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# Evaluation of rapid reading hay moisture meters for field use

Joseph Keith McDonald

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To the Graduate Council:

I am submitting herewith a thesis written by Joseph Keith McDonald entitled "Evaluation of rapid reading hay moisture meters for field use." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering.

Bobby L. Bledsoe, Major Professor

We have read this thesis and recommend its acceptance:

John I. Sewell, Zachary A. Henry, Fred D. Tompkins

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by Joseph Keith McDonald entitled "Evaluation of Rapid Reading Hay Moisture Meters for Field Use." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Mechanization.

Bobby L. Bledsoe

Bobby L. Bledsoe, Major Professor

We have read this thesis
and recommend its acceptance:

Zachary A Henry

John I Sewell

Accepted for the Council:

Hilton A. Smith

Vice Chancellor
Graduate Studies and Research

# EVALUATION OF RAPID READING HAY MOISTURE METERS FOR FIELD USE

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

Joseph Keith McDonald
December 1976

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## ABSTRACT

An instrument for use by farmers and agricultural research workers to quickly, accurately, and economically determine the moisture content of hay in the windrow would significantly improve the efficiency of forage crop production. However, no method or technique has been shown to be a successful tool for obtaining such determinations simply, precisely, and with easily portable equipment. An experiment was designated to field test a commercially available conductance-type moisture meter and to identify needed revisions of the meter or a measuring technique that might improve its accuracy. An experimental conductance-type meter was also built and tested in an attempt to develop a more accurate method for hay moisture content measurements.

Three electrical moisture meters, a hydraulic compression device, sample probe, hay sample chopper, and other related swithing gear were purchased or designed and constructed. The meters were tested on three different hay types, at various sample pressures, and at two geographical locations. The performance of the meters was compared to oven drying moisture determinations.

Results of these series of tests revealed several factors which affect the accuracy of the meters as determined from simple linear regression equations relating meter readings to actual hay moisture content.

1. The use of a cylindrical holder eliminated error caused by the prod pins completely penetrating the windrowed

hay and entering the soil surface.

2. Sample pressure affected meter readings. No specific pressure was best overall, but a constant pressure was mandatory for consistent results.
3. Fields, type of crop, or time of test also affected meter readings and calibration equations.
4. Chopping of hay samples improved the accuracy and consistency of meter readings.
5. No one single meter proved to be statistically better than the others tested.

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# CHAPTER I

# INTRODUCTION

## I. BACKGROUND AND STATEMENT OF THE PROBLEM

Improved forage crop practices for packaging, storing, handling, and feeding are important to more efficient agricultural production. When forage is cut, the conservation of quality becomes a problem and is related to moisture content. Under practical storage conditions, moisture content is a principal factor governing the quality preservation of forage crops. Common types of freshly cut hay have moisture contents of 65 to 80 percent. At present, this forage must be dried to 15 to 20 percent moisture content for safe storage using a common, small package baler (33).

Proper control of moisture in hay is especially critical at baling time and before storage (34). Because of its importance, the greatest possible accuracy consistent with practical operations should be maintained in determining moisture content. The fast determination of moisture allows an operator of a process to quickly determine the moisture state of a material and take corrective action when needed (62). A method to quickly determine moisture content, whether it be a device or technique, would prove invaluable to the grower in avoiding physical damage to the forage crop. When moisture is great enough and the hay densely packed, spontaneous combustion occurs and causes many disastrous fires (70). These same conditions on a lesser scale also can cause discoloration, mold development, and fungus damage that reduce food value and sometimes cause food poisoning (18, 34, 70).

Even the most experienced plant and soil scientist concedes difficulty in accurately estimating the moisture content of partially dried hay. Confirming the proper degree of dryness for safe storage has been more of an art than a science, and the techniques learned have been passed on from one generation of farmers to the next (23). Hay has been twisted, smelled, rattled, or scratched with the fingernail to estimate moisture content (23). This casual estimation of moisture in forage crops by the appearance or feel of texture leaves much to be desired (1). Quick moisture determination is not possible with the standard oven method of determining moisture content since it requires about 24 hours (1, 49). So two alternatives can be considered: (a) to dry faster or (b) to eliminate the drying process in determining moisture content (29).

Recent development of big package haying machines has prompted studies to determine the optimum moisture content for hay stored in these packages. In a study conducted at The University of Tennessee, a commercially available electrical conductance-type moisture meter was used to measure the moisture content of hay before baling. These moisture determinations were checked by taking samples of the forage during the packaging process and measuring the moisture content by the standard oven drying method. A comparison made between the meter readings and the oven drying determinations showed the meter to be inaccurate. The need for a more extensive evaluation of the meter was evident (6).

The accuracy of conductance-type moisture meters was shown to be impressively accurate in tests conducted by Hartstack and Aronovaski (1, 33). Thus, the conductance-type moisture detector was proposed as being capable of providing the needed accuracy desired in determining the moisture content of windrowed hay, possibly with some calibration modifications and improved usage techniques. Ideally the method has been reported to be fast, accurate, simple, inexpensive, and versatile for detecting the moisture content of a wide range of plant materials (61).

## II. OBJECTIVES

The purpose of this study was to evaluate conductance-type moisture detectors for accurately measuring the moisture content of hay in the field. Specific objectives were:

(1) To field-test a commercially available conductance-type moisture tester by comparing it to the standard oven drying method for accuracy and precision.

(2) To identify revisions in the conductance-type commercial moisture meter that might improve its accuracy for future use in forage research.

(3) To test an experimental conductance-type meter developed by Hartstack and modify it for more accurate hay moisture content measurements.

# CHAPTER II

# REVIEW OF LITERATURE

## I. MOISTURE DETERMINATION

### Factors Affecting Moisture Determination

Success of an instrument in determining the moisture content of a material depends on: (a) the type of equipment used, (b) the atmospheric conditions prevailing, (c) the procedural techniques employed, and (d) the type of the materials to be tested. Each material has different characteristics and the best method of moisture determination must be found for each (26).

The absorption-retention of water by biological materials is an extremely complex process, due largely to the intricate physical and chemical make-up of most biological systems and also to the fact that water can be present in several different forms (51, 79). The relative amount of the different forms of moisture depends on the previous moisture history of the material, a fact that complicates calibration procedures for moisture measuring instruments (39, 79).

Moisture is held by plants in three distinct phases: (a) that chemically bound to constituents of the plant material, (b) that physically bound to plant cells by surface forces, and (c) that free liquid held by capillary action witnin voids in the plant structure (51, 75, 79). The first phase is not considered in moisture content determination since it is assumed to be an integral part of the plant material or "bound" water (76).

Atmospheric conditions such as temperature and relative humidity affect moisture content, and any alteration of the plant material affects the measurements. Grinding the plant material could result in moisture loss from the heat produced. The use of hay preservatives, such as propionic acid, also affects moisture content measurements (59).

Procedural techniques, particularly sampling, are most important to accurate moisture determinations. The selection of a representative sample is by far the most difficult and exacting part of the moisture determining process (18). There is no established process for obtaining samples but a few general guidelines for the reduction of sample error can be given: (a) larger samples have a greater chance of representing the true average of the material and help minimize local variations, (b) a thoroughly mixed sample reduces variations, and (c) taking several sub-samples from various locations and mixing to obtain the sample to be tested proves helpful, especially for a large volume of material (24, 42, 43, 49, 53, 79).

## Requirements for a Moisture Determination Method for Farm Use

In general, moisture determinations made on the farm are used for quality control rather than for market transactions (43). Accordingly, the method used should be rapid enough to allow taking a large number of samples in a reasonable length of time so that bulk materials of non-uniform moisture content can be evaluated. The method should be simple to use, and the equipment portable and of low cost. The sample tested should include enough plant material to be representative. The moisture readings should be reliable, repeatable, and sufficiently accurate for quality control purposes (79, 81).

With these general requirements in mind, a review of the methods of moisture determination available was conducted to consider the advantages and disadvantages of each and finally to select one that might be developed for quick measurement of the moisture content of forages.

## II. METHODS OF MOISTURE DETERMINATION

### Broad Classifications

Two broad classifications for moisture determination methods are primary (basic) and secondary (practical). The primary methods are generally relatively accurate, but are too time consuming for most practical purposes (82). These methods also are usually direct determination methods; that is, the water is driven from the product and the loss in product weight or the amount of vapor evolved is used to determine the moisture content of the product. Some chemical methods also are included in this group. A few examples of this group are oven methods, drying with desiccants, tolene distillation, and the Karl Fisher method of extracting plant moisture (5, 49, 82).

The secondary methods are practical methods designed for rapid, routine determination of moisture content of different materials. For the most part, the secondary methods are ones which have to be standardized against one of the basic or primary methods. These indirect methods involve the measurement of properties of the materials which are functions of moisture content. Some examples are the methods based on relative humidity measurement, electric moisture meters, nuclear methods, spectroscopic methods, and ultrasonic methods (49, 82).

## Methods Considered for Rapid Measurement of Moisture in Forages

The following is a list of the methods that were considered for possible use in the determination of moisture content in forages. A short description follows each method together with advantages and disadvantages of its use.

### Oven Methods

Oven methods involve calculation of moisture content of a material by gravimetric means (weight loss during the drying process) (51, 81). They provide simple and direct measurement of material moisture content (43, 46, 79). The oven method is widely used because ovens are common items in any laboratory, more than one sample can be run at a time, and the required skill is easily acquired (26, 43). In biological materials, it is very difficult if not impossible to remove all moisture by the application of heat without at the same time driving off other volatile substances or causing decomposition of some of the constituents to form moisture not originally present as such (26, 51, 75, 78, 81).

Oven methods are very empirical in nature because of the arbitrary parameter values, such as time and temperature, which have been selected in the standards (49, 51). There is a possibility of incomplete drying of the material being tested causing an error in the result (51). Therefore, the proper operating procedure and calibration are essential

(49, 81). The results depend on the degree of subdivision of the material being tested (whole, chopped, ground, etc.), time, temperature, and atmospheric pressure under which drying is accomplished. Moisture can be gained or lost during grinding if the sample must be reduced in size (26, 79, 81). These methods require considerable oven space and a drying time requirement of from 1 to 72 hours which varies between materials (29, 51). Accuracy depends on the two weighing operations (43).

Water and vacuum oven methods utilize lower temperatures which may decrease deterioration of the dry matter (79, 81). The water oven method requires a longer drying time because temperatures above the boiling point of water are not applied to the sample being dried. The vacuum oven method decreases the temperature required by decreasing the atmospheric pressure applied to the sample thus maintaining the same drying rate and time. Or, the temperature can be held constant while the atmospheric pressure is lowered to speed up the drying rate and decrease the time required. The vacuum oven method leads to higher losses due to the removal of products of decomposition from the system with reduced pressures (79).

The exhaust method is a modified air oven method in which higher temperatures are used to speed up the determination. The higher temperatures in turn accelerate decomposition by heat. This method is of relatively low cost and rapid enough to follow the drying in most farm processes. However, the drying rate is not rapid enough to encourage the testing of many samples. A correction factor must be calculated relating percentage of moisture loss for a given time and temperature for each material to be tested. Accuracy is not affected by secondary factors such as ambient temperature, humidity, sample species and variety, or by non-uniform moisture distribution in the sample. However, significant amounts of residual moisture remain and are condensed in colder parts of the sample. This method was applicable over a full range of moisture contents measured in grains and forage crops but required constant observance to prevent charing or burning of the sample (18, 43, 46, 81).

### Chemical Analysis Methods

Chemical methods are based on stoichiometric chemical reactions in which water is one of the reactants. These methods should theoretically produce high accuracy and be suitable for determining moisture content at any level (47, 51, 76, 79, 80, 81). Since the water within materials is bound to some degree by physical forces, it might be questionable as to whether all of the water present enters into the reaction. Moisture may be lost or gained while grinding the material to a suitable size for reaction. The sample is destroyed by the reaction which means that check tests cannot be run on the exact same sample. Some analytical and technical skill is required to use any of the chemical methods (32, 79).

The Karl Fisher method, the dichromate method, and gas chromotography are among the chemical methods. The Karl Fisher method requires expensive equipment which can test only a small sample. This method is restricted to the laboratory, is too time consuming, and requires a specific partical size for the material tested (26, 51). It is difficult to completely extract all water from the material using the Karl Fisher method (27, 28). The dichromate method requires that a "dichromate factor" be determined for each type of product tested, based on the results of a standard oven method (71, 81). Variations in this factor are expected due to the inherent variability of materials. This method measures dry matter rather than the water present in the sample. It was designed for the measurement of water in fresh or moist materials and has limited applicability for dry materials (47, 70, 79). Gas chromotography is a very complex, time consuming analytical method with a high cost of equipment which makes it unsuitable for "field test" applications. Volume, pressure, and temperature all must be measured and controlled to obtain maximum accuracy (61, 79).

### Drying with Desiccants

Drying with desiccants consists of putting a portion of finely ground material in a closed container with a relatively large quantity of efficient desiccant. Moisture content is determined by the loss in weight of the material after the desiccant absorbs moisture. These methods are very accurate and useful for some low moisture content materials (2, 81). Heat is not required for drying, thus avoiding decomposition by heat. The time required to determine moisture content of certain materials is too great for this method to be of widespread practical importance. Due to the lengthy time required for drying, molds and bacteria may cause decomposition of the high moisture material before the sample is of low enough moisture to inhibit such growth. Again, moisture may be lost or gained by grinding the sample to a size suitable for use with the desiccants (79, 81).

## Distillation Methods

Distillation methods determine moisture content of a material through heating it in oil or some other nonaqueous liquid and measuring either the loss of water by weight from the sample and nonaqueous material or the volume of water distilled (13, 81). These methods allow large samples to be tested in an inert atmosphere so sample water only is measured. Distillation methods are usually simple, inexpensive, quick, and fairly accurate. The oil effectively prevents local overheating or burning while allowing the use of a large amount of heat and very rapid evaporation (21, 36, 81). Some technical skill is required to use distillation methods, and more space is required per determination than for oven methods. If water is a product of decomposition, it is collected in addition to moisture driven from the test material. So are other substances which are soluable in water. These extra weights or volumes cause errors (26). The time required to obtain complete distillation of the water is uncertain, and moisture can be lost or gained during the grinding process to reduce sample size. The sample is destroyed in this moisture determination process (79).

The tolene distillation method is more accurate than oven methods (13). This method requires expensive equipment which has to be cleaned frequently. The nonaqueous liquid which is used in this type of distillation is either Tolene or Xylene. The boiling points of these liquids are 232°F (111°C) and 280°F (138°C), respectively. Thus, any substance that boils below these temperatures would be distilled. The time required for most of these determinations is about 1 hour which drastically limits the number of samples which may be taken. Some analytical skill is required to run the Tolene distillation test (36, 79, 81).

The Brown-Duval distillation method is somewhat empirical in that time and temperature magnitudes are set arbitrarily for a standard on all materials to be tested. It is basically a method using heat to drive off moisture. Proper operating procedure and accurate calibration are essential for each type of crop (49, 81). The time requirement for each determination is 20 to 25 minutes. Too much heat gives higher values for moisture content than those of the laboratory oven method (13, 21).

## Electrical Moisture Meters

Electrical moisture meters measure certain electrical properties which are influenced by the moisture content of a material. These meters are convenient, simple to operate, and give quick readings. They are more economical than conventional direct determinations, and the sample is not destroyed. The instruments are portable and applicable to a variety of crops (11, 36, 42, 49, 50, 51, 62, 68, 76, 79, 80, 81). These meters are sometimes inaccurate because variables other than moisture affect the electrical properties of biological materials, and different meters are affected differently by these variables. The variables change from year to year with the introduction of new varieties of crops and different methods of handling them. Generally speaking, separate calibrations are required for each kind of crop and often for individual classes of a single kind of crop (3, 33, 81, 82). Temperature corrections must be applied when tests are made at temperatures other than that for which the calibration was established. Sample density variations have been shown to affect meter readings (70, 79). The ratio of "free" to "bound" water must be constant at a given moisture content (79). There also is a variation in the performance of meters, both between different types and between different models of the same type (69). The above facts apply to both the capacitance-type and the conductance-type electrical moisture meters.

The capacitance-type electrical moisture meter is less subject to errors resulting from uneven moisture distribution, and from mustiness or sourness within the sample material than are conductance-type meters. These are capable of measuring a wider range of moisture content, and physical contact is not as critical as in the conductance method (79, 81). One author stated that it is the most accurate and efficient type of electrical moisture meter (3), but other authors said the same for the conductance-type moisture meters (36, 81). The capacitance-type moisture meter depends on the dielectric constant of a mixture of water, dry matter, and air which requires density corrections for many materials (38, 40). Difficulties occur when this method is applied to hay because of the nature of packaged hay; it is difficult to orient the sample uniformly between the conducting surfaces (33, 81). The density of the package also affects capacitance readings and repeatability of results (62, 81, 82). Capacitance-type meters are difficult to keep in adjustment, particularly among individual instruments (79, 81). Also, the rate of change in capacitance with moisture content is two orders of magnitude less than the change in conductance; thus, they are less sensitive to moisture changes than are conductance-type meters (12, 31).

The capacitance-type meter is sensitive to temperature, product weight, and product density. Resistance also affects capacitance-type meters (49).

The conductance- or resistance-type electrical moisture meter has resistors in series to adjust the range of the meter. These meters are easy to keep in adjustment and in agreement with one another (51, 69, 79, 81). When used in connection with cottonseed, this type of meter proved satisfactory in accuracy, showed good repeatability, and was considered sound and practical (77). The accuracy of this type of meter is dependent on moisture distribution and has an effective range from 6 to 50 percent moisture content (33, 36, 49, 52, 67, 69, 77, 81, 82). Resistance varies with material density and acid index. Some of these meters have been found to change internally with time. Hay samples which contain a few wet pieces give a completely erroneous indication of moisture content (36). Surface moisture (dew), density variations, and nonhomogeneous moisture content of the measured product greatly affect the meter readings obtained by the conductance-type moisture meter (49, 62, 77, 81). Musty, moldy, or sour materials often fail to give normal readings (49, 81). While checking bales of hay, one author found readings taken over 25 percent moisture content to be very inaccurate (1). Salt concentration affected meter readings in other tests (7, 9). Electrode design was found to affect the readings of the conductance-type moisture meter (77).

## Nuclear Methods

Nuclear methods sense the hydrogen content of a material from which the water content is calculated (53, 63, 81). These methods are rapid, highly accurate for properly calibrated instruments, and the sample is not destroyed, allowing for further study. The neutron scattering method showed good correlation when working with soils, was not dependent on texture, structure or concentration, but was very sensitive to bulk density. Therefore, each sample required an accurate bulk density determination which added to this method's high instrumentation costs (51, 53, 63, 79, 81). Because of sensing total hydrogen rather than water hydrogen and because there are different energy forms of water, problems exist in separating hydrogen of water signals from non-water hydrogen signals (64, 79). To further complicate this method, other elements such as boron, magnesium, chlorine, and iron may affect neutron scattering readings (73, 79). Varietal differences also have a significant affect on the moisture content-neutron count relationship. Non-water hydrogen must remain constant to attain accurate readings from sample to sample. The neutron moisture meter is a strictly empirical instrument since no theoretical relationship has been developed between the slow neutron density and moisture content (53, 79).

## Relative Humidity Methods

Relative humidity methods are based on the relationship between product moisture content and the relative humidity of the air surrounding the product after the two come into equilibrium (42, 79, 81). It takes several hours for a material to reach equilibrium with air in a closed container (23). Sample size, temperature, and ambient air relative humidity affect the rate of rise in relative humidity (33, 81). Relative humidity measurements are simple, rapid, and inexpensive but equilbirium is reached too slowly for these methods to be practical for field use. Some relative humidity methods used small samples which were not destroyed (19, 22, 33, 37, 79). The relationship between moisture content and relative humidity is complicated in that it differs among materials, between samples of the same material, and within varieties of the same crop. Thus, the material being tested and the previous history of the material are factors to be considered when using this method of moisture determination (20, 79). Hysteresis in the drying curves caused variations from calibration curves (44, 79). These methods were inaccurate at high relative humidities. Dampness on the outside of relatively dry materials would produce humidities approaching 100 percent. Readings needed to be below 80 percent to give an acceptable degree of accuracy (23, 79). Some samples which were stored in a container that prevented air exchange molded (23). These methods were not very accurate and were usually only adapted to grain drying determinations and were not recommended for high moisture hay (20 to 30 percent) because of humidity readings of over 100 percent (20, 33, 37).

### Light Absorption Techniques

Light absorption techniques involve relating the energy absorption at one of the water absorption bands to the amount of water present in the material (4, 72, 79, 81). These methods do not destroy the sample and are quick. With proper calibration, they are also very accurate (15, 51, 52, 53, 58). Since these methods are based on a fundamental property of water, the determination is not dependent on variations in temperature and surface conditions (52, 56, 69, 79). These methods are used to determine water content of a wide range of materials such as liquids, grains and seeds (51, 57). Light absorption techniques are: (a) too expensive for practical use, (b) very sensitive to bulk density, and (c) require equipment calibration for each product tested (51, 79). Authors do not agree on the effective range of these techniques. One stated the range to be 10 to 30 percent while another said 0 to 30 percent. Yet another stated that 0 to 50 percent was the effective range (51, 58).

Two known absorption bands of the water molecule are found within the accessible microwave region (74). Such a measurement can be carried out independently of variety, quality, shape of the material, moisture distribution, and salt concentration (58). There are also two vibrational modes of water which result in the absorption of infrared region waves (72). In tobacco, the infrared-type instrument was designed for only one thickness of leaf which automatically induced a bulk sampling problem (50, 51, 52). Optical region waves were used primarily in determining moisture content in liquids (16). Due to the large energies of radiation in the optical region, more overlap of absorption bands of other materials was expected (14). Most light transmission techniques have been unsuccessful because of the inconsistent texture and density of hay samples. Grinding the sample was not practical for field operations, and not many facts were known about the variables associated with spectral absorption (33). Thus, assumptions were made about praticle size, size distribution, particle reflectivity and refractive index, sample thickness, pigment distribution, pigment absorption coefficient, as well as instrumental factors of stray light, optical pass band, linearity, and accuracy (56). Results from spectrophotometric tests indicated that water in different forms gave different results. Dry matter absorbs some energy and presents calibration difficulties, as does moisture distribution (79).

### Ultrasonic Methods

Ultrasonic methods involve measuring the absorption of pressure waves greater than audible sound passing through a material to be tested and relating the propagated energy of the material to its moisture content. Although moisture distribution and chemicals did not affect the results, the method was very expensive and different frequencies had to be used for evaluation of different materials (10, 81).

## III. METHOD SELECTED FOR EVALUATION AND DEVELOPMENT

Probably the most accurate methods for moisture determination now available are the Karl Fisher method and gas chromatography. Both depend on extracting all the moisture from the material with methanol. The time required for this extraction is somewhat indefinite which introduces an empirical factor in the determinations. Otherwise, these methods have been found to be theoretically and experimentally highly accurate. However, the equipment and time required make these methods unsuitable for many routine inspection-type measurements for field tests. Oven methods are too slow for determining the moisture content of forages, while light absorption techniques are too erratic (79).

The accuracy of the microwave absorption and nuclear magnetic resonance methods are probably higher and the time required per determination is not much greater than electrical methods, but the cost is greater. The microwave meter approximated absolute moisture values, but again the effect on accuracy of the different forms of water was not certain. The nuclear magnetic resonance technique offers promise of an absolute moisture meter, but the effect of "bound" and "free" moisture ratios on the measurements has not been ascertained. Neutron scattering methods have been found very useful in soil moisture measurements but are too expensive for practical field use. Equilibrium relative humidity methods are used for monitoring forage crops while in storage, but the time requirement is too great for rapid moisture determination. When using chemical, desiccant, or distillation methods, some technical skill is required along with an excessive time period. Not enough is known about ultrasonics for consideration as a solution to the moisture determination problem in the near future (79).

The most rapid moisture measurement methods are electrical, based on measurement of either conductance or capacitance. The variability of the electrical properties of a material and the uniformity of the moisture distribution must be considered in choosing between the two methods (79). Both methods have been used successfully in measuring the moisture content of grain (33). Electrical moisture meters potentially satisfy many of the design requirements for a moisture meter used to measure forage moisture content by farmers. They provide an instant reading, are portable, and can be applied to other crops by calibration (42). The newer and more rapid methods of determining moisture content of materials such as grain, lumber, and paper by measuring the electrical conductivity or dielectric loss of these materials seemed to offer the best possibilities for testing baled straw and other agricultural residues (1). J. B. Dobie showed that the conductance-type moisture meter was reliable (24). Hartstack's work with alfalfa indicated that meter accuracy was closely related to a uniform density of the hay sample (33). He obtained good results (88 percent of variation explained by a simple linear regression of the meter readings on oven determinations) by compressing the hay sample to a uniform density. Based on these previous successes, the electrical conductance-type moisture meter was the method selected for study and development.

## IV. HISTORY OF DEVELOPMENT OF THE CONDUCTANCE-TYPE MOISTURE METER

The problem of determining the moisture content of food products using electrical methods has received much attention. Electrical measurements, although providing indirect determinations of moisture, are faster and less costly than conventional direct determinations. The rapid determination of moisture allowed an operator of a process to quickly determine the moisture state and take corrective actions when needed. Faster determination enabled more frequent sampling with reduced error (37, 50).

The first attempts to measure moisture electrically used simple conductance measurements. Since the conductance of a material correlated with its moisture content (as product moisture increased, resistance decreased, and conductance increased), determinations of current allowed an indirect determination of product moisture (37, 50, 62, 77).

A number of instruments have been designed to measure moisture of products other than hay and are on the commercial market. Some of these instruments have been adapted to hay measurement. None of them provide for a relatively large sample and uniform arrangement of hay fibers. The most widely recognized method for determining moisture content in hay is by oven drying known weights of hay and calculating moisture content from weight loss. This method is accurate but too slow to be used satisfactorily in the field. However, the oven method has been used as the standard to which electrical measurements are compared (1, 24, 33). This comparison usually has been shown, when graphed, as the logarithm of resistance (ohms) versus percent moisture content by the oven method (43).

Early conductance-type instruments marketed had insufficient range, were entirely too delicate and bulky for field use, and were found to be much too expensive for general use. Accordingly, special instruments were devised for field use. Such an instrument was developed by Bouyoucous and Crabb in 1949 for use in soil research (7).

Bouyococous and Crabb stated that to obtain a dependable conductance-type moisture meter determination, two devices were needed: (a) a suitable resistance element, and (b) a resistance bridge especially adapted for the purpose. The instrument developed on this principle was a self contained unit, ruggedly built to provide a high degree of sensitivity and an extremely wide range. It consisted of a modification of the Wheatstone bridge circuit using a high-frequency electronic oscillator housed in a wooden case to aid in shielding from ground currents that caused difficulties in satisfactory operation of metal-cased bridges. A large condenser was incorporated in the circuit to counteract the capacitance found in the field currents. These two factors, ground currents and capacitance, caused serious derangement of results unless compensated or eliminated. The instrument used self-contained dry batteries which activated a 2000-cycle-per-second oscillator. To obtain a very wide range of sensitivity, two series of standardized resistances were inserted in opposite arms of the bridge. Through the use of multiplier switches, the resistances were properly combined, and a final balance obtained through adjustment of a logarithmic potentiometric rheostat. The bridge was balanced by manipulation of five dials. The instrument could be balanced very precisely with a sharp null point over a range of 5,000,000 ohms (7).

Conductance-type moisture meters have been evaluated for determining the moisture content of hay. Aronovski and Sutcliffe conducted tests on the Delmhorst Model RC instrument to determine the amount of moisture in straw. The instrument was found to be satisfactory in measuring moisture content up to 25 percent; beyond this range, it was useful only for indicating whether the straw was slightly or extremely wet. The instrument was simple, compact, portable, and rapid reading (1).

Whitten and Holaday (77) stated that the principle of electrical conductivity measurement of the moisture content of cottonseed was sound and practical. It proved to be a simple method that required no weighing of the sample and was satisfactory from the standpoint of accuracy. The test took about 4 minutes per determination. James (45) stated that the data he obtained essentially confirmed previous results for resistance meters as to accuracy and dependability for use with wood. All these authors suggest that this principle should work equally well with other agricultural products.

From conductance-type moisture tests on waffered alfalfa hay, Dobbie and Goss (24) found that with the proper regression curve, the instrument was sufficiently accurate to be a useful tool for farmers but did not provide the accuracy needed for most experimental procedures. Issacs and Wiant (42) described an electrical resistance method for determining moisture content of hay in the windrow. A wheel, containing a number of paired electrodes, was rolled along the windrow and the average moisture or conductance was observed from a meter attached to the wheel. This automatic averaging or scanning principle reduced the variability of moisture content measurements made as a function of electrical resistance of alfalfa and alfalfa-brome hay.

Factors affecting conductance-type moisture meter performance included design of the electrical probe, type of current meter used (a.c. or d.c.), sampling technique, nonhomogeneous moisture content, density or sample pressure fluctuations with use of compression devices, calibration methods, and inconsistencies and biological effects due to moisture condition, temperature, chemicals, and soil conditions (1, 7, 8, 24, 33, 38, 45, 49, 50, 59, 62, 77, 81, 82).

The probing device most promising was the pin type which gave much more consistent results than compressing a ground material between two parallel plates. Multi-pin probes eliminated the necessity for finely grinding the sample and uniformly loading the sample container (24). Obviously, the pin points had to be a fixed distance apart since the electrical resistance or conductivity was a function of distance between points of measurement (77). These needles had to retain their configuration during penetration of the sample (50). The probe needed to penetrate the sample to give better averaging of the material being tested, and the sharper the points the better (minimum of 30 degree included angle ) (77). A disadvantage of metal needles was that the metal-material contact provided many pathways for current flow, and a wet spot would completely saturate the system (50). Another disadvantage of the pin-type electrode was that when pressure was applied on the electrode, the pins completely pentrated the hay and contacted the soil (60).

The conductance current could either be alternating current (A.C.) or direct current (D.C.) (50). Bouyoucos (8) listed interesting characteristics of the d.c. conductance-type meter: (a) the d.c. meter was not sensitive and reliable in measuring soil moisture at higher levels of moisture content; (b) the d.c. meter readings tended to give very rapid and pronounced drifting and erratic performance, especially at higher moisture levels; (c) the d.c. meter readings were markedly influenced by polarization and hydrolysis; and (d) the batteries in the d.c. meter were short lived, and in large scale continuous operations they had to be replaced, offsetting the low initial cost of the instrument. The a.c. type of moisture meter was found to be a satisfactory and dependable method for measuring soil moisture, especially for irrigation purposes. A provision for voltage regulation was essential to compensate for changes in line voltage. The regulation was usually accomplished by a variable resistor to maintain the meter at some reference point to assure proper alignment of the instrument (77). Such instruments also had calibration resistors to check the sensing circuit (50).

Sampling technique was important. The conductance or resistance type moisture meter was found to be of limited value for testing moisture content of forage samples because of the difficulty in obtaining a representative measurement based on the specific location of the probe. The possibility of rapid testing of numerous samples enhanced the potential of the electrical conductance-type tester as a useful tool for the farm. Reasonable accuracy required that a minimum of 10 samples be taken and the readings averaged. The larger the number of readings, the greater the accuracy (24). The accuracy of the meter readings was closely related to the care spent in sampling the hay to be tested. In relation to the other methods, sample preparation was simple for the conductance-type moisture meter. More tests were required whenever the variation among readings was greater. If there were high moisture areas, samples from these locations were taken. Various moisture readings were taken in different areas of the windrow and averaged (33, 59, 60).

Electrical conductance-type moisture meters have been subject to errors due to nonhomogeneous moisture content of the measured product (62). The most accurate measurements made with the conductance-type moisture detector have been those of samples with the moisture evenly distributed throughout the hay. Even moisture distribution can be accomplished by grinding or chopping the hay. When sample particle size was reduced, the readings were expected to be accurate within three percentage points even though there were large differences in moisture content of hay from different parts of the windrow as well as between leaves and stems of the same plant (60).

Electrical conductance-type moisture measuring instruments also are subject to errors due to density or sample pressure variations of the measured product (1, 62, 77). The sample had to be kept under uniform pressure while it was being tested. Low pressures were found to give surprisingly good results with homogeneous materials but gave erratic readings when more fiberous materials were tested. The advantage of lower sample pressures was that the design of the pressure mechanism could be simplified and the cost reduced. However, pressure control became more critical at low pressures. At high pressures, on the other hand, control of the pressure was less critical, but more expensive equipment was required. Another effect attributable to pressure was the positive meter deflection or "creep" (increasing conductivity) which continued for approximately 2 minutes after the required pressure was applied to the sample (77). In some cases, the application of high pressure caused juices to be extracted from the product which made the resulting erratic meter reading meaningless (33). A device used for density control was a probe with a spring loaded compression handle for inserting the pins into the sample; this device reduced the need for operator judgement as to what pressure to apply (24). Hydraulic pressure for controlling sample density was selected as being a more practical and economic method than either the mechanical (spring) or pneumatic (air pump) methods (77).

All electrical meters were found to require calibration for each product by one of the direct methods (49). Each sample was tested by the appropriate basic method and the corresponding meter reading ascertained. From the data pairs so obtained, the best possible calibration was derived. Although the resulting calibration chart, table, or scale makes it possible to determine average moisture content accurately, tests on individual samples were in error by considerable amounts. Reliable calibration of any make or model of electric meter must be based on tests made on a large number of hay samples of each kind of crop, including wide ranges of moisture contents, areas of production, and data taken during several crop years (81, 82).

Plant biological effects on meter readings were numerous. The "bound" water in a material is not measured by conductance-type moisture meters. The change in conductance with moisture content is due almost entirely to the change in the amount of "free" water within the material. If the conductance-type meter is to give dependable results, the "bound" water must remain in the same ratio with "free" water (38). Chemicals alter internal functions in plant materials and can cause erratic readings as was the case when using methyl bromide on cottonseed (77). Variety differences affected meter determinations to some degree, and preliminary tests indicated that calibrations must be performed for each type of hay (33, 77). The accuracy of the meter was affected by temperature (33, 45, 77).

Hartstack (33) constructed an instrument with consideration for many of the developments and effects previously discussed. In his instrument, the circuit consisted of a transistor oscillator and amplifier combined with a differential Wheatstone bridge. The output of the oscillator was approximately 4 volts at 140 hertz which was applied across a bridge circuit. The output of the bridge was fed through two stages of amplification and rectified for indication on a d.c. microammeter. The legs of the bridge were made up of a 10-turn, 100 kilohm potentiometer with a readout microdial attached to its shaft, the measuring electrode, and a bank of adjustable resistors that could be interchanged to alter the sensitivity or range. The bridge was balanced by turning the 10-turn potentiometer until a minimum reading was obtained on the microammeter.

The Hartstack meter was protected from prolonged, extensive current by a push button switch so that the meter was out of the circuit except when a reading was being taken. The circuit was simple, drew very little current, required no zeroing, and was very reliable. Drift in the transistors, caused by temperature or aging, had no effect on the reading of the bridge circuit. As the meter required no warm-up, it was always ready for immediate use. Nine-volt transistor radio batteries worked very well for a power source. The sample holder was a metal cylinder 5 inches (12.7 cm) in diameter by 6 inches (15.2 cm) tall which enabled the use of 0.44 to 0.55 pounds (200 to 250 grams), dry matter of hay. A 5 to 8 ton (4,500 to 7,300 Kg) rated capacity hydraulic jack with a force gauge was used to power the sample compression device (33).

Hartstack evaluated his meter with alfalfa hay. Fifty samples were tested in the laboratory by drying freshly cut hay to a range of moisture contents from 10 to 50 percent. The moisture content was measured by the conductance-type moisture meter and then oven dried. When readings from the meter were plotted against oven determinations, the relation was not linear for the entire range but nearly so throughout most of the range (a simple linear regression equation explained 88 percent of variation about the mean). Attempts to improve this correlation with quadratic regression curves were unsuccessful. Using the data and regression line calculated from the laboratory tests, the fixed resistors in the bridge circuit were adjusted so that each scale would be in a step of 5 percent moisture. Calibration curves were calculated for each scale for a temperature of 75°F (24°C). Data from further field tests gave a standard error of estimate for the hay moisture meter of ± 2.04 percent moisture, and a simple linear regression of meter readings on oven drying moisture determinations explained 88 percent of variation about the mean. Only the first 7 of 11 scales of the meter were used in the evaluation tests (33).

Hartstack's test procedure called for (a) filling the sample container by folding the hay sample, (b) placing the sample holder under the compression device, (c) exerting a pressure on the sample by 600 psi (4100 kilopascals) pressure on the hydraulic jack, and waiting one minute for the hay pressure to drift downward; then again adjusting the ram pressure to 600 psi (4100 kilopascals), and (d) reading the instrument. The calibration chart was referred to for the actual moisture content of the hay (33).

# CHAPTER III

# DESCRIPTION OF INSTRUMENTATION AND EQUIPMENT

Two conductance-type moisture meters were selected for evaluations: (a) the commercially available Delmhorst Model F-4 Moisture Detector with the Model H-2 handle and Number 831 Short Pin Prod, and (b) an experimental moisture detector built according to the design of Hartstack (33). A hydraulic compression device patterned after Hartstack's design (33) was built and used to precompress hay samples to a known density for improved moisture detector accuracy. The actual resistance in ohms between electrode pins pressed into hay samples was measured by two ohmmeters during the series of evaluation tests. A Heathkit Model IM1202 Digital Multimeter was used during the first series of tests. A Simpson Model 270-4 Volt-Ohm-Milliammeter was used during the later series of tests. Rapid reading moisture determinations were compared to moisture content determined by oven drying, using a forced air, thermostatically controlled oven with capacity of 100 samples of hay each containing 0.44 to 0.55 pounds (200 to 250 grams) of dry matter. A brief description of the specifications for instruments and equipment used follows.

## I. THE DELMHORST MODEL F-4 MOISTURE DETECTOR WITH MODEL H-2 ELECTRODE HANDLE AND SHORT PIN PROD NO. 831

The Delmhorst Model F-4 Moisture Detector (Figure 1), advertised as being compact, portable, rugged, and ready to use, was a battery operated instrument designed to test moisture in hay or straw. It was built to measure moisture contents in the range of 10 to 50 percent, wet basis (34, 59, 60). The instrument measured the electrical conductivity between pins pressed into a forage product (17, 59). The meter consisted of a solid state direct current logarithmic amplifier circuit and was calibrated for direct reading of moisture content in hay and straw. The wiring diagram for the instrument is shown in Figure 2 (25). This meter was originally intended for testing the moisture content in baled hay (60). The moisture detector was calibrated with alfalfa hay at a temperature of 80°F (27°C) on a wet weight basis (17). The power source for this instrument was two-nine volt batteries. The Delmhorst meter had an adjustment switch and variable resistor in the circuit to set the instrument to a known resistance for a certain moisture reading. The resistance range of the meter was 630 megohms to 33 kilohms (17). The size of the instrument was 2.8 inches (7.0 cm) wide, 4.8 inches (12.1 cm) long, and 1.8 inches (4.4 cm) deep. Its weight was less than 1 pound (450 gm) and it cost $110.00 (17, 54).

The Delmhorst Instrument Company data indicated that tests with hay at high moisture contents, over 25 percent, were less accurate due to variability in moisture distribution within the hay sample (48, 59, 60). The company noted that above a certain level of moisture, the calibration curve flattened such that changes in meter deflection were

FIGURE 1. Arrangement of equipment during testing. The components are:

(1) The Delmhorst Model F-4 Moisture Detector
(2) The Hartstack Moisture Meter
(3) The Simpson Model 270-4 Volt-Ohm-Milliammeter
(4) The Electrical Switching Device
(5) The Delmhorst Model H-2 Electrode Handle with Short Pin Prod Number 831.

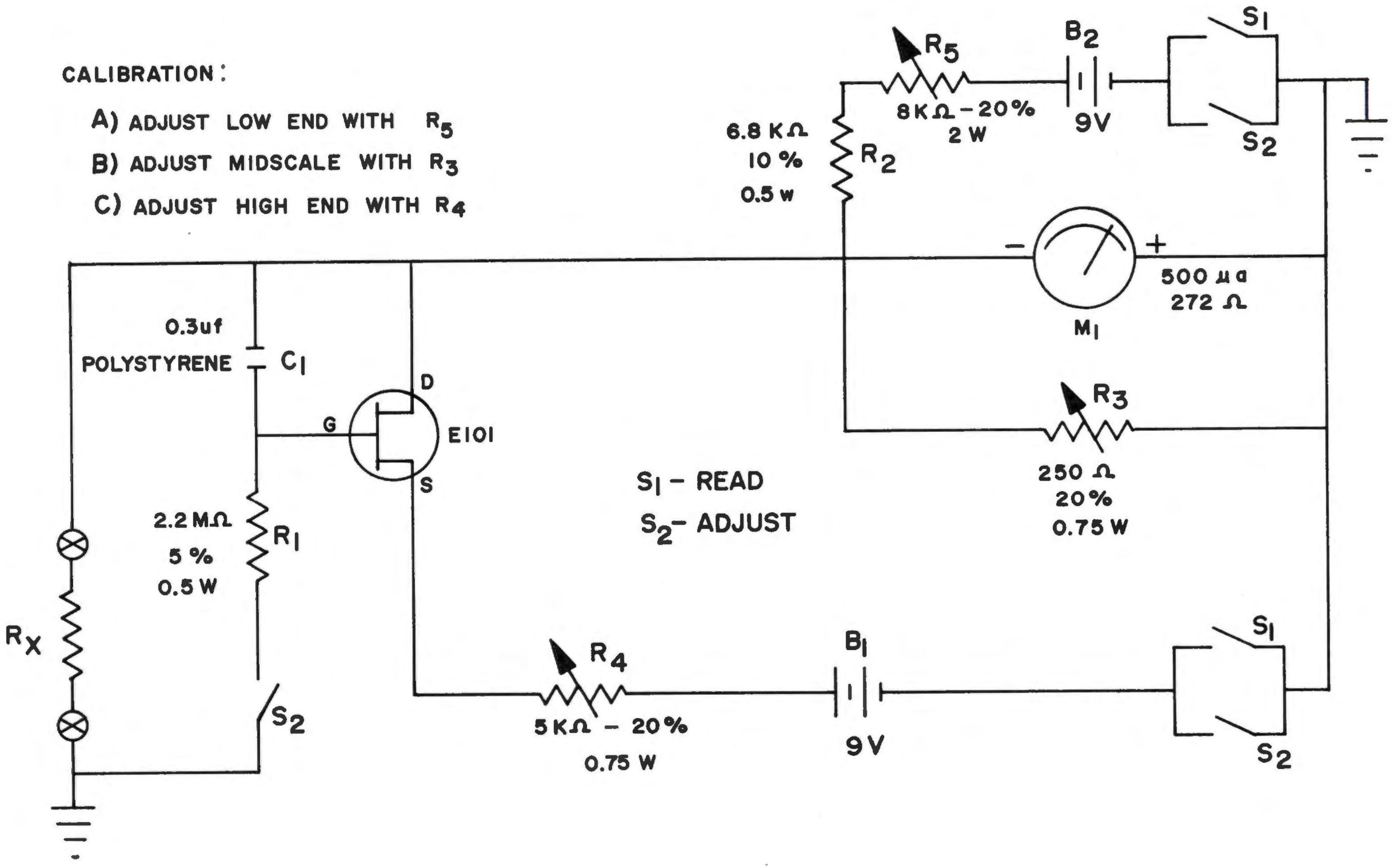

FIGURE 2. Circuit diagram for the Delmhorst hay moisture meter.

not a valid and discriminating indication of moisture content. At high moisture contents, the resistance measured was so low that other factors, not necessarily related to moisture, affected the meter readings. From this information, the inference was that the instrument was built only for use with hay containing about 20 percent moisture. Temperature also affected the meter readings, in that samples at temperatures greater than the temperature at which the meter was calibrated gave greater than actual moisture readings. Temperatures lower than 80°F (27°C) caused the meter to indicate lower than actual moisture content. The temperature correction factor was approximately 1 percentage point for every 20°F (9°C) difference from 80°F (27°C) (17, 59).

The Delmhorst H-2 electrode handle and short pin prod number 831, shown in Figure 3, was used to engage the hay in this series of experiments. The cost was $15.00 for the handle and $10.00 for the short pin prod (54). By applying force to the "Pressure Button" at the end of the electrode handle, the electrode pins were pushed into the windrowed hay supposedly with uniform pressure from sample to sample. This pressure button compressed an internal spring which acted on the prod. The pressure applied to the sample by the spring loaded handle was calculated to be from 6 to 7 psi (43 to 48 kilopascals) with 27 to 30 pounds (12 to 14 kilograms) applied to the handle (59). The short pin prod had six pins, three of which, in alternating order, were connected in parallel, and made up one side of the electrical probing device circuit.

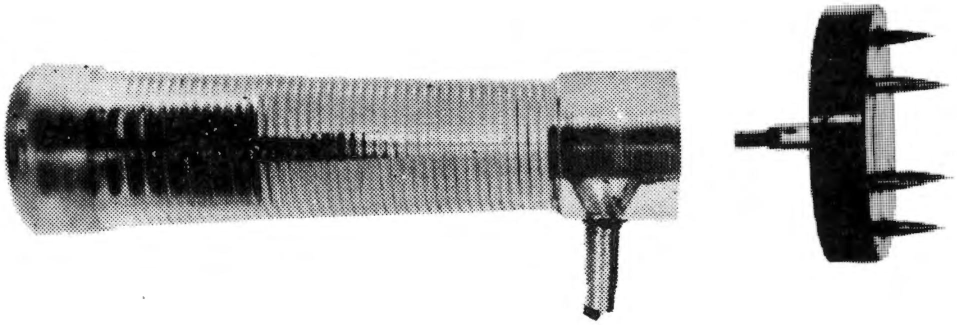

FIGURE 3. Delmhorst H-2 handle and short pin prod number 831.

## II. THE HARTSTACK MOISTURE METER AND HYDRAULIC COMPRESSION DEVICE

The Hartstack Moisture Meter, as originally designed, was meant to be accurate, fast, capable of accepting large representative samples, portable, and inexpensive. The key element of the instrument was a Wheatstone bridge (Figure 4). The bridge was excited with a.c. power, supplied by a phase shift oscillator. One leg of the bridge consisted of the resistance between the electrode pins on a prob thrust into the hay sample. A group of standard resistors comprised the variable resistance leg of the bridge. These were connected into the bridge by a switching device. The sensing circuit amplified the error signal received when a change occurred in the probe resistance, increased the signal level, rectified it to d.c., and gave a reading on the d.c. null indicator.

In tests with alfalfa hay, meter readings regressed on oven drying moisture determinations gave a correlation coefficient value of 0.94 and an r-square value of .88, meaning that 88 percent of the variation about the mean value was explained by the linear regression equation fitted to the test results (Figure 5). A temperature correlation factor was required for the meter. An average of 1°F (0.6°C) above the calibration temperature, 75°F (24°C), raised the indicated moisture content by 0.1 percent. Evaluation tests were made with 0.44 to 0.55 pound (200 to 250 grams) samples compressed with a pressure of 600 psi (4,100 kilopascals) on the ram of the hydraulic jack used to drive the electrode probe pins into the hay sample. Each moisture determination using this device took

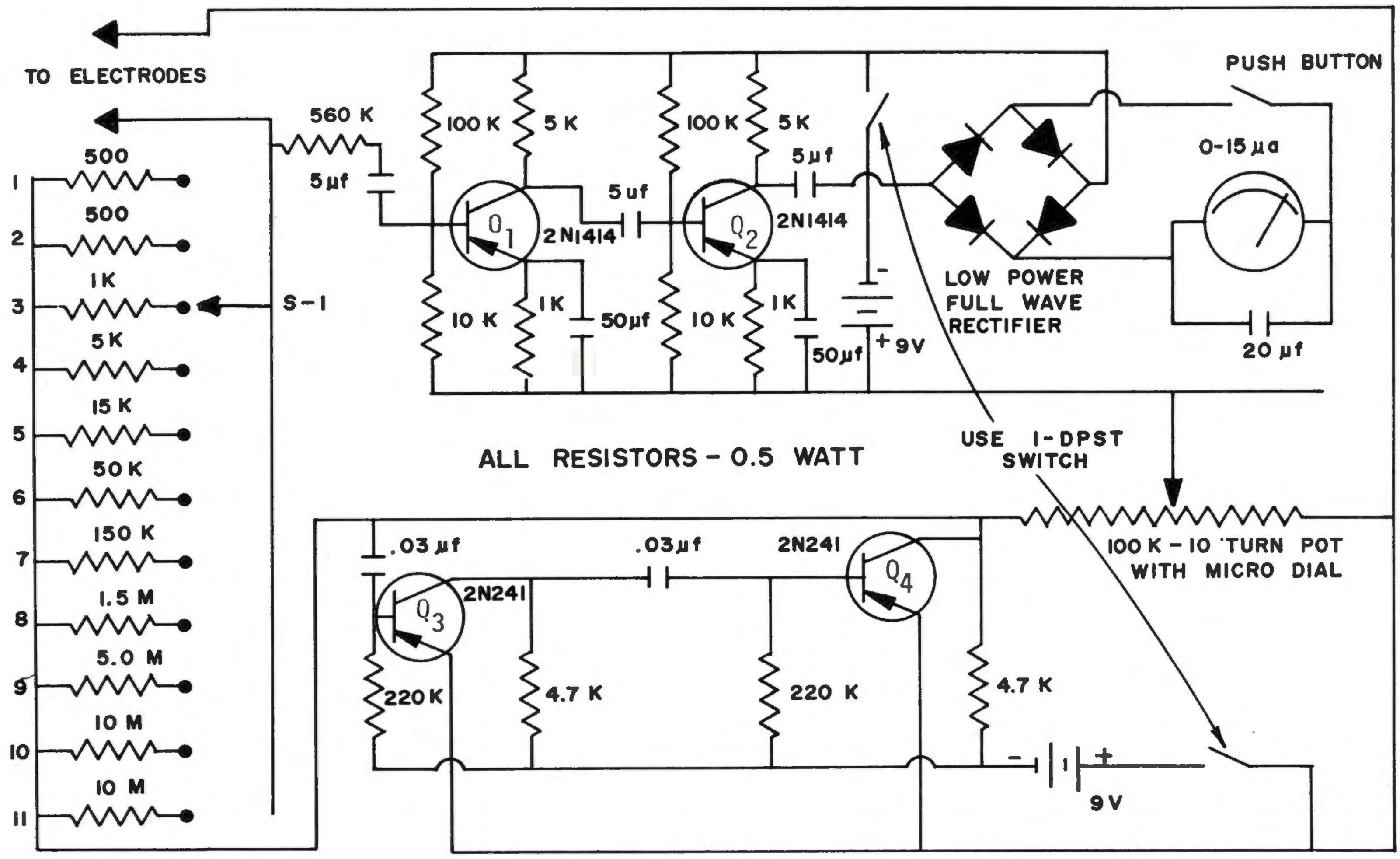

FIGURE 4. Circuit diagram of Hartstack's moisture meter.

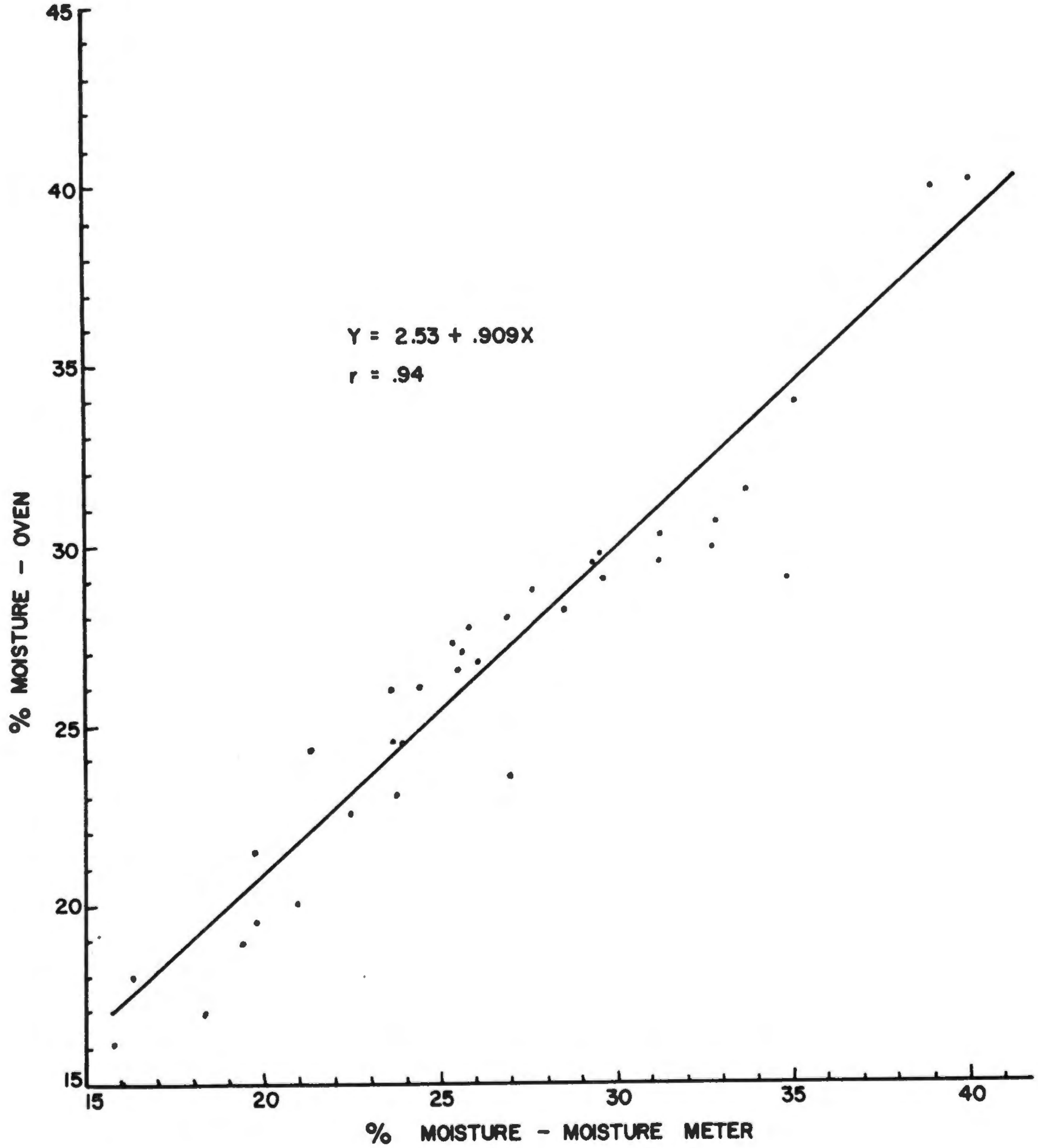

FIGURE 5. Plot of experimental data taken by Hartstack using a constant density sample for determining moisture content of alfalfa hay.

2 to 3 minutes. It was found that high moisture hay (above 50 percent wet basis) caused inaccurate readings because hay juices were extruded by the ram force resulting from 600 psi (4,100 kilopascals) pressure. For high moisture hay, it was suggested that lower ram pressures be used (33).

The Hartstack type meter (Figure 1, page 32) used in this study was built by the Electrical Engineering Department of The University of Tennessee, according to the wiring diagram shown in Figure 6. Its general characteristics were: (a) the basic meter circuit was a Wheatstone bridge, the branches of which were the probe, a bank of resistors, and the two sections of a 100 Kilohm variable potentiometer; (b) the test signal was generated from Q3 and Q4; and (c) the error signal was sensed by Q1 and Q2. The oscillator circuit, according to Hartstack, produced a 400 Hertz sine wave signal. However, the output signal of the oscillator circuit built (using different transistors) had a frequency of 100 Hertz. By incorporating a modification (changing the 220 Kilohm resistor to a 100 Kilohm resistor) the oscillating frequency was raised to 1400 Hertz at 4 volts peak output. The gain of the circuit was calculated and verified to be 1200. The indicating dial or scale used was a surplus meter with full scale deflection at 2 microvolts. Maximum current for the meter was 200 microamps.

Hartstack's calibration procedures using the eleven selectable resistors was attempted but the meter was too sensitive for this approach. Consequently, a variable resistor was added for a sensitivity adjustment (Figure 7). Hartstack used many discrete components in his design, and calibration values were given only for the first seven selectable

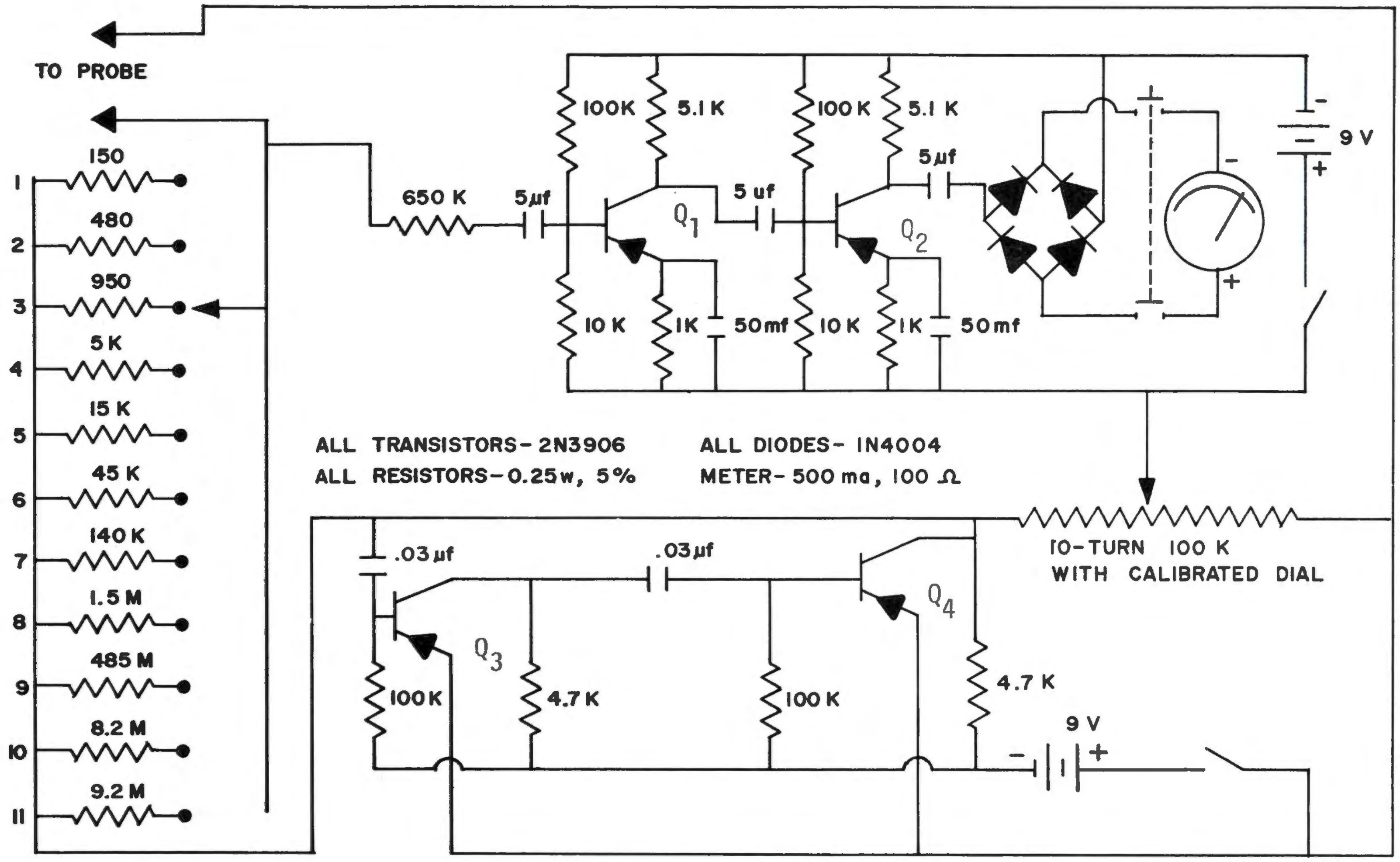

FIGURE 6. Our version of Hartstack's meter circuit diagram for Hartstack type meter built at The University of Tennessee.

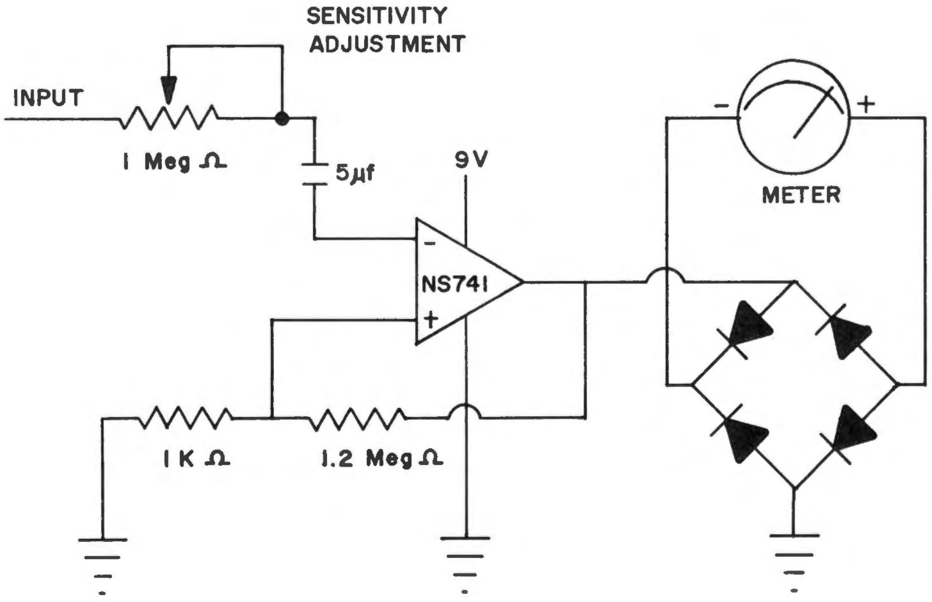

FIGURE 7. Circuit diagram for meter sensitivity adjustment.

resistors (scales). A modified design replaced the original detection unit. It used a single operational amplifier (NS741), and this change eliminated seven components.

Figure 8 shows a circuit proposed to eliminate the eleven scale resistors. This design would give higher resolution and better separation. $R_1$ would be chosen on the basis of resistance in hay of mid-range moisture content. $R_2$ and $R_3$ would be 100 Kilohm, 10-turn potentiometers unless the value of $R_1$ required a different resistance. Resistors $R_2$ and $R_3$ would form the fine adjustment and variable resistor $R_4$ would replace the band of scale resistors as the course adjustment. The percentage of moisture contained in the hay sample would be correlated to the two potentiometer dial readings. The meter would not have to be calibrated or be extremely sensitive. It may even be possible to eliminate correlation charts by using the coarse-fine adjustment design.

A compression device to maintain constant sample density was designed by Hartstack for the use with the moisture meter. The device (Figure 9) used a hydraulic jack to compress the hay sample. A similar device was constructed in the Agricultural Engineering Research Shop at The University of Tennessee. The revisions were: (a) an industrial check valve was installed in the hydraulic circuit to prevent fluctuating pressures because of leakage around the internal valves in the jack; (b) a 1.5 ton (1.36 metric tons) rated capacity jack replaced the 5 to 8 ton (4.5 to 7.3 metric tons) rated capacity jack used by Hartstack (Figure 10). Hydraulic pressure (psig) was read from a gauge connected directly to the hydraulic ram cylinder.

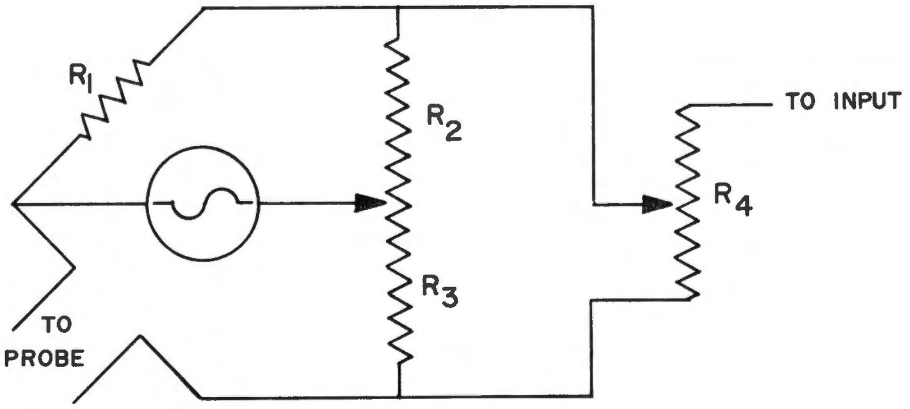

FIGURE 8. Circuit proposed to replace the 11 selectable scale resistors.

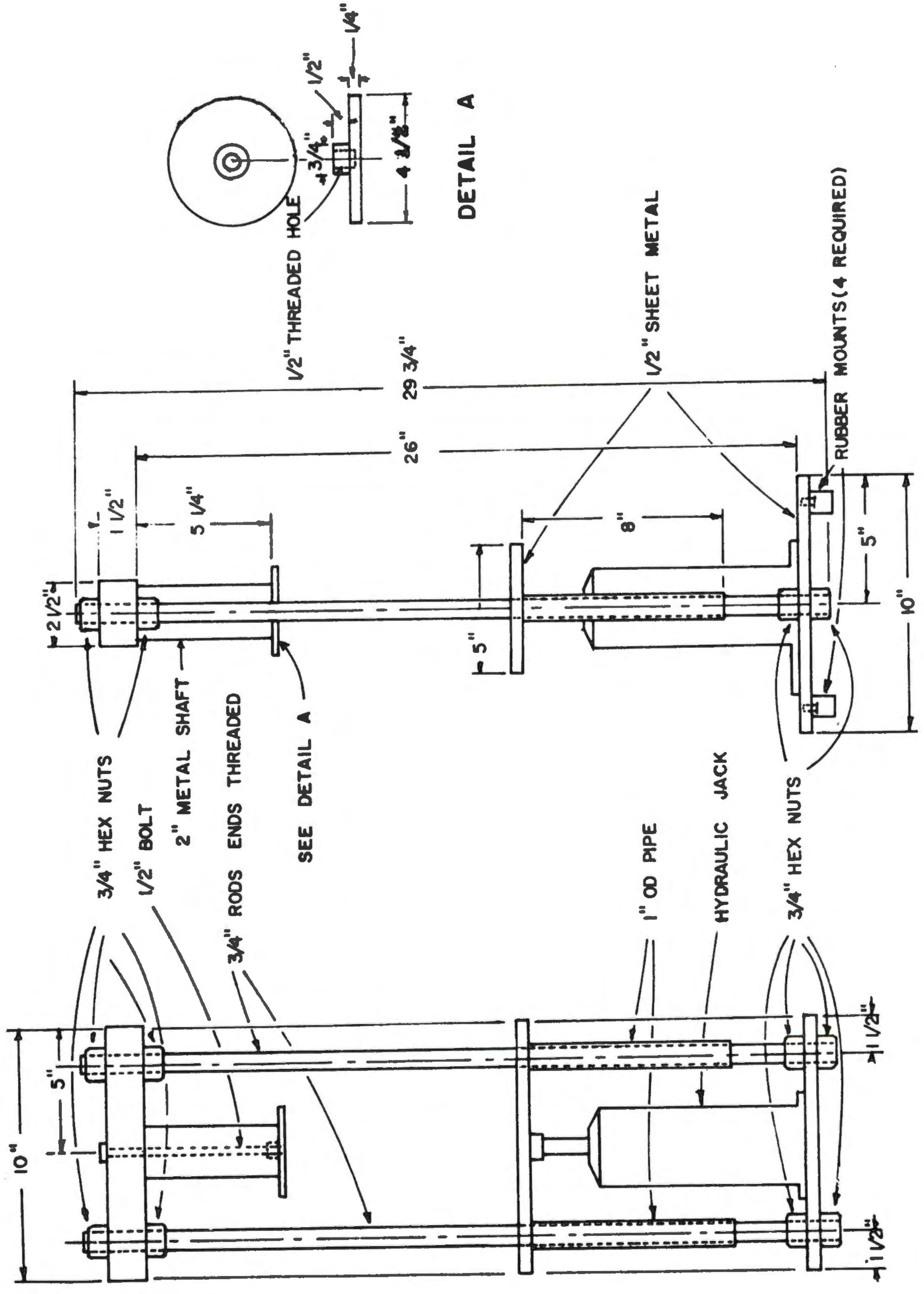

FIGURE 9. Drawing of Hartstack's compression device for hay samples.

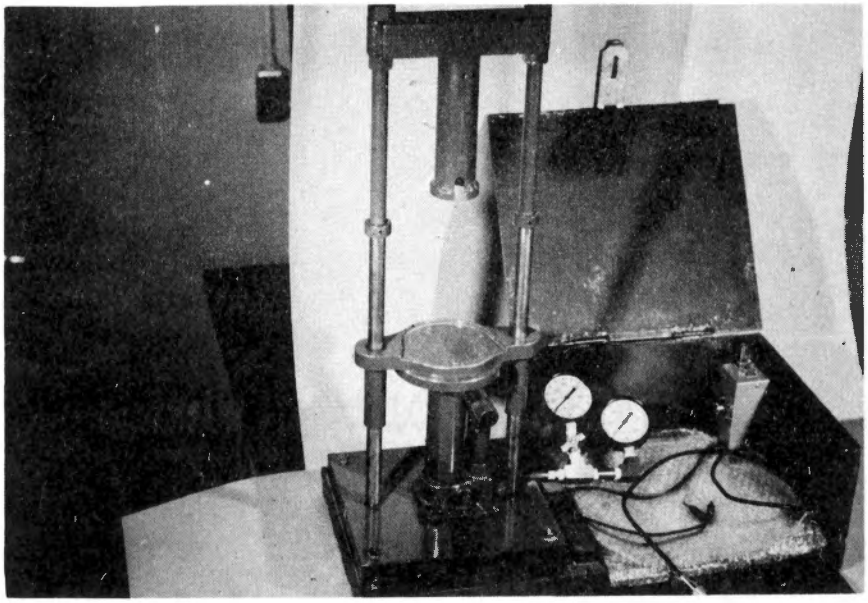

FIGURE 10. Compression device built according to Hartstack's plans.

The electrode handle prod diameter was 2.4 inches (6.0 cm) while the jack ram diameter was 0.95 inches (2.4 cm). Using these dimensions, the correlation between hydraulic pressure acting on the ram (psig) and pressure applied to the hay sample (psi) in the sample container was calculated. The calculations indicated that 1 psig = 0.16 psi sample pressure. The hydraulic pressure comparable to the pressure applied by the Delmhorst handle spring was 38.5 to 41.8 psig (260 to 290 kilopascals).

## III. THE HEATHKIT MODEL IM-1202 DIGITAL MULTIMETER

The Heathkit Model IM-1202 Digital Multimeter measured resistance values and displayed them on cold-cathode tubes and indicator lamps. Solid state circuitry was used throughout the instrument for reliability and compactness. The five resistance ranges available were 0-200, 2K, 200K, and 2000K (2 meg) ohms. The accuracy at full scale was ± 1 digit and for the resistance scale ± 2 percent. The power requirement for the IM-1202 was 8 watts at 110-130 volts a.c. or 220-260 volts a.c. at 50 to 60 Hertz. The ohmmeter circuit was equipped with a fused overload protection device (35).

## IV. THE SIMPSON MODEL 270-4 VOLT-OHM-MILLIAMMETER

The instrument used to measure resistance in the later series of tests was the Simpson Model 270-4 Volt-Ohm-Milliammeter (Figure 1, page 32). The resistance capacities of the meter were well suited for the measurements required. Three resistance scales were available on the Simpson meter, RX1, RX100, and RX10,000, with ranges of 0-2K, 200K, and

20 megohms. The accuracy of these ranges were 1.5, 1, and 1 percent of arc, respectively. These high accuracies were attained through use of 0.5 percent resistors in the instrument. The instrument had a mirrored dial to eliminate paralax. A 1-ampere, 250-volt fuse was provided for protection of the circuits in the ohmmeter section. Two batteries powered the ohmmeter circuits, a 1.5-volt NEDA 13 F D size for the TX1 and RX100 ranges and a 9 volt NEDA 1604 for the RX10,000 range. The zero ohms control was located on the lower right of the panel. The instrument included a variable resistor in the ohmmeter circuit that compensated for variations in voltage of the internal batteries (65).

## V. THE CYLINDRICAL SAMPLE CONTAINER

A cylindrical sample container was constructed for use with the hydraulic compression device. Hartstack used a sample container 5 inches (12.7 cm) in diameter and 6 inches (15.2 cm) tall. A similar cylinder was constructed, using PVC (polyvinalchloride) tubing for these tests (Figure 11).

## VI. THE CHOPPER FOR HOMOGENIZING HAY SAMPLES

To secure more homogeneous hay samples for moisture determination, a small field chopper was designed and built. A 2 h.p., 3600 RPM Briggs and Stratton gasoline engine provided the operating power. A five-blade lawn mower reel and stationary shear bar, shortened to 8 inches (20.3 cm) comprised the cutting device. Hay was fed into the cutting reel by a set of rubber rollers made from a standard washing machine wringer. Desired reel speed was 600 RPM with an engine speed of 3000 RPM. A

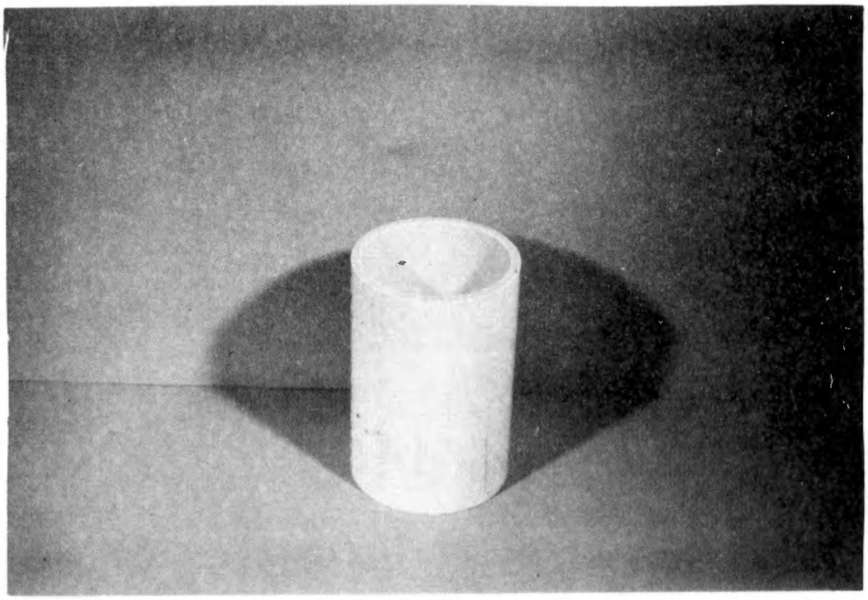

FIGURE 11. The cylindrical sample cylinder.

drive ratio of 1 to 5 was obtained by a 12 tooth driver sprocket on the engine and a 60 tooth driven sprocket on the reel. The hay was to be cut to a length of 0.5 inches (1.3 cm). Since five cuts are made for each reel rotation and the feed rollers were 1.5 inches (3.8 cm) in diameter, 4.81 inches (12.0 cm) in circumference, the required drive ratio for the feed roller drive was calculated to be one roller rotation for each 1.9 reel rotations. This ratio was closely approximated by a 12 tooth driven sprocket on the roller and a 22 tooth driver sprocket on the reel. The actual cutting length attained was calculated to be 0.51 inches (1.21 cm) (assuming no slip). Operating speeds for the various components were: 3000 RPM for the engine, 600 RPM for the reel, and 327 RPM for the rollers. The machinery was mounted on a rigid frame which included safety shielding and a sample catch box (Figure 12).

## VII. THE ELECTRICAL SWITCHING DEVICE

An electrical switching circuit (Figure 13) was designed to enable the operator to quickly switch from one moisture meter to another and take readings on the same sample at the same probe pressure in a very short period of time. The device was a simple group of switches wired in such a way that each meter could be connected in turn to the probing device. Figure 14 illustrates the completed switching device.

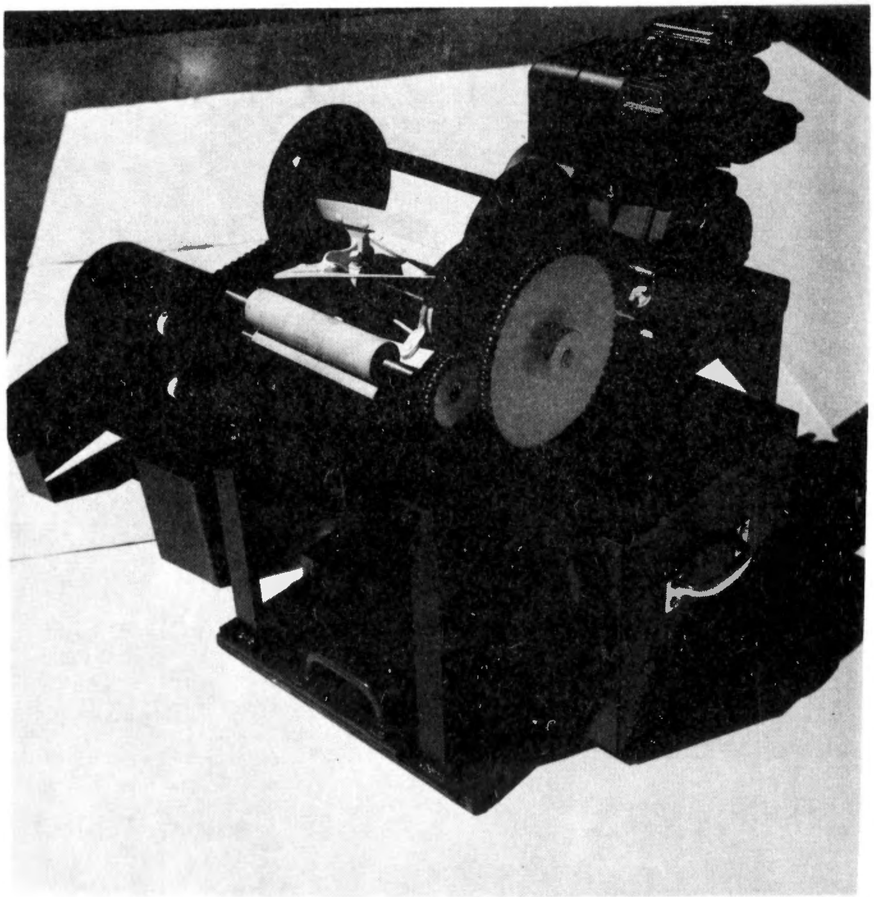

FIGURE 12. The chopper used to homogenize hay samples.

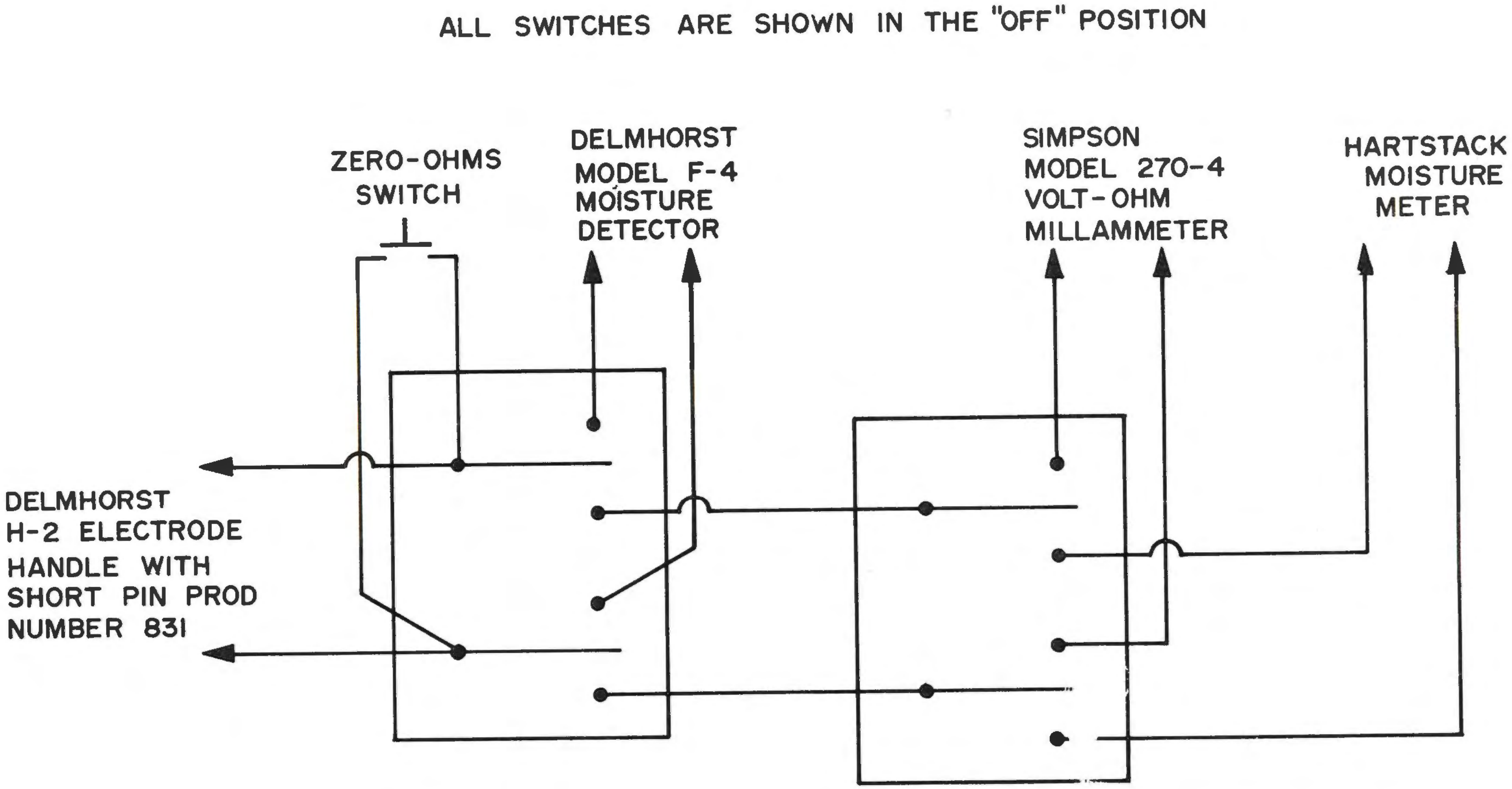

FIGURE 13. Circuit diagram for switching device.

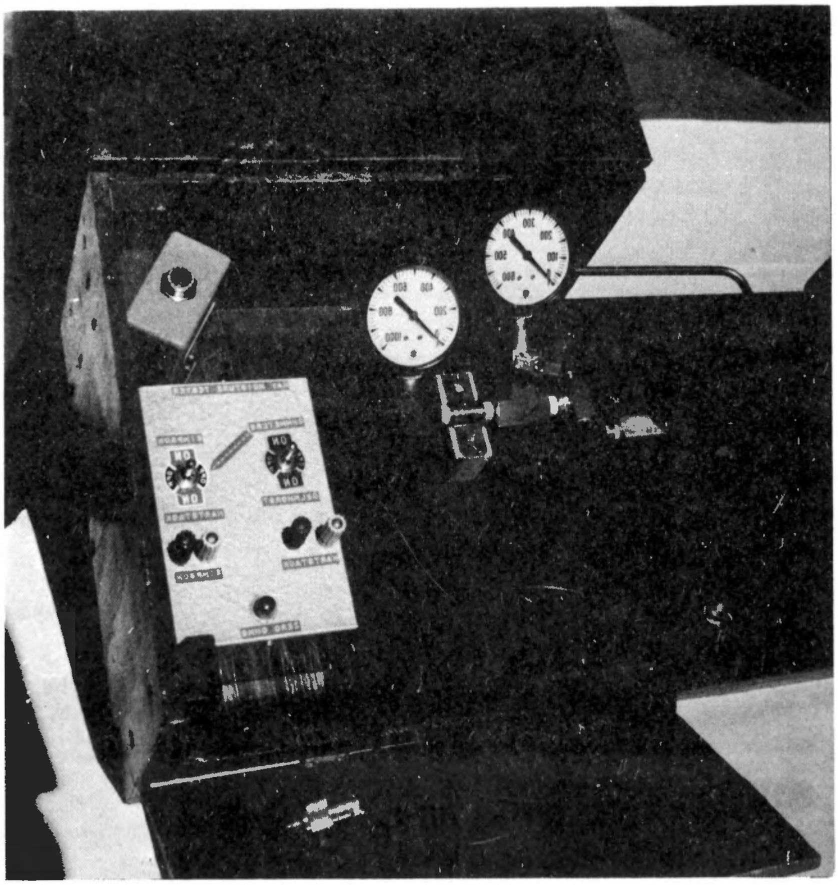

FIGURE 14. The electrical switching device.

# CHAPTER IV

# PROCEDURES

## I. GENERAL EXPERIMENTAL PROCEDURES

All conductance-type measurements made to evaluate windrowed hay moisture content used the Delmhorst H-2 handle and short pin prod to engage the hay sample. The handle was linked to the prod through a spring so that a known force could be applied through the prod to the hay when readings were taken. Thus, each hay sample was compressed to approximately the same density before the conductance reading was made to evaluate the moisture content of the hay.

The various readout (moisture or ohms indicating) meters were calibrated before the experiments were begun, kept in adjustment, and supplied with fresh dry cells for power throughout the tests. Ohmmeter pointers were readjusted to zero each time the resistance range switch was changed and before each measurement.

The Delmhorst probe was applied directly to windrows of hay for one series of measurements. However, most measurements were made on hay samples of approximately 0.7 lb (300 gm), wet weight, of hay taken from the windrow and compressed into a cylindrical sample container. Density of the sample was varied by pressing the hay against the prod (positioned at the top of the cylinder) with different forces (varying the compression force).

The procedure followed to obtain measurements of windrowed hay moisture content with the instrument prod applied directly to the windrow with the Delmhorst meter for readout was in accordance with the Delmhorst operating instructions: (a) The electrode was connected to the instrument. (b) The adjust button was pressed to check the meter calibration and battery voltage. If necessary, the "Adjust" knob was turned to set the meter pointer to the "ADJ" position on the meter face. (c) The H2 handle with short pin prod number 831 was used. (d) The electrode was applied to the hay and the "Read" button pressed. (e) The H-2 electrode handle pressure button was pushed until the screw in the end of the handle touched the palm of the hand. (f) Moisture content was read directly on the meter scale. (g) Several tests were made on hay exposed to the sun, then the windrow was turned over, and an equal number of tests were made on the ground side. The various readings were then averaged (60).

For measurement of moisture content (and of electrical resistance of hay path between prod pins) of hay placed into the cylindrical sample container, the procedure used was as follows: uniform windrow sections were sought, and one moisture determination made for each sample as prescribed above. Then a sample of hay was taken from the exact windrow location from which the Delmhorst meter reading was made and placed immediately in the cylindrical container. The H-2 electrode probe was disconnected from the Delmhorst meter, both meter and probe were connected to the special switching circuit, and the meter was readjusted. The other meters were already connected to the circuit and "zeroed." Readings then were taken of resistance (ohmmeter) and moisture percentage

(Delmhorst or Hartstack) using the H-2 handle to probe the sample in the cylinder. The next steps were to place the H-2 electrode handle with short pin prod in the hydraulic compression device (similar to Hartstack's design), place the sample container on the compression stand, apply various pressures to the samples, and take meter readings as illustrated in Figure 15. The wet samples were then placed in a pre-weighed perforated paper bag. The sample and bag were weighed, placed in an oven for a minimum of 24 hours at 275°F (135±°C), then removed and weighed again. The dried hay sample was discarded, and the dry paper bag weighed. The method follows the standard oven method for determining moisture content of forages established by the American Society of Agricultural Engineers (ASAE Standard S358, The 1975 ASAE Yearbook). The percentage moisture content was calculated on wet basis.

## II. PROCEDURES FOR SPECIFIC EXPERIMENTS PERFORMED

The hay moisture meter evaluation tests were conducted at Ames Plantation near Grand Junction, Tennessee, and at the Plateau Experiment Station near Crossville, Tennessee. Ames Plantation provided three test fields, two of which were Midland bermudagrass (Fields 17 and 18) and one lespedeza (Field 26). Two fields were used at the Plateau Experiment Station. One field consisted of a mixture of timothy, orchardgrass, and crimson clover (Field 1), and the other of orchardgrass (Field 2). After the hay was cut and allowed to partially dry, samples were selected at random from the fields for the moisture meter tests. Table 1 gives a summary description of the various tests performed.

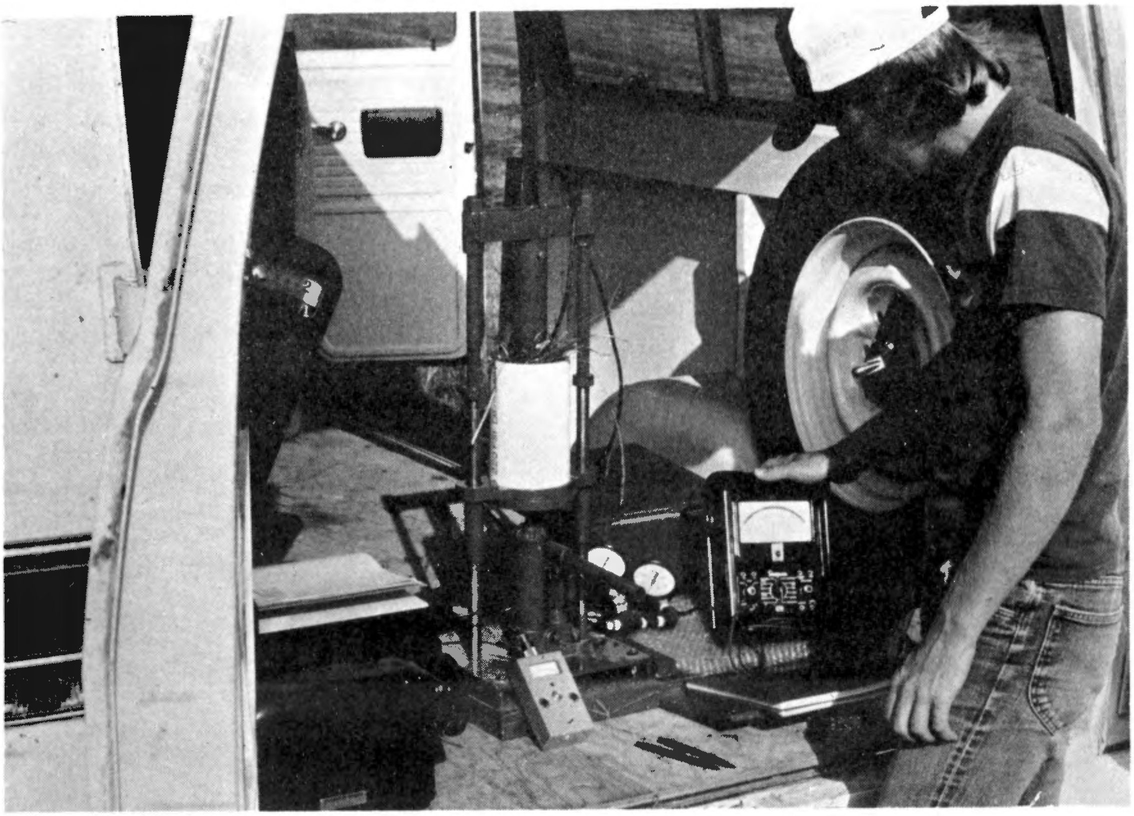

FIGURE 15. Use of moisture meter evaluation equipment in the field.

TABLE 1. Description of the four test series for evaluation of hay moisture measurement instrumentation.

| Test Series | Meters | Sample Pressure (psi) | Sample Preparation | Location and Field | Dates and Forage Tested |
|---|---|---|---|---|---|
| 1 | Delmhorst<br>IM-1202** | 8-13*<br>97 | In Windrow And Compressed Within Cylinder | Ames Plant.<br>17<br>18 | June 24-25, 1975<br>(Bermudagrass)<br>(Bermudagrass) |
| 2 | Delmhorst<br>Simpson** | 8-13*<br>16<br>32<br>64<br>97 | Compressed In Cylinder | Crossville<br>1 | August 22-23, 1975<br>(Mixture of Timothy orchardgrass and crimson clover) |
| 3 | Delmhorst<br>Simpson** | 8-13*<br>32<br>64<br>97 | Compressed In Cylinder | Ames Plant.<br>17<br>18<br>26 | September 3-9, 1975<br>(Bermudagrass)<br>(Bermudagrass)<br>(Lespedeza) |
| 4 | Delmhorst<br>Simpson**<br>Hartstack | 8<br>16 | Both Chopped And Unchopped And Compressed Within Cylinder | Crossville<br>2 | May 24-27, 1976<br>(Orchardgrass) |

*Obtained by compression spring in probe handle.

**For measuring resistance through hay sample between prod pins.

## Test Series One

The first test series was conducted at Ames Plantation on Fields 17 and 18 (Midland bermudagrass), June 24-25, 1975. In this test series only, the Delmhorst Model F-4 Moisture Detector and the Delmhorst H-2 Electrode Handle were used to measure moisture content of hay in the windrow according to operation instructions of the manufacturer. The meter was adjusted properly, and the H-2 electrode handle with short pin prod was applied to the hay with pressure on the handle spring adequate to cause the screw recessed in the handle to touch the palm of the hand. This indicated that the handle internal spring, used as the sample compression device, was at the correct position for a reading. The meter scale was read directly after pressing the "Read" button. Afterward, a sample of the hay was taken from the same windrow location and placed immediately in the cylindrical sample container. The Delmhorst meter and handle were then connected to the electrical switching device and the meter readjusted. The Model IM-1202 Digital Multimeter for resistance readings was already connected to the switching device. Readings of moisture percentage and resistance were taken using the spring pressure of the H-2 handle probing the hay sample in the cylinder. The H-2 prod was then placed into the compression device, and the sample container was placed on the compression device stand. The hydraulic jack then moved the stand toward the stationary prod to press the hay sample against the prod. Meter readings were taken with a pressure of 97 psi (669 kilopascals).

## Test Series Two

The second test series was conducted at Crossville on Field 1 (a mixture of timothy, orchardgrass and crimson clover) during August 22-23, 1975, with the following procedural changes: (a) a range of sample pressures were used: 16, 32, 64, and 97 psi (110, 220, 441, and 669 kilopascals), and (b) a Simpson Model 270-4 Volt-Ohm-Milliammeter was substituted for the Model IM-1202 Digital Multimeter to take resistance readings.

## Test Series Three

During the first two test series, maintaining a constant hydraulic pressure on the jack while taking readings at different sample densities was difficult. Leakage past the hydraulic control valve seemed to be the problem. An industrial-grade hydraulic control valve was installed as a replacement for the original valve, which corrected the problem. The third test series was conducted at Ames Plantation on Fields 17 and 18 (Midland bermudagrass) and 26 (lespedeza), September 3-9, 1975. The same procedure was used during test series two with the exception that the sample density resulting from 16 psi (110 kilopascals) sample pressure was eliminated.

## Test of Delmhorst H-2 Handle Spring Pressure

Experience gained during the first three series of tests indicated that the Delmhorst handle spring gave varying pressures with the same operating procedure. Therefore, variation in the Delmhorst spring pressure was tested using the Hartstack hydraulic compression device. The H-2 handle was positioned slightly off center, pressure applied, and results recorded. The handle was turned 90° and tested again. The handle was then positioned directly on center and spring pressures measured. Finally the spring handle was lubricated with a thin oil and the procedure repeated. These tests were conducted in the Electronics Shop of the Agricultural Engineering Department at The University of Tennessee, Knoxville.

### Test Series Four

The fourth test series included moisture measurements with a newly constructed Hartstack conductance-type moisture meter, along with the Simpson and Delmhorst meters. Also, a small field chopper was used to provide a homogeneous sample of hay chopped to 0.5 inch (1.3 cm) length for comparison with the long hay samples previously used. The chopped samples prevented a single piece of hay from being penetrated more than once by the prod pins. Sample pressures of 8 psi (55 kilopascals) and 16 psi (110 kilopascals) were used.

## III. STATISTICAL ANALYSIS

The Statistical Analysis System (SAS) linear regression program was used to evaluate the data collected. Moisture content data collected for each meter were regressed on standard oven determinations for moisture content of identical samples for each test series. For the ohmmeter data, the logarithms of these resistance readings were compared to the standard oven determinations of moisture content.

# CHAPTER V

# RESULTS AND DISCUSSION

## I. TEST SERIES ONE, TWO, AND THREE

Results of a simple linear regression analysis for each of the first three test series are given in Tables 2, 3, and 4. In these analyses the dependent variables, electrical meter readings, were regressed on the independent variable, oven drying determined moisture content values. The tables show the fields used; compaction pressure of the sample; standard deviation from regression, which represents a mean difference between the observed values and those calculated by the regression equation; the goodness of fit of the observed data to the predicted regression line (percentage of deviation about the mean explained by the regression line); the coefficients of the regression line equation; and the number of observations in each regression analysis.

In the first three test series, results were not consistent. Sample pressure appeared to have an effect on the variations about the regression lines; but the response was not the same for the different fields, types of hay, and test dates. The ohmmeter readings were more closely correlated to actual moisture contents than were the indicated moisture content readings of the Delmhorst meter. The regression equations explained none of the variation in readings for the lespedeza hay that was heavily infested with cocklebur plants. Since the stems of the cocklebur plants were much larger than the hay stems and dried slower,

TABLE 2. Results of a simple linear regression analysis on all samples with oven drying moisture determinations between 20 to 45 percent of Test Series 1 taken June 24-25, 1975, at Ames Plantation using midland bermudagrass hay.

| Field | Meter | Sample Pressure (psi) | $s_{y \cdot x}$ | R-Square | Intercept | Slope | Number of Observations |
|---|---|---|---|---|---|---|---|
| 17 | Delmhorst | 8-13 | 4.090 | 0.433 | 5.640 | 0.465 | 11 |
| 17 | IM-1212* | 8-13 | 1.074 | 0.504 | 17.582 | -0.146 | 10 |
| 17 | Delmhorst | 97 | 10.502 | 0.025 | 32.321 | 0.229 | 8 |
| 17 | IM-1202* | 97 | 1.559 | 0.138 | 13.156 | -0.081 | 11 |
| 17 | Delmhorst | 8-13** | 4.947 | 0.018 | 25.035 | 0.086 | 11 |
| 18 | Delmhorst | 8-13 | 4.044 | 0.454 | 6.829 | 0.442 | 17 |
| 18 | IM-1202* | 8-13 | 0.6-6 | 0.516 | 15.361 | -0.093 | 11 |
| 18 | Delmhorst | 97 | 8.206 | 0.447 | 7.622 | 0.903 | 15 |
| 18 | IM-1202* | 97 | 1.239 | 0.488 | 15.529 | -0.147 | 16 |
| 18 | Delmhorst | 8-13** | 6.139 | 0.364 | 7.296 | 0.557 | 16 |

*These results were from an analysis using the logarithms of the ohmmeter readings (the Delmhorst meter read moisture content (wet basis) directly based on a self contained logarithmic conversion of conductance values).

**Readings taken with the probe applied to the windrow (all other readings were taken with the sample compressed in a cylindrical container).

TABLE 3. Results of a simple linear regression analysis of all samples with oven drying moisture determinations between 20 and 45 percent of Test Series 2 taken August 22-23, 1975, at the Plateau Experiment Station with a mixture of timothy, orchardgrass, and crimson clover hay.

| Field | Meter | Sample Pressure (psi) | $s_{y \cdot x}$ | R-Square | Intercept | Slope | Number of Observations |
|---|---|---|---|---|---|---|---|
| 1 | Delmhorst | 16 | 7.192 | 0.195 | 18.997 | 0.593 | 65 |
| 1 | Simpson* | 16 | 0.969 | 0.397 | 15.864 | -0.134 | 80 |
| 1 | Delmhorst | 32 | 5.891 | 0.049 | 34.858 | 0.217 | 46 |
| 1 | Simpson* | 32 | 0.834 | 0.378 | 14.428 | -0.111 | 80 |
| 1 | Delmhorst | 64 | 5.152 | 0.017 | 39.429 | 0.144 | 20 |
| 1 | Simpson* | 64 | 0.742 | 0.422 | 13.821 | -0.108 | 80 |
| 1 | Delmhorst | 97 | 4.303 | 0.025 | 42.355 | 0.130 | 13 |
| 1 | Simpson* | 97 | 0.618 | 0.497 | 13.308 | -0.105 | 80 |
| 1 | Delmhorst | 8-13 | 6.662 | 0.076 | 24.174 | 0.320 | 75 |
| 1 | Simpson* | 8-13 | 1.011 | 0.365 | 16.217 | -0.131 | 80 |

*These results were from an analysis using the logarithms of the ohmmeter readings (the Delmhorst meter read moisture content (wet basis) directly based on logarithmic conversion of conduction values).

TABLE 4. Results of a simple linear regression analysis on all samples with oven drying moisture determinations between 20 and 45 percent of Test Series 3 taken September 3-9, 1975, at Ames Plantation with midland bermudagrass hay from Fields 17 and 18 and lespedeza hay from Field 26.

| Field | Meter | Sample Pressure (psi) | $s_{y \cdot x}$ | R-Square | Intercept | Slope | Number of Observations |
|---|---|---|---|---|---|---|---|
| 17 | Delmhorst | 32 | 6.615 | 0.333 | 11.994 | 0.744 | 37 |
| 17 | Simpson* | 32 | 1.054 | 0.306 | 14.386 | -0.107 | 49 |
| 17 | Delmhorst | 64 | 5.884 | 0.213 | 20.585 | 0.518 | 29 |
| 17 | Simpson* | 64 | 0.969 | 0.321 | 13.627 | -0.102 | 49 |
| 17 | Delmhorst | 97 | 5.945 | 0.205 | 23.308 | 0.556 | 27 |
| 17 | Simpson* | 97 | 0.964 | 0.329 | 13.329 | -0.103 | 49 |
| 17 | Delmhorst | 8-13 | 6.438 | 0.270 | 10.076 | 0.639 | 45 |
| 17 | Simpson* | 8-13 | 1.209 | 0.382 | 16.491 | -0.145 | 49 |
| 18 | Delmhorst | 32 | 6.464 | 0.333 | 13.732 | 0.540 | 34 |
| 18 | Simpson* | 32 | 0.806 | 0.415 | 14.523 | -0.080 | 35 |
| 18 | Delmhorst | 64 | 5.150 | 0.285 | 20.484 | 0.399 | 28 |
| 18 | Simpson* | 64 | 0.718 | 0.450 | 13.758 | -0.077 | 35 |
| 18 | Delmhorst | 97 | 5.659 | 0.207 | 24.890 | 0.364 | 27 |
| 18 | Simpson* | 97 | 0.653 | 0.484 | 13.274 | -0.075 | 35 |
| 18 | Delmhorst | 8-13 | 5.172 | 0.278 | 13.800 | 0.379 | 35 |
| 18 | Simpson* | 8-13 | 0.904 | 0.388 | 15.671 | -0.085 | 35 |

TABLE 4. (continued)

| Field | Meter | Sample Pressure (psi) | $s_{y \cdot x}$ | R-Square | Intercept | Slope | Number of Observations |
|---|---|---|---|---|---|---|---|
| 26 | Delmhorst | 32 | 8.288 | 0.002 | 31.723 | 0.061 | 31 |
| 26 | Simpson* | 32 | 1.148 | 0.011 | 11.035 | 0.020 | 42 |
| 26 | Delmhorst | 64 | 7.936 | 0.005 | 32.335 | 0.100 | 24 |
| 26 | Simpson* | 64 | 1.093 | 0.020 | 10.224 | 0.025 | 42 |
| 26 | Delmhorst | 97 | 6.944 | 0.002 | 40.191 | -0.063 | 20 |
| 26 | Simpson* | 97 | 1.099 | 0.008 | 10.065 | 0.016 | 42 |
| 26 | Delmhorst | 8-13 | 8.199 | 0.033 | 37.589 | -0.263 | 40 |
| 26 | Simpson* | 8-13 | 1.351 | 0.027 | 11.693 | 0.037 | 42 |

*These results were from an analysis using the logarithms of the ohmmeter readings (the Delmhorst meter read moisture content (wet basis) directly based on logarithmic conversion of conductance values.

meter readings were greatly affected by the presence of these weeds.

The data did not clearly reveal whether or not sample pressure affected the slope of the regression lines relating meter readings to actual moisture content. If the pressure did not significantly affect the slope, then the data among pressures within each field and meter type could be pooled to give a more accurate estimate of the true slope of the regression line for each meter. Therefore a test of homogeneity of regression coefficients among sample pressures for each meter within each field was conducted. The procedure followed is that outlined by Steel and Torrie (68, pp. 319-320), and results are tabulated in Tables 5, 6, and 7.

For each meter within each field, sample pressure was determined not to affect the slope of the regression equation relating meter readings to actual hay moisture content (at the 95 percent confidence level). However, the same analysis showed the intercepts of the regression equations to be significantly different for each sample pressure; that is, sample pressure was a significant main effect influencing the intercept but not the slope of the regression equation for each meter within each field. Table 8 summarizes the regression coefficients calculated for each data set and for the pooled (over sample pressure) data sets. Since for each meter, sample pressure was a significant main effect, sample pressure must be held constant at a selected level for best correlation of meter readings with actual hay moisture content.

Since the slopes were found to be homogeneous at different sample pressures for a given meter within fields, the data sets for different

TABLE 5. Test of homogeneity of regression coefficients for determination of significant differences in slope of regression equations using pressure as a main effect on data taken June 24-25, 1975, at Ames Plantation.

| | | Field and Meter | | | |
|---|---|---|---|---|---|
| | Quantity | Ames 1-17 Delmhorst | Ames 1-17 IM-1212 | Ames 1-18 Delmhorst | Ames 1-18 IM-1202 |
| Residuals from Individual Regressions at 8 psi Sample Pressure | SS | 150.575 | 9.228 | 245.399 | 3.993 |
| | DF | 9 | 8 | 15 | 9 |
| Residuals from Individual Regressions at 97 psi Sample Pressure | SS | 661.795 | 20.890 | 875.533 | 21.519 |
| | DF | 6 | 9 | 13 | 14 |
| Total of Individual Regressions | SS | 812.370 | 31.118 | 1120.932 | 25.512 |
| | DF | 15 | 17 | 28 | 23 |
| Totals for Single Regression | SS | 1032.263 | 32.141 | 1244.997 | 29.628 |
| | DF | 19 | 19 | 30 | 31 |
| Difference for Homogeneity of Regression | SS | 219.893 | 1.023 | 124.065 | 4.116 |
| | DF | 4 | 2 | 2 | 8 |
| Total Individual Mean Square | | 54.158 | 1.830 | 40.033 | 1.109 |
| Difference Mean Square | | 54.973 | 0.512 | 62.033 | 0.515 |
| Computed F-Value | | 1.015 | 0.280 | 1.550 | 0.464 |
| Tabular F-Value* | | 3.060 | 3.590 | 3.340 | 2.380 |

*At 95 percent confidence level.

TABLE 6. Test of homogeneity of regression coefficients for determination of significant differences in slope of regression equations using pressure as a main effect on data taken August 22-23, 1975, at the Plateau Experiment Station.

| | Quantity | Field<br>Delmhorst Field 1 | <br>Simpson Field 1 |
|---|---|---|---|
| Residuals from regressions at 16 psi sample pressure | SS<br>DF | 3258.362<br>63 | 73.380<br>78 |
| Residuals from regressions at 32 psi sample pressure | SS<br>DF | 1526.974<br>44 | 54.328<br>78 |
| Residuals from regressions at 64 psi sample pressure | SS<br>DF | 477.725<br>18 | 42.945<br>78 |
| Residuals from regressions at 97 psi sample pressure | SS<br>DF | 203.680<br>11 | 29.793<br>78 |
| Residuals from regressions at 8-13 psi sample pressure | SS<br>DF | 3240.686<br>73 | 79.662<br>78 |
| Totals of individual regressions | SS<br>DF | 8707.427<br>209 | 208.108<br>390 |
| Single regression | DF<br>SS | 8901.736<br>213 | 282.110<br>394 |
| Difference for homogeneity of regressions | DF<br>SS | 194.309<br>4 | 2.002<br>4 |
| Mean square of total individuals | | 41.862 | 0.720 |
| Mean square of difference | | 48.577 | 0.501 |
| Computed F-value | | 1.160 | 0.695 |
| Tabular F-value | | 2.41 | 2.39 |

*At 95 percent confidence level.

TABLE 7. Test of homogeneity of regression coefficients for determination of significant differences in slope of regression equations using pressure as a main effect on data taken September 3-9, 1975, at Ames Plantation.

| | | Field and Meter | | | |
|---|---|---|---|---|---|
| | Quantity | Ames 2-17 Delmhorst | Ames 2-17 Simpson | Ames 2-18 Delmhorst | Ames 2-18 Simpson |
| Residuals from regressions at 32 psi sample pressure | SS | 1531.962 | 52.233 | 1338.993 | 21.438 |
| | DF | 35 | 47 | 32 | 33 |
| Residuals from regression at 64 psi sample pressure | SS | 934.716 | 44.203 | 689.684 | 17.004 |
| | DF | 27 | 47 | 26 | 33 |
| Residuals from regression at 97 psi sample pressure | SS | 883.779 | 43.695 | 800.584 | 14.086 |
| | DF | 25 | 47 | 25 | 33 |
| Residuals from regressions at 8-13 psi sample pressure | SS | 1782.491 | 68.697 | 882.775 | 26.975 |
| | DF | 43 | 47 | 33 | 33 |
| Totals of individual regressions | SS | 5132.948 | 208.828 | 3710.036 | 79.503 |
| | DF | 130 | 188 | 116 | 132 |
| Single regression | SS | 5166.876 | 211.403 | 3752.739 | 79.647 |
| | DF | 133 | 191 | 119 | 135 |
| Difference for homogeneity of regressions | SS | 33.928 | 2.575 | 42.703 | 0.144 |
| | DF | 3 | 3 | 3 | 3 |
| Total individual mean square | | 39.788 | 1.111 | 31.983 | 0.602 |
| Difference mean square | | 11.309 | 0.858 | 14.234 | 0.048 |
| Calculated F-value | | 0.284 | 1.294 | 0.445 | 0.080 |
| Tabular F-value* | | 2.68 | 0.048 | 2.66 | 2.68 |

*At 95 percent confidence level.

TABLE 8. (continued)

| Test | Meter | Homogeneous Slopes | Intercept Significant | Pressure | Intercept | Slope | R-Square |
|---|---|---|---|---|---|---|---|
| Ames<br>Trip Two<br>Field 13 | Simpson | Yes | Yes | All | 14.457 | -0.1141 | 0.4980 |
| | | | | 32 | 14.600 | -0.1141 | |
| | | | | 64 | 13.992 | -0.1141 | |
| | | | | 97 | 13.659 | -0.1141 | |
| | | | | 8-13 | 15.577 | -0.1141 | |
| | Delmhorst | Yes | Yes | All | 16.037 | 0.6327 | 0.4123 |
| | | | | 32 | 15.188 | 0.6327 | |
| | | | | 64 | 17.465 | 0.6327 | |
| | | | | 97 | 21.226 | 0.6327 | |
| | | | | 8-13 | 10.037 | 0.6327 | |
| Ames<br>Trip Two<br>Field 18 | Simpson | Yes | Yes | All | 14.306 | -0.079 | 0.6448 |
| | | | | 32 | 14.488 | -0.079 | |
| | | | | 64 | 13.838 | -0.079 | |
| | | | | 97 | 13.414 | -0.079 | |
| | | | | 8-13 | 15.484 | -0.079 | |
| | Delmhorst | Yes | Yes | All | 18.070 | 0.4266 | 0.4457 |
| | | | | 32 | 17.343 | 0.4266 | |
| | | | | 64 | 19.660 | 0.4266 | |
| | | | | 97 | 23.015 | 0.4266 | |
| | | | | 8-13 | 12.262 | 0.4266 | |

pressures were pooled and another test of homogeneity of regression coefficients was conducted to determine the effect of fields (fields, crop, or time) on the slopes of regression equations relating meter readings to oven drying moisture determinations. Results are summarized in Table 9. A comparison of the calculated F-values to tabular F-values again failed to reject the hypothesis that slopes were homogeneous. The intercepts proved to be significantly different. Thus, fields also proved to be a significant main effect influencing regression line intercept values but not the slope of the line. New regression equations for data pooled over sample pressures and fields were calculated and are shown in Table 10.

During the first three test series, many inconsistencies were noted in the plant material being tested; for instance, the excessive cocklebur plants in the lespedeza field. The degree of weed infestation varied between fields; that is, the ratio of weeds, grasses, and legumes were different for the different fields. When taking meter readings with the Delmhorst prod pressed into the windrow in the first test series, the prod pins sometimes completely penetrated the forage and entered the soil, causing erroneous readings. To avoid this source of error in all subsequent tests, hay was placed in the sample container before the prod was applied to determine moisture content.

In test series two, while taking the moisture readings with the sample compressed in the cylindrical container to maintain a given sample density, fluctuating hydraulic pressure was noted. The pressure would constantly drop necessitating frequent adjustments (pumping the hydraulic pressure back up) to keep a uniform sample density throughout

TABLE 9. Test of homogeneity of regression coefficients for determination of significant differences in slopes of regression equations using fields as a main effect on pooled data taken during Test Series 1, 2, and 3.

| | Residuals from Individual Regressions | | | |
|---|---|---|---|---|
| | Ohmmeter | | Delmhorst | |
| Location | SS | DF | SS | DF |
| Ames 1-17 | 62.529 | 20 | 2796.309 | 20 |
| Ames 1-18 | 45.445 | 32 | 2929.979 | 31 |
| Crossville 1 | 512.357 | 398 | 12225.335 | 217 |
| Ames 2-17 | 315.891 | 194 | 7357.163 | 136 |
| Ames 2-18 | 165.018 | 138 | 5640.025 | 122 |
| Totals of individual regressions | 1101.240 | 782 | 30948.811 | 526 |
| Single regression | 1110.648 | 786 | 31221.852 | 530 |
| Difference for homogeneity of regressions | 9.308 | 4 | 273.041 | 4 |
| Mean square of total of individual | 14.08 | | 58.838 | |
| Mean square of difference | 2.327 | | 68.26 | |
| Calculated F-value | 1.652 | | 1.160 | |
| Tabular F-value* | 2.38 | | 2.38 | |

*At 95 percent confidence level.

TABLE 10. Results of a test for homogeneity of regression coefficients for simple linear regression equations for different field, time, and crop effects; Test Series 1, 2, and 3.

| Meter | Location | Homogeneous Slope | Intercept Significant | Intercept | Pooled* Slope | R-Square |
|---|---|---|---|---|---|---|
| Ohmmeter | All | Yes | Yes | 14.760 | -0.1054 | 0.3037 |
| | Ames 1-17 | | | 15.090 | -0.1054 | |
| | Ames 1-18 | | | 15.024 | -0.1054 | |
| | Crossville 1 | | | 14.334 | -0.1054 | |
| | Ames 2-17 | | | 14.201 | -0.1054 | |
| | Ames 2-18 | | | 15.151 | -0.1054 | |
| Delmhorst | All | Yes | Yes | 19.474 | 0.4022 | 0.2812 |
| | Ames 1-17 | | | 16.556 | 0.4022 | |
| | Ames 1-18 | | | 14.837 | 0.4022 | |
| | Crossville 1 | | | 25.835 | 0.4022 | |
| | Ames 2-17 | | | 21.720 | 0.4022 | |
| | Ames 2-18 | | | 18.422 | 0.4022 | |

*Refer to Table 4, page 64, for slopes for each data set.

the time period used to take the meter readings. To correct this problem, the internal cut off valve was machined for a more leak-proof fit.

In test series three, weeds (broadleaf and johnsongrass) were excessive in all three fields tested. Single pieces of hay were noticed to be pierced more than once by the prod pins engaging the sample to partially short circuit the current path between prod pins. This resulted in erroneous meter readings. Hydraulic pressure was found to be unstable, to a lesser degree, in this test series also. The pressure applied to the jack ram would drift to lower pressures over an extended period of time. An industrial type check valve was installed in the hydraulic circuit to stop drifting of the ram with time.

## II. EVALUATION OF THE METER AND PROBE CIRCUITS

To gain insight into the potential performance of the Delmhorst and Hartstack rapid reading moisture meter circuits and to compare these circuits with that of a standard ohmmeter, a circuit analysis was performed by Dr. Joseph M. Googe of the Electrical Engineering Department at The University of Tennessee.

According to his analysis, the Delmhorst Model F-4 Moisture detector was a conductance type meter which depended on setting a variable resistor to a value that corresponded to 20 percent hay moisture content. This adjustment procedure allowed the variable resistor to compensate for variances in the circuitry, transistor inconsistencies, or battery power loss. If the variable resistor held its value well, the meter would be very accurate at the point it represented (20 percent). Any reading taken above or below this point would not be as accurate; and the farther away from the set point the reading was taken, the less sensitive it would become. The Delmhorst moisture meter had a signal generator in series with a resistance (hay or standard resistor for adjustment) and a conductance indicating meter. The sensitivity of the series circuit could change when being switched from one sample to another. With wet hay, the readings became unreliable because the high moisture section of the scale was the most inaccurate part. The meter could never indicate conductance within a few percentage points because the mechanism does not lend itself to getting very steady and accurate readings (30).

The Delmhorst H-2 handle with short pin prod number 831 was discussed in reference to its capability to adequately sense resistance. The more electrode points used, the better the contact with hay attained, with less chance of erroneous readings due to poor sample contact. Bulk resistance depends on the geometric relationship of the electrodes; thus, the more electrodes used, the more statistically correct the data collected. With two electrodes, the field map of flux lines would be difficult to analyze. By using a survey approach (more electrodes), a much better measurement of flux lines would be attained (30).

The Simpson Volt-Ohm-Milliammeter takes a fixed voltage and puts an unknown resistance in series with it and measures current in a circuit with a known resistance. Before resistance measurements were made, the meter was adjusted by shorting out the meter leads and setting the scale reading to zero which compensated for internal inconsistencies such as battery voltage. This meter had a set of standard resistors in it for calibration of the different resistance ranges. It indicated a semi-logarithmic relationship between current and resistance. Like the Delmhorst meter, it depends on the calibration of the scale to give an accurate readout (30).

The Hartstack Moisture Meter was based on the Wheatstone bridge and had a sensitive null detector. Comparison in a null phase would be better than either calibration to zero (Simpson) or calibration to a given resistance value (Delmhorst). However, the nulling process could be troublesome because there would be more switching to adjust the resistance of the bridge. The meter was supplied with a.c. power by a phase shift oscillator to excite the bridge. The a.c. signal was sent through the hay sample and an error signal received back through the probe. The a.c. error signal was increased by an amplifier, changed to d.c. by a rectifier, and applied to a d.c. meter (null indicator) to be used. This moisture meter had the capability of being accurate throughout the moisture range to be measured because the reading would always be at the same place on the null indicator meter. This moisture meter could be economically built to whatever sensitivity specifications required (30).

## III. THE DELMHORST H-2 HANDLE SPRING PRESSURE TEST

During the first three test series, the operator noticed that the force being applied to the handle spring button seemed to be inconsistent from sample to sample. The force was supposed to be 27 to 30 pounds (12.3 to 13.6 kilograms) (59). Calculations indicated that 6.2 to 7.0 psi (43 to 48 kilopascals) sample pressure would result from the desired force range. A test of sample pressure resulting from different forces applied to the spring handle was conducted. Table 11 shows the sample pressures resulting from the test. The range of these pressures was from 8 to 13 psi (55 to 91 kilopascals), about 62 percent above the pressures the handle was designed to produce.

A mechanical relaxation or hydraulic drift down of pressure was noted on the Hartstack compression device used for the spring handle test. This occurred after the initial compression pressure was applied with no apparent change in spring deflection. The loss in pressure did not occur in the same way as had happened previously. At that time the hydraulic drift was such that the pressure usually stabilized at about the same magnitude and the rate of change of pressure was consistent in that it started rapidly and ended slowly. In these tests the stabilizing pressure varied from reading to reading and the rate of change was constant until the stabilizing pressure was reached. The drift continued for 15 seconds.

Results of the spring handle test indicated that: (a) The position of the handle had an affect on the pressure applied to the sample. Consistent sample pressures were attained when force was applied to the center of the handle vertically downward. (b) The difference in the mean initial pressure and mean stabilized pressure was less in Position 3 than Position 1 or 2. (c) Lubrication lowered the initial pressure, stabilized pressure and the difference between these two pressures in nearly all cases. (d) The handle spring was not functioning the way in which it was meant to function.

TABLE 11. Sample pressures resulting from force as measured using the Hartstack compression device.

| Direction of Force | Before Lubrication | | After Lubrication | |
|---|---|---|---|---|
| | Initial Pressure (psi) | Stabilizing Pressure (psi) | Initial Pressure (psi) | Stabilizing Pressure (psi) |
| Position 1 (Slightly off center) | 10.67 | 9.70 | 10.67 | 9.70 |
| | 10.67 | 9.70 | 10.50 | 9.70 |
| | 10.34 | 9.37 | 10.67 | 9.37 |
| | 10.67 | 9.54 | 10.83 | 9.86 |
| | 10.83 | 9.54 | 10.50 | 9.70 |
| Position 2 (Slightly off center) | 11.96 | 10.02 | 10.99 | 9.54 |
| | 13.25 | 11.64 | 10.99 | 9.54 |
| | 13.25 | 10.99 | 10.67 | 9.37 |
| | 12.29 | 9.70 | 10.99 | 9.70 |
| | 13.25 | 10.67 | 10.50 | 9.37 |
| Position 3 (On center-vertical) | 9.05 | 8.08 | 8.73 | 8.08 |
| | 8.73 | 8.08 | 8.73 | 8.08 |
| | 8.89 | 8.40 | 8.89 | 8.08 |
| | 8.89 | 8.24 | 8.89 | 8.08 |
| | 9.05 | 9.05 | 8.89 | 8.57 |

NOTE: The handle was designed to give a sample pressure of 6.2 to 7.0 psi.

## IV. TEST SERIES FOUR

In test series four, a small field chopper and a moisture meter built according to Hartstack's design were added to the equipment used. The results of simple linear regression analysis on data taken are given in Table 12. In the analysis, electrical meter readings were regressed on the oven drying moisture determinations. Three meters were tested under two sample pressures on two conditions of hay samples. Results indicated the two most evident differences in moisture measurements were between meters and conditions of hay.

A test of homogeneity of regression coefficients, as given by Steel and Torrie (68, pp. 319-320), was run using sample pressure as a main effect. The results, summarized in Table 13, support the hypothesis of no difference in slopes of regression equations except that one for the Hartstack meter when testing chopped samples. Hence, no pooling of sample pressure could be done for the Hartstack meter with chopped samples. The intercepts of all the regression equations were found to be significantly different indicating that sample pressure had a significant effect on the constant (intercept) of the regression equations. A test of homogeneity of correlation coefficients, as outlined by Steel and Torrie (68, pp. 190-191), was run. Since pooling over sample pressure for all meters was not possible, correlations for regression coefficients for both sample pressures were tested. Results indicated that chopped sample data all were significantly better than the unchopped in Table 14; that is, moisture content measured by meter readings probing chopped samples were more indicative of actual hay moisture content.

TABLE 12. Results of a simple linear regression analysis for all samples with oven drying moisture determinations between 20 and 45 percent of Test Series 4 taken June 8-10, 1976, at the Plateau Experiment Station with orchardgrass hay.

| Field* | Meter | Sample Pressure (psi) | $s_{y \cdot x}$ | R-Square | Intercept | Slope | Number of Observations |
|---|---|---|---|---|---|---|---|
| 2-C | Delmhorst | 8 | 2.880 | 0.445 | 3.960 | 0.650 | 60 |
| 2-C | Simpson** | 8 | 1.187 | 0.336 | 19.960 | -0.213 | 60 |
| 2-C | Hartstack*** | 8 | 0.261 | 0.512 | -0.689 | 0.065 | 52 |
| 2-C | Delmhorst | 16 | 3.469 | 0.532 | 0.456 | 0.933 | 60 |
| 2-C | Simpson** | 16 | 1.089 | 0.405 | 19.239 | -0.227 | 60 |
| 2-C | Hartstack*** | 16 | 0.499 | 0.661 | -2.899 | 0.167 | 50 |
| 2-U | Delmhorst | 8 | 4.957 | 0.121 | 13.941 | 0.379 | 58 |
| 2-U | Simpson** | 8 | 1.434 | 0.073 | 15.735 | -0.083 | 58 |
| 2-U | Hartstack*** | 8 | 0.517 | 0.155 | 0.105 | 0.044 | 50 |
| 2-U | Delmhorst | 16 | 6.062 | 0.120 | 15.184 | 0.461 | 58 |
| 2-U | Simpson** | 16 | 1.236 | 0.100 | 15.018 | -0.085 | 58 |
| 2-U | Hartstack*** | 16 | 0.750 | 0.224 | -0.484 | 0.082 | 51 |

*C denotes that the hay samples were chopped and U denotes that the hay samples were unchopped.

**These results were from an analysis using the logarithm of the ohmmeter readings (the Delmhorst and Hartstack meters read moisture content (wet basis) directly based on self contained logarithmic conversion of conductance values).

***The results shown were from only scale 5 of the Hartstack meter because there were not enough observations in any other scale to run a valid simple linear regression analysis.

TABLE 13. Test of homogeneity of regression coefficients for determination of significant differences in slope of regression equations using pressure as a main effect on data taken June 8-10, 1976, at Plateau Experiment Station.

| | | Chopped Samples | | | Unchopped Samples | | |
|---|---|---|---|---|---|---|---|
| | Quantity | Delmhorst | Simpson | Hartstack | Delmhorst | Simpson | Hartstack |
| 8 psi sample pressure | SS | 480.967 | 81.685 | 3.407 | 1376.076 | 115.113 | 12.819 |
| | DF | 58 | 58 | 50 | 56 | 56 | 48 |
| 16 psi sample pressure | SS | 698.039 | 68.797 | 11.973 | 2057.855 | 85.606 | 27.582 |
| | DF | 58 | 58 | 48 | 56 | 56 | 49 |
| Totals of individual regressions | SS | 1179.006 | 150.482 | 15.380 | 3433.931 | 200.719 | 40.401 |
| | DF | 116 | 116 | 98 | 112 | 112 | 97 |
| Single regression | SS | 1215.308 | 150.573 | 19.760 | 3438.344 | 200.721 | 41.291 |
| | DF | 117 | 117 | 99 | 113 | 113 | 98 |
| Difference for homogeneity of regressions | SS | 36.374 | 0.091 | 4.380 | 4.413 | 0.002 | 0.890 |
| | DF | 1 | 1 | 1 | 1 | 1 | 1 |
| Total individual mean square | | 10.163 | 1.297 | 0.157 | 30.660 | 1.792 | 0.417 |
| Difference mean square | | 36.374 | 0.091 | 4.380 | 4.413 | 0.002 | 0.890 |
| Calculated F-value | | 3.579 | 0.070 | 27.898 | 0.143 | 0.001 | 2.134 |
| Tabular F-value* | | 3.93 | 3.93 | 3.94 | 3.93 | 3.93 | 3.94 |

*At 95 percent confidence level.

TABLE 14. Test of homogeneity of correlation coefficients to test the hypothesis that meter readings with unchopped samples were equally as good as meter readings with chopped samples when compared to a standard oven moisture determination from data taken June 8-10, 1976, at the Plateau Experiment Station.

| Meter and Compression | Condition of Sample | Number of Observations | r | Tabular z | $\frac{1}{n-3}$ | z* Statistic | Tabular Probability of This Value of z by Chance Alone |
|---|---|---|---|---|---|---|---|
| Delmhorst | | | | | | | |
| 8 psi | Chopped | 60 | 0.667 | 0.811 | 0.0175 | 2.36 | 0.0091 |
| | Unchopped | 58 | 0.348 | 0.365 | 0.0182 | | |
| 16 psi | Chopped | 60 | 0.729 | 0.929 | 0.0175 | 2.99 | 0.0014 |
| | Unchopped | 58 | 0.346 | 0.365 | 0.0182 | | |
| Simpson | | | | | | | |
| 8 psi | Chopped | 60 | 0.580 | 0.662 | 0.0175 | 2.04 | 0.0207 |
| | Unchopped | 58 | 0.270 | 0.277 | 0.0182 | | |
| 16 psi | Chopped | 60 | 0.637 | 0.758 | 0.0175 | 2.25 | 0.0122 |
| | Unchopped | 58 | 0.316 | 0.332 | 0.0182 | | |
| Hartstack | | | | | | | |
| 8 psi | Chopped | 52 | 0.716 | 0.908 | 0.0204 | 2.43 | 0.0075 |
| | Unchopped | 50 | 0.394 | 0.412 | 0.0213 | | |
| 16 psi | Chopped | 50 | 0.813 | 1.127 | 0.0213 | 3.01 | 0.0013 |
| | Unchopped | 51 | 0.473 | 0.510 | 0.0208 | | |

$$*z_{\text{Statistic}} = \frac{\text{Difference of } z}{\sqrt{\text{Sum of } {}^{1}/n\text{-}3}} .$$

For comparing the three meters, two tests of homogeneity of multiple correlation coefficients were used, one for each sample pressure. In each case, the null hypothesis tested was that the meters had homogeneous correlation coefficients. A Chi-square test was performed to determine the validity of the hypothesis according to procedures given by Steel and Torrie (68, pp. 189-191). Results show that the meters were not significantly different in either test. The tests are summarized in Tables 15 and 16.

Using the data from test series four, typical 95 percent confidence limits for moisture content of hay samples indicated to be of 35 percent moisture content by the regression equations for chopped hay samples for each meter at 16 psi (110 kilopascals) sample pressure are given in Table 17. These values were calculated by a relationship given by Snedecor and Cochran (66, p. 159), which predicted the independent variable (oven drying moisture determination) from a selected value of the dependent variable (electrical meter reading).

TABLE 15. Test of homogeneity of multiple correlation coefficients for meter readings regressed on oven determinations at 16 psi sample pressure for data of chopped samples taken at Plateau Experiment Station June 8-10, 1976, with orchardgrass hay.

| Meter | Number of Observations ($n_i$) | $R^2$ | r | $z_i$ | $z_i-\overline{z}_w$ | $(n_i-3)(z_i-\overline{z}_w)^2$ | Upper (CL) | Lower (CL) |
|---|---|---|---|---|---|---|---|---|
| Delmhorst | 60 | 0.532 | 0.729 | 0.929 | 0.002 | 0.000 | 1.194 | 0.664 |
| Simpson | 60 | 0.406 | 0.637 | 0.758 | -0.169 | 1.628 | 1.023 | 0.493 |
| Hartstack | 50 | 0.661 | 0.813 | 1.127 | 0.200 | 1.880 | 1.421 | 0.833 |

NOTE:

$$\overline{Z}_w = \frac{(60 \times .929)+(60 \times .758) + (50 \times 1.127)}{(60 + 60 + 50)} = 0.927.$$

Confidence Limits (CL) = $z_i \pm t_{.05}\ (s_z)$ where $s_z = \sqrt{\frac{1}{n_{i-3}}}$ .

Calculated $X^2$, 2df = 3.508.

Tabular $X^2$, 2df = 5.99 ($\alpha$ = .05).

TABLE 16. Test of homogeneity of multiple correlation coefficients for meter readings regressed on oven determinations at 8 psi sample pressure for data taken June 8-10, 1976, at the Plateau Experiment Station with chopped orchardgrass hay.

| Meter | Number of Observations ($n_i$) | $R^2$ | r | $z_i$ | $z_i-\bar{z}_w$ | $(n_i-3)(z_i-\bar{z}_w)^2$ | Upper (CL) | Lower (CL) |
|---|---|---|---|---|---|---|---|---|
| Delmhorst | 60 | 0.445 | 0.667 | 0.811 | -0.002 | 0.000 | 1.076 | 0.545 |
| Simpson | 60 | 0.336 | 0.580 | 0.662 | -0.151 | 1.300 | 0.9274 | 0.3966 |
| Hartstack | 52 | 0.512 | 0.716 | 0.908 | 0.095 | 0.442 | 1.1954 | 0.6206 |

NOTE:

$$\bar{z}_w = \frac{(60 \text{ X } .881) + (60 \text{ X } .662) + (52 \text{ X } .908)}{(60 + 60 + 50)} = \frac{139.796}{172} = 0.813.$$

Confidence Limits (CL) = $z_i \pm t_{.05} (s_z)$ where $s_z = \sqrt{\frac{1}{n_i-3}}$ .

Calculated $X^2$, 2df = 1.742.

Tabular $X^2$, 2df = 5.99 ($\alpha$ = .05).

TABLE 17. Typical confidence limits expected for actual moisture content of hay samples with use of the three meters, based on the regression equations for chopped hay samples at 16 psi sample pressure from data taken June 8-10, 1976, at the Plateau Experiment Station.

| Meter | Meter Moisture Reading (%) | Actual Moisture Content | | |
|---|---|---|---|---|
| | | Upper Confidence Limit (%) | Lower Confidence Limit (%) | Percent Moisture Difference |
| Delmhorst | 35 | 43.5 | 27.5 | 16.0 |
| Simpson | 35 | 44.5 | 25.5 | 19.0 |
| Hartstack | 35 | 43.8 | 30.7 | 13.1 |

NOTE: (Delmhorst):

$n = 60$
$s_{y \cdot x} = 3.4692$
$\Sigma X^2 = 912.1833$
$b = 0.9326$
$t = 2.0024$

$$c^2 = \frac{t^2 s_b^2}{b^2} = \frac{1}{\Sigma X^2} \left(\frac{t\ s_{y \cdot x}}{b}\right)^2$$

$$= \frac{1}{912.1833} \left(\frac{2.0024\ (3.4692)}{0.9326}\right)^2$$

$$= .0608.$$

$$y = a + bx = 0.4556 + (0.9325)\ (35) = 33.0931$$

$$\hat{X} = (X-\overline{X})/b - (33.0931 - 25.9)/.9326 = 7.7130$$

$$X-\overline{X} = x = \frac{\hat{X} \pm \frac{t\ s_{y.x}}{b} \sqrt{\frac{(n+1)}{n}(1-c^2) + \frac{\hat{x}^2}{\Sigma X^2}}}{1-c^2} ;$$

$$x = \frac{7.7130 \pm \frac{2.0024\ (3.4692)}{.9326} \sqrt{\frac{(60+1)}{60}(1-.0608) + \frac{(7.7130)^2}{912.1833}}}{1 - .0608}$$

$$= 8.2123 \pm 8.0102$$

$$= 16.2225 \text{ and } 0.2020$$

$$X = \overline{x} + x = 27.2833 + 16.2225 = 43.5058 \text{ and}$$

$$27.2833 + 0.2020 = 27.4853.$$

# CHAPTER VI

# SUMMARY AND CONCLUSION

## I. SUMMARY

The capability to measure moisture content of hay in the windrow has been sought by many farmers and researchers. However, an instrument for attaining this measurement with speed, accuracy, and economy has not been completely proven in evaluation tests. The conductance-type moisture detector was chosen for evaluation in this study because of good results from this type meter reported by several authors (1, 24, 33).

Instrumentation for evaluating three electrical meters in measuring windrowed hay moisture content was designed and constructed. The Electrical Engineering Department at The University of Tennessee assisted with design and construction of the Hartstack-type meter. Two auxiliary pieces of equipment, a hydraulic compression device and a hay chopper, were designed and constructed for meter evaluation tests. The three meters were evaluated at two locations in five fields containing three different types of hay. Performance of the three moisture measuring instruments was compared using the standard oven method for determining the actual moisture content of hay.

The hydraulic compression device was designed with provisions for varying the pressure applied to the sample of hay. In field tests the hydraulic compression device was operated at sample pressures of 8, 16, 32, 64, and 97 psi (55, 110, 220, 441, and 669 kilopascals). The small field chopper was used to give a more homogeneous sample to be compared with unchopped samples for an evaluation of this effect on indicated moisture content. The Statistical Analysis System was used to evaluate test data.

## II. CONCLUSIONS

In this study, the conductance-type hay moisture determination method did not prove to be an adequate way of indicating hay moisture content. The instruments and techniques used in this evaluation did not provide the accuracy nor the precision for on-the-farm use or for experimental research work. However, results of these experiments point to methods desirable for obtaining more accurate moisture measurements with conductance-type meters. The findings were that:

1. The use of a cylindrical sample holder did not have a detrimental affect on the quality of data collected. In fact, the sample cylinder eliminated error which was caused when prod pins sometimes completely penetrated the windrow entering the soil surface.

2. A stable sample density was very important in obtaining consistent results. Sample pressure was shown to be a significant main effect on intercept value of the simple linear regression equation relating meter reading to actual moisture content. Both the prod handle spring and hydraulic compression device were found to have pressure fluctuation problems.

3. Fields, type of crop, or time also was found to be a significant main effect on the intercept value while the slopes of the simple linear regression equation fitted to the observed data were homogeneous. Thus a separate regression equation would be required for each field for optimum accuracy.

4. Chopped hay samples gave more accurate meter readings for hay moisture content than did the unchopped.

5. Even though the circuitry of one meter was evaluated as being the most electronically sound, test results did not show it statistically different from the other meters in hay moisture content readings. Typical confidence limits calculated for each meter showed expected accuracy to be plus 9 and minus 8 percent when measuring hay with actual moisture content of 35 percent for the Delmhorst meter, plus 10 and minus 10 percent for the Simpson meter, and plus 9 and minus 4 percent for the Hartstack meter.

## III. RECOMMENDATIONS FOR FURTHER STUDY

An evaluation of the electrical meter approach to indicating hay moisture content should be conducted on many different forage crops, at more than one geographic location, at a stable sample pressure, and over a number of years to be able to explain how much error is actually due to differences in the biological material. Chopping of the hay samples should be continued, and the Hartstack meter should be evaluated throughout its range with enough points in each range to give a statistically valid regression analysis. A modification should be added to the Hartstack meter to make it less cumbersome for adjustment to null.

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# VITA

Joseph Keith McDonald was born in McMinnville, Tennessee, on November 24, 1949, the son of Mr. and Mrs. A. Q. McDonald. His family soon thereafter moved to Cookeville, Tennessee, where he attended Jere Whitson and Capshaw Elementary Schools, Cookeville High School, and graduated from Putnam County Senior High School in 1968. After one quarter at Tennessee Technological University, he enlisted in the United States Navy and served for three years as an Aviation Electrician.

In September, 1971, he re-entered Tennessee Technological University, and in June, 1974, he received a Bachelor of Science degree in Agricultural Science. Supported by a Graduate Research Assistantship, he immediately entered the Graduate School at The University of Tennessee and began study toward the Master of Science degree in Agricultural Mechanization. He is an associate member of the Student Branch of the American Society of Agricultural Engineers and the Agricultural Mechanization Club where he served as a representative to the Student-Faculty Council. He also holds membership in Gamma Sigma Delta and Sigma Phi Epsilon.

He is married to the former Carolyn Ruth Dunham of Sparta, Tennessee.