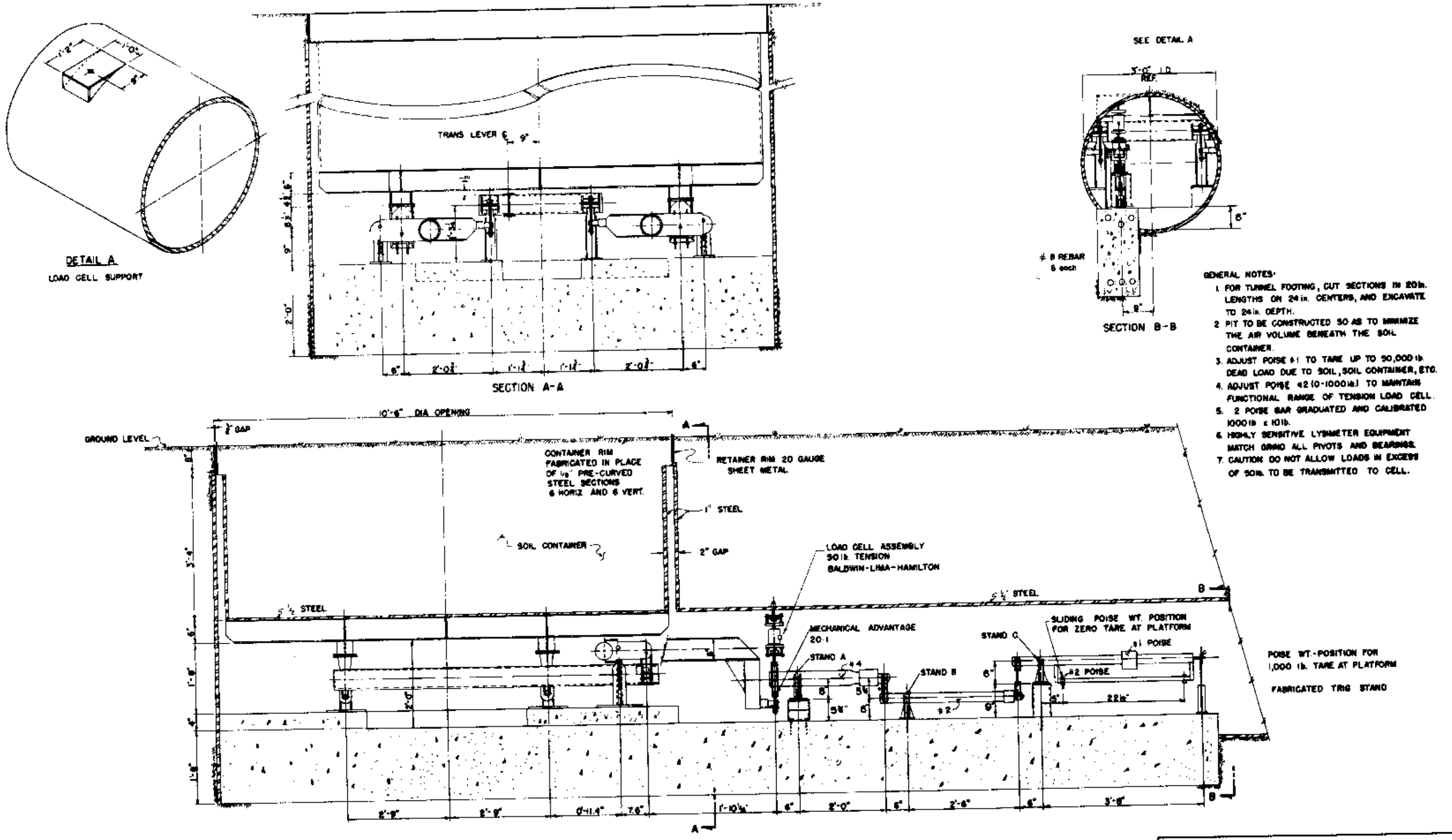
[2] Thompson Pipe and Steel Co., Denver, Colorado.



GENERAL NOTES:

1. FOR TUNNEL FOOTING, CUT SECTIONS IN 20 ft. LENGTHS ON 24 in. CENTERS, AND EXCAVATE TO 24 in. DEPTH.
2. PIT TO BE CONSTRUCTED SO AS TO MINIMIZE THE AIR VOLUME BENEATH THE SOIL CONTAINER.
3. ADJUST POISE #1 TO TARE UP TO 50,000 lb. DEAD LOAD DUE TO SOIL, SOIL CONTAINER, ETC.
4. ADJUST POISE #2 (0-1000 lb.) TO MAINTAIN FUNCTIONAL RANGE OF TENSION LOAD CELL.
5. 2 POISE BAR GRADUATED AND CALIBRATED 1000 lb ± 10 lb.
6. HIGHLY SENSITIVE LYSIMETER EQUIPMENT MATCH GRIND ALL PIVOTS AND BEARINGS.
7. CAUTION DO NOT ALLOW LOADS IN EXCESS OF 50 lb. TO BE TRANSMITTED TO CELL.

Figure 3 Cross Section

DO NOT SCALE PRINT FOR DIMENSIONS NOT GIVEN

INTERNATIONAL BIOLOGICAL PROGRAM
GRASSLAND LYSIMETER

PAWNEE NATIONAL GRASSLANDS — COLORADO

AGRICULTURAL ENGINEERING DIVISION
UNIVERSITY OF WYOMING

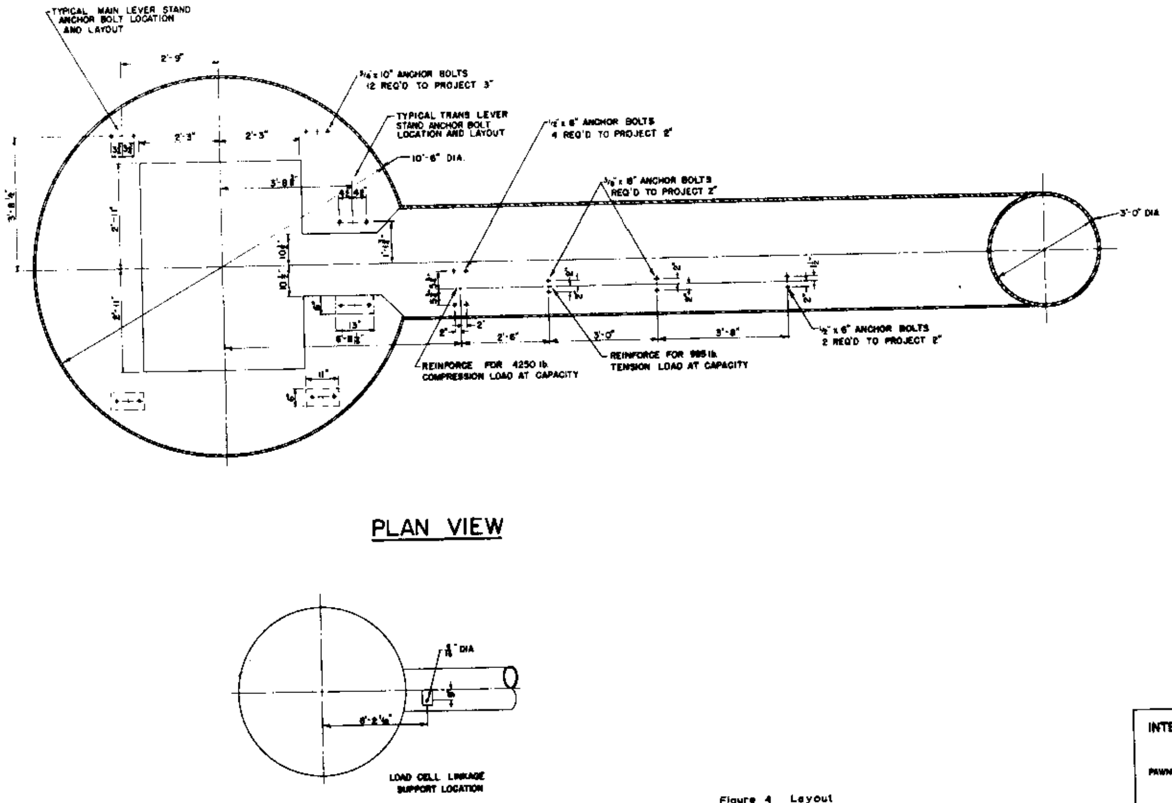


Figure 4 Layout

INTERNATIONAL BIOLOGICAL PROGRAM
GRASSLAND LYSIMETER
PAWNEE NATIONAL GRASSLANDS — COLORADO
AGRICULTURAL ENGINEERING DIVISION
UNIVERSITY OF WYOMING
1971

strain gauge load cell. The mechanical scale counterbalances most of the soil weight, while the load cell detects, through proportional output voltage, the minute weight changes of the soil caused by water losses or gains. A tunnel houses the load cell assembly, scale counterbalance mechanisms, and provides service access via a manhole entry.

Soil Container

The container is a steel cylinder (Fig. 5) with a basic inner diameter of 10 ft and a final depth of 4 ft. The top 8 inches is modified to an inner diameter of 10.42 ft to create a 3/8-inch to 1/2-inch air gap which minimizes the unnatural surface area to 2.0%. The container is made of 1-inch thick steel, a factor which necessitated recessing the cylinder below the ground surface to avoid heat-sink phenomena. The top 8 inches, referred to above, was constructed of 1/8-inch thick steel by welding eight horizontal and eight vertical pre-curved elements onto transitional fabrication with the container in final position (see Fig. 6, 7, and 8 for clarification). Heat warping of the elements made it impossible to attain a constant air gap, despite the interval welding and slow, natural cooling method that was used. The bottom of the container consists of 1/2-inch steel plate welded to the cylinder.

Isolation of the undisturbed soil core was accomplished by the following method. An open ended cylinder (5 ft in depth) was notched on one end to accept a special, heavy steel cross yoke. The center

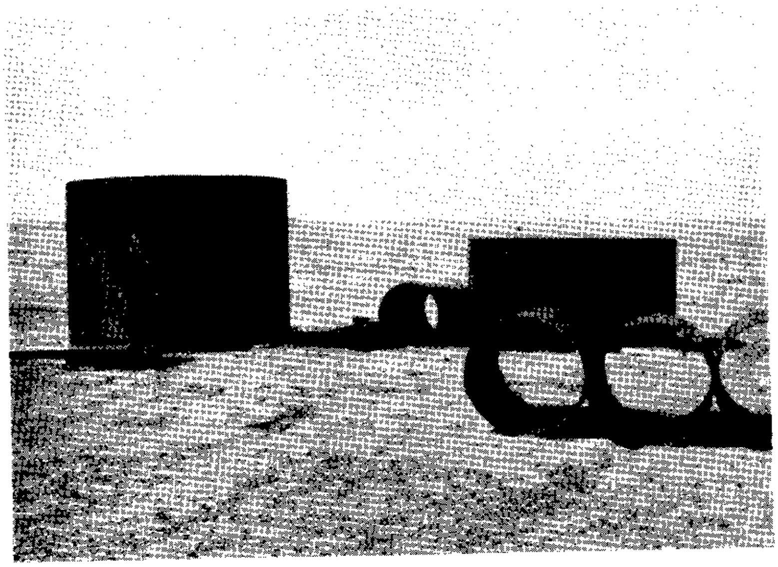


Fig. 5. Steel cylinders for containing retainer and tunnel.

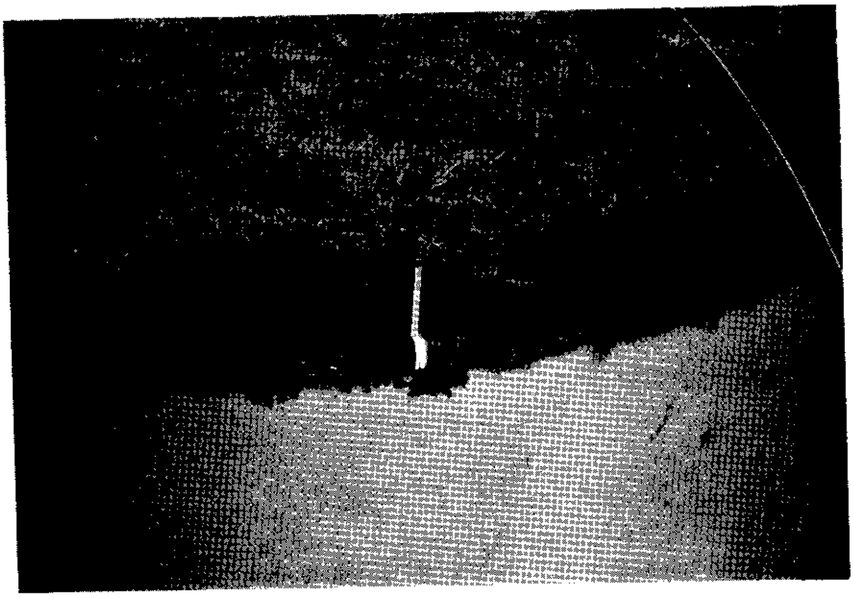


Fig. 6. Soil container with top 20 inches removed by cutting.

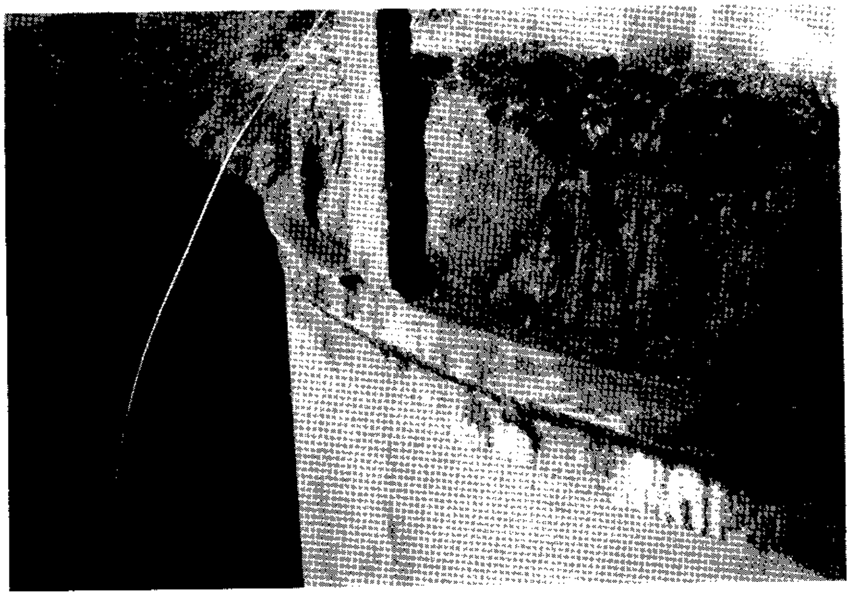


Fig. 7. Transitional fabrication to smooth ragged edge.

Fig. 8. Welding rim components on soil container.

of the cross yoke accepted the drive shaft of a large caisson drilling rig which rotated and screwed the cylinder into the ground. This operation was aided by two levels of removable bracing to avoid distortion, a beveled screwing edge, and minor water lubrication. Recall that the soil is a tight, uniform silt, essentially non-plastic, but with sufficient cohesion to facilitate the operation. Minor plowing effects occurred adjacent to the cylinder walls, but otherwise the enclosed soil core appeared undisturbed. Fig. 9, 10, 11, and 12 sequentially illustrate this operation.

Following the caisson operation (a period of 2 hr), the enclosed core was allowed to fallow except for occasional watering to deter burning through the hot summer months. During this time, the retainer site (a few hundred feet distant) was prepared. In the fall the core area was excavated, isolating the cylinder (Fig. 13 and 14), and the bottom was attached. This was done by hand-augering two horizontal bores beneath the cylinder, anchoring 6-inch WF steel guide beams on massive bridge timbers, placing the steel plate onto extensions of the beams, and pushing the plate under the cylinder. Deflection of the plate at the outer areas was prevented by two channel beams anchored in timbers. A 100-ton hydraulic hand jack coupled with a large concrete footing provided the thrust. Movement of the entire soil container during jacking was prevented by laying two 4-inch steel channel beams over the steel plate and welding one end to the container and imbedding the other end in the concrete footing. Tension in these two beams during jacking was sufficient to

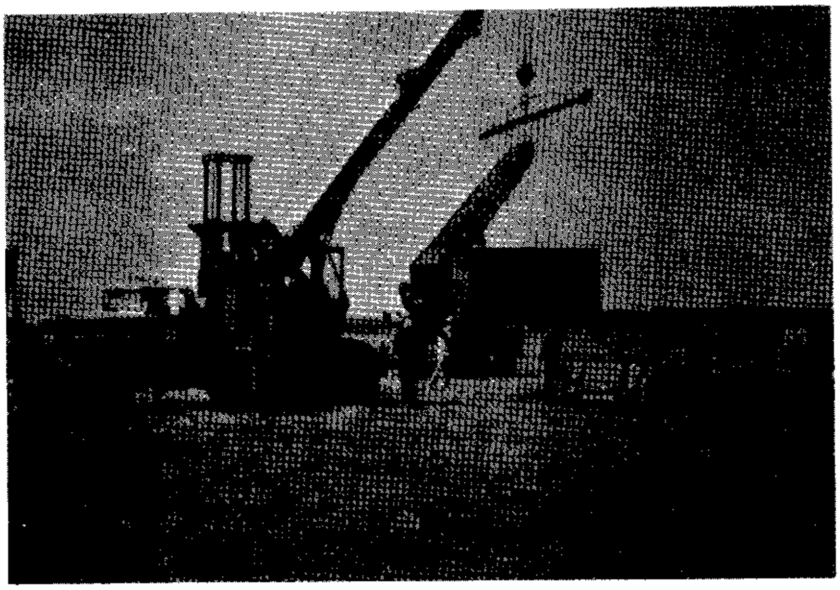


Fig. 9. Preparing steel cylinder for drilling rig.

Fig. 10. Soil cylinder and drilling rig.

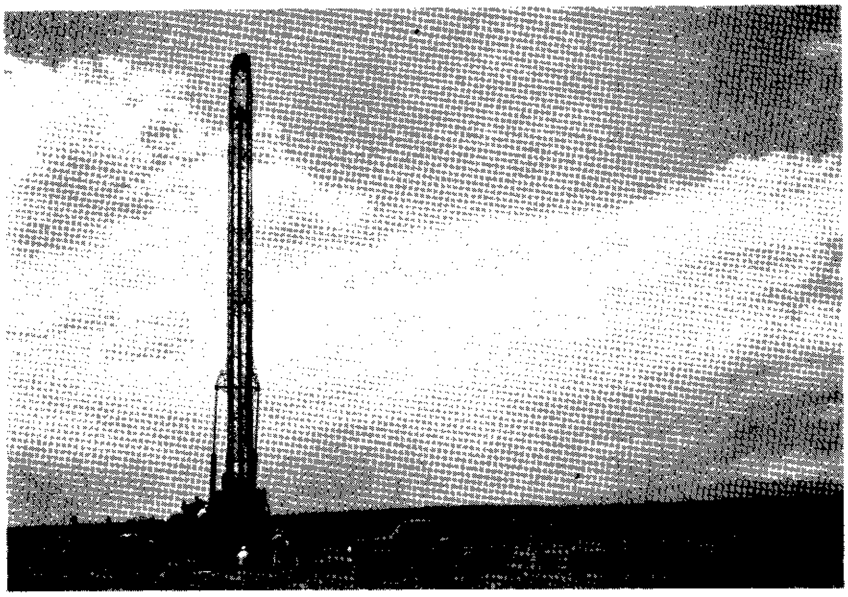


Fig. 11. Drilling rig rotating cylinder into ground.

Fig. 12. Soil container cylinder in ground.

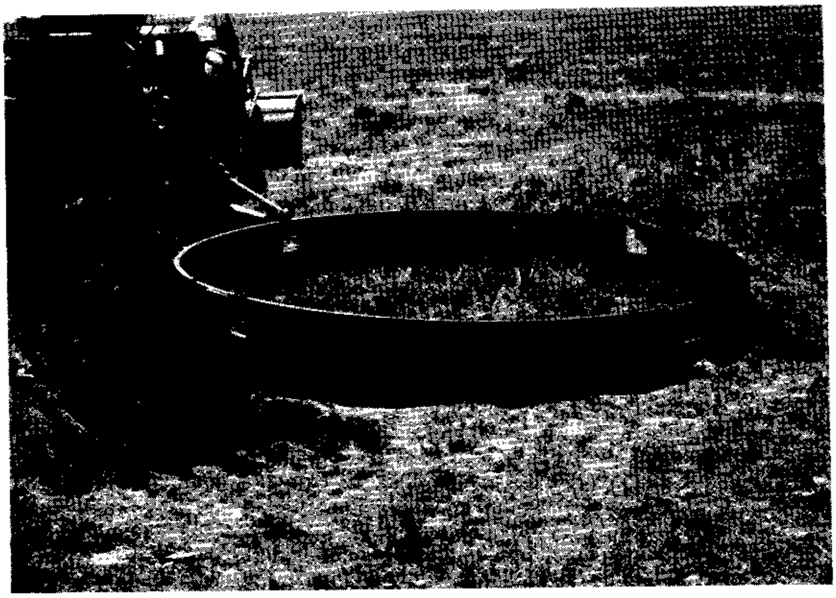


Fig. 13. Excavating to isolate container with soil.

Fig. 14. Soil container isolated.

break the welds on three occasions. The rate of pushing the plate was further slowed by the short throw (4 inches) of the jack and by frequent (and ineffective) blocking changes. Two months were consumed during this monotonous operation. The bottom plate was then temporarily welded with angle iron struts to the cylinder. Fig. 15, 16, 17, and 18 clearly depict this phase.

To install the drainage assembly (described later) on the bottom plate, a crane was used to tip the cylinder onto its side, using precautionary measures against sluffing and distortion. The bottom was released, the drainage plates attached (Fig. 19, 20, 21, and 22), the bottom rewelded, and the cylinder set back into an upright position. The bottom plate was then permanently welded and trimmed.

Cutting of the top 20 inches of the steel cylinder was done to remove the notched portion and to accommodate the special rim which extends to the surface. A carbon-arc blow process was used which necessitated application of copious amounts of water to avoid burning the plant cover and roots. Steel belt transitional fabrication atop the resulting ragged edge followed (Fig. 7), and the soil core was ready for insertion into the retainer. Using a crane, flatbed truck, and frozen ground conditions, the soil core was transported to the retainer site and inserted atop the scale (Fig. 23 and 24). Final positioning was done by tediously raising and lowering the core using three hydraulic jacks from beneath. The 8-inch (depth) surface rim was then assembled (Fig. 8) and painted. It was necessary to place a strip of sod (2 1/2 inches wide) around the perimeter to fill in the void created by the surface rims.

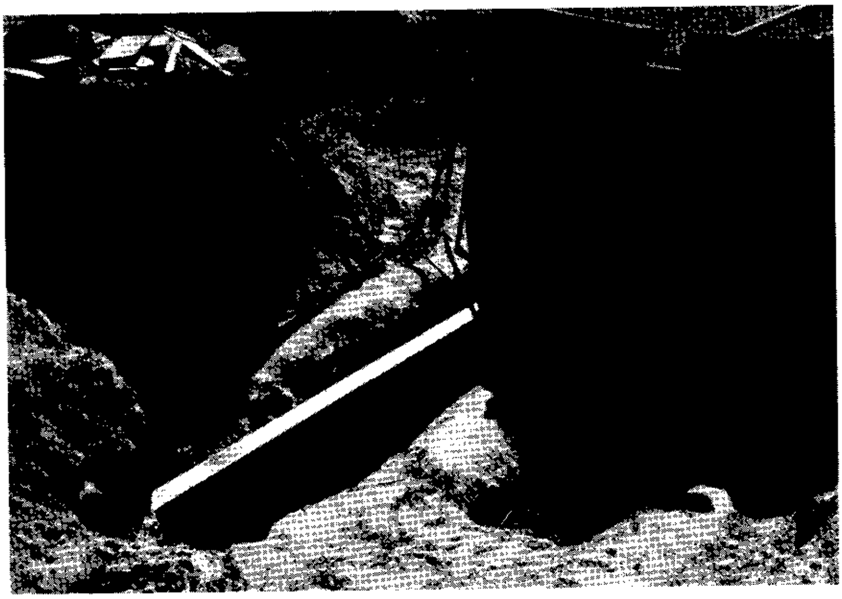


Fig. 15. Hand augering horizontal bores under container.

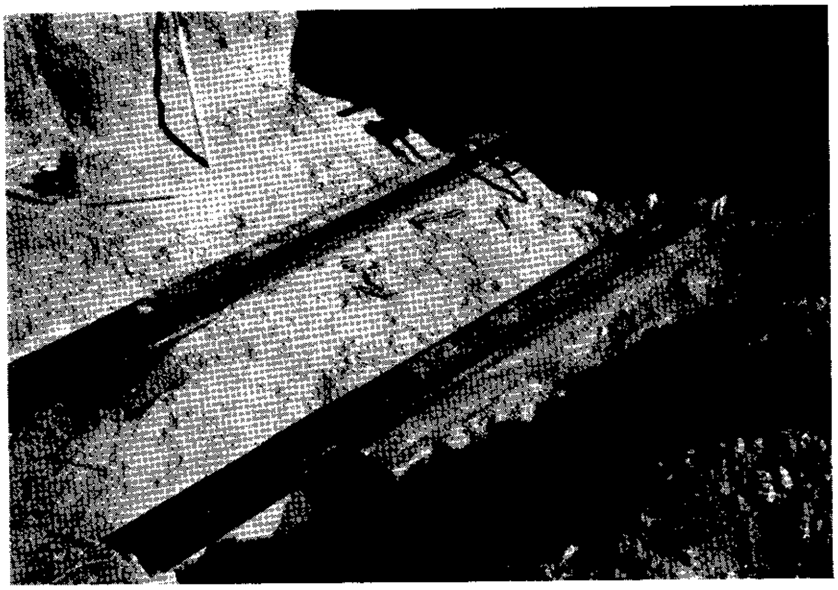


Fig. 16. Six-inch guide beams and extensions.

Fig. 17. Section of bottom 1/2-inch plate ready for jacking.

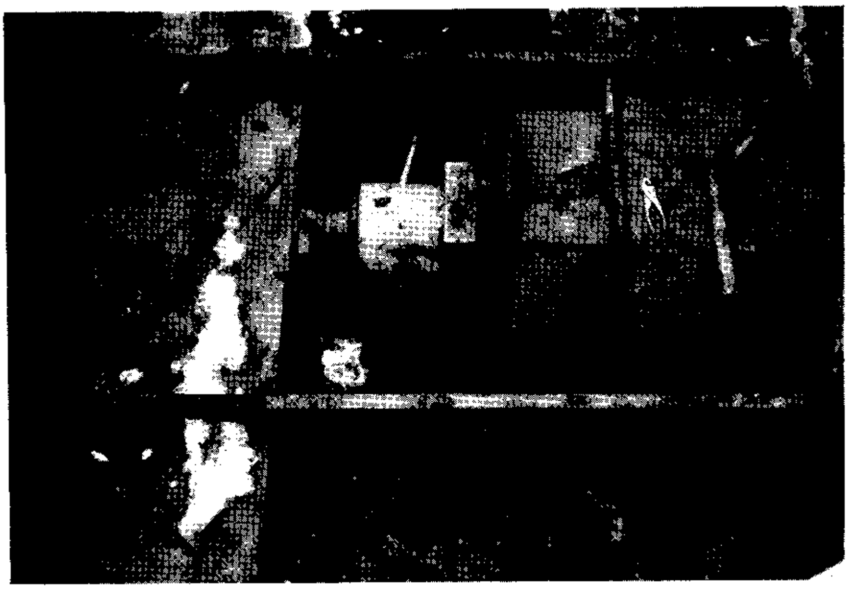


Fig. 18. 100-ton hydraulic jack pushing bottom plate.

Fig. 19. Tipping the soil container on its side.

Fig. 20. Soil container on side with bracing.

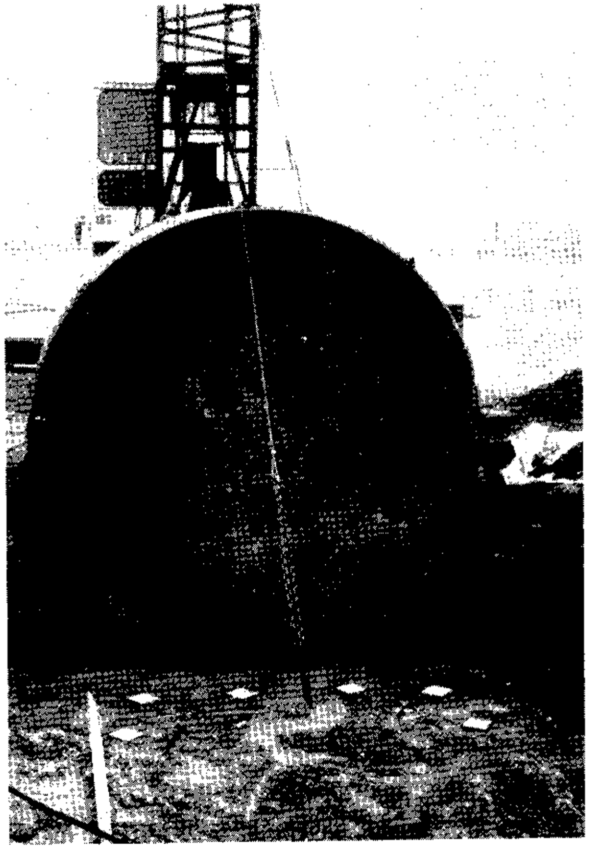


Fig. 21. Exposed bottom of soil core.

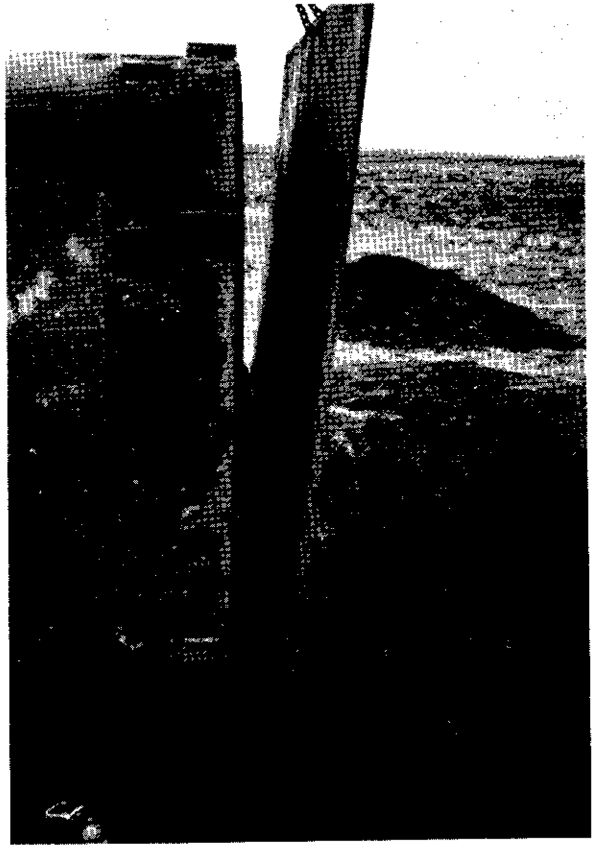


Fig. 22. Replacing bottom on soil core after drainage installation.

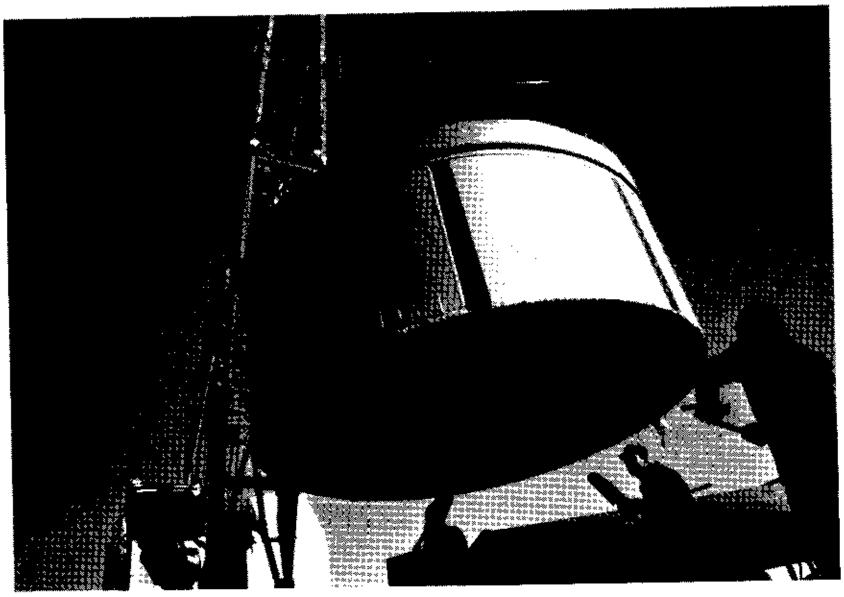


Fig. 23. Raising soil container for transfer to retainer.

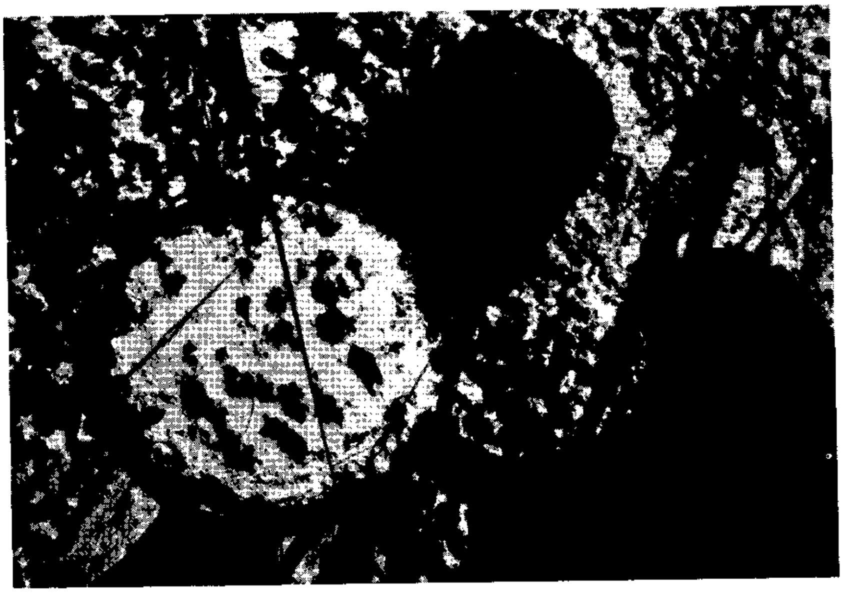


Fig. 24. Lowering soil container into retainer.

Retaining Silo

The retainer is a cylinder of 1-inch thick steel with a depth of 7 1/2 ft and an inner diameter of 10 1/2 ft (Fig. 5). This diameter allows an air gap of 2 inches between the walls of the concentric cylinders. The cylinder, recessed into the ground 8 inches, is topped with a 20-gauge (.0375 inch) sheet metal rim. The bottom 2 ft of the retainer contains a reinforced concrete footing, anchor bolts, and pads to support the scale mechanism. The reinforcing steel is welded to the retainer wall to assure that differential settling does not occur (Fig. 25 and 26).

Installation of the retainer was accomplished utilizing stilted work platforms, conveyor systems, dump truck, canvas covers, and rudimentary hand tools. The cylindrical excavation was dug with a pick and shovel, using the conveyor system to remove the excavated material. Preservation of perimeter surface conditions was achieved by removing and rotating, daily, the platforms, etc., and allowing the grass to recover (Fig. 27, 28, 29, and 30).

Placement of the concrete was done quickly using 1-inch plywood sheets to spread the wheel loads of the ready-mix truck. Accuracy of placement of anchor bolts and pads is critically important and was assured with the use of a precise plywood template and an engineer's level. The concrete mix design is given in Table A-2.

Tunnel

The tunnel, 18 ft in length and 3 ft inner diameter, is lined with 1/2-inch thick steel. The manhole is similar and has a depth of

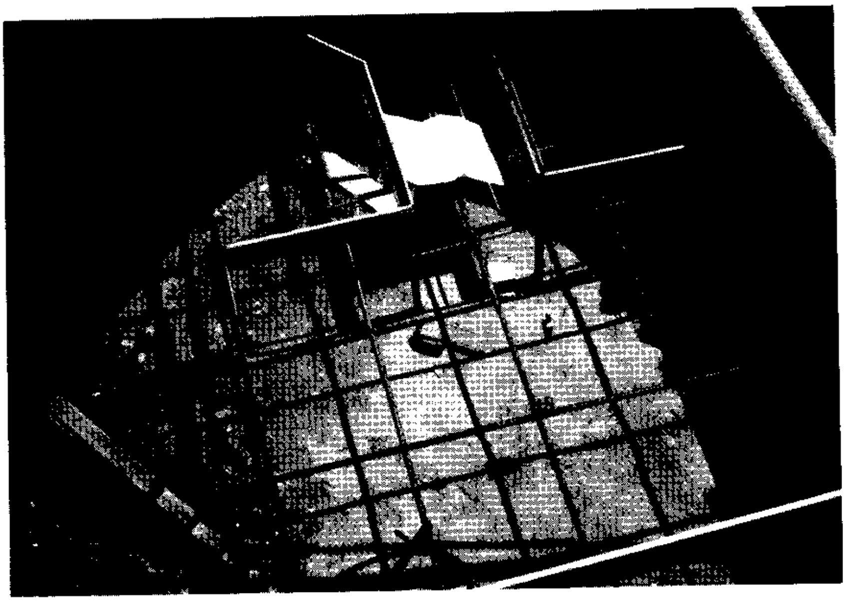


Fig. 25. Forms and reinforcing bars for concrete footing.

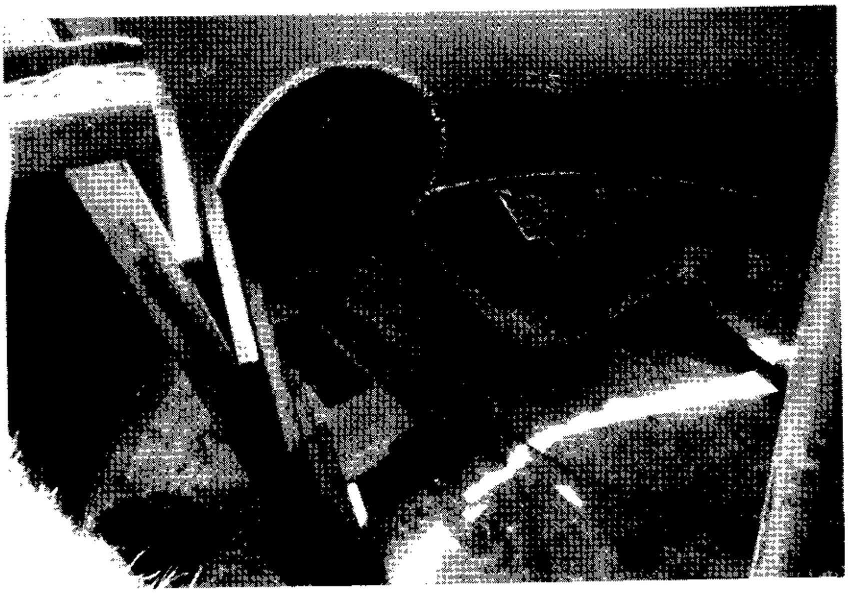


Fig. 26. Concrete footing with steel pads for scale.

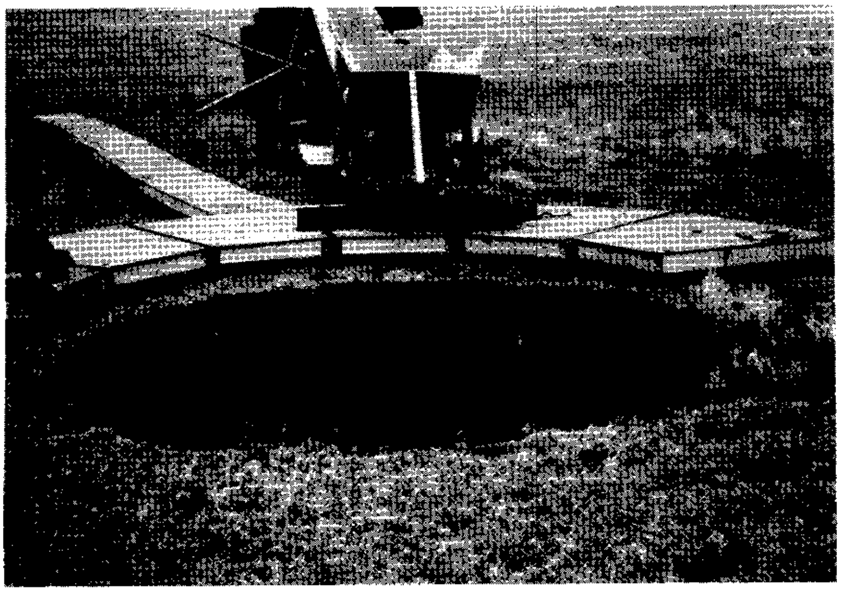


Fig. 27. Begin excavation of retainer.

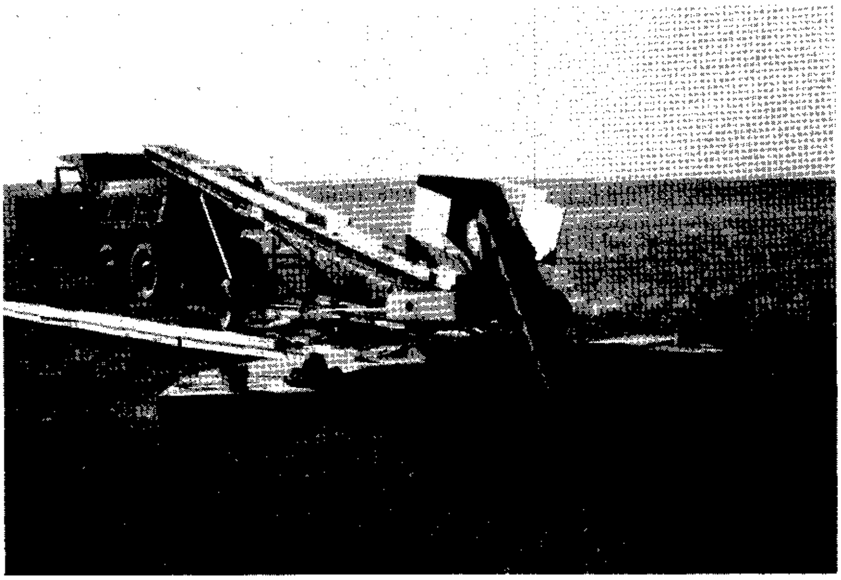


Fig. 28. Excavation of retainer.

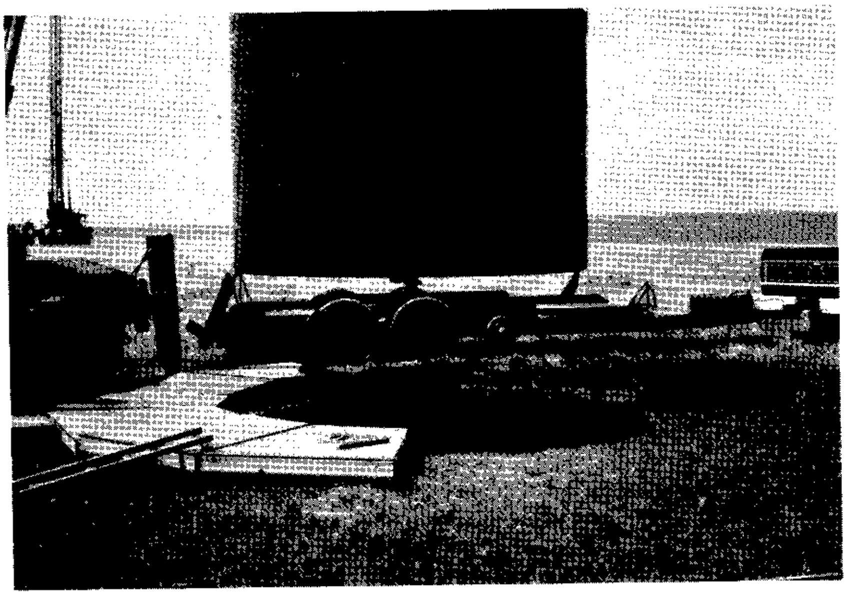


Fig. 29. Lowering retainer cylinder into excavation.

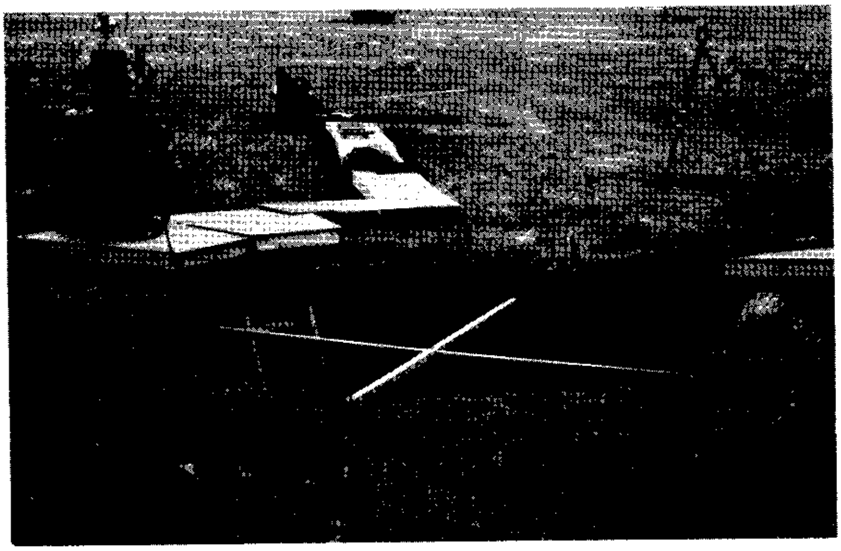


Fig. 30. Retainer cylinder in place.

7 ft. A concrete footing (20 inches in depth) protrudes through the tunnel floor and supports the counterbalance mechanisms. Conventional lighting was installed throughout. (Fig. A-3 shows a simple circuit diagram.)

Construction of the tunnel began prior to concrete operations by cutting a 3-ft diameter hole in the wall of the retainer. Excavation of the tunnel followed using the pick, spade, and bucket routine. The manhole was set utilizing a mechanical auger. To line the tunnel, a steel beam track was fixed to the tunnel floor (by using a concrete bulkhead at the manhole end and welding the other end to the retainer) and extended into the retainer area. Using a tripod, hoist, and elevated steel beam railway at ground level, 5-ft sections of the pipe were rolled to the retainer rim and lowered onto the beam track. A successive jacking and welding method was used to pull the pipe lining into the tunnel. The tunnel sequence is shown with Fig. 31, 32, and 33.

Placement of the tunnel footing required cutting discontinuous 20-inch sections of steel out of the floor and spoon excavating. Four inches of steel (longitudinally) were left between the 20-inch cutouts for encasement in the concrete footing. Reinforcement bars were spot welded to the re-bar extensions of the retainer footing. These features, along with the concrete bulkhead and welding of the tunnel cylinder to the retainer, give added insurance against differential settling. Reinforced ready-mix concrete was placed and anchor bolts and pads were set. Following grinding of the steel surface, lead

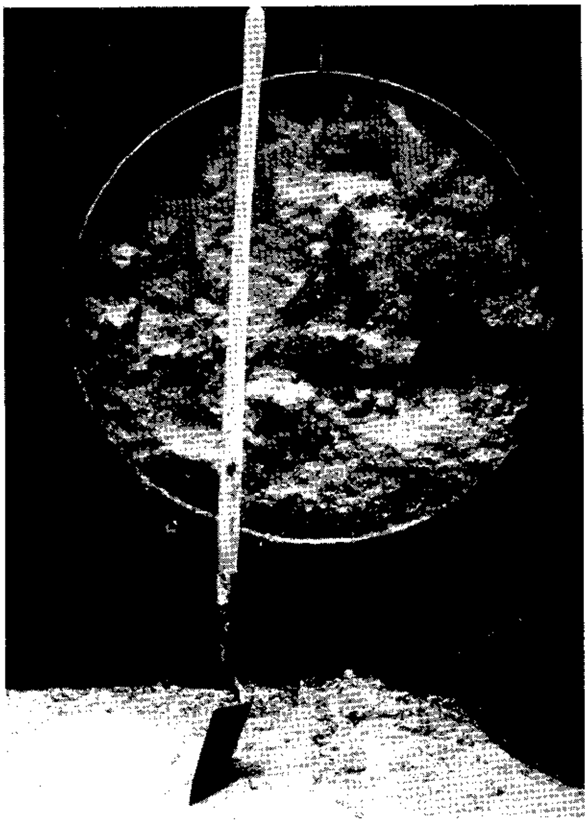


Fig. 31. Cut-out of retainer wall to begin tunnel.

Fig. 32. Tunnel excavation.

Fig. 33. Lowering 5-inch section of 36-inch pipe for tunnel lining.

primer and aluminum paint were applied. Fig. 34 shows the completed tunnel.

Weighing Mechanism

The soil container rests on a commercially available 50,000-lb. capacity floor stand tank scale. The container is set on a steel beam weighbridge (Fig. 35 and A-4) which is bolted to four girder chairs. The chairs transfer the dead load to fulcrum pivot assemblies which are supported by four main lever stands positioned on the concrete footing (Fig. A-5). The four fulcrum pivots, in turn, transfer the load to two main pipe levers (Fig. 36). Two splice arms, one each connected to an end of a main pipe lever, transfer the load to a short transverse pipe lever through two transverse lever stands (Fig. 37 and A-6). Connected to the transverse pipe is a longitudinal beam from which begins the counterbalance mechanisms (Fig. 38). Through a series of shaft-like arms, supported by three fulcrum pivots (Fig. A-7), the load is counterbalanced at the end of the system by a 10-lb. weight and a 1/2-lb. weight (Fig. 39). Counterbalance capacity of the large weight is the full range of 0 to 50,000 lb., while the small weight allows fine adjustment with a range of 1,000 lb.

Nearly all of the soil container weight is counterbalanced with the scale system, leaving a maximum of 500 lb. as a weight range in which the electronic load cell functions. As the soil container gains or loses weight, the counterbalance weights are manually adjusted to maintain the load cell in its functional range.

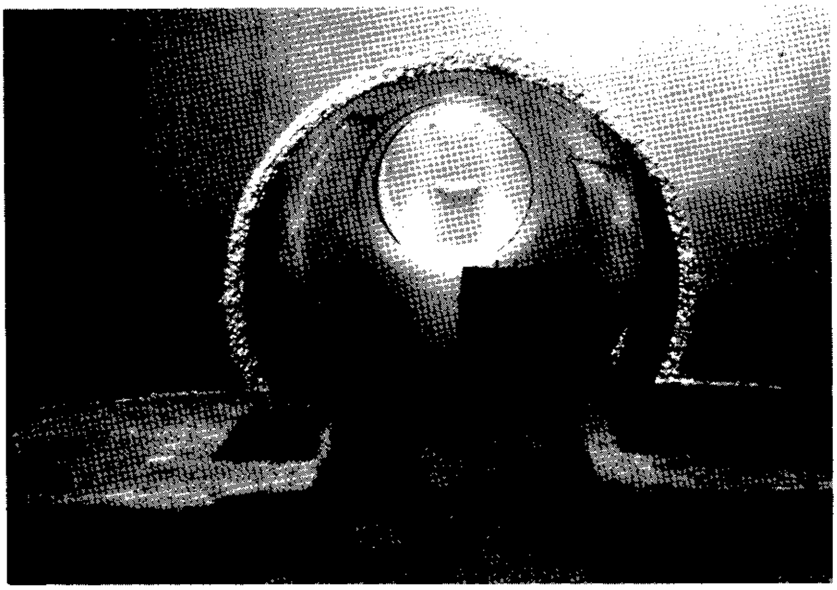


Fig. 34. Tunnel complete with footing and anchor pads.

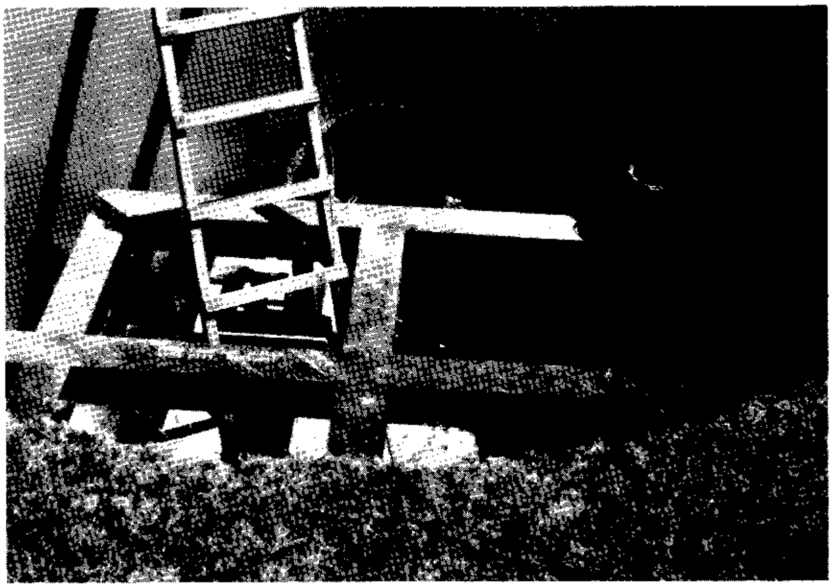


Fig. 35. Weighbridge in position within the retainer.

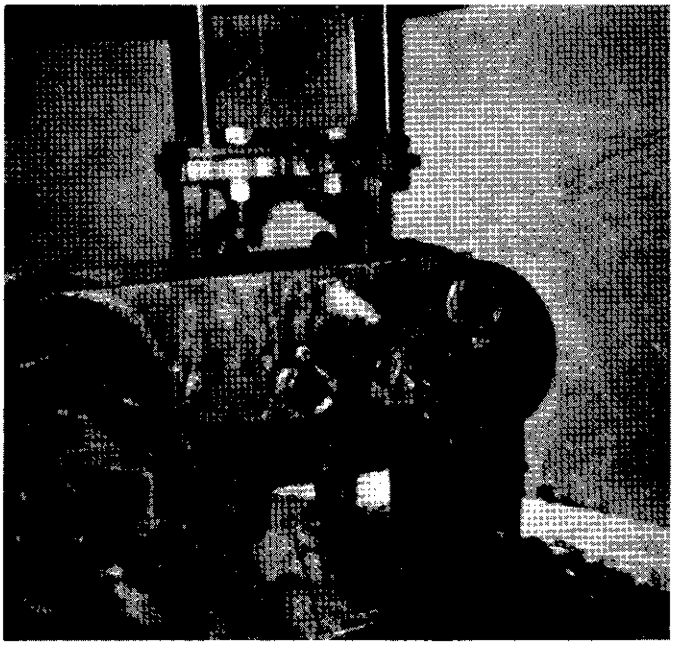


Fig. 36. Weighbridge, girder chair, fulcrum pivot, and main pipe lever.

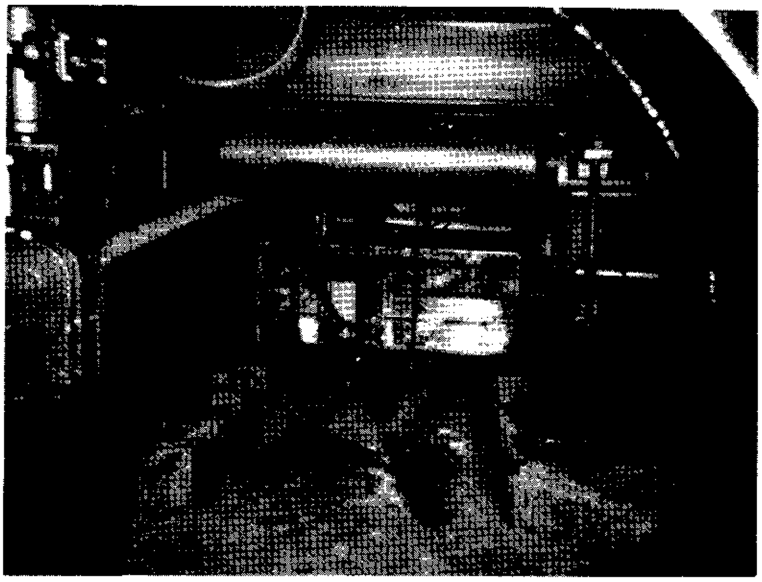


Fig. 37. Transverse pipe lever accepts load from splice arms through fulcrums and transfers load to longitudinal beam.

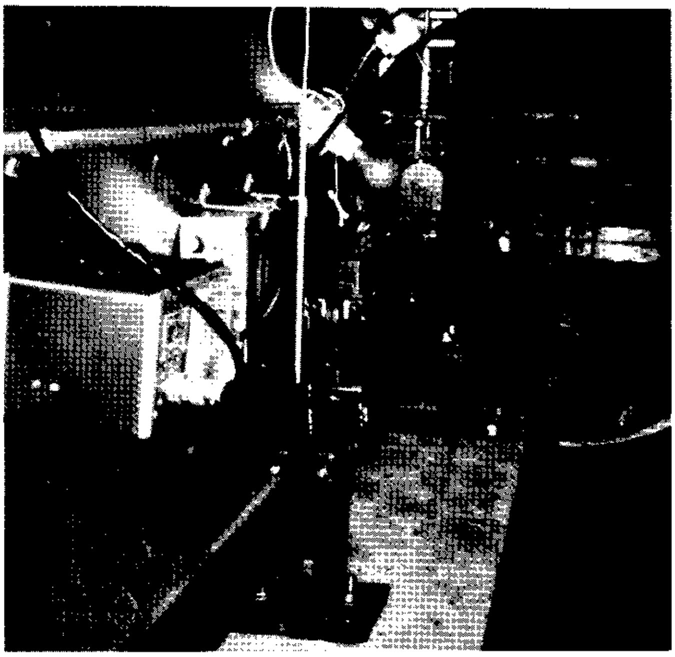


Fig. 38. Load cell and counterbalance mechanisms. Voltage supply unit behind output voltage amplifier.

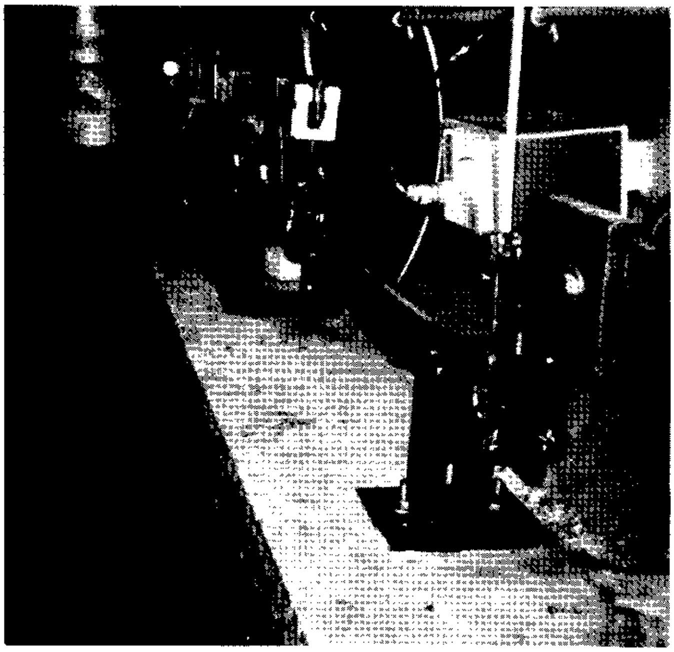


Fig. 39. Counterbalance mechanisms and weights, output voltage amplifier, and manhole entry ladder.

The scale system has a mechanical advantage of 20:1 at the load cell. All pivots are matched ground knife edges to increase precision. Operational movement, nondiscernible to the eye, is essentially nil, a condition which enhances the life and effectiveness of the edges.

Installation of the scale mechanisms was eased by the placement accuracy of the steel pads and bolts in the concrete. No problems occurred because of construction, but a few resulted from quality control of the manufacturer. The first and worst surprise occurred when the two main pipe levers did not fit in the retainer. Luckily, cutting a 4-inch corner off of each lever solved the problem and did not affect the system. Likewise, the U-shaped hanger beneath the load cell flexure (left edge of Fig. 37) required several inches of shortening. But these problems seem minor when one considers the many headaches that could have arisen with horizontal positioning of the several linkages.

Load Cell System

A precision strain gauge load cell[3] (Fig. 38) is used to translate weight changes in the lysimeter to voltage changes. The load cell is a tension type with a capacity of 50 lb. and a manufacturer's accuracy rating of 0.1% of capacity. Hanging the load cell proved to be a difficult task. The load cell is mounted in a flexure unit which aids in maintaining the loading vertical. However, alignment and position are still critical and were complicated by the restricted space and curvature of the tunnel wall. It was necessary to cut out

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[3] Baldwin-Lima-Hamilton, Waltham, Massachusetts, Model T3P1 50-lb. capacity.

a portion of the overhead tunnel and replace it with a horizontal plane. Careful closure of the plane section to the tunnel was required to assure strength and rigidity and to prevent intrusion of soil and water into the tunnel. The plane section was then drilled and tapped to hang the flexure unit and load cell. While the pull on the plane section is less than 50 lb., fixed rigidity is an absolute necessity as even the slightest displacement will affect the load cell strain-output function.

The output of the load cell is 3 millivolts (mv) per volt input to the strain gauge bridge. Constant voltage input is supplied by a commercial high stability, precision DC power supply.[4] Load cell output is amplified by a factor of 250, to 0 to 5 volts, utilizing a chopper stabilized operational amplifier[5] in a system designed for the author by Richard Weeks.[6] Fig. 40 shows the design of the amplifier.

Data Recorder

The load cell output and soil temperatures are recorded on an existing system (27) designed for the Agricultural Engineering Division by the Natural Resources Research Institute of the University of Wyoming. The system, utilized for meteorological data acquisition, continuously integrates and records 1-min values on magnetic tape

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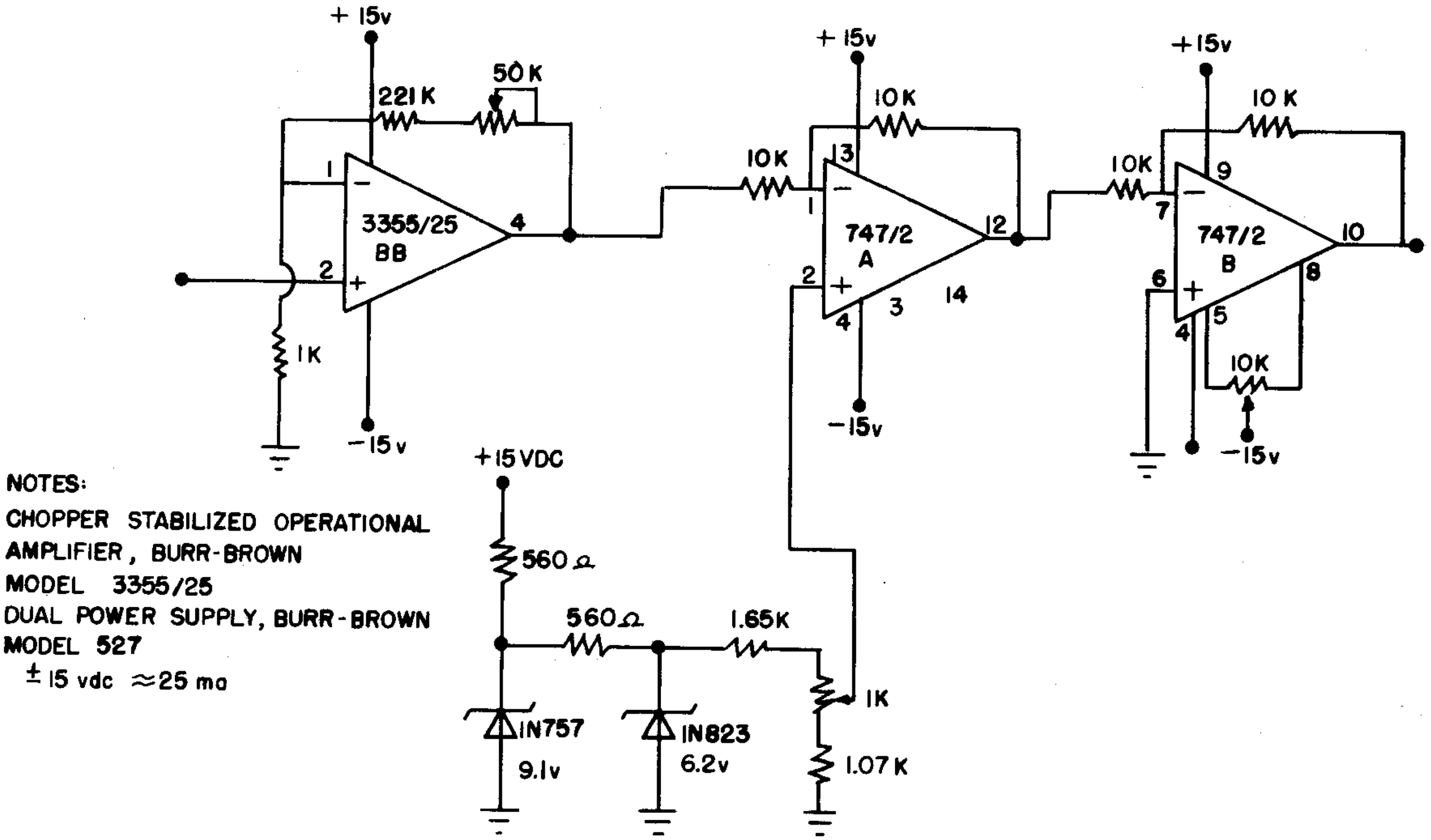
[4] Raytheon Co., Sorenson Operation, Manchester, N. H., Model QHS40-.5.

[5] Burr-Brown Research Corp., Tucson, Arizona, Model 3355/25, Power Supply Model 527.

[6] <u>Acknowledgement</u>--Assoc. Professor Richard Weeks, Electrical Engineering Department, Univeristy of Wyoming, Laramie.



NOTES:
CHOPPER STABILIZED OPERATIONAL
AMPLIFIER, BURR-BROWN
MODEL 3355/25
DUAL POWER SUPPLY, BURR-BROWN
MODEL 527
± 15 vdc ≈25 ma

Fig. 40. **AMPLIFIER FOR LYSIMETER LOAD CELL**

for 36 parameters simultaneously. The system records counts, 0 to 1000, with one count equal to 1/2 lb. weight change at the lysimeter.

Drainage System

To assure moisture conditions within the soil container are similar to conditions in the natural soils surrounding the lysimeter, a drainage system was installed. The primary components of the system are 16 sintered stainless steel suction plates[7], 15 cm^2, utilized in a simple design. The water permeable plates are used in a sandwich with plexiglass and spacer to form a collecting basin from which a stainless steel tube is connected to drain water. The tubes drain into a common manifold which is connected to one tube which extends through the wall of the soil container. The system is mounted on the soil container floor as shown in Fig. 41.

The one tube drains, by gravity, into a 20-gal plexiglass draintank (Fig. 37) which hangs from the steel beam weighbridge. Within the drain tank is a pump which, upon submersion, automatically ejects the water through an outlet tube fixed to the tunnel roof. A U-section of flexible rubber tubing in the outlet tube assures that no drag occurs.

Following installation of the plates (described under soil container), a porthole was cut top side while the soil cylinder rested on its side. Through this porthole, washed concrete sand was poured and

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[7] Grade H, 1/8-inch thickness, Pall Trinity Micro Corp., Cortland, New York.

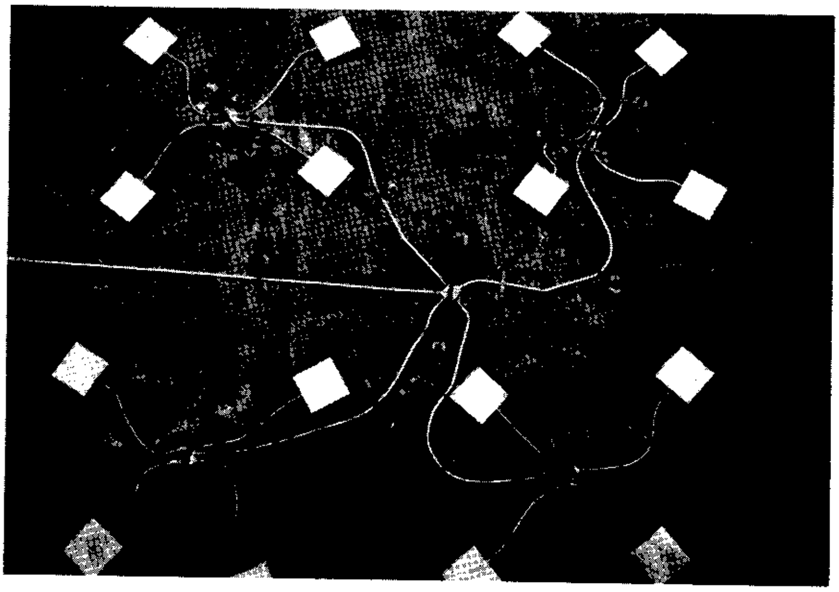

Fig. 41. Drainage plates.

vibrated resulting in a depth of 4 inches covering the suction plates. The sand prevents clogging of the plate pores and enhances drainage from the entire bottom of the soil core.

The system has a bubbling pressure of approximately -75 mb at the filter plate surface. Water could be added to the soil through the drainage system during a prolonged drying cycle when upward water flux is occurring in the field soil at depths of the lysimeter floor--an event that is highly improbable at the Pawnee Site.

Moisture and Temperature Monitoring Devices

To compare moisture and temperature gradients within the soil core to corresponding gradients in the surrounding natural soils, monitoring devices were installed. Electrical diodes continuously relate two soil temperature profiles, while four access tubes (two inside and two outside) allow periodic soil water comparisons by nuclear methods.

Costs

Overall cost of the lysimeter totalled $51,670. A breakdown of the costs is as follows.

Equipment and Materials:

Item	Cost
Scale	$ 3,060
Steel	3,920
Drilling Services	2,450
Crane Rental	740
Conveyor Rental	420
Jack Rental	390
Blow-Arc Process	325
Load Cell	500
Power Supply	350
Amplifier	130
Force Guage	190
Reinforced Concrete	400
Standard Weights	500
Vacuum Pump	135
Miscellaneous	1,480
Sub Total	$14,990

Labor:

One Engineer-Constructor (author)[8]	
19 months @ $800 + 42% overhead =	$21,580
8 months @ $900 + 48% overhead =	10,670
One Technician-Aide	
5 months (est.) @ $600 + 48% overhead =	4,440
Sub Total	$36,680

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[8] An additional academic year of graduate assistantship plus 3 1/2 months (summer 1972) @ $500 was provided to check the first year of operation and write the lysimeter thesis = $7,000 (includes 50% overhead).

CHAPTER V

CALIBRATION

The task of calibrating the lysimeter was done in two stages, first by a rough visual method without the electronics, and then with care and precision utilizing the electronics. The two phases and conclusions are discussed in this chapter.

Preliminary Calibration

Upon completion of the scale system, a method was needed to easily manipulate and observe the scale in operation. A proving ring-strain gauge device with a direct dial readout was purchased and modified to hang in tension in the position of the load cell. The first test was to place known weights on the lysimeter surface and check if the 20:1 mechanical advantage design was actually achieved at the load cell point. The initial test indicated some hanging up of the mechanisms, requiring complete dismantling of the tunnel portion of the scale. Bases were re-slotted, allowing refinement in horizontal alignment, knife edges were checked and lubricated, and the system was reassembled. Various amounts of weight were added and, correspondingly, 1/20 of the amounts were joyously observed on the gauge dial.

The next test involved checking the tare capability of the scale. It was already known that the scale was capable of counterbalancing all or portions of the soil container. However, testing revealed that the lower bar did not tare as indicated by the graduations. The problem was easily solved by removing the graduated strip and approximating another by adding known weights. The approximate strip was later carefully graduated using the electronics, resulting in a better range than that designed. Fig. 42 shows the tare bars and counterbalance weights. Operation of the bar will be discussed in Chapter VI.

Precise Calibration

Knowing the behavior of the lysimeter system, the electronics were placed in use and the precise calibration began, but first it was necessary to have the weights calibrated and certified. One week of brushing, drilling, adding and subtracting lead weights, and painting was enjoyed by the author at the Wyoming Weights and Measures Laboratory (Department of Agriculture). Lacking help during his busy time of year, State Metrologist Elvin Leeman personally tested the weights. A summary of the tests is included in Table A-3 to document the lysimeter weights.

At the outset it was decided to calibrate the system so that after output voltage amplification, 1 volt = 100 lb. The amplification factor is 250; therefore, computing backwards results in .04 mv of load cell output per pound of weight change. As stated, the load cell is rated at 3 mv/volt input. The Sorensen constant voltage supply unit, factory certified and field lab checked, was manipulated until an approximate load cell output of 0.04 mv/lb. was obtained. This was

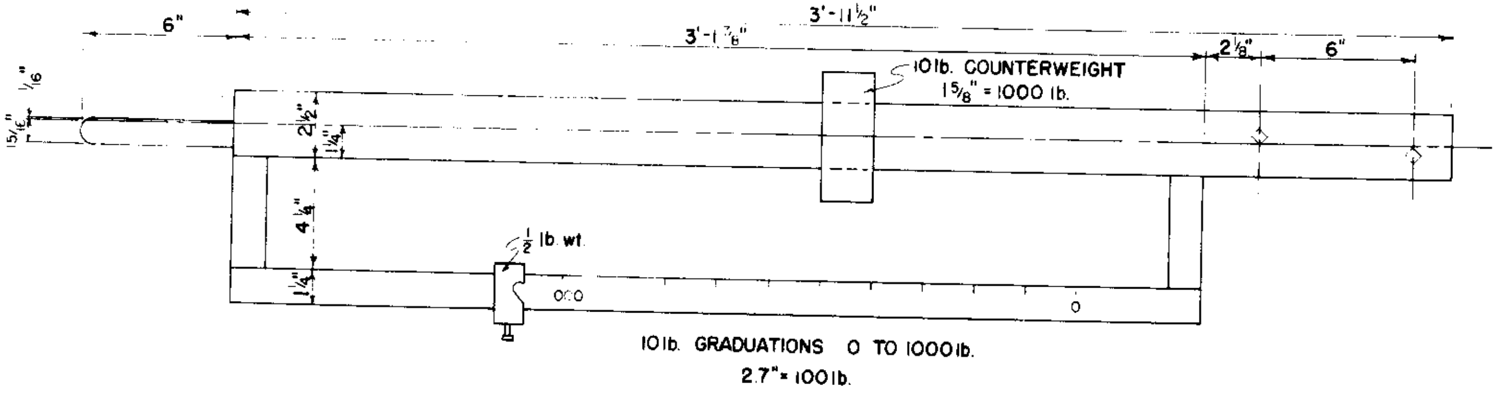


Figure 42 Weigh Bar

INTERNATIONAL BIOLOGICAL PROGRAM
GRASSLAND LYSIMETER
PAWNEE NATIONAL GRASSLANDS-COLORADO

AGRICULTURAL ENGINEERING DIVISION
UNIVERSITY OF WYOMING

done quickly using a visual display digital voltmeter (Model 350, Data Technology Corp.). A check at the amplifier output end indicated that design amplification was close.

With everything appearing in order, precision precautions were placed in effect. Using 1/2-inch steel rod, a snap ring was constructed and used to hold a polyethylene cover on the lysimeter surface to prevent evaporation during calibration. A stock tank was purchased and inverted over the lysimeter to create calm conditions for easier calibration. Along the tank-ground interface, blankets were laid to further deter wind intrusion. Instrument reading was done at the bottom of the manhole with the cover firmly in place. It was even necessary to limit subsurface lighting to the manhole, only, to prevent heating effects in the tunnel. Despite all of these precautions, wind effects made it necessary to calibrate during calm, early dawn hours.

Using a precision potentiometric bridge (Model Portametric PVB 300, Electro Scientific Industries, Portland, Oregon) at the load cell output point, a voltage input was selected and the range of weights, 0 to 1000, was applied and removed sequentially through a hole in the stock tank. This monotonous procedure was repeated until at last an input excitation voltage of 15.935 volts was established for the voltage supply unit (Fig. 43 and 44 depict the operation).

With the same arrangement, a variety of testing was repeatedly performed. Hysteresis was checked by noting the output voltage as weights were added and comparing the voltages to those obtained as the

Fig. 43. Calibration cover and snap ring.

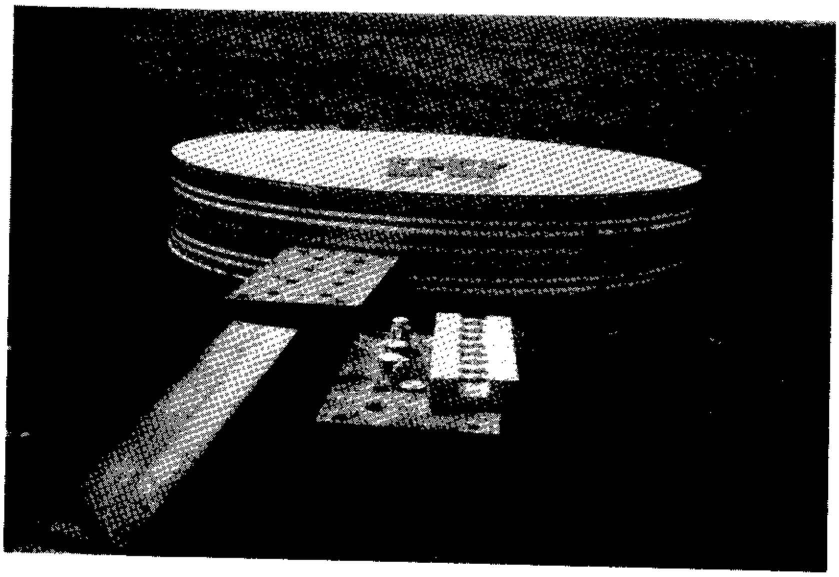


Fig. 44. Calibration--inverted tank and standard weights.

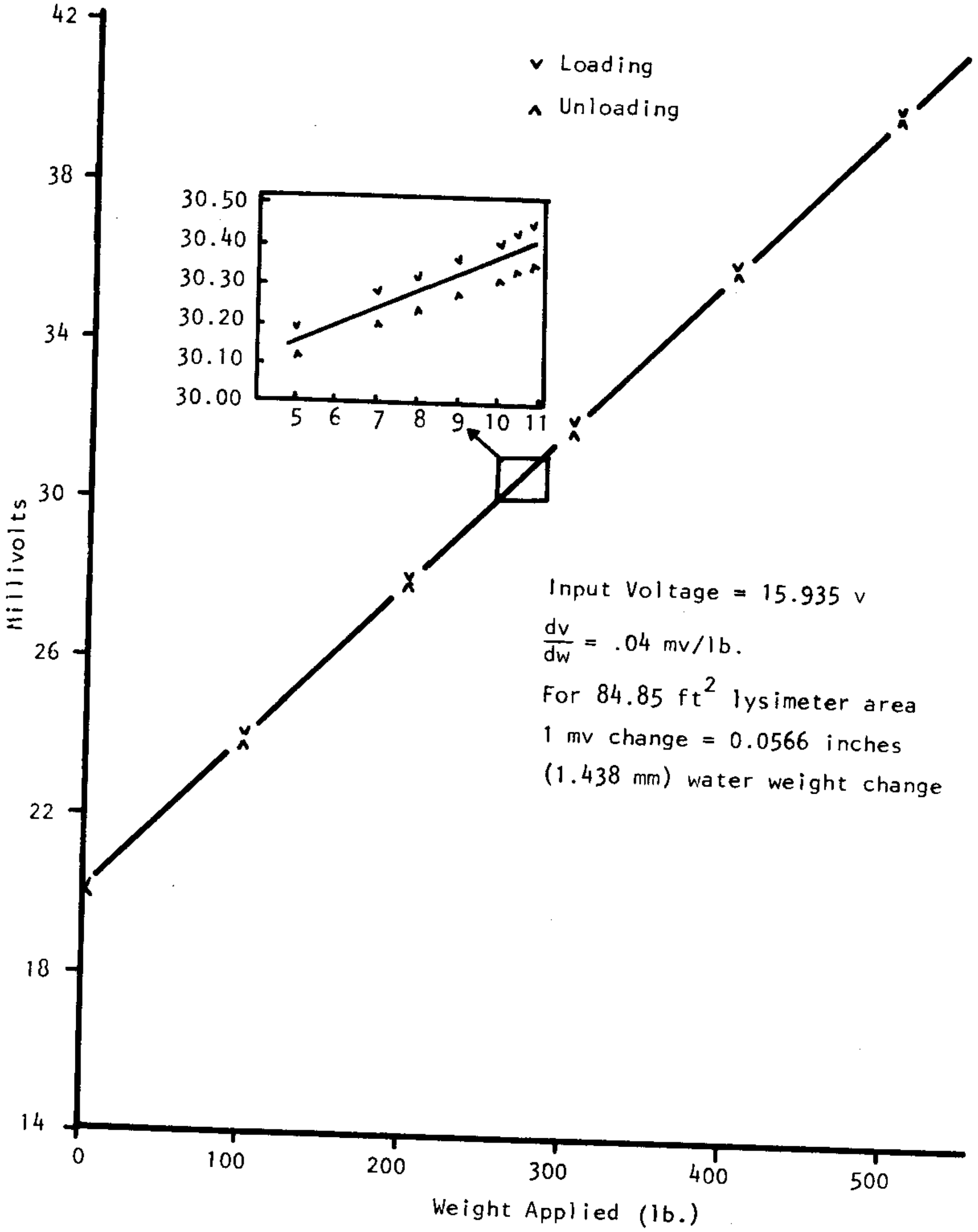
weights were removed. Short-term drift was checked by allowing the system to idle over a period of hours and comparing initial and final readings. Linearity of the output voltage was checked throughout those procedures.

The entire operation was duplicated at the output end of the amplifier. The laboratory calibration of the amplifier proved to be true, as only a minor adjustment of the input offset voltage was necessary. As a final check, simultaneous readings were taken at the load cell output and amplifier output.

Finally, the ultimate calibration was done at the data recorder. The recorder receives the amplified voltage output signal and converts the signal to counts. A received signal change of 0.01 volts produces a change of two counts which is equivalent to 1 lb. of lysimeter weight change. The recorder continuously receives the signal. Each minute, the signal is integrated and the average is recorded and displayed. For calibration purposes the counts were observed on the display while the weights were applied to or removed from the lysimeter.

Results

The final calibration curve, as observed at the output end of the load cell, is shown on Fig. 45. Nonlinearity (including hysteresis) of the relationship between load cell output voltage and weight changes varied from essentially nothing during still dawn hours to 0.3% during windy calibration conditions. It would seem that the



Input Voltage = 15.935 v

$\frac{dv}{dw}$ = .04 mv/lb.

For 84.85 ft^2 lysimeter area
1 mv change = 0.0566 inches
(1.438 mm) water weight change

Fig. 45. Lysimeter calibration curve at load cell.

calibration precautions used would effectively rid the calibration of wind effects. The calibration was done in May, during which time winds were usually accompanied by clouds and electrical action. Perhaps atmospheric electrical noise and local variations in atmospheric pressure could affect the calibration. Table 1 gives an example of values from a calibration performed on the same day. Part A indicates the stable, linear readings with essentially no hysteresis that were obtained at the beginning of the calibration during serene morning conditions. Part B shows the readings toward the end of the calibration during a thunderstorm front that had moved into the area. Hysteresis prior to the turbulent conditions was only a maximum of 0.007 mv, while at the height of the unsettled conditions values reached 0.135 mv. In poundage terms the comparison is 3.4 to 0.2. Similar results were obtained with linearity and during other comparable conditions. Whatever the reasons for this weird phenomenon, the integrating-averaging process of the recorder accounts for it, as will be shown.

The calibration at the recorder was successful, as no adjustments were necessary. There appeared to be an overall error of 1%. For example, for a total weight application of 300 lb. the recorder may indicate 303 lb. However, for small weights of 0.4, 1, 2, 5, and 10 lb., corresponding counts of 1, 2, 4, 10, and 20 were observed. This indicates that the error is equally distributed throughout. Using this same procedure without the stock tank cover during windy conditions confirmed the capability of the recorder to average out

Table 1. Comparison of calibration readings during calm and turbulent conditions.

Weight (lb.)	Readings (mv)		Variation (mv)
	Applying	Removing	
Part A: Calm			
100	30.580	30.578	0.002
120	31.380	31.373	0.007
130	31.777	31.773	0.004
135	31.971	31.970	0.001
137	32.049	32.049	0.000
138	32.089	32.089	0.000
139	32.129	32.126	0.003
139.4	32.144	32.142	0.002
139.6	32.152	32.150	0.002
139.8	32.160	32.160	0.000
Part B: Turbulent			
500	46.540	46.405	0.135
520	47.305	47.202	0.103
530	47.685	47.605	0.080
535	47.870	47.805	0.065
540	48.055	48.000	0.055
542	48.126	48.085	0.041
543	48.156	48.130	0.026
544	48.196	48.170	0.026
545	48.235	48.225	0.010
545.4	48.240	48.240	0.0
545.6	48.248	48.248	0.0
545.8	48.255	48.255	0.0

wind effects during the 1-min integration period. Essentially the same results were obtained.

Throughout the past year of operation an occasional weight was applied to the lysimeter and a visual reading was observed just to assure that a major malfunction had not occurred. Otherwise, the system was allowed to function undisturbed to allow a check on long-term drift. On May 31, 1972, ten months after the preceding calibration at the recorder, another calibration was done. Only the polyethylene cover and snap ring were used. Table 2 gives the results and indicates that no long-term drift occurred. During this 10-month period, frequent visitations to the lysimeter occurred, including inspections of subsurface features. These potential disturbances apparently had no effect on the stability of the lysimeter.

The last calibration was performed on June 21, 1972 following the first malfunction of the lysimeter (discussed later). Upon resuming operation, a calibration, including a check for hysteresis, gave results essentially the same as results from the preceding calibration (Table 2). Thus, the stability of the lysimeter was given more confirmation.

Ultimate sensitivity of the lysimeter, independent of the recorder, was determined during the calibration. Utilizing the precautions described, during still evening conditions when ET had lessened (and without morning dew effects) the potentiometric bridge was used at its maximum sensitivity (e.g., 0.001 mv). The bridge reader in the manhole was able to simultaneously detect a needle movement when a

Table 2. Calibration of the lysimeter following 10 months of continuous operation (July 31, 1972).

Weight Applied (lb.)		Reading (counts)		Time
Increment	Accumulative	Actual	Theoretical	(MST)
0	0	446	446	--
50	50	545	546	0630
--	--	545		0631
50	100	646	646	0633
--	--	647		0634
20	120	686	686	0636
--	--	686		0637
10	130	706	706	0639
5	135	716	716	0641
5	140	727	726	0643
--	--	727		0646
2	142	731	730	0648
1	143	732	732	0650
--	--	733		0651
1	144	735	734	0653
--	--	734		0654
0.4	144.4	735	735	0656
--	--	736		0657
--	--	735		0658
50	194.4	835	835	0700
50	244.4	936		0702
--	--	936	935	0703

quarter (U.S. currency) was placed on the lysimeter. Balancing the bridge indicated that the quarter caused an output signal increase of 0.002 my, or 0.05 lb. Therefore, if the scale counterbalancing function remains constant, detection of an ounce change appears possible. Admittedly, to prove this the surface cover should be sealed at the edges to prevent minute ET losses during calibration.

While 0.05-lb. detection (1 ppm) seems intuitively unreal, due to the many mechanical and electrical components, the author believes that weight detections of 0.2 lb. (1:250,000) are realistic. This means that an ET loss of 0.0005 inches (0.012 mm) is detectable at the load cell. See Appendix I for computations of ET. When considering that a detection of 0.025 mm is desirable for crop studies, an amount of 0.012 mm may prove to be necessary for short-period ET studies of grassland.

Future Calibrations

The frequency of future calibrations is recommended at twice yearly, in April and in October. The type of calibration can simply be by covering the lysimeter with the polyethylene cover and snap ring and observing the visual display of the recorder. The standard weights are kept on a stand near the lysimeter, the ring lies in the grass adjacent to the lysimeter, and the polyethylene material is stored in the recorder trailer. A calm morning or evening is recommended for calibration.

At weekly intervals it is recommended that a few weights be applied to the lysimeter and corresponding counts be observed at the recorder. This rough procedure will guard against major malfunctions that are not always apparent, as will be shown by a case incident in Chapter VII.

Should any of the mechanical or electronic components be replaced, a precise calibration will be necessary. An exception to this might be when replacing the load cell with an identical model (one is stored in the trailer). Upon replacing the cell, it would be worthwhile to perform the simple, routine calibration. It is quick and may indicate that the system is still in order.

The author will soon depart and it is recommended that someone be assigned the responsibility of the lysimeter. Operation and maintenance responsibilities will be discussed in the following chapters.

CHAPTER VI

OPERATION

Operation of the lysimeter is relatively simple and can be divided into two parts--resolution and field procedures. Resolution dictates how the system will be operated and field procedures describe manipulation of the system.

Resolution

Initially, it must be decided what resolution is desired of the lysimeter. This depends on what the researcher may deem necessary for his study. Presently, a resolution of 0.029 mm (1/2 lb.) of equivalent ET is being obtained. This amount was selected rather arbitrarily as being sufficient for initial ET study. Other lysimetric studies have used 0.025 mm as an optimum need for short-term energy studies of crops.

The data recorder is limited in its ability to detect minute voltage changes. A voltage of 0.005 volts can be readily detected. Thus, the amplifier was designed to step up the load cell output voltage by a factor of 250 with a range of 0 to 5 volts. Presently, the excitation voltage into the load cell is being maintained at a rate to cause an output voltage of 0.04 mv/lb. The data recorder, with its capacity of 0 to 1000 counts, accepts the amplifier output voltage at a rate of 0.005 volts (250 × 0.00004) per 1/2 lb. per count. This results in an operation whereby the lysimeter can fluctuate a total of 500 lb. and be detected by the recorder.

To adjust the resolution, all that is necessary is to change the excitation voltage into the load cell. Bear in mind that the finer the resolution, the smaller the total weight range will be. For example, to double the resolution and obtain a sensitivity of 0.014 mm (1/4 lb.), the excitation voltage is adjusted to produce a load cell output voltage of 0.08 mv/lb. The amplifier multiplies (250 × 0.00008) to give 0.02 volts/lb., or 1 volt = 50 lb. With the range of 0 to 5 volts, the result is a weight range of 250 lb. Correspondingly, at the recorder 1000 counts = 250 lb. or 1 count = 0.25 lb. In a similar manner, adjustments could be made so that 1 count = 1 lb., resulting in a weight range of 1000 lb.

There are boundary conditions. The upper boundary is determined by the load cell capacity of 50 lb. With a 20:1 mechanical advantage, a weight fluctuation of the soil container of 1000 lb. is detectable. There is a safety factor due to the manufacturer's overload rating of 250%. Therefore, if a 2000-lb. hereford bull should, somehow, wander across the lysimeter, the load cell would not be ruined.

With the present load cell, there is a maximum excitation voltage that is quoted by the manufacturer--20 volts. Since it presently requires 15.935 volts of excitation to produce an output of 0.04 mv/lb. weight change, it is likely that the 0.08 mv/lb. is not possible. It is recommended that a different load cell with the proper specifications be employed. It is a simple task to remove and remount the flexure and load cell system. Care should be taken when mounting the load cell so that the adjustment nuts are not taken up too tightly by hand, resulting in over-tension of the cell upon release of the counterbalance mechanisms.

The range of detectable weight, 250-500-1000 lb., affects the capacity of the lysimeter to measure rainstorms. A thunderstorm with 1 inch of precipitation could add 441 lb. of water to the lysimeter if total percolation occurred. During the past year of operation, only two storms have exceeded 1 inch of precipitation.

Field Procedures

The primary field operation is to periodically check the data recorder readout to assure that the lysimeter load cell is in its 500-lb. functional range. The numerical display board should be registering between 0 and 1000. In addition, the meter on the recorder should register a needle reading that corresponds to the display count. The needle should also have a floating appearance that reflects the wind-induced motion of the soil container. A still or abruptly changing needle indicates that the soil container may be touching the retainer or that a malfunction is occurring.

The data recorder has 36 channels. Each accumulates a meteorological parameter for 1 min and then records the integrated average on magnetic tape. (More details will be given when data are discussed.) Channel 17 records the lysimeter data. Presently, the recorder is inspected on alternate days of the work week, during which channel 17 is observed. If necessary, the taring mechanisms of the scale are adjusted.

Taring Strategy of the Scale

If the inspector observes normal behavior of the recorder, as described above, and a high count reading (e.g., 800+), he may elect to increase the tare weights so that a reading of 200 to 300 counts is observed. This is particularly true if it is during the rainy spring or early summer when thundershowers occur frequently. Lowering the counts to 200 allows a storm to deposit 400 lb. (nearly an inch) of water on the lysimeter before the counts exceed 1000. However, if the time of year is the dry season during clear, high-pressure days, the count of 800 can be left for two days until the next inspection.

As the count number falls to about 200 and the weather consists of warm, high evaporative days, it is advisable to decrease the tare weights until a count reading of about 500 is observed. If not done, evapotranspiration may occur to the extent that the count reading will fall below zero. This has occurred over a weekend of hot weather following a period of high precipitation and subsequent high soil water conditions.

Fig. 42 illustrates the tare weight mechanisms. To adjust the tare, enter the tunnel, turn on the lights, and carefully lock the bar and move the counterbalance weights accordingly. The 1/2-lb. weight has a range of 1000 lb. while the 10-lb. weight has the capability of counterbalancing all of the soil container. The 1/2-lb. weight has a strip graduated in 10-lb. increments, allowing manual interpolation to approximately 2 lb. The 10-lb. weight does not have a graduated bar but can be adjusted at a rate of 1 5/8 inches = 1000 lb. The amplifier has a meter graduated from 1 to 5 volts to aid in setting the tare. A meter reading of one volt = 100 lb. = 200 counts.

During the rainy season, the weights should be positioned so that the 1/2-lb. weight is near zero. If a large storm should deposit 2 to 3 inches on the lysimeter, the count number on the recorder would exceed 1000. To determine the magnitude of the storm, the 1/2-lb. weight can be moved to tare out sufficient weight to return the recorder to its count range. By noting the amount of increased tare and the new count reading, the pounds of precipitation can be determined. As stated, the 1/2-lb. weight can be set with an accuracy of about 2 lb., which is equivalent to 0.005 inches of precipitation. It is believed that such an accuracy is superior to any standard precipitation gauges on the market.

Conversely, if over an unattended, lengthy time period the recorder count falls below zero, the extent of fall may be determined. First, do not touch the tare weights but apply enough standard weights to the lysimeter surface until the recorder once again indicates that the count number is in the 0 to 1000 range. Observe the amount of weight applied and the new count reading to ascertain the lost reading. If a small rain shower occurs during one of these periods, it would not be detected. Either it would cause the count number to return to range, thereby masking the true low point that had occurred, or it would cause a small undectable rise in the readings.

Care should be taken when operating within the cramped space of the tunnel. While free swinging of the tare bar has occurred without apparent ill effects, it is not recommended practice. The tip of the tare is contained by a steel ring and lock mechanism. The ring was field modified so that it restricts the vertical movement of the tare bar, thus avoiding the possibility of ruining the load cell by accidental jostling.

Upon entering and leaving the tunnel, it is extremely important that the lights are turned off and the manhole cover is secured. Heating of the subsurface areas can result by failing to do either.

CHAPTER VII

MAINTENANCE

This chapter describes routine maintenance, predicts the lifetime and replacement of the lysimeter components, and makes recommendations for purchasing of replacement components. A detailed case study of the sole malfunction and its remedy are included in Appendix II as a guide for repairing future malfunctions.

Routine Maintenance

The lysimeter is relatively maintenance-free; however, there are a few practices that are essential to its good performance. Lubrication of scale mechanisms is recommended every 4 months with a light application of a high grade, low viscosity, non-gumming lubricant (gun oil is one type). For the past year satisfactory performance has been obtained from the lubricant-cleaner-rust inhibitor, 5-56, by CRC Chemicals of Dresher, Pennsylvania, available in most automotive stores. Applied from a spray can, the lubricant readily reaches all of the knife edges and linkages of the scale.

The air gap between the container and retainer rims should be inspected regularly. To avoid condensation of water vapor in the subsurface areas, the gap has not been closed (others have used flexible rebber membranes or grease). Air circulation has prevented condensation, but intrusion of snow, ice, dust, and insect accumulations can occur to cause hanging of the soil container. Using a long-bladed knife (kept in the manhole), the gap can be penetrated to rid it of potential clogging. To date, hanging of the soil container has not been a problem.

Occasional house cleaning is also recommended to rid the tunnel and components of insect accumulations. Buildup of black widow spider populations and debris threatened to take over the load cell at one time, as well as to alarm inspecting scientists.

Lifetime and Replacement of Components

Pursuant to good management of any long-lived research facility, an estimate of the life of the components and of the effort required to replace the components is needed. The components can be categorized into replaceable and non-replaceable items.

Replaceable Components:

1. Load Cell. The manufacturer makes no attempt to predict the life of the load cell, citing variables according to use. Other load cells in similar operations have endured several years. Five years is not unreasonable and is expected of the grassland cell. A replacement is on hand. Mounting of the load cell, referred to under calibration, is quite simple and is apparent upon observation of the system. It is important to remove all of the tension load with the weigh bar prior to removing the load cell.
2. Voltage Supply. The complexity of design and the use of electronic components from various manufacturers result in a warranty of only 1 year. However, precaution and uniformity of use are in effect and should contribute to long life. The raw voltage into the

voltage supply unit is conditioned by a common voltage stabilizing transformer (see circuit diagram of Fig. A-3). Temperature conditions within the tunnel are stable with only gradual changes due to climate. The voltage supply unit is operated at a constant voltage, another factor conducive to long life. Neither the voltage supply or load cell showed functional effects from a recent direct strike by lightning. Based upon these factors, 5 years of continuous operation appears reasonable.

Acquisition of the voltage supply unit is difficult due to the large demand. As yet, a standby unit has not been purchased. Based on performance, it is recommended that a similar unit be purchased. Mounting and operating the unit is relatively easy. Manufacturer's manuals for the load cell, power supplies, and amplifier unit are included with the NREL copy of this paper at Colorado State University.

3. Amplifier System. A 5-year life for the amplifier system is also predicted. Electronic components shown on the design plan (Fig. 40) are normally bench items except for the primary amplifier and power supply. It is recommended that standby units be purchased (see footnotes 4-5, manufacturers). A competent electronics technician can maintain the system utilizing the design plan. The lightning strike, referred to above, did immobilize the amplifier system, but neither the primary amplifier unit or power supply were affected. Details will be given in the case study.
4. Scale. The entire scale has a rust-preventive coating of paint, and condensation is not evident. Therefore, it seems that the

scale warrants assignment of a typical 50-year engineering life. An exception may be the matched knife edges. A total of 18 matched pairs exist (Fig. A-5, A-6, and A-7). The knife edges are made of extremely hard bearing tool steel. Movement of the edges and subsequent grinding are not perceivable. However, bearing does occur and contributes to wearing, resulting in a shorter life of the knife edges. Discussion with the scale people resulted in an estimate of 20 years of effective life. As this is only a guess, discussion on replacement is added.

The knife edges of the counterbalance arms would likely be the first to wear, but are easily and inexpensively replaced. Merely lift and block beneath the tip of the longitudinal beam (below the load cell) to remove the loading from the arms and pivots. The four pairs of knife edges are then removed by pulling the appropriate cotter pins. Purchase of the standard edge blocks can be done quickly from the manufacturer when the need arises.

Replacement of the knife edges beneath the soil container is more difficult. The easiest edges to replace would be those at the end of the two splice arms and transverse lever stands (Fig. A-6). Two low profile 25-ton jacks (purchase or rental) would be needed to simultaneously lift and block the splice arms to remove the load from the hanger rods. One knife edge at each of the four upper pivots is integrally constructed and would necessitate grinding and sharpening; the others can be easily replaced.

Repair of the knife edges at the four main supports would require similar treatments and lifting of the soil container. From experience with jacking the container for positioning within the retainer, the following method is recommended. At three balance points, lift simultaneously with hydraulic jacks, advancing screw jacks as you go for safety. All should be 20-ton capacity. Three steel jack stands were field fabricated and left beneath the container for future lifting.

5. Drainage System. Durability of the materials used in the drainage plates and tubing would seem indefinite (stainless steel plates and tubing, epoxy, plexiglass). Clogging of the plate pores could eventually occur despite the sand packing, but is not anticipated. Also, it is doubtful if water passage will ever occur through the lower soil horizons. This subject will be discussed in Chapter VIII.

   Replacement of the drainage plates would require lifting the soil container out of the retainer and utilizing the methods used originally. The four lift tabs, protrusions of the container cylinder, are 4 inches beneath the surface and are referenced on the rim.

   The plexiglass tank and submersible pump are durable and simple items to replace.

6. Soil Container. The 1-inch steel can be assigned a 50-year life. The noncorrosive characteristics of the soil coupled with the semiarid climate should offer long live. The exterior of the cylinder is treated with lead primer and aluminum, bridge-specification paints. The 1/8-inch rim is treated similarly, including

the inside surface. In addition, the horizontal welds are coated with asphaltic seal.

The most vulnerable area is the container floor. Protective treatment was lost during construction and it is possible that a free water film could prevail on the plate. Rusting through could eventually occur in many years, requiring either patching in place or lifting and replacing.

7. Soil Water and Temperature Monitoring Devices. The neutron access tubes are aluminum with thick steel plugs and will last the life of the project. The temperature diodes are minor and easily replaced.

Non-replaceable components include the retainer, concrete footings, tunnel, and manhole. The author fully expects (hopes) to observe these components in service after 50 years.

The Appendix II case study of the malfunction of the lysimeter concludes the dull but necessary subject of maintenance.

CHAPTER VIII

REPRESENTATIVENESS

While the functional aspects of the lysimeter are highly important, they are of value only if the lysimeter truly represents the prairie grassland. The criteria for representativeness were outlined in Chapter II. Undisturbed installation and unnatural surface area have already been discussed. This chapter will dwell on three other primary criteria--soil water, soil temperature, and plant cover.

Soil Water

In general, the soil water picture of the soil container has varied from full depth saturation (free water) following construction to fairly representative conditions one year later.

An oversight during construction contributed to the initial imbalance of soil water conditions. The bottom plate of the soil container was welded and sealed prior to cutting off the top 20 inches of the container cylinder. Large amounts of cooling water were added to prevent burning during the steel cutting. Despite winter conditions, much of the cooling water may have drained through if the bottom had not been sealed. Water was also applied during the welding of the container rim.

The applied water apparently froze within the container and lay dormant until the spring thaw (elation over discovery of the successful functioning of the drainage system was dimmed by the flooded conditions within the tunnel). The drainage system was allowed to drain by gravity, during which time approximately 125 gal of water were removed. This was followed by application of suction to the outlet line by a simple vacuum pump-bottle system for several weeks. It is estimated that about 1 bar of suction was attainable with the pump. Soil water amounts were reduced to approximately 20% by volume, as detected by neutron probe techniques. Discussions and course work with Dr. Arnold Klute (Professor, Agronomy Department, Colorado State University) (28) revealed that further soil water reduction by pumping would be impractical due to the very large suctions required. Substantiation of this was shown by Van Haveren and Galbraith (1971) (29) in their water retention studies of Ascalon sandy loam. The desorption curves of Fig. A-8 relate the applied matric potential in bars to percent water by volume. A sharp rise of nearly asymptotic nature occurs at about 20%, indicating that beyond that point desorption requires a rapidly increasing amount of work. Pumping was discontinued and the container soil was allowed to dry under natural conditions for the ensuing year.

Soil water amounts, within and outside the lysimeter, were again determined in June 1972, and were found to be in balance for about the top 20 inches of soil. Below 20 inches the in situ soil water leveled off at about 10% moisture by volume while within the container the leveling occurred at about 15%. Fig. 46 compares soil water content at depths within the soil container to those outside the container. The location of the neutron probe access tubes are shown on the same figure. The same types of curves are shown in Fig. 47 for June 7, 1972,

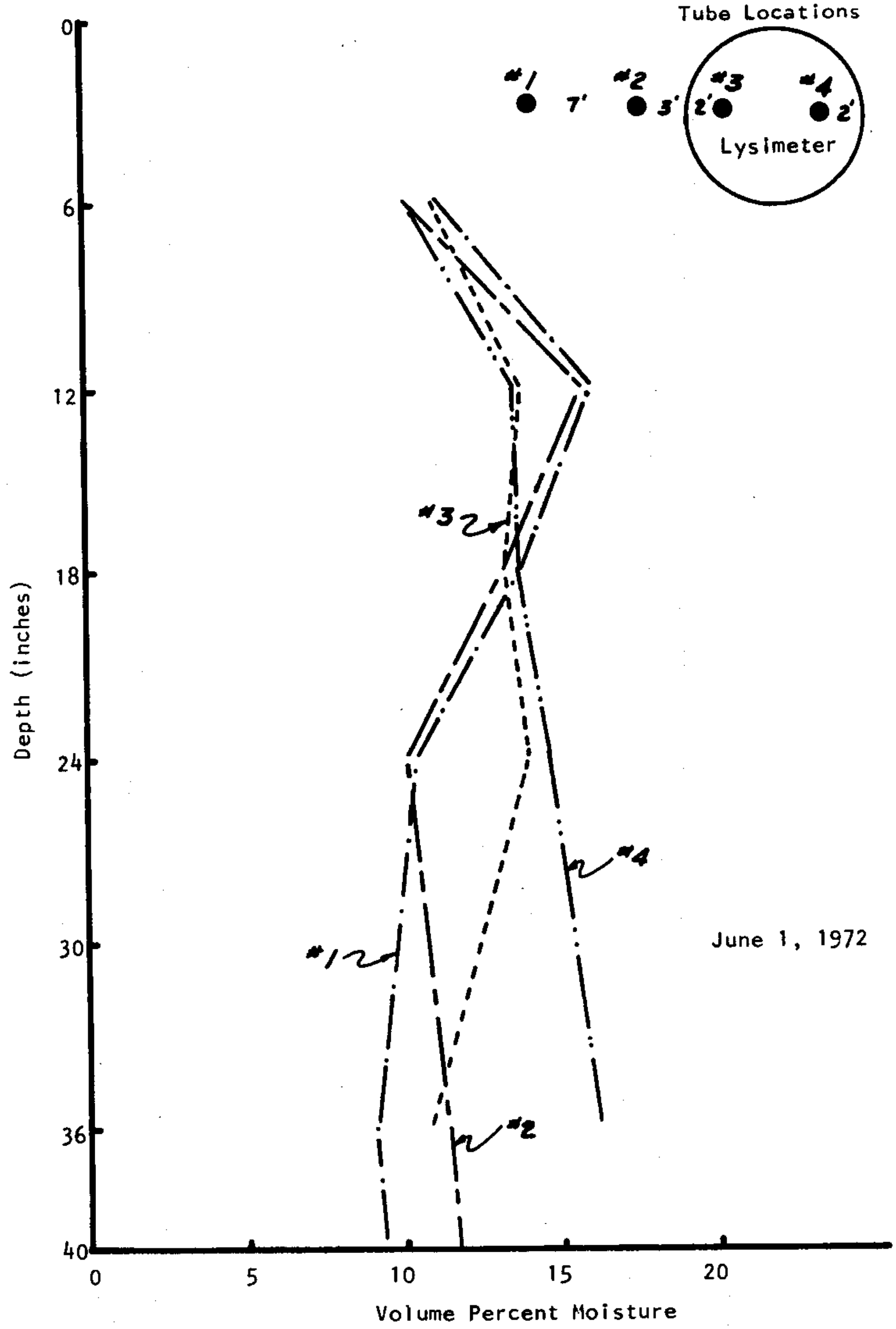


Fig. 46. Soil water content 1 week before 3-inch storm.

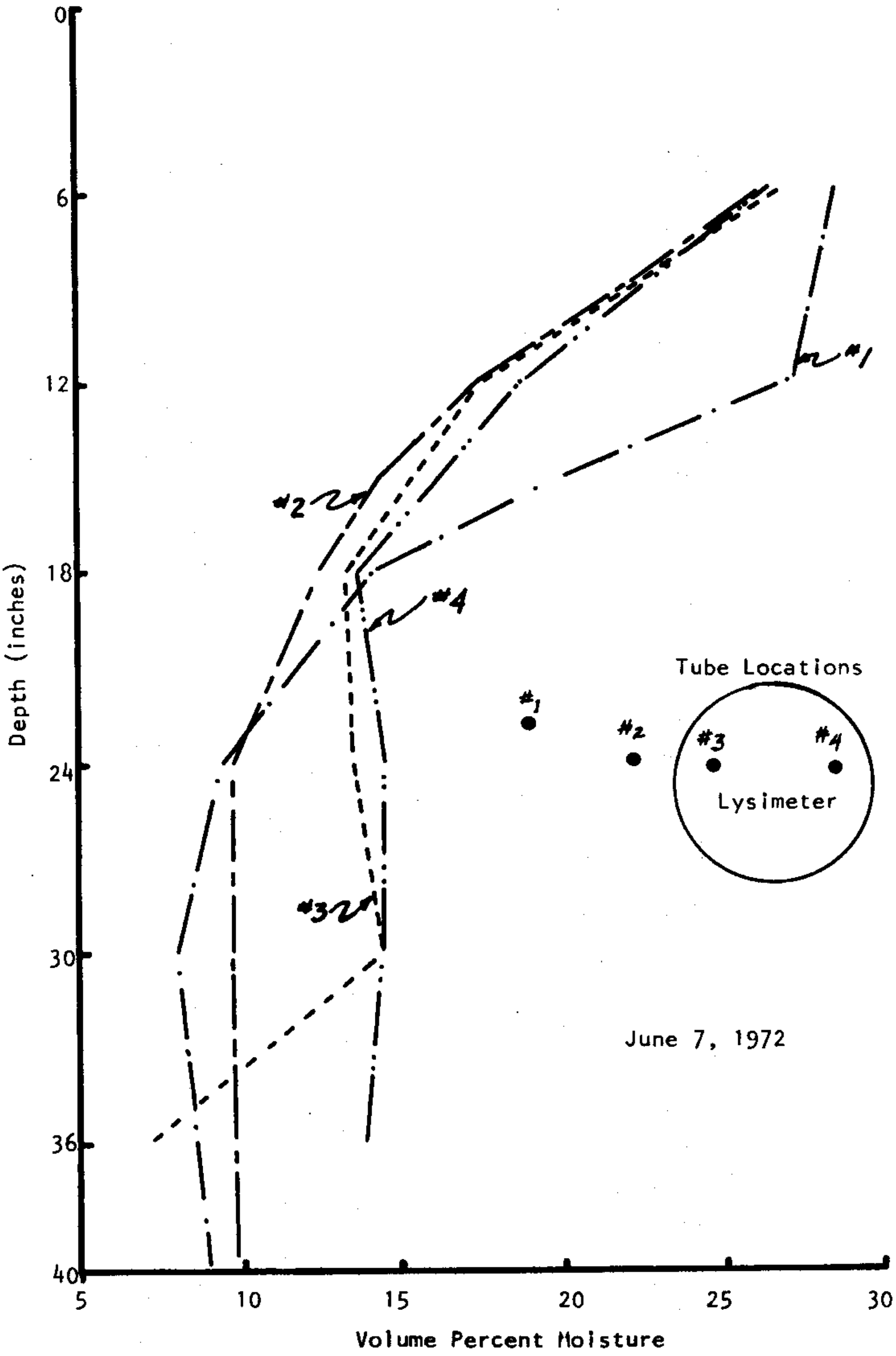


Fig. 47. Soil water content 18 hours after 3-inch storm.

following precipitation of 3 inches. The significance of the curves are that they show no increase in soil water below 15 to 18 inches depth, despite the tremendous magnitude of the storm.

The soil water determinations just discussed were obtained by the author using a Troxler depth moisture gauge and probe. Beginning July 21, 1972, the lysimeter was included in the weekly routine of neutron probe reading of access tubes of the Pawnee Site. The routine is performed using a Nuclear-Chicago scale and moisture probe. Correlation between the two types of instruments has not been done, and future soil water evaluations should limit comparisons to the soil water curves of this paper to trends only and not absolute values.

Two sets of the routine data (7-21-72 and 7-28-72) have been evaluated. In general, the data support the curves of Fig. 46 and 47 and indicate that soil water amounts at lower depths are approaching equality. In addition, the data readings compare favorably in magnitude with corresponding readings of the neutron access tubes of the microwatershed studies of the Pawnee Site.

While the soil water picture looks good, there is cause for wariness. The top 30 cm (12 inches) of the container soil has dried to approximately 2% less soil water (by volume) than surrounding soils. As yet, such comparisons may not be sufficiently significant to establish a trend, but it is recommended that the routine readings be promptly analyzed, lest a trend go unnoticed.

Soil Temperatures

The importance of the thermal regime has been stressed. Presently, the only indicator of thermal stability is the soil temperature profile. Calibrated electrical diodes at depths of 3, 6, 10, 20, 51, and 122 cm offer a temperature profile within the soil container and another outside in nearby soils. The temperatures can be continuously recorded on channels 16 through 5, respectively (odd for lysimeter), of the data recorder. In addition, the author installed metal probe-like temperature sensors at a nearby site. The sensors, at corresponding depths, are connected to surface meters and offer a visual inspection of subsurface temperatures.

The diode profiles were begun in June 1971 and operated through December 1971. The lysimeter profile was discontinued at that time to provide channel space for additional meteorological instruments. The diodes and wire leads are still in place and could be connected in service if the need arises.

Computer output data is available in hourly averages for the full June through December period. Generally, the temperature comparisons between the lysimeter soil and the surrounding in situ soil are good. Typical soil temperature profiles for a hot summer day (August 31, 1971) are shown in Fig. 48 and 49. Likewise, curves for a winter day (December 8, 1971) are given in Fig. 50.

The differences in temperatures at corresponding depths of the two profiles vary from nothing to 4°C, with 1-2 being prevalent. Such variations were observed from soil temperature data taken simultaneously

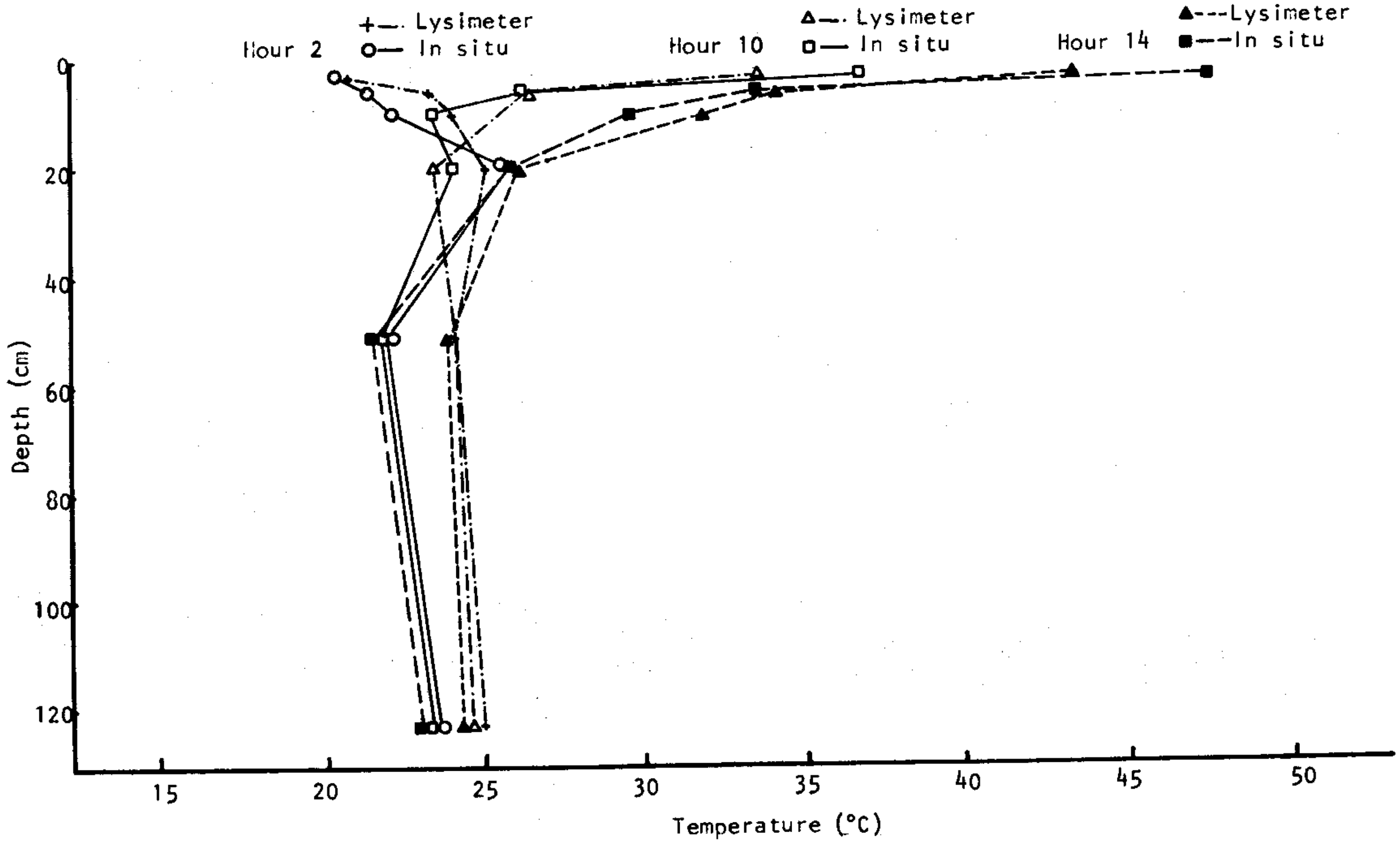


Fig. 48. Soil temperatures, August 31, 1971.

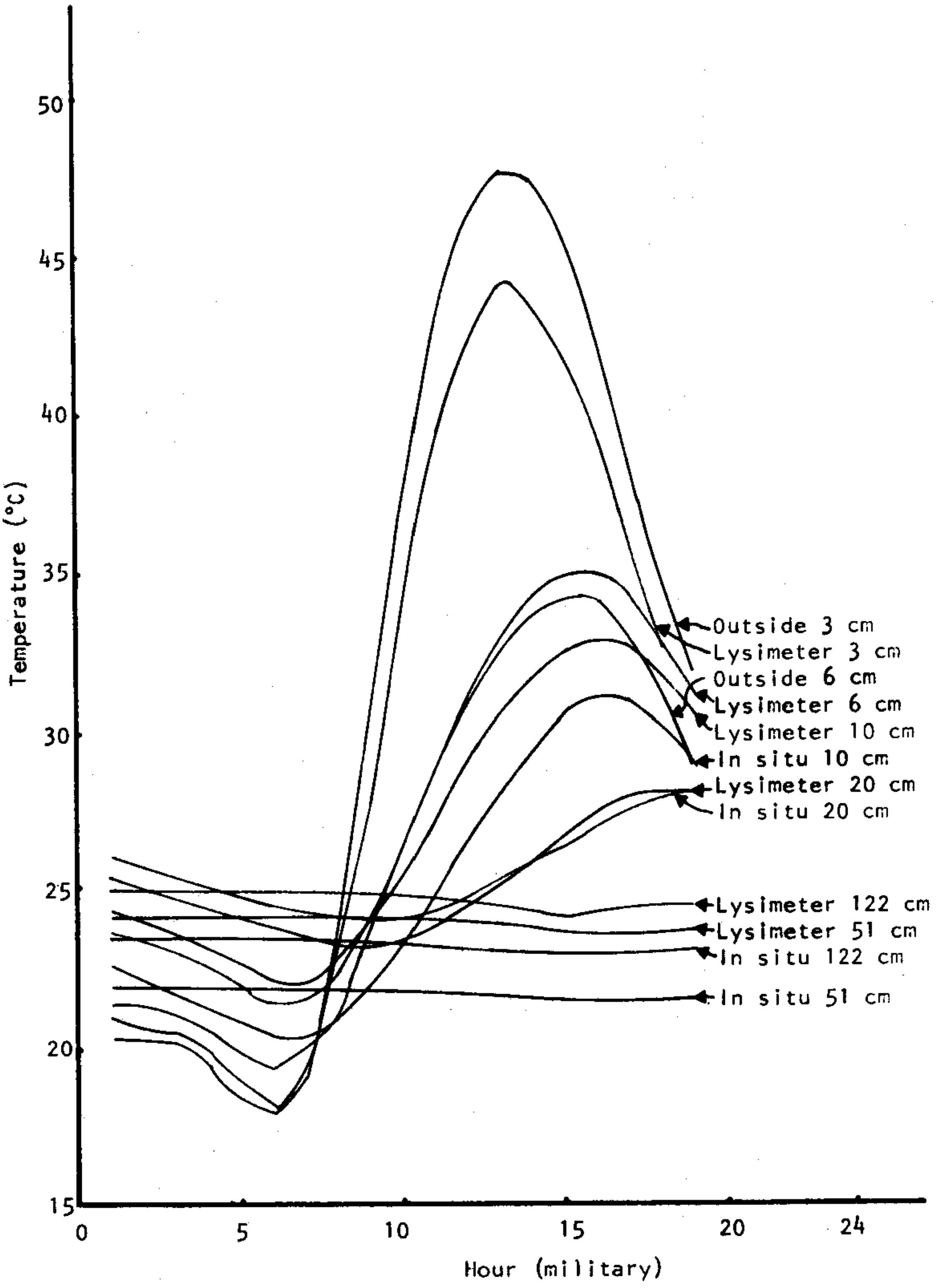


Fig. 49. Soil temperatures, August 31, 1971.

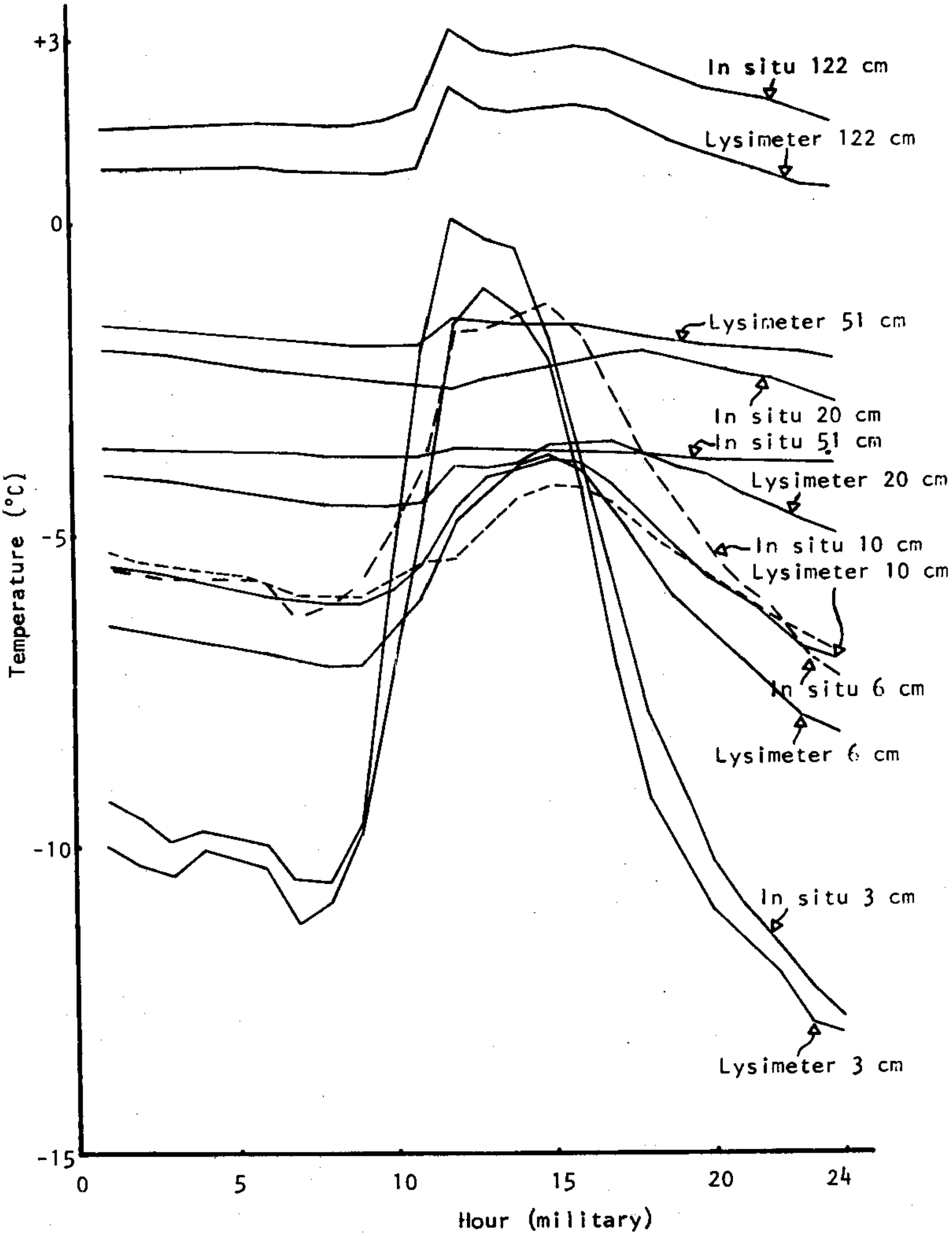


Fig. 50. Soil temperatures, December 8, 1971.

from two in situ profiles in 1970 prior to construction of the lysimeter. Therefore, it is felt that the lysimeter-in situ profile comparison is reasonably good. Of more importance than the recorded temperature differences are the shifts of position of relative magnitude from summer to winter.

Looking at the 51 and 122-cm depths, the summer day profiles show the lysimeter as being constantly warmer by 1 to 2°C. The winter day profiles show the in situ temperatures warmer for 122 cm (½ to 1°C) and colder for the 51-cm depth (2°C). This may be explained by the soil water conditions. Certainly for August 31, 1971, the soil was still very wet, resulting in a higher than normal heat conductivity. Thus, the soil within the container was able to conduct sensible heat more readily than the relatively dry in situ soil, resulting in greater temperatures. Similarly, the 122-cm depth of the container soil is colder for the winter day because of the heat loss induced by the wet conditions. The winter day phenomenon of warmer conditions within the container soil at 51 cm is more puzzling. Both 51-cm depths are at temperatures less than freezing (-1½ to -3°C), while the 122-cm depths are not. Perhaps freezing of the wetter container soil retarded heat loss by conduction, thereby maintaining the 51-cm depth warmer than the corresponding in situ depth. If freezing occurred, it is possible that heat of fusion taken from the soil gas phase may have been entrapped rather than conducted out of the soil block.

Despite the seemingly small differences in the lysimeter and in situ profiles, it would be of value to further examine the temperatures. It is recommended that the lysimeter soil temperature diodes be placed in service for short periods of time. As the lysimeter conditions are now nearing equilibrium, current soil temperatures would aid in substantiating the representativeness of the lysimeter.

The aforementioned sensors with meter readout were frequently observed and compared to the thermometer readings within the tunnel. At depths equal to that of the tunnel, comparable readings were observed. Although far from sophisticated, the comparisons lend further credence to the claim of a balanced thermal regime.

Vegetation

During the 1971 growing season, a difference in plant cover between the lysimeter and the surrounding area was visually apparent. The lysimeter had a more luxuriant cover that persisted through the entire summer. In addition, it appeared that certain plants were in abundance in the lysimeter but were not growing in the surrounds. This growth accelerated the soil water loss from the lysimeter. Drying of the lower levels infers that the root systems penetrated those depths to decrease soil water amounts through consumption and transpiration. Consultations with Dr. Klute (28) supported this premise and added assurance that the nonrepresentative growth and roots would expire when the soil water of the container decreased to natural levels.

The 1972 growing season dawned with drought predictions and apprehensions that the lysimeter would once again stimulate exotic growth. The 3-inch rain storm in early June shattered the prediction, and the prairie and lysimeter bloomed equally. Although the 1972 season has not yet ended, it appears that the plant cover has equilibrated and that the lysimeter is representative of the surrounding grassland.

The vegetation was observed in August (1972) and the following plant conditions were found to be prevalent on the lysimeter. The reader is referred to Dickinson and Baker (1972) (30) for a complete description of plants on the Pawnee Site.

> Basic ground cover of blue grama grass, approximately 120 g/m^2 with considerable amount of greenthread (*Thelesperma filifolium*). Small amounts of red three-awn (*Aristida longiseta*), bottlebrush squirreltail (*Sitanion hystrix*), sand dropseed (*Sporobolus cryptandrus*), threadleaf sedge (*Carex filifolia*), and scarlet globe mallow (*Sphaeralcea coccinea*). Traces of needle and thread (*Stipa comata*), slimflower scurf pea (*Psoralea tenuiflora*), plains pricklypear (*Opuntia polyacantha*), and a single broom snakeweed (*Gutierrezia sarothrae*).

While the plant list serves to add to the overall picture of the lysimeter, notes on root biomass will aid in the summation of representativeness. Smith (1971) (31) reports on root biomass measurements of the Ascalon soils. His studies revealed that 73% of the root biomass was in the top 10 cm, 14% in the 10 to 20-cm layer, 8% in the 20 to 40-cm layer, 2% in the 40 to 60-cm layer, and 3% in the 60 to 80-cm layer. Intuitively, the extent of development of root biomass would reflect the depths of soil most frequented by water. This statement is not to imply that the amount of root biomass and the relative importance to the well-being of the plant are necessarily equal.

Summary

The discussions on soil water, soil temperature, and vegetation lead to the conclusion that the lysimeter is reasonably representative of the grassland. However, there is room for further discussion concerning the lower depths of the soil container. As stated, the lower 2 ft contain more soil water than corresponding in situ depths. It is the author's experience that only by correlation to soil sampling can the water amounts be absolutely determined. Not wishing to sample within the lysimeter for obvious reasons, the relative soil water determinations of the neutron probe are accepted, and an attempt will be made to de-emphasize the importance of the somewhat higher soil water conditions within the bottom of the soil container. This may be academic since the lower depths are approaching comparable soil water profiles. Regardless, delving further into soil water may lend light to later analysis in this paper.

It is generally agreed that soil water activity below the 40-cm depth is quantitatively nil on the Pawnee Site. The 95% plant biomass above that depth seems related. Also, as stated in the soil water discussion, the 3-inch rainfall caused little, if any, increase in soil water at 15 to 18 inches (40 to 47 cm). Prior to the storm, the prairie was generally dry and only minor ponding resulted from the storm. Because of level terrain, runoff at the lysimeter area did not occur to any extent. Despite these conditions and the size of the storm, the soil water increase was limited to about 40 cm. This penetration was measured by neutron probe readings 18 hr after the storm.

Results of exhaustive rainfall simulation experiments and infiltration studies by Smith (1971) (32) give precise soil water information for the major soils of the Pawnee Site, including the Ascalon. Penetration measurements of 8 to 11 inches were prevalent. In addition, gravimetric sampling indicated water content increases to values of 27% near the surface following the simulated rainfalls. These results give integrity to the observations that were made following the lone 3-inch storm upon the lysimeter.

CHAPTER IX

DATA

The data for the lysimeter is obtained through one of 36 channels of the recorder of the meteorological data acquisition system (27). Through channel 17 the counts of 1 to 1000, corresponding to the untared lysimeter weight, are received and recorded on tape. On a continuous basis, 1-min integrated values are stored on the tape. Using a conversion constant (0.0286, as computed in Appendix I), the counts are converted to equivalent millimeters. With the computer, a list of hourly averages has been or will be compiled for each day, beginning August 1, 1971, for the lysimeter. (Two months of previous lysimeter data was voided due to frequent adjustment interruptions.) Printout of data averages for shorter time periods (minimum of 1 min) can be obtained by special request.

An example of computer printout is not shown in this paper as it consists simply of tabulations of millimeters (to nearest hundredth) for the appropriate time. The meteorological parameters are listed simultaneously and, as will be shown, are essential for evapotranspiration (ET) modelling and lysimeter comparison work. To obtain an hourly ET loss or precipitation gain in millimeters, it is necessary to compute the difference between a tabulated number and its succeeding number.

The computer programming encompasses all of the channels and parameters and, therefore, is quite extensive and will not be repeated in this paper. A short procedural description will follow to give the reader an idea of the effort that is entailed in securing the data. The chapter will be concluded with a trace of the data for the period of August through December 1971 and portions of 1972, as dictated by available data.

Data Processing[9]

A computer program was developed to transfer field data obtained on tape at a density of 200 BPI (bits per inch) to another tape with a density of 800 BPI. Introductory comments including type of data, intervals of sampling, and conversion constants were included on the compacted tape. This 800 BPI tape was made in a format compatible with the data analysis routines of the Natural Resource Ecology Laboratory of Colorado State University.

A program entitled "Compact 556" was designed to screen and transfer all data from 200 BPI field tapes to keyed LABEL tapes with a density of 556 BPI. This LABEL tape was necessary to augment modelling efforts where data for specific intervals and averaged over various periods were required. From this program, a list "KEYS" program was developed which indicates each hour when at least one minute's worth of data was recorded. This keyed list is then the basis from which all averaging, plotting, and modelling programs function.

"Average 556" computes averages from a LABEL tape by utilizing the starting and ending times (KEYS) and the interval over which the

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[9] <u>Acknowledgement</u>--Mrs. Alice McColloch, Computer Consultant, and John Nunn, Agricultural Engineering Division, University of Wyoming.

averages are to be computed. The output from this program displays the starting and ending times, the interval which was averaged, and the corresponding averages of data from all 36 channels.

Program "D-Plot" was designed to plot averages over any time period where the number of data points is less than or equal to 100. Each graph may contain 100 data points per plotted channel with a limit of two channels. The control cards must specify the starting and ending times (KEYS) of each plot and which channels are to be plotted (any combination of two from the 36 measured as well as a single channel). All observations that are plotted are printed out previous to each graph to aid in its interpretation.

Processing the LABEL tapes has yielded a set of hourly and daily averages. Verification of all information has been attempted and an informatic data summary sheet, through 1971, was prepared (27). All samples taken are in the process of being or have been compacted at 800 BPI on 1/2-inch magnetic tape. These tapes are available at the Central Data Processing Center at the Natural Resource Ecology Laboratory at Colorado State University. The 200 BPI data field tapes, from which the compacted 800 BPI tapes were made, are located at the Agricultural Engineering Division, University of Wyoming.

Presently, the programs are being modified to encompass the several steps into one program and thereby simplify the obtainment of data. As of this writing, a successful run of the new program has just been accomplished and 1972 data are now becoming available.

Trace of Data and Performance

A continuous trace of the lysimeter data has been done to illustrate the output and check reliability of the data. Although time consuming, hand tracing the data involved a rigorous inspection of all the hourly output values, resulting in an evaluation of the performance of the lysimeter. (In the future, plotting by the computer is recommended.)

In general, the lysimeter system is performing well. Exceptions are down-time periods and recorder malfunctions induced by electrical storms and power failures. These periods are very infrequent and are quickly remedied during the routine inspections of the recorder system. Obvious, unexplained bulls in the data occurred less than 0.10% of the time. Occasionally a 1-min reading, taken from the recorder display during routine inspections, did not agree sufficiently with the hourly average printed by the computer for the corresponding time. This is probably due to the recorder clock which may stray due to power-caused variables. The clock is corrected as need be at the recorder, and adjustment of any erroneous times is done with the computer program. To avoid confusion, the person noting an observation of the recorder display should write down his wristwatch time as well as the time indicated by the recorder. It is also recommended that a daily display reading of the recorder be taken for the lysimeter during the routine reading of the other instruments at the exclosure site.

The data traces were done on a monthly basis with a scale sufficient to plot hourly values at 4-hr intervals for each day. The abscissa represents the total untared weight of the lysimeter in equivalent millimeters. That is, the portion of the total lysimeter weight, monitored by the load cell, is translated to counts at the recorder, is converted to equivalent millimeters, and is plotted directly on the abscissa. Therefore, it is necessary to take the difference of two points on a trace curve to find the gain or loss of water in millimeters over the corresponding time interval.

The seasonal trends and the frequency of adjusting the tare of the scale are readily shown by the traces. The selected functional weight range of 500 lb. for the lysimeter has proven to be workable. The frequency of tare adjustment ranged from four times in June 1972 to 6 months between adjustments during the winter.

Rates of Evapotranspiration

Study of the trace curves reveal apparent trends of evapotranspiration loss by the lysimeter. The trace for August 1971 (Fig. 51) shows a stair-step trend in the early part of the month that indicates little or no ET during the night, followed by a daytime rate of about 2.8 mm/day. The overall rate for the period was about 1.0 mm/day. Following this period, a rain of 4.3 mm (0.17 inch) occurred in an evening and evaporated at a rate of 0.8 mm/day through the night. Daytime conditions brought a loss rate of about 6.5 mm/day for an 8-hr period, after which the ET behavior returned to its leisurely pre-rain pace. During the last half of the month only slight, intermittant showers occurred and the lysimeter sustained a net water loss

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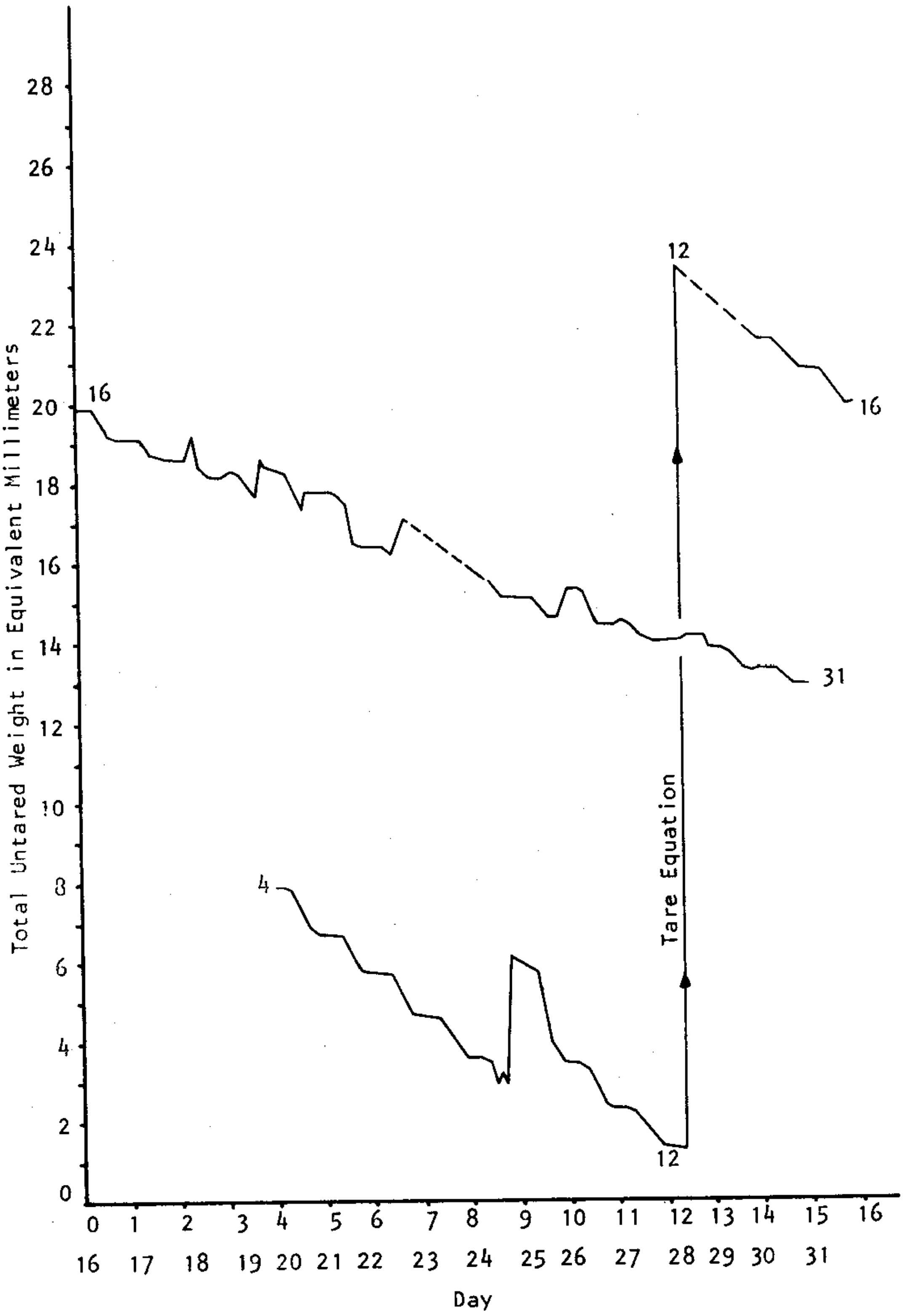

Fig. 51. Lysimeter data trace, August 1971.

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at an overall rate of about 0.5 mm/day, reflecting the increased drying condition of the grassland.

The rapid rate of ET (6.5 mm/day) for the 8 hr following the rain is probably near the maximum rate. Observations of the recorder display taken during the previous months of June and July indicated that the maximum rate of weight loss was 10 counts/hr, which is equivalent to a rate of 6.9 mm/day. The rapid return to the pre-rain rate, referred to above, correlates to the simulated rain studies of Smith (32) who measured soil water tensions at various depths following an application of water. Four hr after the application, the tension at the 10-cm depth rebounded from nothing to 15 bars. Also, the soil temperature at 10 cm remained constant for nearly 5 hr after the application and then began to rise, implying that during this time all the energy was utilized in latent heat of evaporation.

The month of September, 1971 (Fig. 52), was analyzed in a similar manner and supports the trends of August. The initial 2 days of September reflect the dry end of summer with a water loss rate of only 0.4 mm/day. A small rain revived the situation, but not sufficiently to recharge the soil, and the water loss rate returned to 0.5 mm/day within 2 days. The occurrence of three large rains serves to substantiate the existence of a maximum ET rate and to suggest rates that can occur when soil water, to a much lesser extent, is not limiting ET. The first storm deposited 20.32 mm (0.8 inch), creating an ET rate of 6.0 mm/day for about 8 hr following the storm. Thereafter, for a period of 1 week sunny, warm weather prevailed (high temperatures in

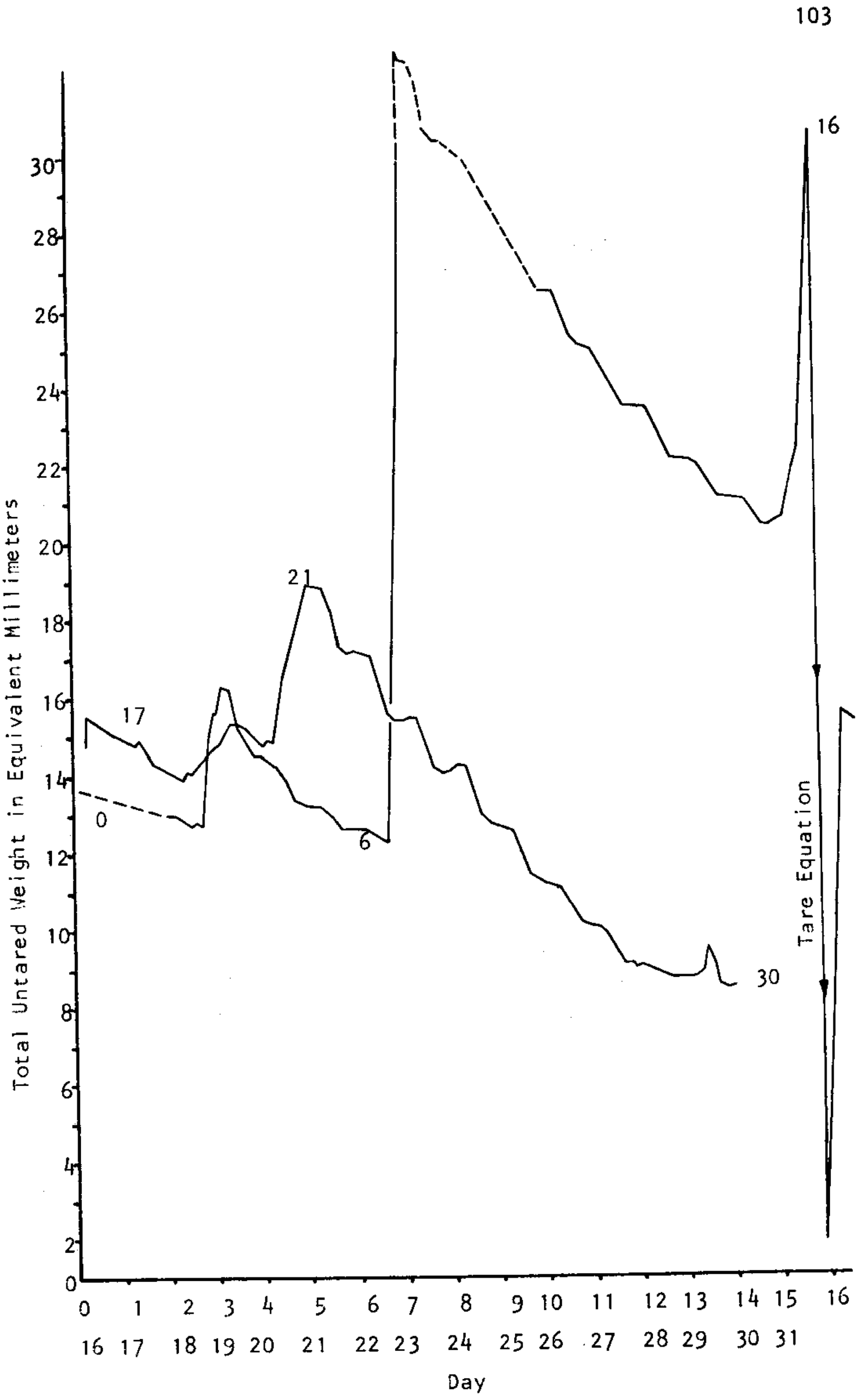

Fig. 52. Lysimeter data trace, September 1971.

the 70's and 80's (°F) and radiation of 520 to 600 langleys/day), and the ET rate was very low at night, 4.3 mm/day during the day and 1.3 overall.

Before drying occurred to reduce the ET rate appreciably, a second storm precipitated 23.56 cm (0.9 inch) of water (including a 4-inch snowfall). Cold temperatures and minor amounts of precipitation followed for 4 days; after which 4.04 mm (.16 inch) of rain fell in one storm. Indian summer prevailed for the remainder of the month. This cumbersome, play-by-play description leads to some apparent conclusions. Despite the addition of another inch of water by the second and third storms, the ET rate and following trend was nearly identical to the period after the first storm. This may suggest that under September conditions the maximum prevailing ET rate is about 4.3 mm/day. Immediately following the rains, the 6.0 mm/day figure (slightly less than August) was evident.

The curves for October, November, and December reflect the decreasing amount of solar energy available and show the resulting decrease in water loss rates to only 0.1 mm/day during the first half of December and to a nearly horizontal curve for the last half. The traces for these months are contained in Fig. A-8, A-9, and A-10.

A final note to this chapter is provided by the initial 2 weeks of data output for 1972. A trace curve was done for the period July 24 to August 6, 1972, to compare ET trends with those of 1 year previous. It was thought that such a comparison might reflect the greater soil water conditions prevalent in the lysimeter in 1971. Fig. 53 depicts

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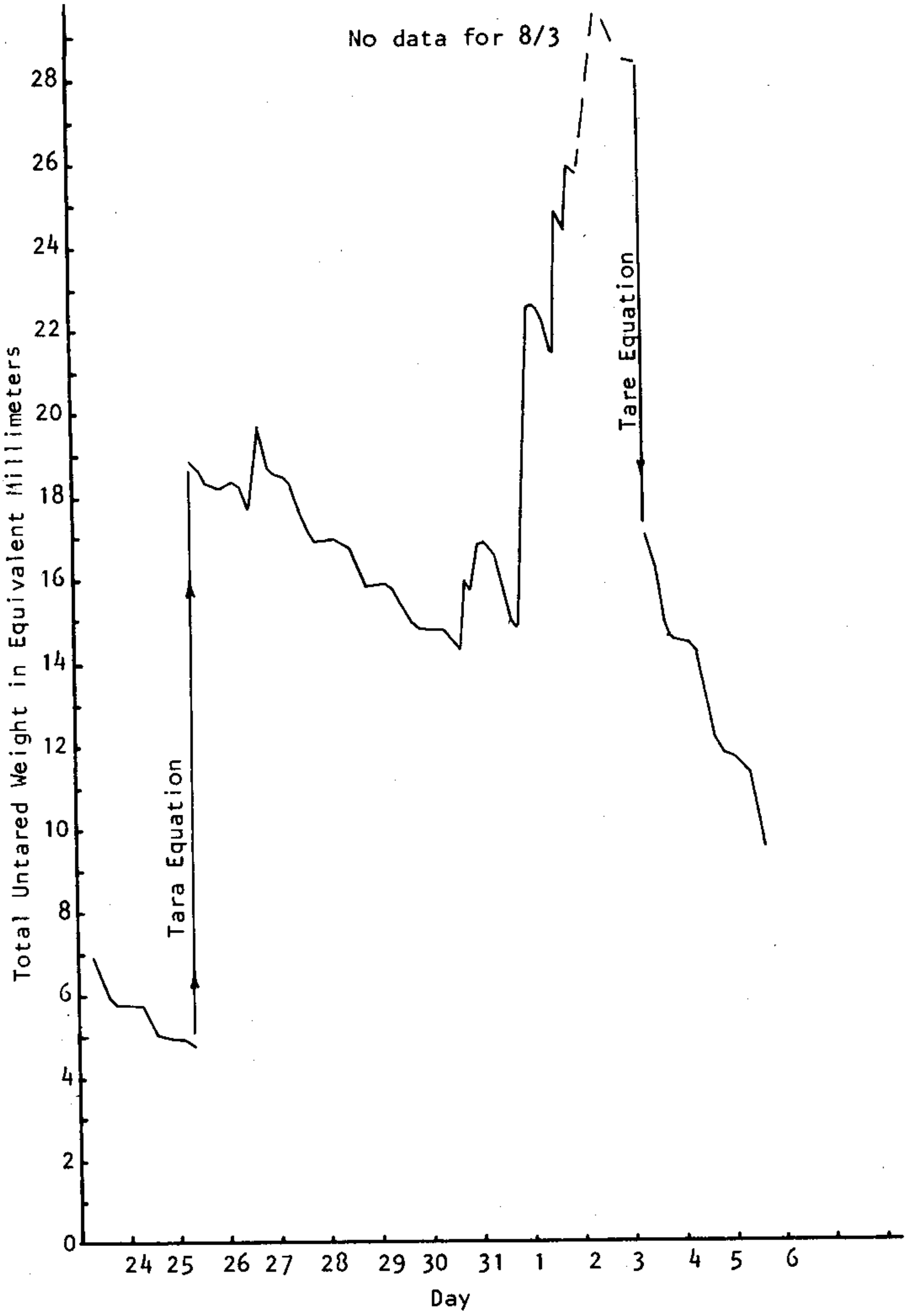

Fig. 53. Lysimeter data trace, July 24-August 6, 1972.

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the trace curve for this period and gives trends that parallel those of 1 year previous.

The first week was characterized by a daytime water loss rate of 3.0 mm/day, which compares favorably to the corresponding rate of 2.8 mm/day 1 year earlier (Fig. 51). Precipitation (approximately 0.6 inches) occurred in the form of light drizzle in the initial 2 days of the second week. Foggy, overcast conditions and high temperatures in the 50's (°F) prevailed--described colloquially as a "soaker." Following this soaker, sunny conditions returned and, for 3 days of data, daytime water loss rates were at 6.0 mm/day (a familiar number).

Soil water conditions during the 6.0 mm/day rate were probably at a state which nearly approaches a potential ET condition. Limitation of ET by available soil water was likely at the lowest attainable during this period. Future ET modelling efforts would do well to keep this number in mind when playing with potential ET.

CHAPTER X

SOME APPLICATIONS OF THE DATA

Within this chapter, the lysimeter data will be used to compare and explore in four study areas. Comparisons will be made to the data of the rain gauges, the evaporation pan, and the microwatersheds of the Pawnee Site. Following the comparisons to the rain gauges, a discussion of small rainstorms will be given. Finally, a superficial look into the exhaustive area of evapotranspiration modelling will be made.

Comparison to Rain Gauges

The dependence upon the standard U.S. Weather Bureau storage gauge for determination of precipitation is well known. Data from the network of gauges are used in all facets of hydrologic studies. Design storms for hydraulic works and forecasts and planning for agriculture pursuits are based largely upon the information of the standard gauge. In the semiarid grasslands the delicate soil water balance has been repeatedly stated to be the most important limiting factor regulating biological activity.

There is a need, then, for an accurate and dependable means of measuring precipitation, particularly for a precise inflow-outflow water budget analysis. The standard storage gauge does not meet these demands. Comparisons of the lysimeter data to the rain gauge data was done in two ways. First, for the 1971 data the comparison was made to a rain gauge situated at the Pawnee Site headquarters which, unfortunately, is a mile away from the lysimeter. Secondly, for 1972 a standard rain gauge was installed near the lysimeter and connected to the meteorological acquisition system for continuous precipitation monitoring.

Rain Gauge at Pawnee Headquarters

Table A-4 compares data from the rain gauge at headquarters to data from the lysimeter. The distance between the lysimeter and the rain gauge and the periods of missing lysimeter data cause a comparison of monthly totals to be meaningless. For the two large storm fronts of September 7-8 and September 16-17, the lysimeter measured lesser amounts. Using the lysimeter figure as a base, the difference was 7.3% and 4.3%, respectively.

While the comparison of totals can be "bullet riddled," the frequency of the detection of rains becomes apparent. Despite 7 days of missing data for the month of August, the lysimeter detected 12 rains compared to four by the rain gauge. This cannot be explained strictly by spatial variations. It appears, then, that the rain guage is not able to detect small rains and that a certain amount of a rain is used to charge the gauge before accumulation and measurement can occur. The coincident 1972 measurements of the rain gauge of the meteorological system and of the lysimeter should determine the relationship between the two.

Rain Gauge of the Meteorological System

As of this writing, only 2 weeks of 1972 data have hurdled the modified computer procedure, and therefore a complete comparison between the rain gauge and the lysimeter is not possible. However, the 2 weeks of data contain several small rains, and two other rains were observed at the data recorder as they actually occurred. These rains will serve to exemplify the comparison; and if or when further 1972 data becomes available, it will be used for confirmation.

On May 19, 1972, a small rain occurred in the early afternoon. During a 16-minute period a net total of 0.83 mm (0.03 inch) of rain fell on the Pawnee exclosure area. Table A-5 gives the actual readings that were observed at the recorder. Alternate times for channels 17 and 35 were required since only one channel can be shown on the visual display board. The results are simply that the lysimeter was visually seen to respond to the light rain, while the standard rain gauge gave no indication of the rain.

A more convincing comparison was made from the 2 weeks of coincident data. Table 3 shows that a rain of 2.07 mm (0.08 inch) went unnoticed by the rain gauge, and that only 17% of a 3.58-mm (0.14 inch) rain was detected. In other words, the rain would have been reported on a weather report as only 0.02 inches, a sevenfold error.

The data indicate that approximately 3 mm of rain are needed to charge or overcome surface tension forces of the rain gauge receptacle. Note that on August 2 the rain gauge detected 89% of a small rain of 1.62 mm. This is explained by the foggy, high humidity conditions that

Table 3. Comparison of precipitation measurements of the standard rain gauge of the meteorological system to coincident readings of the lysimeter (July 24-August 6, 1972).

Date	Channel 17 Lysimeter (mm)	Channel 35 Rain Gauge (mm)	Difference[a] (percent)
July 27	0.09	none	--
27	2.07	none	--
31	1.66	none	--
31	1.03	none	--
August 1	7.73	5.53	28.5
2	3.58	0.60	83.2
2	1.62	1.44	11.1
Totals	17.78	7.57	57.4

[a] As percent of lysimeter value.

persisted and the 3.58-mm rain that occurred 4 hours earlier. The rain gauge receptacle was still moist and cool, thereby allowing more efficient detection of the second rain.

Discussion of Small Rains

While it is true that the relatively few heavy rain storms of 1 inch or greater cause the greatest fluctuations and recharge of soil water, the frequent light showers are likely to be the life-perpetuating factor on the grassland. One has only to experience several days of seemingly rainless, hot summer days with high surface temperatures to marvel at the ability of the grassland to survive. Surface temperatures, though not recorded on the Pawnee Site, are reported by Geiger (1966) (33) as having reached 50 to 60°C in Europe. Correlating to the 3-cm depth temperatures of nearly 40°C observed by the Pawnee meteorological system, surface temperatures as high as 60°C (140°F) might be expected.

A better appreciation of a rain of only 3 mm can be gained by playing with numbers. Such a rain will deposit 52 lb. or 6.3 gal of water on the lysimeter and 26,800 lb. or 3210 gal on an acre of land. Such figures seem appreciable, and yet they may go unnoticed by the standard rain gauge.

As stated by Smith (31), "conventional wisdom about the availability of soil water to plants says that, nominally, growth and photosynthesis begin to be curtailed when soil water tension exceeds 2 bars and proceeds very slowly after 15 bars." In light of the high soil tension values that prevail during summer periods in the semiarid prairie, one can suppose that the frequent light rain showers are crucial to the grassland and should be included in studies of soil-water-plant relationships.

Comparison to Evaporation Pan

A standard U.S. Weather Bureau Class A pan functions continuously within the fenced exclosure that contains the lysimeter and the meteorological instruments. The pan is read daily in the evening, and the data are reported on monthly weather reports for the Pawnee Site. Two periods, one in the spring and the other in midsummer, have been selected for comparison of the pan evaporation to water losses of the lysimeter. Both periods are characterized by rainless days followed by days with rainfall, thus the effect of available soil water can be observed.

The comparison of data is given in Table A-6 and a summary is illustrated by Fig. 54. Although no obvious correlations appear, the curves do offer an answer to a question frequently asked of the author, "What sort of relationship exists between the lysimeter and the pan?" As would be expected, the availability of soil water dictates the results of the comparison. Following the soaking drizzle of August 1-3, 1972, the water loss from the lysimeter was 87% of the pan evaporation. In contrast, during typical, dry summer periods the ratio falls to approximately 0.10.

Few phases of the hydrologic cycle have been so extensively investigated as evaporation. Much of this investigation has been done

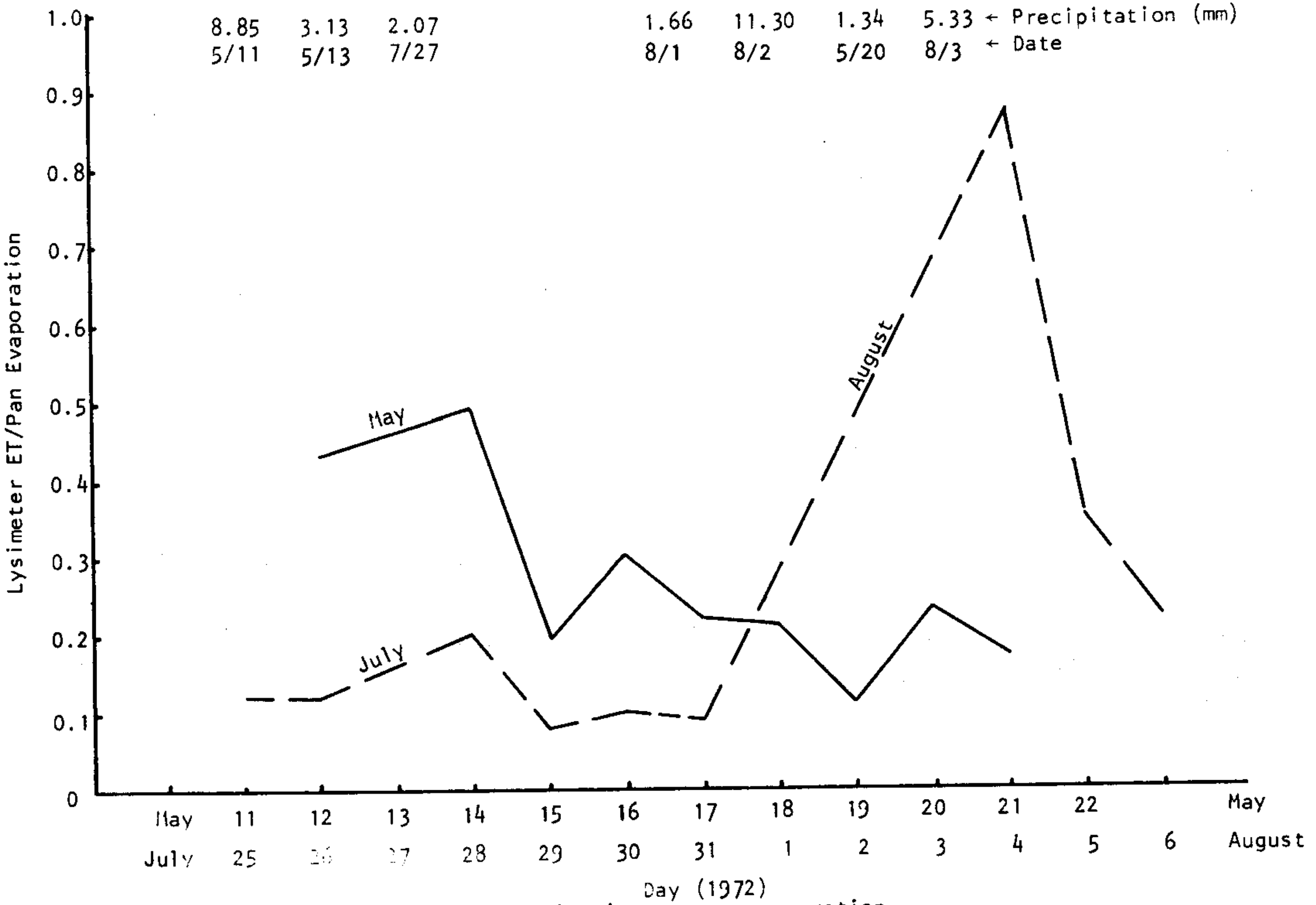

Fig. 54. Daily ratios of lysimeter evapotranspiration to pan evaporation.

with evaporation pans, which has yielded many general relationships of evaporation to temperature, month, elevation, geographical location, and vegetation. The hydrologist is often concerned with total water losses and must consider evaporative losses. Perhaps the Grassland Biome lysimeter offers a means by which correlations can be derived that will make the evaporation pan a better tool to predict actual soil water losses.

Comparison to Microwatershed Data

One of the major field experiments for hydrologic studies on the Pawnee Site is the series of microwatersheds described by Smith and Striffler (1969) (34). Eight watersheds are located in sections 23 and 15, approximately 1 mile northeast to 2 miles north of the lysimeter (Fig. 1). The eight sites represent various range uses and topography, but all are constructed in Ascalon soils similar to the lysimeter soil. Extensive soil water studies have been and are being conducted with the microwatersheds. See Galbraith (1969) (35) and Van Haveren (1971) (29) for details of published work done to date.

Utilizing neutron probe techniques, the soil water status of the watersheds has been monitored. Periodically, the amount of soil water present within various depth intervals of the soil is determined from neutron readings of 10 access tubes in each watershed. A mean value of the 10 tubes is computed for each depth interval for each watershed. Summing the interval means for the top 120 cm of soil depth (equal to the depth of the lysimeter soil core), a total amount of centimeters of water for each watershed is computed. Table A-7 gives the mean values for portions of the years 1971 and 1972. An average of the eight watersheds for each determination date has been computed as an areal average. The differences between successive areal averages were then compared to corresponding periods of lysimeter water loss. Table 4 gives results of the comparison, which is surprisingly good. The two periods of 1972 varied only 4%. A last minute attempt to obtain more summer of 1972 data to continue this comparison proved fruitless. However, the limited data does give cause for optimism, and continued study into the lysimeter-microwatershed relationship is recommended. It is also suggested that the total soil water amounts within the upper 40 cm of the microwatersheds be compared to the lysimeter data to further the claim that most of the soil water activity occurs in this upper regime.

Calibration of Neutron Probe Equipment

The comparison of the lysimeter to neutron probe data suggests still another area for the lysimeter. Calibration of neutron probe equipment has received considerable research in recent years. This author spent many hours with the highway research group at the University of Wyoming constructing standards and calibrating nuclear scalers and probes. Calibration efforts have been extensive on the Pawnee Site, and much of the soil water investigation is being based upon the integrity of these calibrations. Included have been tedious endeavors of calibrating within actual soil conditions.

Utilizing the two access tubes within the lysimeter, soil water changes could be determined with the neutron probe and compared

Table 4. Change in soil water contained in upper 120 cm of soil as shown by microwatersheds and lysimeter.

Date	Change in Soil Water (cm)	
	Lysimeter	Microwatersheds[a]
July 26, 1971	-1.52	-1.15
August 10, 1971	-0.93	-0.28
August 24, 1971	+1.17	+3.1
September 10, 1971	+1.11	+0.58
September 26, 1971	-1.45	-1.27
November 7, 1971		
April 20, 1972	+0.93	+0.89
May 15, 1972	--	--
June 15, 1972	-3.05	-3.14
June 27, 1972		

[a] Areal average for eight watersheds.

directly to the lysimeter changes. The two aluminum tubes are stopped at the bottom end with a steel plug, which is double grooved to allow crimping of the tube. Epoxy and silicone treatments were added to deter water intrusion. The soil bores were done carefully by hand resulting in a tight fit of the tube, the installation of which required an application of a tension force via the bottom plug. In short, it is believed that the quality of installation is sufficient to facilitate calibration of the neutron equipement.

Wright (1971) (36) has utilized hydraulic lysimeters and neutron scatter techniques to draw correlations in measuring evapotranspiration from semiarid rangelands in eastern Montana. Using a budget approach, Wright has demonstrated that neutron methods can be useful for determination of ET under semiarid conditions, provided that correlation to lysimetry is first obtained. Using the more precise Grassland Biome lysimeter, similar correlations could be developed at the Pawnee Intensive Site for application to general rangeland use.

Evapotranspiration Modelling

As indicated by the title of this paper, the development of the Grassland Biome lysimeter has one dominant purpose--to provide a means of developing a mathematical model to predict evapotranspiration. Utilizing the meteorological parameters of Table A-8, it is hoped that models can be developed (and confirmed with the lysimeter) that will have general application to the semiarid grasslands of the world. Initially, correlations will be made to the nine satellite comprehensive IBP Grassland Biome sites of the western United States.

The scope of such an endeaver is obvious and will lead to several theses and papers. It had been hoped that groundwork and preliminary modelling could be achieved in this thesis. However, limited time and availability of the data have reduced this hope to the cursory treatment that will follow. Modification of the meteorological acquisition system to include parameters necessary for ET modelling was done in the late spring of 1972, and de-bugging of the various instruments is nearing completion. The severe electrical storm of mid-June burned several of the instruments and components of the data recorder, but it appears that operations are nearly ripe for modelling of ET.

History is full of a variety of studies pertaining to ET. Beginning with Keen's, "The Evaporation of Water from Soil," in 1914, 241 selected references are listed in a review of evapotranspiration by Rosenberg (1968) (37). Despite the voluminous writings that exist on ET, only a few have dealt with arid regions, and essentially none have involved natural grassland. Efforts to date have been oriented toward crops under irrigated or humid environments. In addition, modelling has primarily dealt with potential ET, defined as the ET when soil water is not limiting.

At this point, an orderly and lengthy review of ET literature would be in order. In addition to providing a base of departure, the literature would provide models that offer skeletal applications to modelling of the grassland. Modification and refinement of these potential models will likely require repetitious trial and error attempts requiring the use of the computer. Such attempts are beyond the scope of this paper. For review, the reader is directed to the aforementioned publication by Rosenberg (37), and to Tanner (1967) (38).

Three general types of evaporation and ET models are agreed upon by soil scientists: (1) the water balance or hydrologic methods, (2) micrometeorological methods, and (3) empirical methods. The water balance method is an input-output budget method that is being used with the microwatershed experiments previously discussed. The micrometeorological methods in greatest use are the profile methods (also called aerodynamic or mass transport methods), the energy balance method, and combinations of each. Tanner describes empirical methods as formulas relating climatological measurements and evapotranspiration. These relations usually apply to a given locale, vegetation, stage of crop development, and season. "Constants" in the formulas frequently must be changed to meet changes in these variables. Empirical methods are based on radiation, mean temperature, saturation deficit-wind product, water tanks and pans, and atmometers.

Micrometeorological methods appear to be favored, providing that funding allows the purchase of the costly instruments necessary for the precise parameter measurements. A profile method, as described by Pasquill (1950) (39), was one of several methods that were used in a rudimentary attempt to illustrate potential modelling approaches. A description of the method and results obtained are included in Appendix III. While this example may appear to be an exercise in futility, it does demonstrate the formidable task that is represented by ET modelling.

CHAPTER XI

CONCLUSION

The development of the lysimeter for the Grassland Biome of the International Biological Program has been accomplished. The lysimeter, because of its undisturbed installation qualities and setting within a natural ecosystem, is unique in the world.

Characteristics of the lysimeter (e.g., sensitivity, ratio of unnatural to natural surface areas) rank with the best lysimeters in existence. A year of continuous operation has proven the stability, reliability, and performance of the lysimeter.

Of great importance to any designed system are operation and maintenance. Simplicity of operation and minimal maintenance cause the lysimeter to be an easy tool with which to work.

Finally, the lysimeter has been shown to be representative of the grassland. This feature and the success of preliminary data analysis are indicators of future contributions of the lysimeter to the grassland study effort.

The abiotic measurements of the Pawnee Intensive Site have contributed much to the understanding of the energy-dependent biological processes of the grassland. The lysimeter will fill the gaps and greatly aid in attaining a complete understanding.

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APPENDIX I

COMPUTATIONS FOR EVAPOTRANSPIRATION

1. Surface Area of Lysimeter

   a) I.D. of retainer = 10.500 ft

   b) Thickness of 20 gauge sheet metal rim = 0.0375 inch

   c) Assume average air gap = 3/8 inch

   d) Thickness of container rim = 1/8 inch

   e) Summation of b), c), and d) × 2 = 1.2750 inch = 0.1062 ft

   f) Diameter of soil = 10.5000 - 0.1062 = 10.3938 ft

   g) Area of soil = 84.848 ft^2

   h) Area of retainer using I.D. = 86.590 ft^2

   i) Unnatural area = 1.742/84.848 × 100

   = 2.05%

2. Output Voltage

   a) At load cell 0.04 mv/lb. of weight change

   therefore, 1.00 mv/25 lb. of weight change

   b) At amplifier 250 × 0.0004 volts = 0.01 volts/lb.

   therefore, 1 volt = 100 lb.

3. Equivalent Weight Change in Water

   a) For 1 lb. of change:

$$\frac{1 \text{ lb.} \times 12 \text{ inches/ft}}{84.848 \text{ ft}^2 \times 62.43 \text{ lb./ft}^3} = 0.002265 \text{ inches or } 0.0575 \text{ mm}$$

   b) For 0.2 lb. = 0.000453 inches or 0.0115 mm

   c) Recorder: 2 counts = 1 lb. = 0.002265 inches or 0.0575 mm

   1 count = $\frac{1}{2}$ lb. = 0.001133 inches or 0.0287 mm

APPENDIX II

CASE STUDY OF LYSIMETER MALFUNCTION

After one year of continuous and accurate operation, the lysimeter malfunctioned on June 10, 1972. A severe electrical storm pelted the region with hail and lightening. It is believed that the recorder trailer, meteorological instruments, and lysimeter absorbed a direct strike by lightening. Severity of the strike was verified by charred electronic parts in the recorder, several scorched instruments, and burned outlets in the trailer.

Detection of the lysimeter malfunction went unnoticed during the routine recorder inspection, which emphasizes the need to scrutinize the recorder meter and counter. Examination by the author revealed that the meter needle was fixed and the recorder counts were erratic. Inspection of the tunnel confirmed the trouble, as the weigh bar had been exceeded, yet the amplifier was showing 1½ volts (equal to 300 counts). Manipulation of the weigh bar did not induce movement of the meter needle. Unfortunately, a rare 3-inch storm was missed by the lysimeter. However, some consolation was derived from the fact that the failure was due to a blown integrated circuit amplifier in the amplifier system, and no damage occurred to the Sorensen voltage supply unit, the load cell, or the main amplifier unit and its voltage supply.

Determination of the reason for malfunction is outlined in the following steps.

1. Check output voltage of the Sorensen voltage supply unit with a digital voltmeter (DVM). For this case, the supply was set for 15.935 volts of output, and the DVM read 15.9 volts; therefore the supply unit was all right.
2. Check output voltage of load cell at input line to amplifier system. The electrical plug on the face of the amplifier box contains both the input line to and the output line from the amplifier. The pins on the plug are stamped with identification letters: E is output and common to ground A; D is input and common to ground C. Using the DVM, check for varying load cell output voltage as the weigh bar is manipulated up and down. A down movement should have a corresponding voltage decrease and vice-versa. For the case study, the procedure checked okay.
3. Set the 10-lb. tare weight so that the weigh bar is a little above the middle of the tip ring with the 1/2-lb. weight at zero. Allow the bar to stabilize as much as possible and try to get an average reading of the rapidly fluctuating DVM display. (This may be difficult if windy conditions prevail.) Then move the 1/2-lb. weight sequentially in 100-lb. increments on the graduated strip, obtaining an average reading at each increment. A decreasing linear trend of the millivolt output should appear at a rate of 4 mv/100 lb. For this case, the load cell reacted favorably.
4. By similar testing the amplifier system can be checked. However, by elimination it was apparent that the amplifier

system was the culprit. The amplifier box was unbolted from the wall and dismantled on the electronic work bench of the trailer.

5. Refer to the amplifier design sheet (Fig. 40) and to the manufacturer's (Burr-Brown) literature. First check the output of the power supply (B-B 527 unit) for ±15 volts (okay for the case study). Next, check the chopper stabilized amplifier unit (B-B 3355/25). It is necessary to provide an input voltage into the unit from a precision voltage source such as a Fluke instrument, or as in this case, the Portametric potentiometric bridge served as a voltage supply. Supplying 10 mv to the input pins (described in step 2 as D and C) resulted in a direct output reading from the 3355/25 unit of 2.5 volts. Recall the gain is 250, therefore the amplifier unit was functioning properly. Satisfied that the primary components of the amplifier system were all right, the minor components were checked as follows.
6. Check the two zener diodes, IN823 and IN757, for voltages of 6.2 volts and 9.0 volts, respectively. Affirmative. By elimination, the 747 unit was determined to be in need of replacement. The 747 was removed and replaced by a new unit (cost $4), and the entire amplifier system was remounted in the box.
7. Providing an input voltage into the amplifier system and checking the system output indicated that the magic box was

once again providing the 250 amplification. Very minor offset adjustment was necessary.

Checks at the recorder were also made and generally include the unity gain offset amplifier in the card rack for channel 17, the card labeled "lysimeter." (Detailed descriptions and design drawings of the data recorder are contained in an unfinished thesis by John Nunn, Agricultural Engineering Division, University of Wyoming.) Check for unity gain and zero volts offset with the lysimeter data output line from the tunnel amplifier system disconnected and shorted out at the lysimeter. This is to insure that any induced voltages into the line can be trimmed out at the recording system.

Upon insertion of the amplifier into the lysimeter system, the standard weight-count calibration should be done.

One last word on maintenance of the lysimeter concerns consultation in the event of puzzling trouble. The author recommends George Twitchell, Electronics Technician, Mechanical Engineering Department, University of Wyoming. Mr. Twitchell has considerable first-hand experience with the data recorder and accompanied the author on much of the lysimeter work.

APPENDIX III

EXAMPLE OF A MICROMETEOROLOGICAL METHOD FOR DETERMINING EVAPORATION

Beginning with some basic theory, the increase of wind speed over an extended uniform surface is represented by

$$u = \frac{u_*}{k} \ln \frac{z-d}{z_o} \qquad (1)$$

when the atmosphere is near a state of neutral stability. (Corrections for stability are applied at the end of the computations.) u is the velocity at height z aboveground, z_o is a roughness constant, d is needed to allow for the effect of the vegetation in effectively displacing ground level upward, k is a universal constant of von Karman = 0.41, and u_* is a constant of the particular profile, given by

$$u_*^2 = \frac{\tau}{\rho} \qquad (2)$$

where τ is shearing stress of moving air, and ρ is density of air. It has been found that over a period of 10 minutes or longer the average value of τ is unchanging with height up to about 3 m. This implies that the downward flux of momentum is constant in the same layer. Then by definition

$$\frac{\tau}{\rho} = K_M \frac{du}{dz} \qquad (3)$$

where K_M is the transport constant for momentum or coefficient of eddy diffusivity. By combining the three equations, we get

$$K_M = ku_*(z-d)$$

Assuming that the mechanism that transports momentum also transports heat and water vapor, and that the eddy diffusivities for each are equal, i.e., $K_M = K_H = K_V$, it can be shown that

$$Q = \rho c k^2 \frac{(T_1-T_2)(u_2-u_1)}{\left(\ln \frac{z_2-d}{z-d}\right)^2} \quad \text{cal/cm}^2\text{/sec}$$

and

$$E_* = \frac{\rho \varepsilon}{p} \; k^2 \frac{(e_1-e_2)(u_2-u_1)}{\left(\ln \frac{z_2-d}{z-d}\right)^2} \quad \text{g/cm}^2\text{/sec}$$

Q is the sensible heat transfer, c is the specific heat of air, E_* is the evaporation, ε is the ratio of the densities of water vapor and dry air at the same temperature and pressure (=0.622), p is the total pressure (e and p to be expressed in identical units), and t, u, and e are temperature, wind velocity, and vapor pressure.

Two things become evident, requiring further assumptions for this grassland model. First, the zero plane displacement, d, requires wind measurements at three or more heights. The value of d is found by trial when the value gives a straight line when u is plotted against ln(z-d). Wind velocity is measured at only two heights (50 and 200 cm) at the meteorological site. However, in contrast to crops, the shortgrass prairie can be assumed to have a negligible value of d.

Secondly, only one measurement of vapor pressure is available from the meteorological system, and that measurement is at 300 cm. An attempt to utilize soil heat flux measurements to correlate with a computed value of Q, sensible heat, was not successful due to malfunction of the flux apparatus.

Using August 4, 1972, at hour 0900-1000, a sensible heat flux of 1.1×10^{-2} cal/cm^2/minute was computed. Several attempts to compute an evaporation amount, E_*, met with failure for lack of a vapor pressure gradient. Improvisations and rather arbitrary assumptions proved to be meaningless. However, the almost insignificant value of sensible heat that was computed offers a speck of hope. The selected time immediately followed the soaking rain previously discussed. Smith (31) found that following simulated rains, temperatures remained constant, which indicated that nearly all incoming energy was being utilized in latent heat of vaporization. Little or none was being utilized for sensible heat flux into the soil.

APPENDIX IV

APPENDIX TABLES

Table A-1. Texture of Ascalon soil series.

Horizon	Depth (inches)	Gravel[a/] >2mm	Sandy (mm)						Silt (microns)				Clay (microns)		
			2-1	1-.5	.5-.25	.25-.1	.1-.05	Total	50-20	20-5	5-2	Total	2-.2	<.2	Total
A	0-6	2	4	9	11	26	14	64	13	5	2	19	5	11	17
B_{2t}	6-11	1	2	7	10	24	12	56	12	5	2	18	6	20	26
B_{3t}	11-15	0	2	7	9	24	14	56	11	5	2	18	6	20	26
C_{ca}	24-30	1	2	8	13	39	13	75	7	3	2	12	5	9	14
C_2	30-48	14	4	9	13	35	14	75	6	3	2	11	4	10	14

[a/] Gravel as percentage of total soil weight.

Table A-2. Concrete mix design. The concrete used for the retainer and tunnel footings conforms to Class B, Type II of the Wyoming Highway Department. This particular batch was a portion of that prepared for Interstate Highway I-25-1 (34) 17, bridge deck, by Read Ready-Mix of Cheyenne.

One Sack Proportions:	Cement	94 lb.
	Sand	190 lb.
	Rock	304 lb.
	Water	5.29 gal
	Protex	2 oz
Field Tests:	Slump	2 3/4 inches
	Yield	6.01 sacks/yd^3

Table A-3. Calibration of weights for the lysimeter.

Wt No.	Amount (lb.)	Deviation (g)	Wt Added (g)	Description of Weight
1	50	OK	--	Cast iron, solid handle[a/]
2	50	-6.5923	6.6653	Cast iron, solid handle
3	50	OK	--	Cast iron, solid handle
4	50	-2.3027	1.5693	Cast iron, solid handle
5	50	-6.8021	7.2774	Cast iron, solid handle
6	50	-5.9665	6.1049	Cast iron, solid handle
7	50	-2.7012	2.5050	Cast iron, solid handle
8	50	-8.6245	8.7606	
9	50	OK	--	Cast iron, solid handle
10	50	-2.2550	2.1855	Cast iron, solid handle
11	50	-2.7725	2.7012	Cast iron, solid handle
12	50	-1.2422	--	Cast iron, solid handle
13	50	-2.2295	2.8369	Cast iron, solid handle
14	50	-3.5466	3.4827	Cast iron, solid handle
15	50	-3.7489	2.4777	Cast iron, solid handle
16	50	-2.2201	--	Cast iron, solid handle
17	50	-1.9794	--	Cast iron, solid handle
18	50	-2.0030	--	Cast iron, solid handle
19	50	-2.2185	--	Cast iron, solid handle
20	50	-3.3085	3.7860	Cast iron, solid handle
UW	20	-2.6682	1.9197	Cast iron, U.S. Standard Manufacturer
UW	10	-193 mg	--	Knob weight, Toledo Manufacturer
UW1	5	-0.3020	0.4677	Nest weight, unknown manufacturer
UW2	5	-0.1604	--	Nest weight, unknown Manufacturer
UW	2	-0.1026	0.1309	Knob weight, Toledo Manufacturer
UW1	1	-0.1633	0.1152	Knob weight, Toledo Manufacturer
UW2	1	--	--	Knob weight, Toledo Manufacturer
UW3	1	--	--	Slot weight marked 5 lb.
UW	0.4	-.3259	[b/]	Slot weight marked 2 lb.
UW	0.2	-.4280		Slot weight marked 1 lb.
UW	0.2	-.1714		Slot weight marked 1 lb.

[a/] Fifty-lb. weights do not conform physically, due to solid handle, with specifications for Class F weights.

[b/] Weight not added to 0.4, 0.2, 0.2 weights.

The field standards described above have been compared to Wyoming state standards and found to be accurate within the tolerances for Class F.

Table A-4. Comparison of data from standard rain gauge at Pawnee Site headquarters and the lysimeter for August and September, 1971.

Day	Lysimeter (mm)	Rain Gauge (mm)
	August	
6	0.04	--
9	4.56	4.1
15	0.05	--
16	0.07	--
19	0.58	--
20	0.87	--
21	0.51	0.5
23	0.96	1.5
26	0.82	--
27	0.04	0.5
28	0.07	--
29	0.22	--
Totals	8.79	6.6
	September	
3	3.10	--
4	0.78	3.8
7	12.48	3.3
8	7.84	18.5
16	14.83	10.2
17	9.04	14.7
18	0.10	3.8
19	0.79	--
20	0.70	--
21	4.21	2.5
22	0.12	1.3
23	0.21	--
28	0.05	--
29	0.04	--
30	0.89	0.8
Totals	55.18	58.9

Note: No lysimeter data for following dates: August 1, 2, 3, 12, 13, 14, 24, and September 1, 2, 9, and 10.

Table A-5. Comparison of data from the standard rain gauge of the meteorological acquisition system and the lysimeter during observed rain of May 19, 1972.

Time	Channel 17-Lysimeter		Channel 35-Rain Gauge	
	Recorder Counts	Equivalent Millimeters	Recorder Counts	Equivalent Millimeters
1243	211	6.03		
1244			018	0
1245	221	6.32		
1246			018	0
1247	226	6.46		
1248			018	0
1249	234	6.69		
1250			018	0
1251	232	6.63		
1252			018	0
1253	234	6.69		
1254			018	0
1255	233	6.66		
1256			018	0
1257	236	6.74		
1258			018	0
1259	240	6.86		
1300			018	0
1301	239	6.83		

Table A-6. Daily amounts of evaporation indicated by the standard 4-foot pan compared to corresponding data from lysimeter.

Date	Evaporation (mm)		Ratio Lysimeter/Pan	Precipitation (mm)
	Lysimeter	Pan		
May 11, 1972	--	--	--	8.85
May 12, 1972	2.3	5.3	0.43	
May 13, 1972	--	--	--	3.13
May 14, 1972	3.5	7.1	0.49	
May 15, 1972	2.5	13.0	0.19	
May 16, 1972	2.1	7.1	0.30	
May 17, 1972	2.2	10.2	0.22	
May 18, 1972	1.7	8.1	0.21	
May 19, 1972	0.9	8.1	0.11	
May 20, 1972	2.5	10.7	0.23	1.34
May 21, 1972	1.6	9.4	0.17	
July 25, 1972	0.9	7.4	0.12	
July 26, 1972	1.1	9.4	0.12	
July 27, 1972	--	--	--	2.07
July 28, 1972	1.9	9.6	0.20	
July 29, 1972	1.1	13.5	0.08	
July 30, 1972	1.0	10.4	0.10	
July 31, 1972	0.6	7.6	0.08	
August 1, 1972	-0.5	9.14	--	1.66
August 2, 1972	--	--	--	11.30
August 3, 1972	--	--	--	5.33
August 4, 1972	3.3	3.8	0.87	
August 5, 1972	2.8	8.1	0.35	
August 6, 1972	2.5	11.4	0.22	

Table A-7. Soil water contained in upper 120 cm of soil of the eight microwatersheds of the Pawnee Site.

Date	Total Centimeters of Water[a] for Microwatershed								Avg
	1	2	3	4	5	6	7	8	
1971									
July 26-28	10.9	15.8	15.8	12.1	11.4	13.0	13.8	13.0	13.23
August 10-11	9.2	15.0	15.0	11.4	9.8	11.5	12.7	12.0	12.08
August 24-25	8.9	14.5	14.5	10.9	9.8	11.3	12.3	12.2	11.80
September 10		15.8	15.7					13.2	14.90
September 26	13.3	17.8	18.6	14.3	13.4	15.0	16.0	15.4	15.48
November 6-7	12.2	16.5	16.8	13.0	12.2	13.7	14.6	14.7	14.21
1972									
April 6	10.3	14.7	15.1	11.5	10.7	11.8	12.9	13.0	12.50
April 20-24	10.2	14.4	14.7	11.3	10.4	11.6	12.8	12.6	12.25
May 15	11.1	15.1	15.6	12.3	11.6	--	--	--	13.14
June 13-15	17.3	20.0	20.8	16.9	16.1	17.2	19.6	19.7	18.45
June 27-28	14.7	17.1	16.1	14.9	12.0	14.5	17.6	15.6	15.31
July 11-12	11.7	15.5	15.6	11.5	11.7	14.4	15.0	15.1	13.81
July 18-21	14.2	16.9	15.8	13.2	10.6	12.9	13.0	13.0	13.70

[a] Summation of incremental-depth mean values of 10 neutron probe access tubes per watershed.

Table A-8. Meteorological parameter description.

Channel	Parameter	Sensing Height	Units
1	Delta air temperature	5 cm	°C
2	Delta air temperature	50 cm	°C
3	Delta air temperature	152 cm	°C
4	Delta air temperature	200 cm	°C
5	Soil temperature	-122 cm	°C
6	Soil temperature	-122 cm	°C
7	Soil temperature	-40 cm	°C
8	Soil temperature	-20 cm	°C
9	Soil temperature	-10 cm	°C
10	Soil temperature	-6 cm	°C
11	Soil temperature	-3 cm	°C
12	Soil water	-122 cm	% saturation
13	Soil water	-40 cm	% saturation
14	Soil water	-20 cm	% saturation
15	Soil water	-10 cm	% saturation
16	Soil water	-3 cm	% saturation
17	Lysimeter	0 cm	mm
18	Barometric pressure	300 cm	mb
19	Wind velocity	50 cm	cm/sec
20	Wind velocity	200 cm	cm/sec
21	Delta wet temperature	5 cm	°C
22	Delta wet temperature	50 cm	°C
23	Delta wet temperature	152 cm	°C
24	Delta wet temperature	200 cm	°C
25	Net radiation	200 cm	langleys/min
26	Total incoming radiation	300 cm	langleys/min
27	Long wave radiation	200 cm	langleys/min
28	Long wave radiation	200 cm	langleys/min
29	Visible radiation	300 cm	langleys/min
30	Reflected shortwave radiation	200 cm	langleys/min
31	Soil heat flux	5 cm	langleys/min
32	Carbon dioxide		
33	Wind direction	200 cm	° azimuth
34	Hot wire anemometer		
35	Rain gauge	100 cm	mm water
36	Soil thermistor		

APPENDIX V

APPENDIX FIGURES

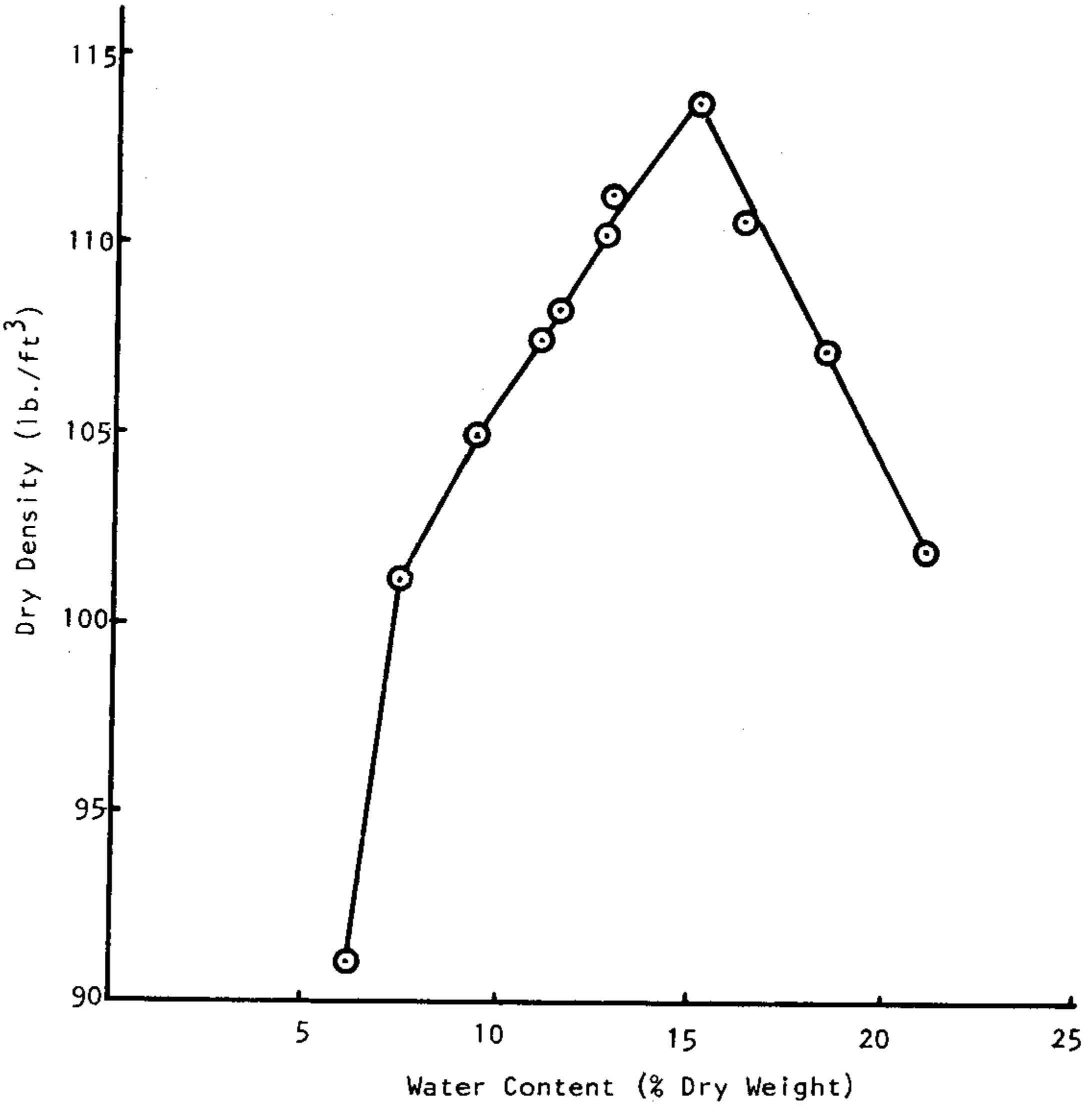


Fig. A-1. Standard proctor, Ascalon series.

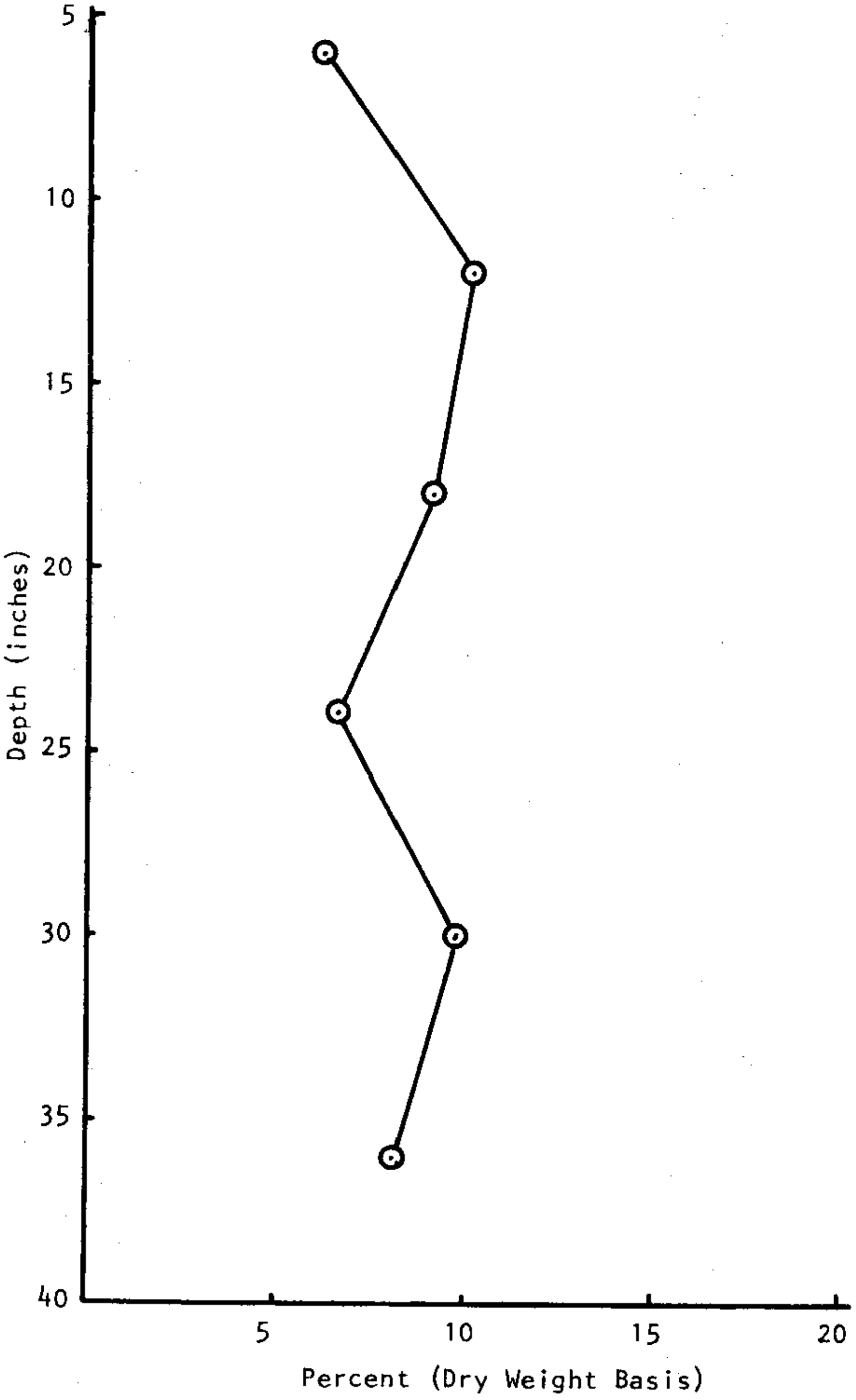
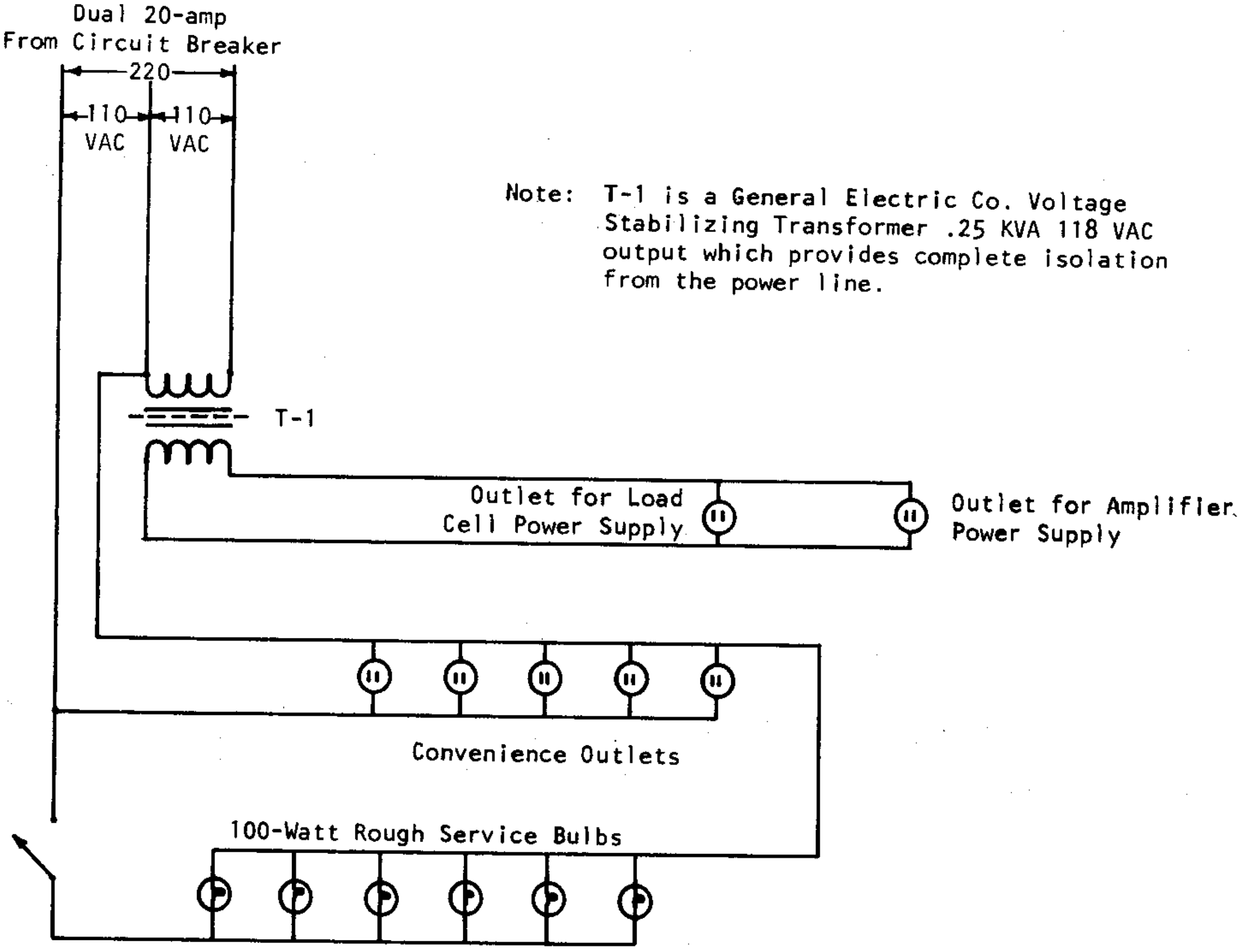


Fig. A-2. Water content vs. depth--Ascalon series, August 1969.



Note: T-1 is a General Electric Co. Voltage Stabilizing Transformer .25 KVA 118 VAC output which provides complete isolation from the power line.

Fig. A-3. Circuit diagram of the Grassland Biome lysimeter.

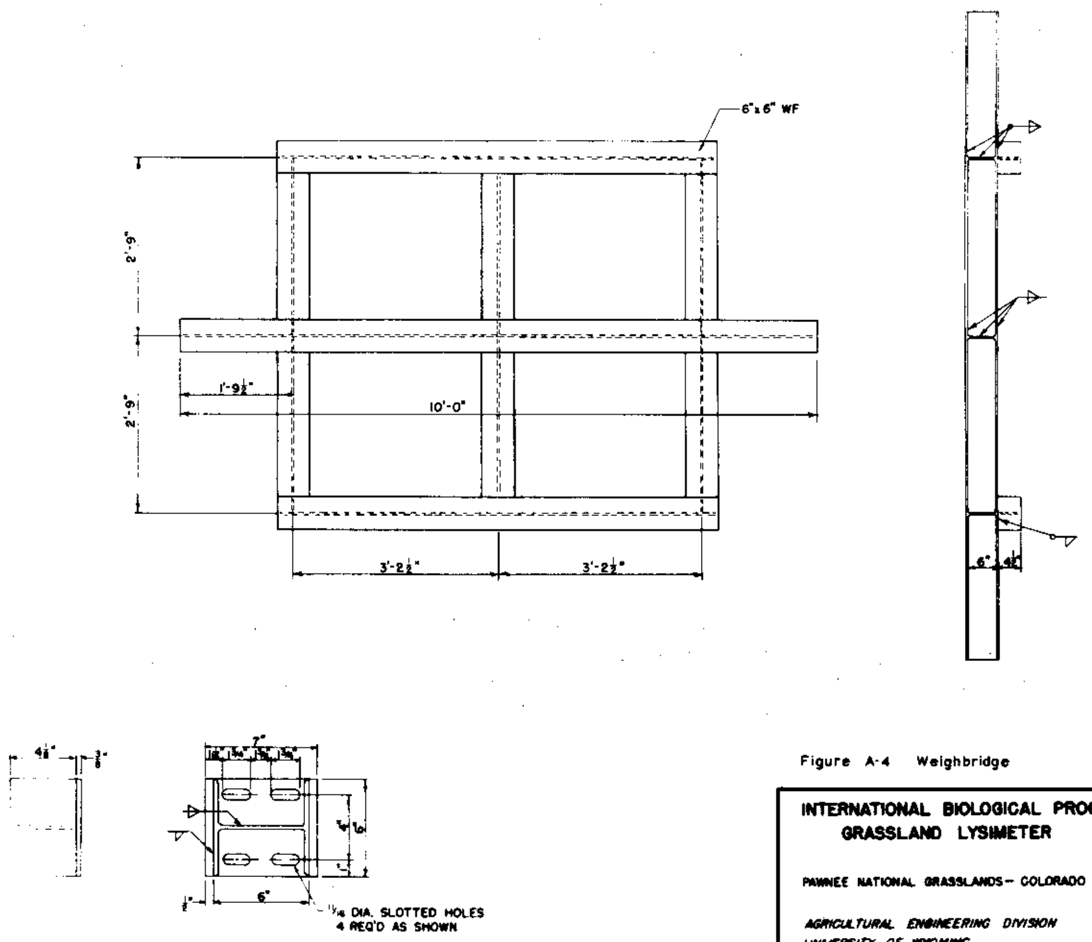


Figure A-4 Weighbridge

INTERNATIONAL BIOLOGICAL PROGRAM
GRASSLAND LYSIMETER

PAWNEE NATIONAL GRASSLANDS – COLORADO

AGRICULTURAL ENGINEERING DIVISION
UNIVERSITY OF WYOMING

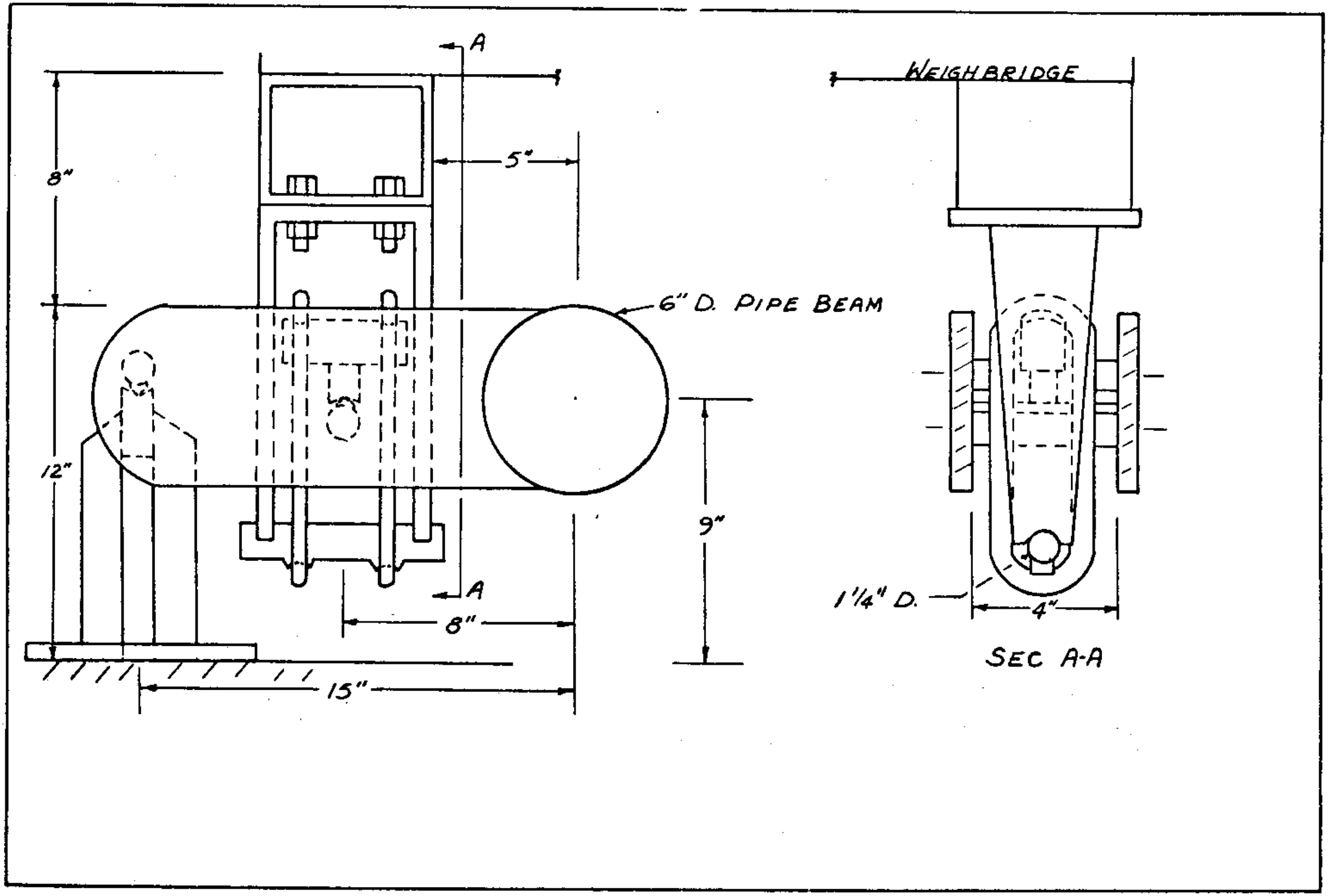
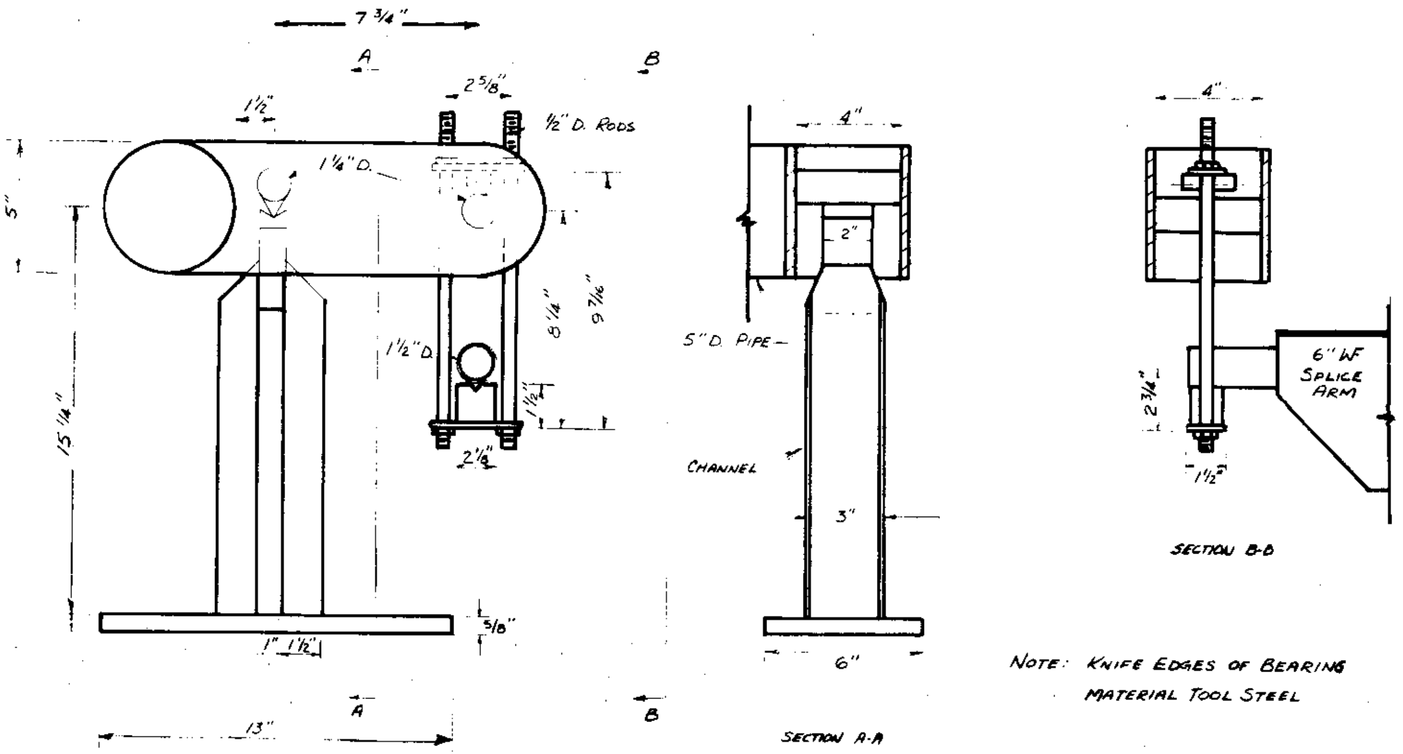


Fig. A-5. Main lever stand assembly.



Note: Knife Edges of Bearing Material Tool Steel

Figure A-6 Transverse Lever Stand

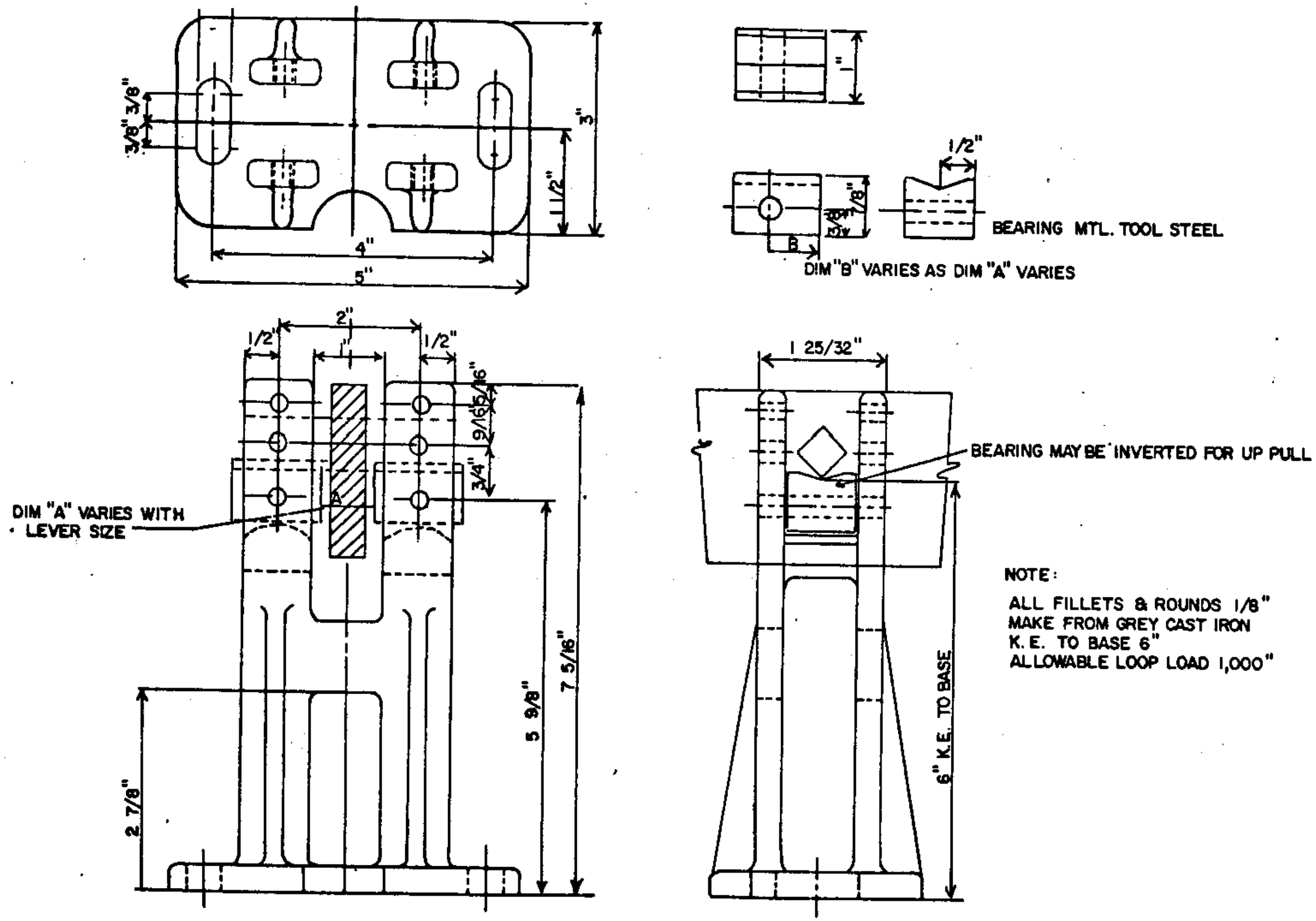


Fig. A-7. Lever fulcrum stand.

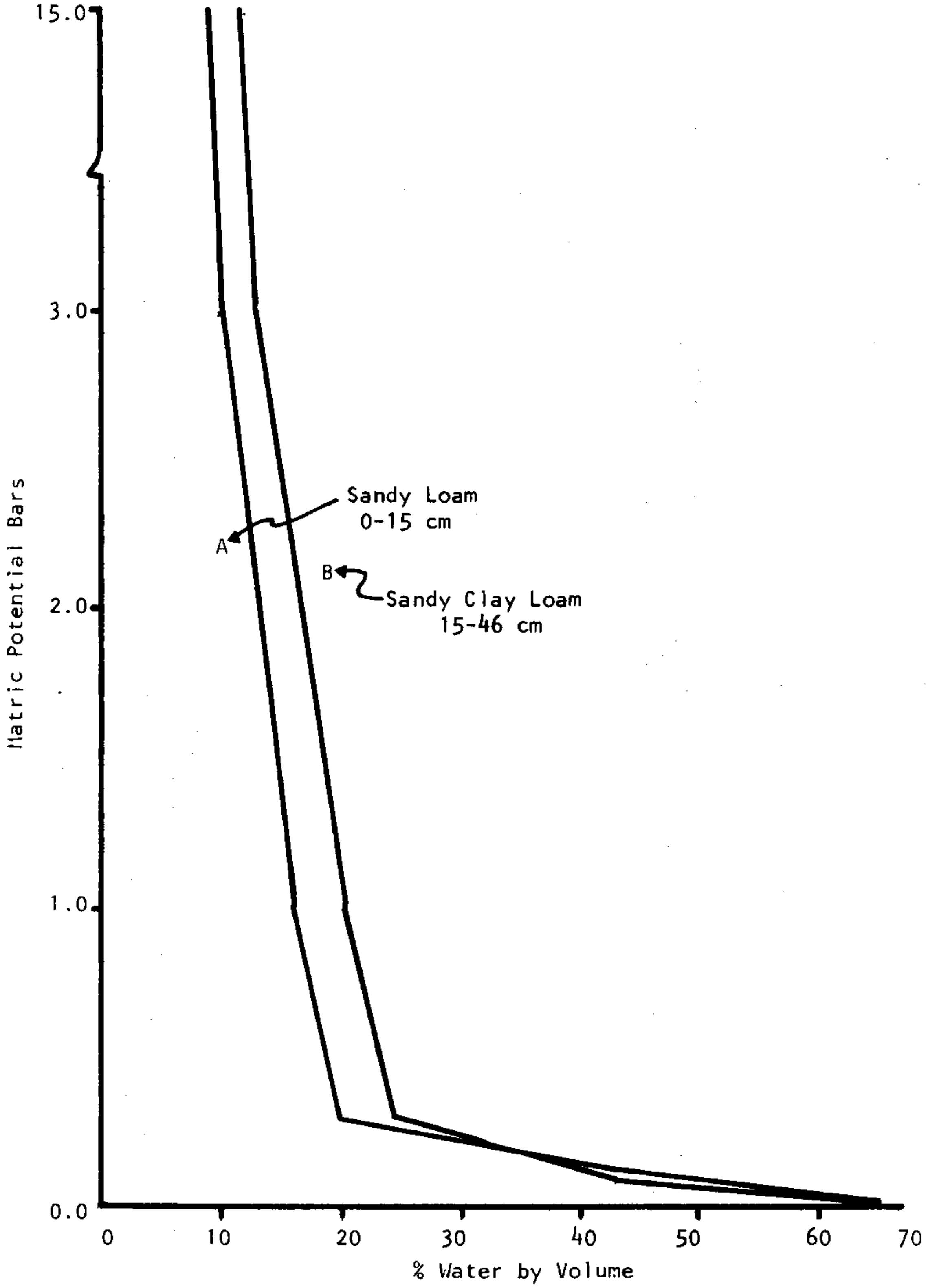


Fig. A-8. Desorption curves for Ascalon sandy loam.

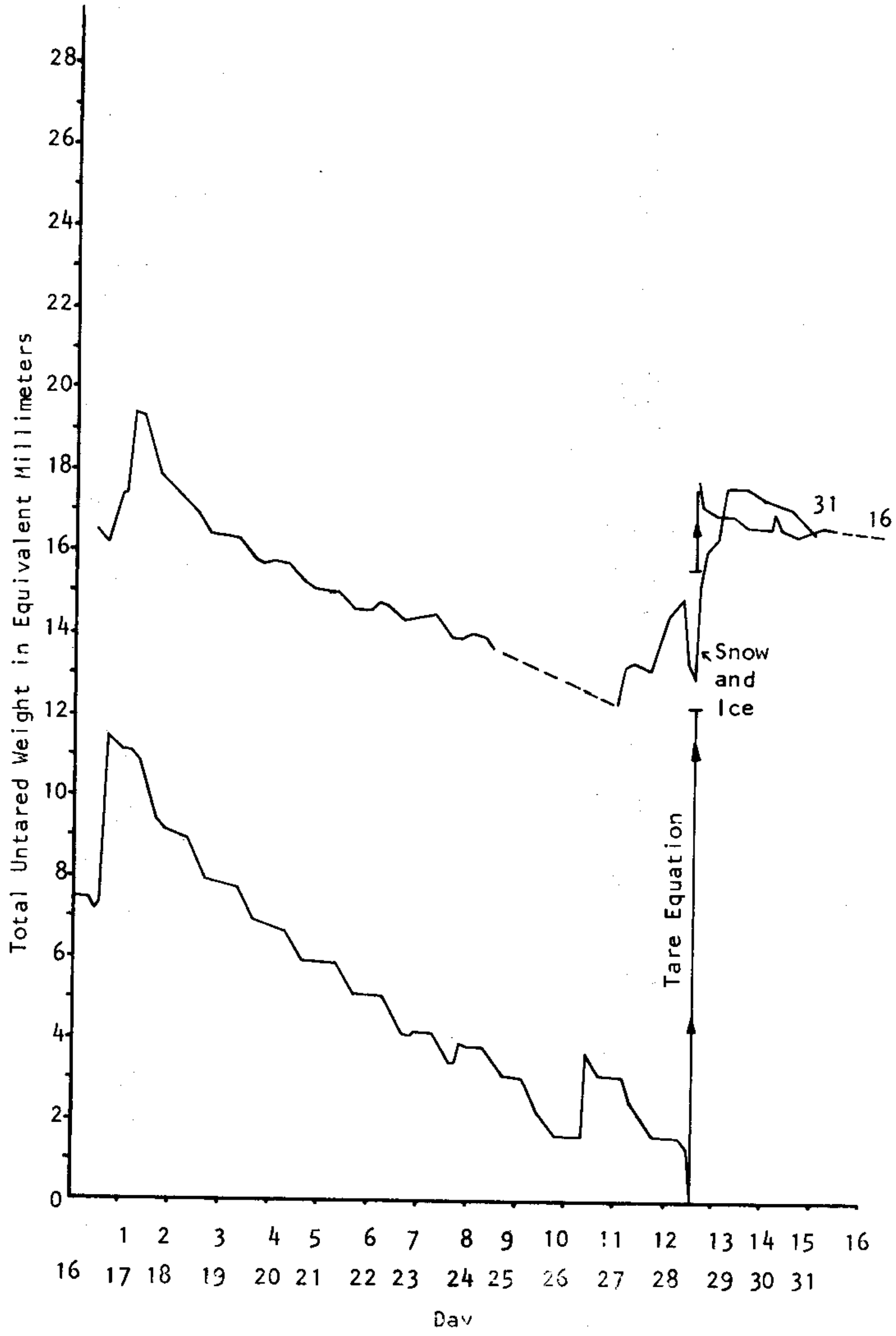


Fig. A-9. Lysimeter data trace, October 1971.

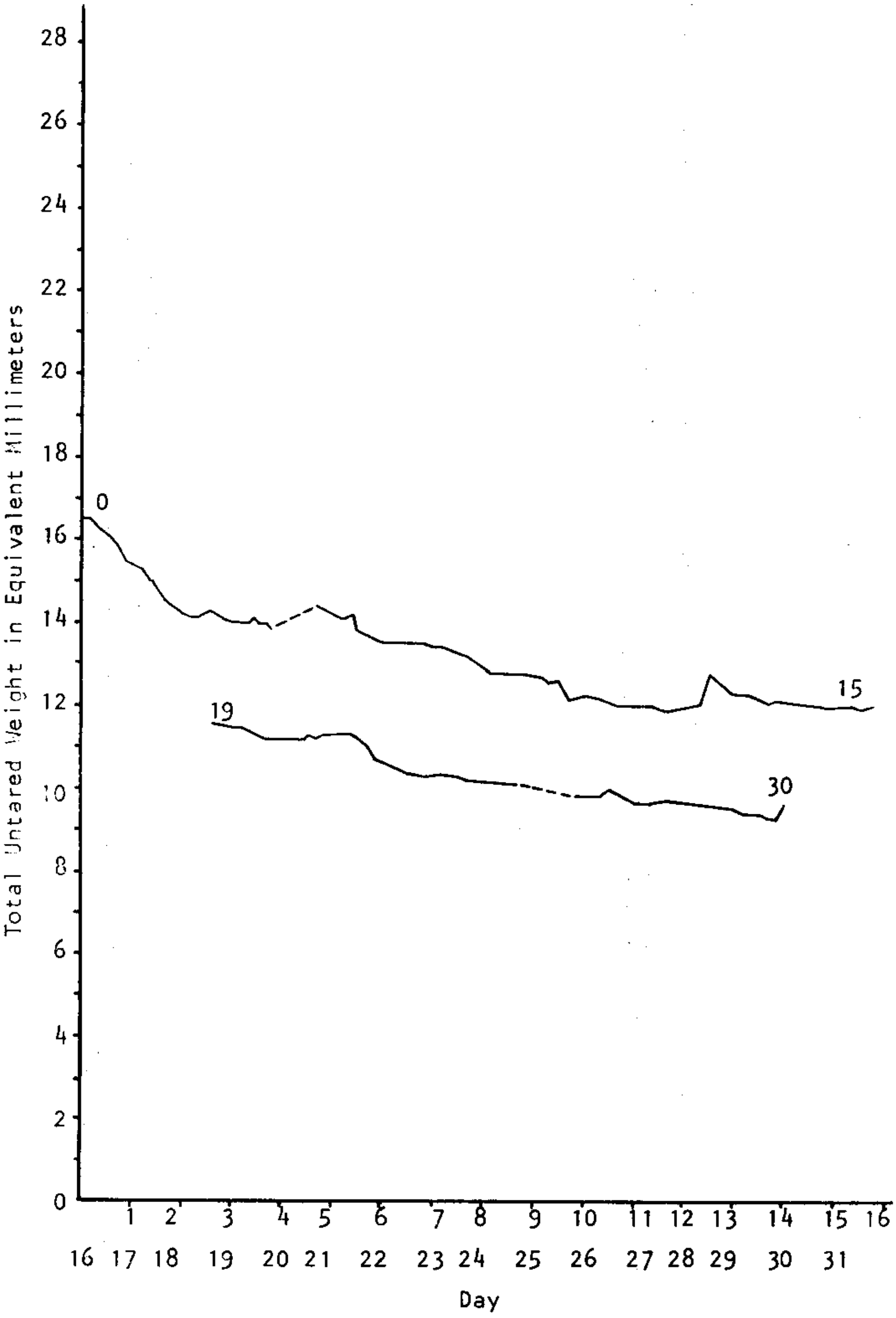


Fig. A-10. Lysimeter data trace, November 1971.

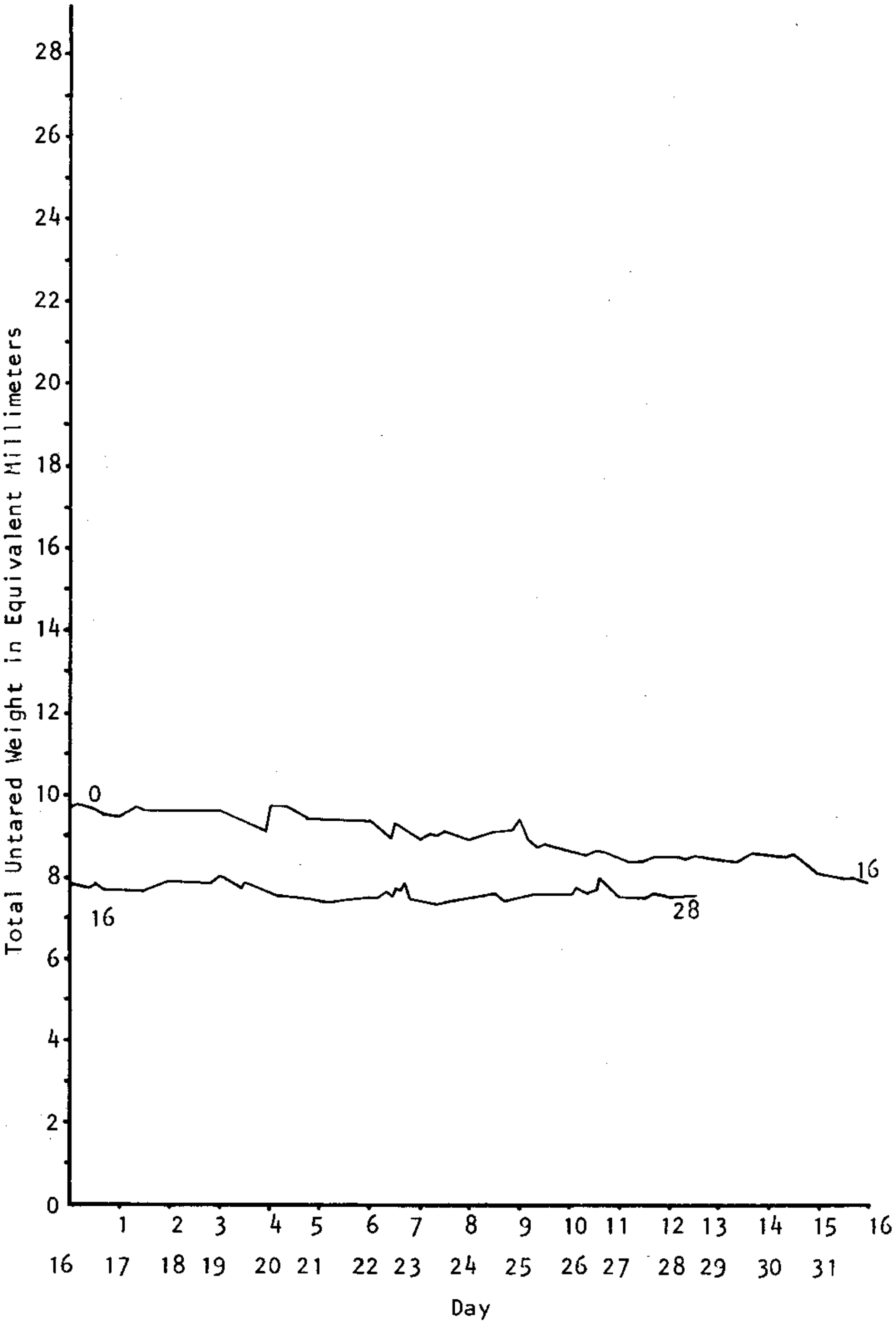


Fig. A-11. Lysimeter data trace, December 1971.