DESIGN AND INSTALLATION OF A WEIGHING LYSIMETER

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ABSTRACT

The design and installation of an sensitive weighing lysimeter are described. Located near Laramie, Wyoming near the Big Laramie River, the lysimeter is at the highest elevation of any similar facility in the United States and should provide unique models for these conditions. The lysimeter consists of a 1.067m diameter cylinder suspended within a 1.118m diameter cylinder by three load rings held in tension. The soil profile depth is 1.372m. Approximately the bottom two-thirds of the soil profile was repacked in 15cm lifts. The top 45cm of the soil profile and the vegetation was installed undisturbed. The load rings are sensitive to approximately .3mm of water on the surface of the lysimeter. The lysimeter drainage system allows simulation of any desired water table depth. The data acquisition system can sample lysimeter data, along with data from an accompanying weather station at any selected interval and store the data for weekly unloading.

INTRODUCTION

Efficient planning and use of available water requires evaluation of all components in the water budget. Each component must be determined using the best available technology. Perhaps the most complex portion of the water budget involves evaluation of vegetative water use or evapotranspiration, henceforth referred to as ET. Lysimeter data are used with environmental and climatic data to calibrate and evaluate various ET models.

Trade or brand names are used only for the purpose of educational information. The information given herein is supplied with the understanding that no discrimination is intended and no endorsement by the University of Wyoming is implied.

The undisturbed weighing lysimeter is a permanent research facility which will contribute to the educational and research programs of the Wyoming Water Research Center and cooperating academic departments. In addition to providing needed research data, it will serve to demonstrate the best available technology for measuring vegetative water use.

The relative sophistication of a weighing lysimeter is such that it requires more attention and greater technical expertise for satisfactory operation than does a non-weighing lysimeter. This could present a serious problem because the time and effort required would be prohibitive if the lysimeter was installed in a remote area.

Fortunately, the Agricultural Engineering Department has installed and maintained both weighing and non-weighing lysimeters continuously for many years. The University, located in a region which produces irrigated meadow hay, is uniquely located for this research. In this area, the weighing lysimeter can be conveniently observed and properly maintained to insure reliable research results. A weighing lysimeter near Laramie is located at the highest elevation of any similar facility in the United States and probably in the world. Models verified under these conditions would be unique. The information obtained should significantly enhance the reliability of vegetative water use models and should thereby enhance the analysis of water use within Wyoming.

The lysimeter facility provides a unique tool for botanists, agronomists and other plant scientists on campus. By recording information such as soil moisture conditions within the lysimeter and plant characteristics such as growth rates and matruation, it will be possible to more closely evaluate and model the influences of environment on plant growth.

The weighing lysimeter represents the best available technology for determining ET. The research reported herein involved designing and installing a weighing lysimeter in the Laramie River Basin near Laramie, Wyoming. The lysimeter is located in a region which produces irrigated meadow hay. Basic criteria for lysimetry such as high sensitivity, minimization of unnatural surface area, minimal soil disturbance, continuous monitoring capability and drainage control provisions were considered. The information obtained should significantly enhance the reliability of vegetative water use models.

OBJECTIVES

The purpose of this research was to develop and install a sensitive, relatively undisturbed weighing lysimeter in the Laramie River Basin. This location will facilitate providing the necessary management to insure continuous and reliable operation.

The lysimeter contains an undisturbed soil profile with accompanying vegetation. To the best knowledge of the authors, the lysimeter is the first system of its type installed anywhere, particularly at high elevations.

Once operational, the lysimeter will be used to:

1. Provide the best direct estimate of water use by vegetation in the Laramie area.
2. Evaluate the accuracy of vegetative water use models.
3. Evaluate the role of rainfall in meeting plant water requirements.
4. Provide comparative data to evaluate the accuracy of non-weighing lysimeters. Results will be used to correct errors or bias introduced into vegetative water use models through data obtained from non-weighing lysimeters. Information will be used for future design.

5. Perform joint studies involving plant scientists. These studies would involve both ET and plant growth factors.

The key to a successful weighing lysimeter is to design a system capable of detecting a change in weight equal to a millimeter of water when the lysimeter itself weighs several kilonewtons. For example, a precipitation event on the surface of a lysimeter equivalent to 1 mm of water may weigh approximately 10 Newtons. To detect a change in weight equivalent to 1 mm of water, the weighing system would have to be sensitive to approximately the 0.1% level. In actual practice, the lysimeter weighing system should be sensitive to approximately 0.03%. This can be accomplished by making the top area of the lysimeter large relative to its depth, by maintaining the water table depth precisely and by using modern high technology sensors on the weighing system and a computer controlled data acquisition system.

Background Information

Much work has been done recently relating evapotranspiration (ET) estimates directly obtained from lysimeters to values derived from one of several empirical formulas. A study of ET rates of high mountain meadows located in southern Wyoming by Swartz, et.al., (1972) concluded that crop coefficients used by Criddle in Utah were low for irrigated mountain meadows. Harrold (1966) experienced similiar findings. Weekly ET values derived from the Blaney-Criddle method were too low in midsummer and too high in the fall when compared with lysimeter values. Harrold also found that ET_0 values resulting from the Penman method multiplied by 0.93 compared well with the lysimeter data.

A method of calibrating the SCS version of the Blaney-Criddle formula is presented by Borrelli, et. al., (1981). Lysimeter consumptive use data was used to fit monthly crop coefficients to the formula given the necessary climatological figures. As demonstrated by Harrold (1966) weighing lysimeters may be used to calibrate crop coefficients for any time periods or field conditions desired. This allows for a much more precise empirical calculation of ET in similar areas under much the same soil conditions.

Other problems associated with the inaccuracy of non-weighing lysimeters are assumptions involving specific yield and the inability to obtain ET values over short periods. Methods of calculating storage changes require that specific yield, estimated by the small change in water storage depth during the measurement period, is assumed to be constant over the total depth of the lysimeter. Varying soil properties actually result in different specific yield values for varying soil profile depths. With non-weighing lysimeters, ET values may only be obtained for the entire measurement periods. Daily ET is only an average value for the measurement period and variations due to daily fluctuations and extremes can not be monitored. These observations concerning soil disturbance and non-weighing lysimeters may be alleviated using procedures recently developed for weighing installations.

Not all of the precipitation falling on an area is effective in meeting plant water requirements. In the context of the irrigation engineer, rain water that neither leaves as surface runoff nor deep percolation may be termed effective. Weighing lysimeters are the most accurate method of measuring effective rainfall because all components of the water balance are known (Dastane, 1974). The weighing lysimeter also provides a means of testing the accuracy of surrounding raingages.

Within a lysimeter, assuming no over-topping, the water balance may be written:

$$D_a + D_p - D_{ET} - D_{re} = D_{\Delta S}$$

where D is the depth of water and the subscripts a, P, ET, re, ΔS signify applied, precipitated, evapotranspirated, removed, and change in stored, water. For a precipitation event, assuming no additional applications during the event, the depth of water removed (D_{re}) is due to deep percolation out of the root zone. The effective rainfall is then equal to $D_p - D_{re}$, without taking surface runoff into account. Previous literature (USDA,SCS-1967) has stated that in arid regions, such as Laramie, where total growing season precipitation is light, losses due to surface runoff are generally negligible.

Design factors involved in lysimetry were reviewed by Harrold (1966) and Tanner (1967). Large surface area to depth ratios are necessary in order to maximize sensitivity. Minimization of unnatural surface area is necessary to maintain a similar thermal regimen between the lysimeter and surrounding field. Soil profile depth, siting, wind and drainage are also important considerations.

Two different types of weighing lysimeters have been developed. These involve counterbalancing the dead load (scales approach) of the lysimeter (Black et.al., 1968; Pruitt and Angus, 1960), or using sensitive load measuring devices, (Armijo et.al., 1972; Ritchie and Burnett, 1968). The latter approach is currently more attractive, particularly because of the accuracy, precision and utility of computer controlled data acquisition systems. Often both approaches are combined in weighing lysimeter construction. Modern microprocessor controlled data acquisition systems allow frequent readings (up to 500 or more times per second) and can compute and store thousands of data samples in the desired output format.

LYSIMETER DESIGN

The general concept of a weighing lysimeter requires four major elements. These include the container to hold the soil, water and vegetation; a rigid foundation; the force measuring or weighing system; and the data acquisition and analysis system. Accessory instrumentation is also required to measure and record climatic data.

The lysimeter designed and installed in this research is illustrated schematically in Figure 1. It consisted of two cylindrical containers, one of which fitted inside the other. The inner cylinder contained the soil, water and vegetation, and its weight was measured using three strain gage load rings. One of the load rings is illustrated in the schematic shown in Figure 2.

The outer cylinder formed the working surfaces of the foundation and, for ease of assembling the lysimeter, was fabricated in two parts. The lower part was installed in the earth in concrete, as shown in Figures 1 and 3. The inner container was then placed in the cavity, and the upper part of the outer cylinder was installed. Referring to Figure 1, note the flange on the inner cylinder to which the bottom of the load ring was attached. The upper part of the outer cylinder was sealed to the lower part and rested on the concrete foundation and provided the attachment point for the top of the load ring. The inner cylinder was thus suspended within the outer cylinder by the three load rings, which measured tensile forces. After installation was completed, undisturbed soil and vegetation was placed around the outer cylinder to restore the original ground surface elevation and vegetation.

CYLINDER DESIGN

Cylinder dimensions were selected based on maintaining a suitable diameter to depth ratio (greater than one), and the availability of large diameter steel pipe. The inner cylinder used in the lysimeter was 1067mm in outside diameter with a 9.5 mm wall thickness and 1372mm long. A 12.7 mm thick steel plate was welded to the bottom.

The outer cylinder was 1118mm in diameter with a 12.7 mm wall thickness. This provided a radial clearance of 12.7 mm between the inner and outer cylinders. Minimal clearance between the cylinders was desirable from the standpoint of reducing effects of surface disturbance on the lysimeter, but some clearance was necessary to facilitate assembling and aligning the two cylinders. Nominal dimensions and clearances for the cylinders are shown in Figure 1.

LOAD RING ATTACHMENTS

Notches were provided in the foundation at 120° intervals, (see Figure 3) to accommodate the load rings and load ring attachments. The load ring attachment to the inner cylinder is shown in Figure 4, and the upper and lower attachments are shown in Figure 5. Refer also to Figure 2 for details.

The method of attaching the load rings to suspend the inner cylinder inside the outer cylinder is shown in Figure 2. Referring to the figure, notice the turnbuckle connections, which were provided to relieve the force in the load ring. This assembly was necessary to facilitate installation and removal of the load rings in the event of a malfunction. The well rod nut on top of the load ring was used to align and level the inner cylinder within the outer cylinder. A vertical plate was placed over the load ring access area and attached using the bolts visible in Figure 5. Silicon sealant was used as a gasket to prevent water from entering the area around the load ring.

LOAD RING DESIGN

Specifications, design calculations and calibrations of the load rings are given in the Appendix. Each load ring was configured in a full bridge strain gage circuit, using MM-WA-06-250BG-120 strain gages. Lead wires were run from each load ring to the data acquisition system.

LYSIMETER LOCATION

The weighing lysimeter was installed in a native grass hay meadow on the Monolith Ranch, located approximately 12 kilometers southwest of Laramie. The meadow is southeast of the Laramie River, at an elevation of approximately 2300 m.

The specific site was selected based on an investigation of subsurface soil and water conditions, condition of the meadow, terrain and accessibility. It was necessary to locate the lysimeter near the outer edge of the meadow to provide a stable foundation. High groundwater during the irrigation season in lower portions of the meadow would have prevented establishment of a suitable foundation.

A small rise in the terrain exists to the southeast of the lysimeter site, but no appreciable rise occurs for more than 75 m. This should be adequate to avoid surface wind disturbance in the southeast-northwest directions. Prevailing winds at the site are from the southwest and should be unaffected by the topography.

LYSIMETER DRAINS

Drains were provided in both the outer and inner cylinders of the lysimeter. The outer cylinder drain (Figure 1) was needed to prevent accumulation of water between the cylinders which could cause the inner cylinder to float. Such a buoyant affect would reduce the apparent weight of the inner cylinder and would cause an incorrect weight reading. Water accumulating between the cylinders may be removed using a small hand operated suction pump.

The drain for the inner cylinder was placed prior to installing the soil and vegetation. This drain consisted of a 50 mm PVC pipe run down along the inside of the vertical wall of the inner cylinder and across the bottom of the cylinder. The drain is shown in Figure 6. The pipe across the bottom was perforated with slits to allow water entry. A filter was formed around the pipe by first placing a fine mesh screen around the pipe, then sand and finally a shallow layer of fine gravel. Installation of the filter was necessary to prevent transport of fine material from the soil into the drain.

In operation, the drain in the inner cylinder will be used to remove excess deep seepage waters from the lysimeter and/or to control the depth of the water table. Using this drain, it will be possible to simulate any desired water table depth and to control the water table depth accurately.

SOIL AND VEGETATION INSTALLATION

Soil and vegetation were placed in the inner cylinder to duplicate as closely as possible natural conditions surrounding the site. Subsoil in the site originally selected was gravelly sandy loam and thus it was not possible to obtain a completely undisturbed soil profile in the lysimeter. The sandy soil could not be retained in the lysimeter and the lysimeter was relocated to a point approximately 1/2 mile south of the originally selected location.

Subsoil was removed from an adjacent pit, and shoveled into the inner cylinder and hand compacted in 15 cm lifts to within approximately 45 cm of the top. This was approximately the same depth as found in the surrounding soil profile. Because of the granular nature of the soil, disturbance should not significantly affect its function in the lysimeter. The subsurface soil was kept-moist and allowed to settle for a week prior to placing the topsoil and vegetation.

The top 45 cm of topsoil and vegetation was installed undisturbed. The sample was obtained by first digging a trench around a selected area, removing the sample and then carving it by hand to fit the top of the inner cylinder. This procedure provided a relatively undisturbed vegetation sample.

When soil and vegetation installation were completed, the lysimeter area was irrigated for the remainder of the 1984 growing season to facilitate re-establishment and healing of any soil or plant wounds within the lysimeter and the construction area around the lysimeter. This level of attention should provide very representative growing conditions for the 1985 season.

DATA ACQUISITION AND RECORDING

The heart of the lysimeter data acquisition system is a Campbell Scientific CR-7 measurement and Control System (Campbell-Scientific, 1982). This system is solar powered, with battery back-up. It has the capability to sample multiple data channels several times a second, perform various calculations using the data and pre-programmed information, and to store the results in any desired format. The stored data can be unloaded on a tape cassette on a weekly basis, and further analyzed with digital computers. Data sampling intervals can be selected ranging from several times per second to hourly.

In addition to recording and analyzing the lysimeter weight data, the CR-7 was used to record climatic data using the following instrumentation:

Solar Radiation - LI-COR, LI-200S Pyranometer

Precipitation - Sierra Tipping Bucket Raingage - RG 2501

Wind Direction - Met-One, 024A Wind Direction Sensor

Wind Speed - Met-One, 014A Wind Speed Sensor

Temperature and Relative Humidity - Phys-Chem Research, PCRC-11
RH Sensor and Fenwell Electronics
UUT51J1 Thermistor (Model 207)

Weather sensors were mounted on a Campbell Scientific CM-10 tripod, located approximately 10 m southeast of the lysimeter. The solar system used to power and charge the CR-7 batteries was a Campbell-Scientific model SX10 photovoltaic power source.

PERFORMANCE and CONCLUSIONS

1. The lysimeter was operated during most of the month of September, 1984. All systems were checked for satisfactory operation and minor problems in programming the CR-7 were corrected.

2. Work on planning, design and installation of the lysimeter began in January, 1984 and was completed in August, 1984. The completed installation is shown in Figure 7. Behavior and performance of the lysimeter observed during September, 1984 provided reasons for an optimistic viewpoint of the future uses of this unique instrument.

3. The lysimeter and its accompanying climatic sensors along with the CR-7 data logger were operated throughout most of the summer of 1985. The data logger was programmed to accumulate lysimeter weight data and climatic information. The program was successfully used and data was transferred to the UW Cyber mainframe computer system. A table of both lysimeter weights and climatic data for about a month's data has been made. The addition of known weights to the lysimeter shows that the desired precision of about 1/2mm of water was achieved. Two minor problems were encountered. First, mice invaded the load cell space and chewed insulation which required reconnecting and taping of joints. Second, loose joints in junction boxes resulted in some frustration. A problem course with the graduate student involved is planned with the final result of a proposed journal article being expected.

4. The final location of the lysimeter is not near a well-irrigated mountain meadow. The location is, however, near native vegetation such as, rabbit brush, which probably receives moisture from a rather shallow water table in the area. A proposal to study water consumption from phreatophyts is now under preparation. At the current time, water use information from

phreatopytes is very limited and is now receiving considerable national attention. The lysimeter is ideally located and suited for this kind of research.

5. Considerable information and experience was gained during the fabrication and installation of the lysimeter. As a result, it is believed that additional lysimeters could be installed for a much lower cost with a very high probability of success. Plans are now being made to seek funding to install additional lysimeters.

ACKNOWLEDGEMENT

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APPENDIX

DESIGN OF LYSIMETER LOAD RINGS

The lysimeter load rings were designed based on the analysis presented by Cook and Rabinowicz (1963). Specifications for the Campbell Scientific CR-7 measurement and control system were given by Campbell Scientific (1982).

For a thin ring in compression, the maximum strain due a radial force occurs at 90° with respect to the load. Further, for a tangential load applied at the same point, the 90° position is a strain node; that is, the 90° position has zero strain for the tangential load. Therefore, a thin ring can be instrumented to measure only radial loads by mounting electrical resistance strain gages on the ring at 90° with respect to the point of application of the load. These strain gages will be sensitive only to the radial load.

Consider the thin ring shown in Figure 1A. At 90° with respect to the load F, the strain is given by the equation:

$$\varepsilon\ 90^\circ = 1.09\ \frac{Fr}{Ebt^2}$$

Where r, b and t are dimensions defined in Figure 1A, and E is the modulus of elasticity of the material used to fabricate the ring.

The following dimensions were used for the lysimeter load rings:

$r = 76.2$ mm
$b = 50.8$ mm
$t = 6.35$ mm

The rings were fabricated from steel for which E = 200 GPa, and the yield point is 517 MPa.

The total weight of the soil and soil container of the lysimeter was assumed to be 33.36 kN, or each of the three rings would support a nominal maximum load of 11.12 kN. For this load, the strain is 2.25×10^{-3}, which is equivalent to a stress of 450 MPa.

Note that on the ring, the outside surface is in tension and the inside surface is in compression. Therefore, when four gages are mounted on the ring, two on the outside and two on the inside, the gages can be wired in a four-arm active configuration as shown in Figure 2A.

The output of a four arm active bridge is related to the input voltage by the equation:

$$\frac{v}{Vo} = GF\ (\varepsilon)$$

where v is the output voltage, Vo is the input voltage, GF is the gage factor (2.08) and is the strain in one gage.

Assuming elastic behavior and an input voltage of 5 volts, the sensitivity of the ring to changes in load can be calculated from:

$$\Delta F = \frac{v}{Vo}\ \frac{Ebt^2}{(GF)(1.09r)}$$

Using the detection limit of the CR-7, equal to 5×10^{-6} volts, the load cell will be sensitive to a change in force of approximately 2.3 Newtons. This is equivalent to approximately 0.3 mm of water on the surface of the lysimeter.

Four identical load rings were fabricated. Design details are shown in Figure 3A. These were calibrated using an Instron Model 1125 testing machine, and exhibited linear load-voltage relationships with the coefficient of regression (r^2) essentially equal to 1 in all cases. Calibration data for a load ring is shown in Figure 4A.

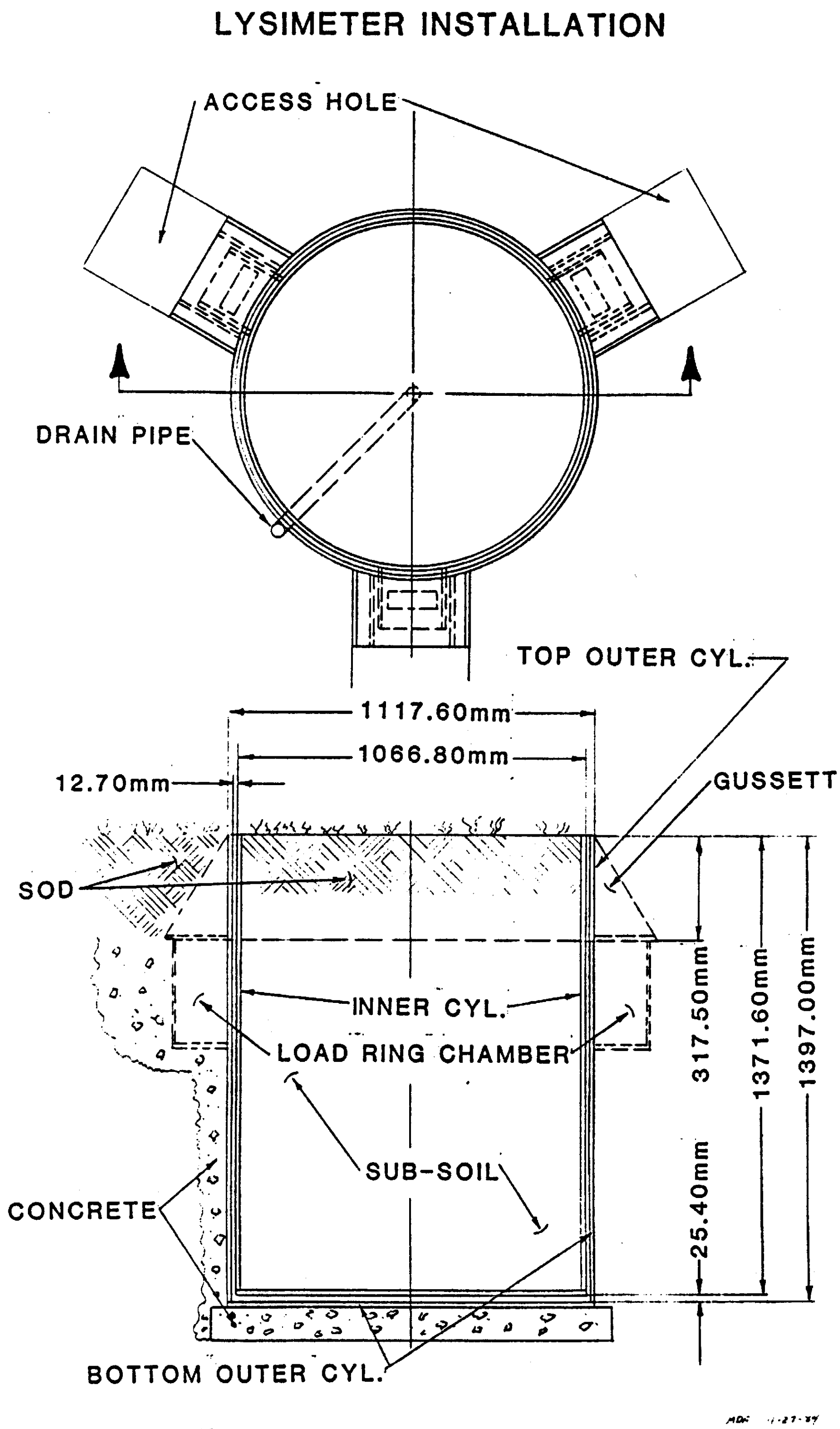

Figure 1. Schematic of weighing lysimeter.

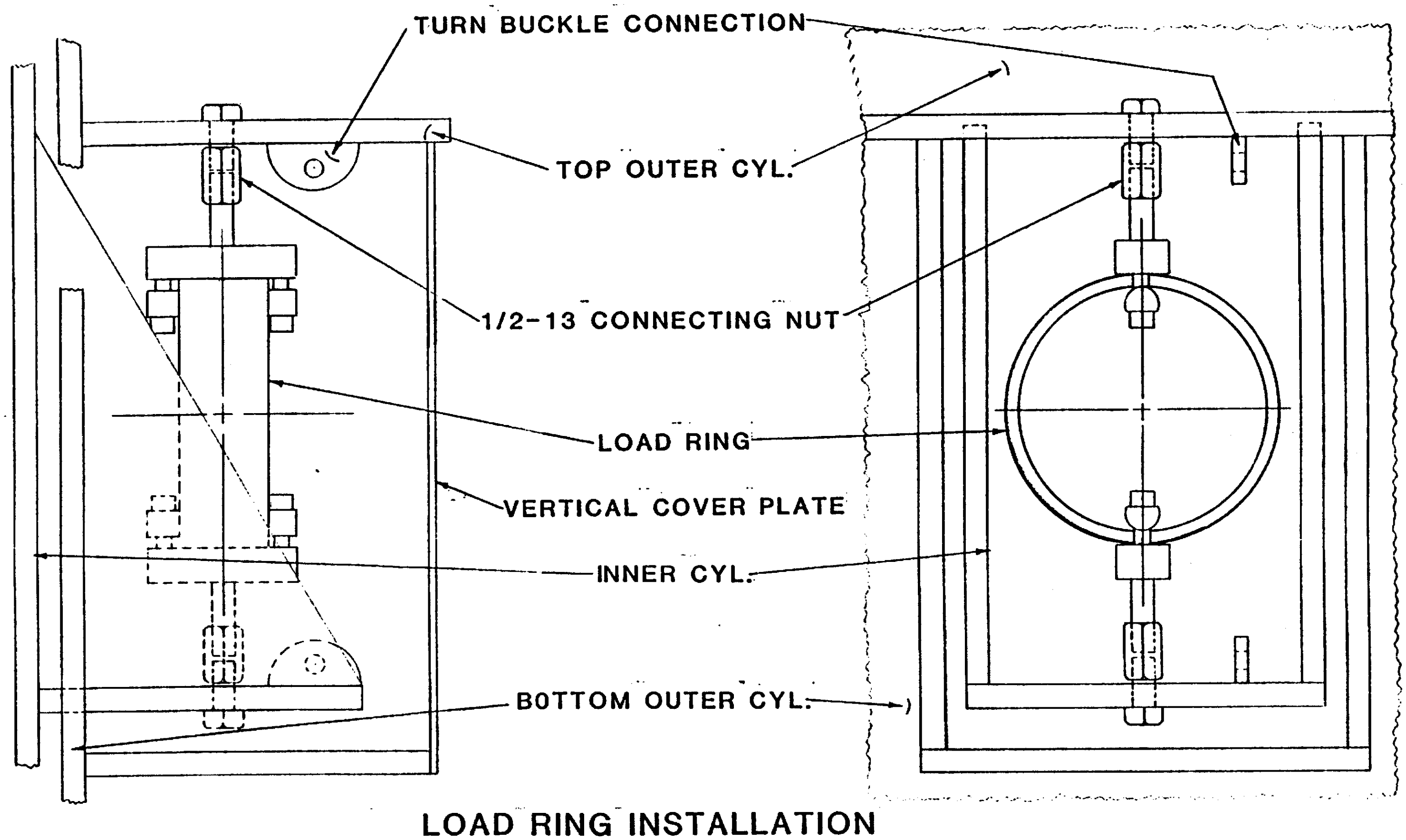

Figure 2. Lysimeter load ring - chamber and load ring installation.

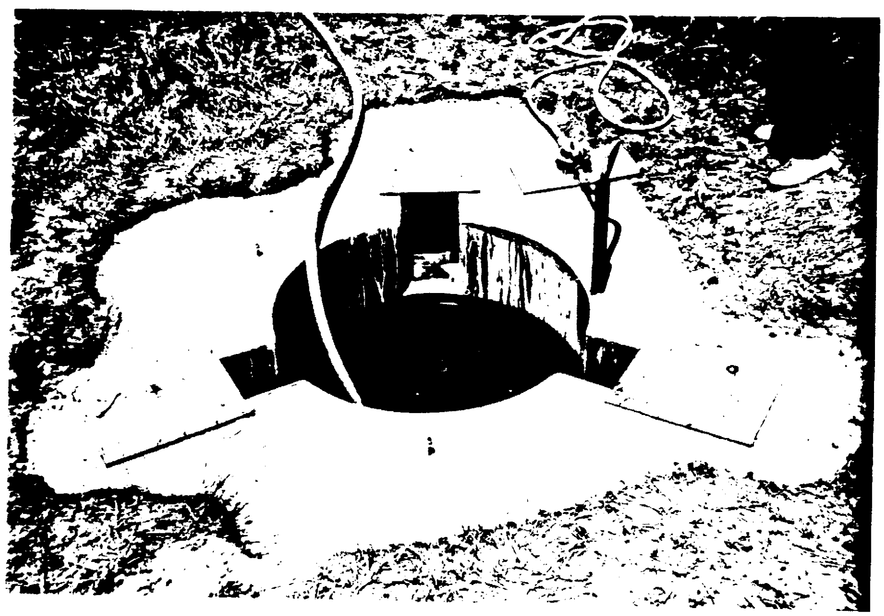

Figure 3. Outer cylinder and concrete foundation.

Figure 4. Inner cylinder load ring attachment.

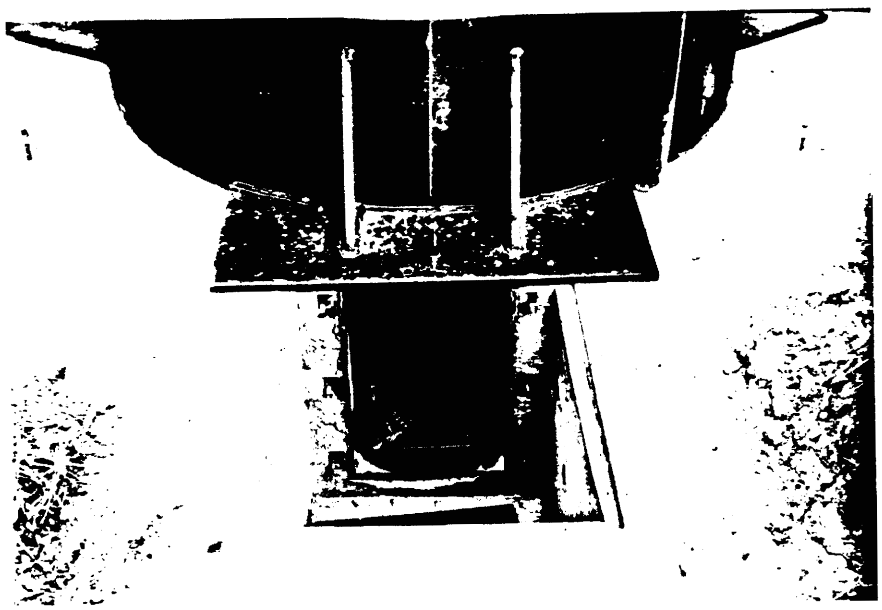

Figure 5. Upper and lower load ring attachments.

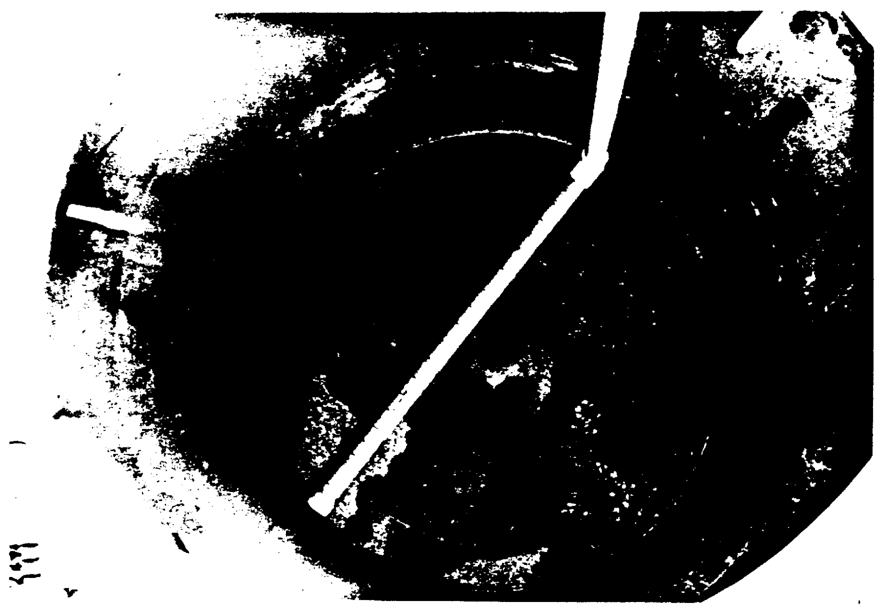

Figure 6. Inner cylinder drain.

Figure 7. Lysimeter installation with weather instrumentation.

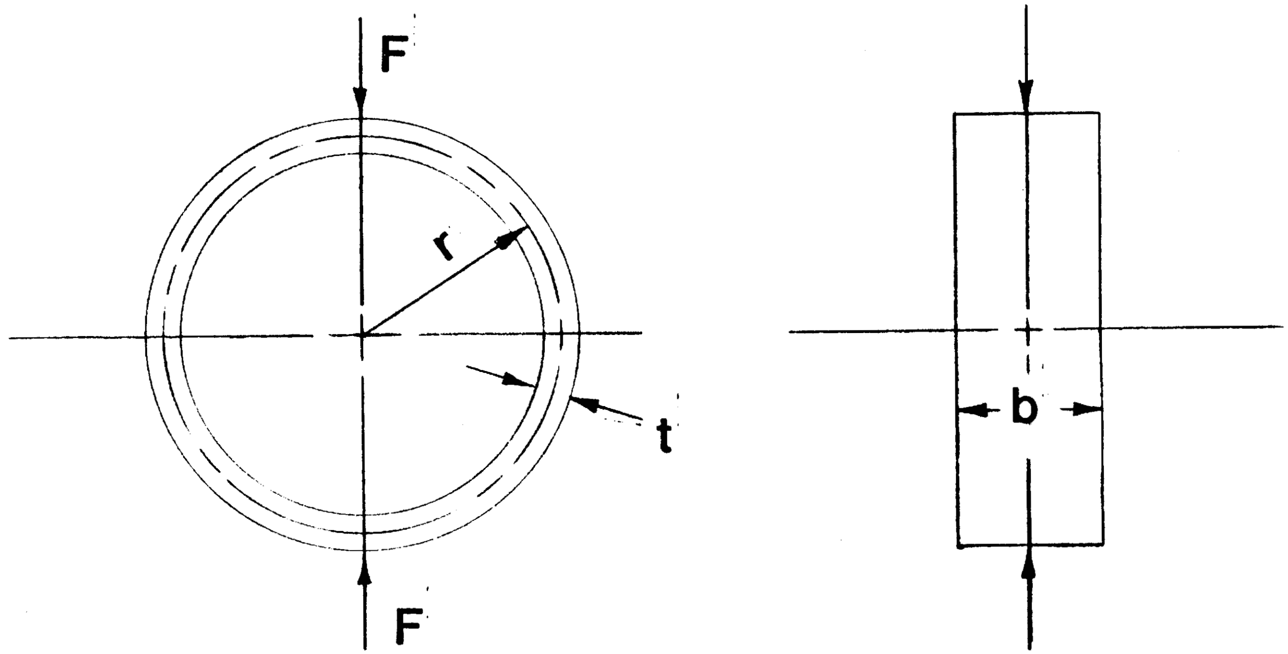

Figure 1A. Thin ring used for force measurement.

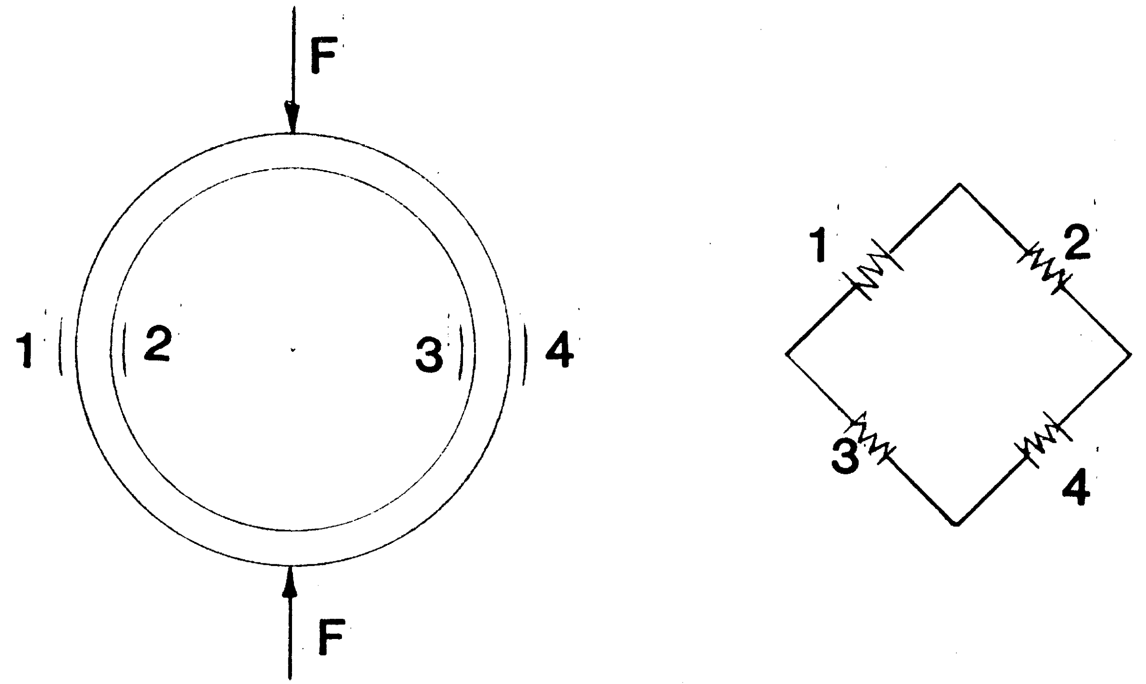

Figure 2A. Strain gage configuration on thin ring.

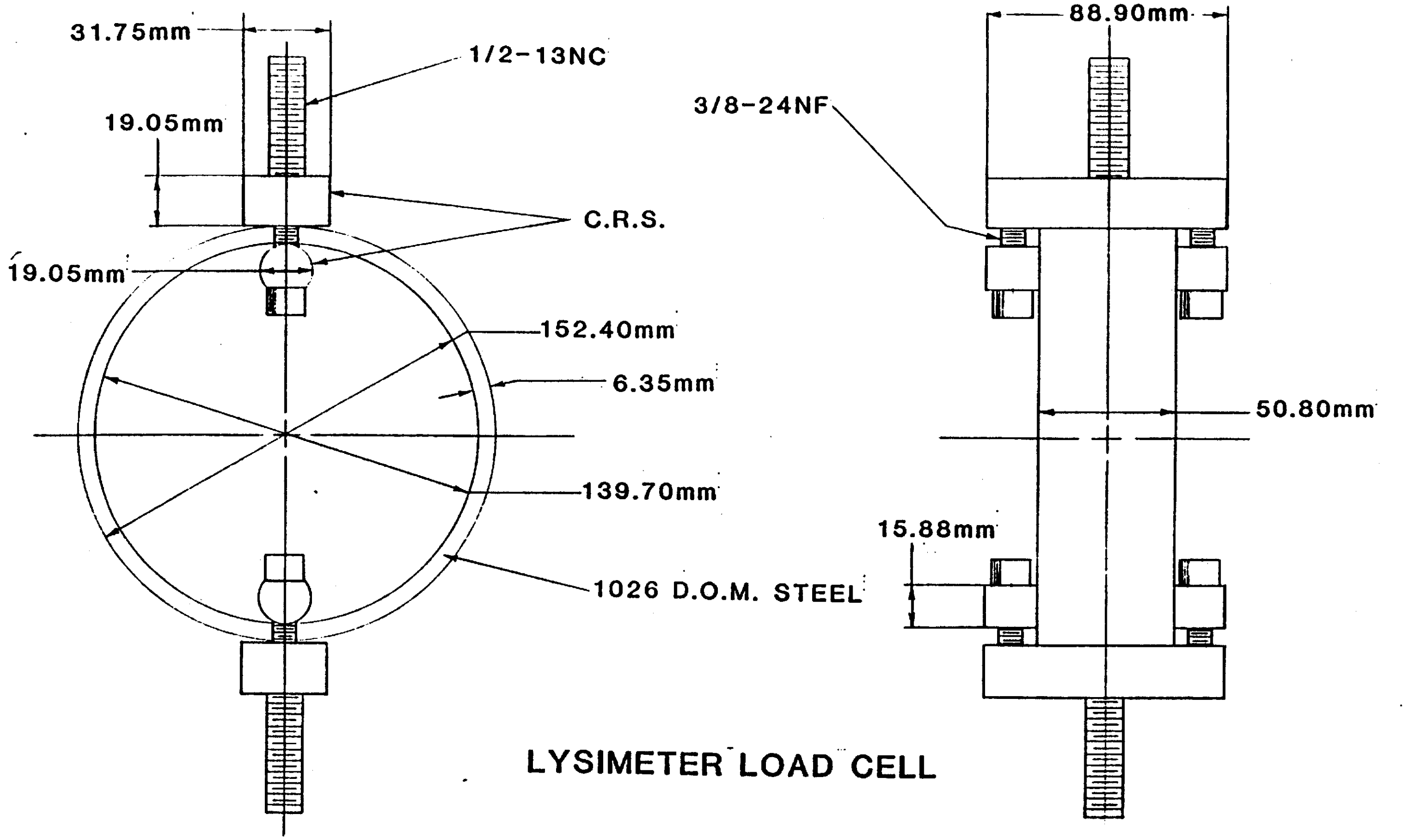

Figure 3A. Load ring design details.

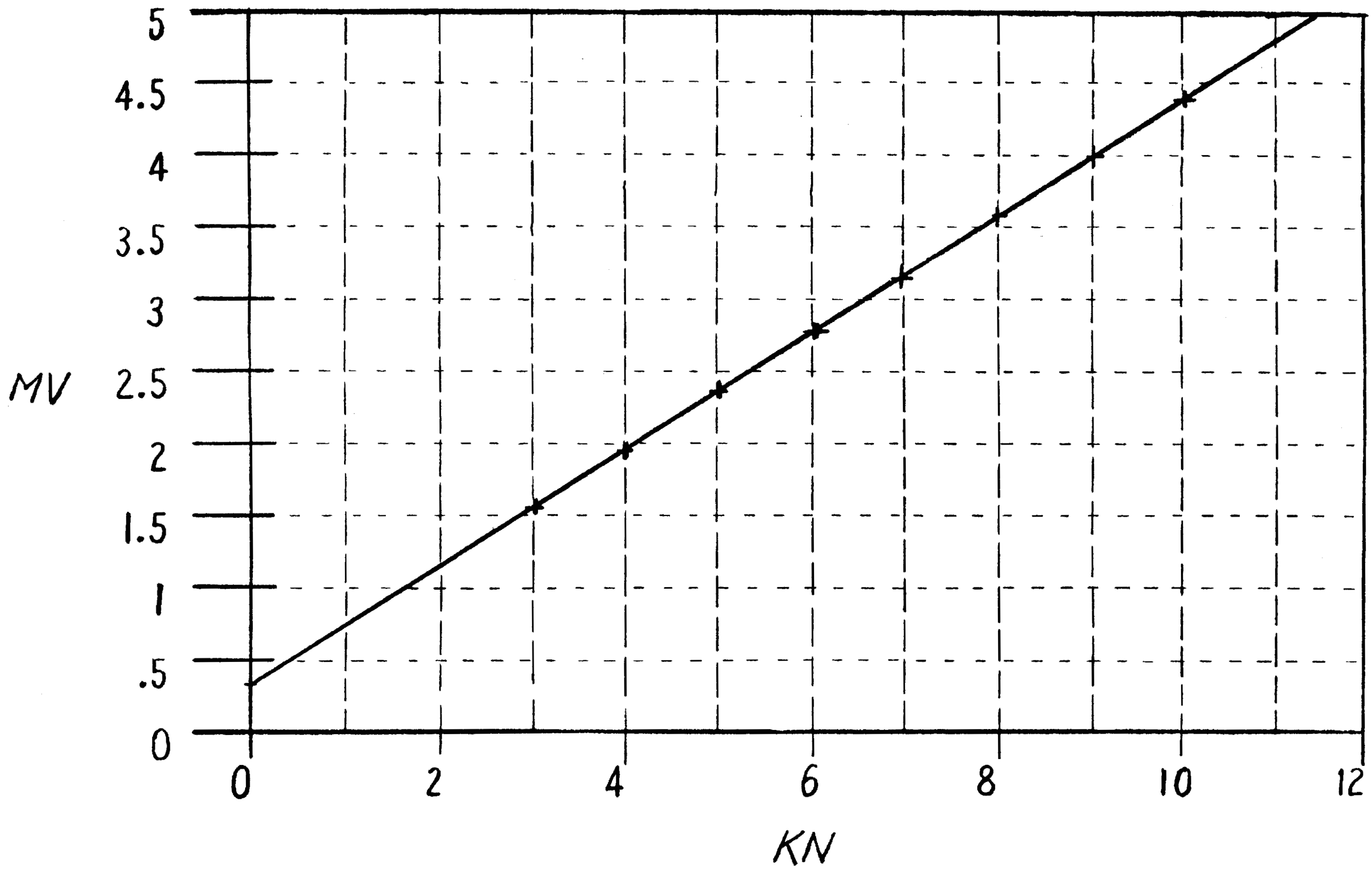

Figure 4A. Load ring calibration, Ring 2.