

THE RAPID DETERMINATION OF HAY
MOISTURE CONTENT

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Earl McCord Sherwood
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This is to certify that the

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of the requirements for

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THE RAPID DETERMINATION OF LAY
MOISTURE CONTENT

By

Earl McCord Sharwood

A THESIS

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THE RAPID DETERMINATION OF HAY MOISTURE CONTENT

I. INTRODUCTION

In an earlier agricultural era, hay was cured in the field until dry enough for safe natural storage. Each farmer had his own peculiar rule to determine when the moisture content of the hay had reached this safe value. Gained through years of experience but probably not too accurate, the personal observation method was the only one available to the farmer.

Today there are about 250 hay driers or finishers in the state of Michigan and over 5,000 in the United States. Numerous research projects have been conducted to determine the proper hay moisture contents at the time of storage for the various systems of driers. This information becomes of little value to the farmer if he must still rely on the old methods of estimating moisture content. Present practices consist of storing the hay at various moisture contents between 25 percent and 45 percent depending on the type and capacity of the system and the amount of hay already placed on the drier. This condition contrasts with the situation before the use of hay driers when the farmer was only interested in one moisture content; that is, the moisture content for safe storage with natural ventilation.

In view of the need and demand for a device which would enable the farmer to rapidly determine the moisture content of hay before storage, the investigations described in this thesis were conducted.

II. REVIEW OF LITERATURE

Methods for determining the moisture content of hay can generally be classified as either direct or indirect. Most present methods employ the direct method which depends on absolute drying of the sample by the application of heat. The sample is weighed both before and after drying and the moisture content calculated from the initial weight and the difference between the two weights.¹ The Brown-Duvel method, Parks method, oven drying method, and Dexter tractor oven method are all examples of the direct measurement of moisture content.

An indirect method consists of using the moist hay to produce changes in a primary detector which can be correlated with the moisture content of the sample. Capacitance methods and resistance methods are examples of indirect measurements.

A. Direct Methods of Measurement

1. Brown-Duvel method. This exact laboratory method has been in use for many years to determine the moisture content

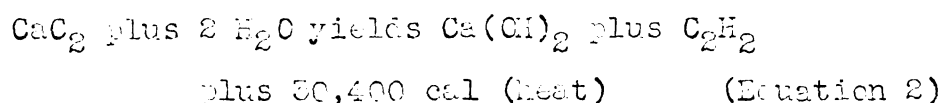
¹ The commonly accepted method for the calculation of moisture content is on the wet basis and is given by the following formula:

$$\text{Percent Moisture equals } \frac{(\text{Wet Weight}) - (\text{Dry Weight})}{(\text{Wet Weight})} \times 100$$

This equation is used throughout this work. (Equation 1)

of all forms of material. The test consists of boiling a weighed sample in an oil or other fluid having a higher boiling point than water thus driving off the water in the form of steam. This steam is then condensed and the condensed water weighed or the volume measured in order to calculate the moisture content of the sample. This method is limited to the research laboratory and is not practical for the farmer.

2. Parks method. In 1938 Davies (14) mentioned a method for determining moisture content by the use of calcium carbide. Parks (38) in 1941 used this principle and developed apparatus to obtain a method for the determination of moisture in forages and grains. This method consisted of mixing a quantity of calcium carbide with the hay sample to obtain a reaction which produced acetylene gas. The chemical equation for the process is as follows:



Parks found it possible to measure moisture in plant tissue to within three percent of the actual moisture content over a range of 10 to 85 percent moisture in from 10 to 25 minutes. A device using this method is manufactured commercially by the Toledo Scale Company, Toledo, Ohio.

Some of the objections to this method have been the small size of sample (30 grams) which limited the significance of the results when applied to the moisture content of the

entire field and the time required to complete the test. The small size of sample required several determinations in order to obtain an average value for the field. With fifteen minutes required for each observation, the amount of time spent in testing was soon excessive.

3. Laboratory oven drying method. Probably the most common moisture determination method used by research workers investigating hay drying practices is the laboratory electric oven. Usually thermostatically controlled, these ovens are operated at a temperature of about 130 degrees F. for a period of 24 hours to drive all moisture from the sample. Temperature control is important in these ovens since any charring of the sample indicates that a chemical reaction is taking place which will result in the loss of some dry matter from the sample in addition to the moisture loss. The nature of the equipment in addition to the long drying period limits the use of this method to the laboratory.

4. Dexter tractor oven method. Dexter (17) in 1947 developed a method for measuring moisture content by the use of an oven attached to the exhaust pipe of a tractor or any other internal combustion engine. The hot exhaust gases were allowed to pass through the sample of hay which was placed in the simple, homemade oven. The temperature of the exhaust gases and hence the heating of the sample was controlled by the speed of the tractor engine.

This method was used by inexperienced operators to determine hay moisture contents which varied not more than three percent from the values determined by the electric oven method for samples from the same population. About six minutes were required for the actual drying process not including the time required to select and weigh the sample and the time necessary to calculate the percent moisture. (A moisture content chart would reduce this time to about one minute)

The main objections to this method appeared to be the following: (a) Haste on the part of the operator may produce high temperatures resulting in burning of the sample and inaccurate results, and (b) Since several tests would be necessary to obtain a representative value of the moisture content of the entire field of hay, the time consumed would be excessive and the tractor may be needed for other work at the same time.

5. Other direct methods. A semi-automatic moisture tester manufactured by the Brabender Corporation, Rochelle Park, Illinois, is an attempt to reduce the amount of labor in weighing and checking samples. The material to be tested is placed in small trays located on the circumference of a horizontal rotating disc. As the disc revolves, the material is weighed in a cool zone and then passes into a hot zone where it is heated and the moisture driven off. Constant

weight of the sample as measured by the sensitive balance built into the machine indicates that the drying is complete. This device is used with excellent results to measure the moisture content of seeds, fruits, berries and any other material when the size of sample is small and the length of the testing period unimportant.

A moisture tester utilizing an infrared heat lamp as the heat source is manufactured by the American Crop-Drying Equipment Company, Crystal Lake, Illinois. The percent moisture is easily read from the calibrated scale of a built-in balance. No operating data are available on this device but the principle objections appear to be the length of the testing period and the necessity for a power connection making it impractical for portable field use..

D. Indirect Methods of Measurement

Any property of hay which varies with moisture content at a consistent, predetermined and measured rate could be used as a basis for the determination of hay moisture content. Using the measurement terminology presented by Lynch and Corson, (27) an analysis of these methods can be outlined as in TABLE I.

Although some research has been done, no one has constructed a successful hay moisture tester using an indirect method. In the development of such a device two problems are encountered: (a) The determination of the rate at which

TABLE I
ANALYSIS OF INDIRECT MEASURES OF MEASURING HAY MOISTURE CONTENT

Quantity measured	Common Name	Basic Element	Input	Physical Effect	Output
Moisture content	Resistor	Resistor composed of hay with attached electrodes	Moisture	An increase in moisture content causes an increase in the conductivity of the hay	Resistance
Moisture content	Thermal conductivity meter	Hot plate apparatus	Moisture	Thermal conductivity increases with moisture content	Temperature
Moisture content	Capacitor	Capacitor with hay as the dielectric	Moisture	Dielectric constant of hay increases with moisture content	Capacitance

the physical effect occurs and (b) the design and construction of a device to measure the output quantity.

1. Resistance methods. Since there is a large difference between the resistance of fibrous or granular materials at various moisture contents, this method would appear to offer good possibilities as an indication of moisture content. The resistance between any two electrodes is actually composed of three resistances, however. These are the resistances at the two contact points and the resistance of the material between the electrodes. With solid materials, an increase in contact pressure at the electrodes above a certain value has little effect on resistance. Anderson (2) found that the contact resistances vary drastically with changes in moisture content when the material being tested is soil. He concluded from the result of his own and other experiments that the electrical resistance between two electrodes placed directly in a mass of soil offered little possibility as an indication of soil moisture. His conclusions can also be logically applied to the measurement of moisture in hay.

Other problems encountered in the resistance method of measuring moisture content are the change in conductivity of water with dissolved impurities and the polarization effects at the electrodes. Millard (23) states that perfectly pure water has a specific resistance of 18,000,000 ohms while ordinary distilled water has a specific resistance of perhaps

100,000 ohms. With an increase in impurities, the resistance decreases rapidly. The use of alternating current instead of direct current eliminates the effect of polarization at the electrodes.

A recent development in an allied field of moisture testing, that of soil moisture, is the result of the work of Bouyoucos (7). The "Bouyoucos Soil Moisture Meter" which is now built and sold commercially measures the resistance of plaster of Paris or nylon blocks having embedded electrodes. These blocks are buried in the soil and maintain a constant state of equilibrium with the moisture content of the soil. Kline (25) applied this method to hay in storage with poor results since good contact between the blocks and the hay could not be maintained. Therefore, the moisture content of the blocks was not in equilibrium with the moisture content of the hay. Even if good contact between the blocks and the hay could be maintained, this method did not offer any possibilities as a method of measuring moisture content in the field since a considerable length of time would be required for equilibrium to be reached.

Several instruments designed for testing the moisture content of wheat operate on the resistance principle. In a study of ten electrical meters for measuring the moisture content of wheat, Hylka, Mortens, and Anderson (23) found that the Tag Heppenstall meter which measures the electrical

conductivity of wheat with a galvanometer gave the most rapid and accurate results. Corrugated steel rollers which crush the grain somewhat are used as electrodes in this apparatus. Of the ten meters tested, two measured the conductance of the sample and eight operated on the dielectric method.

A direct current conductivity moisture meter for grain manufactured by Marconi Instruments, Ltd., London, was submitted for testing to the British Society for Research in Agricultural Engineering. The official report of the test (8) states that the meter was used to test the moisture content of 25 grain samples with moisture contents of three to fourteen percent. The maximum error of two percent was incurred in two samples. This error is quite large compared with the accuracy of another meter manufactured by the same company. (See Capacitance Methods) The report states that the meter was used to test the moisture content of milled dried grass from a pneumatic drier. This practice was considered of questionable value by the officials since "it was not practical to use it with unmilled grass and if the grass has been milled successfully it is already known to be of sufficiently low moisture content for safe storage."

Several other manufacturers produce meters operating on the resistance principle to measure the moisture content of seeds, grain and wood. Dunlap and Bell (19) state that

electrical meters for wood appeared on the American markets about 1930 and that six manufacturers now make instruments that operate on either the resistance, capacitance, or power factor loss principle. According to their investigations, resistance-type meters for wood should have an accuracy of plus or minus one percent between moisture contents of seven and twenty-five percent. They also found that the accuracy is greater below the fiber saturation point (about 30 percent) than above it because of the greater change in resistance with moisture.

From a study of the results of other investigators, and an analysis of the varying resistances involved, a conclusion was reached that moisture meters employing the resistance method were suitable for compact or easily compacted materials such as wood and grain but were not suited for a bulky material like hay.

2. Thermal conductivity method. The thermal conductivity of organic materials such as wood, straw and hay increases with moisture content due to the denser molecular arrangement of water compared with air. No experimental values of the moisture content--thermal conductivity relationship for hay have been published. Rowley and Algren (33) stated a tentative conclusion based on experimental evidence that the thermal conductivity of wood varies substantially in a straight line ratio with moisture content when the

latter is expressed in terms of weight per volume of wood. The variation in k value for soft maple, one of 28 species tested, was found to be 0.9 at zero percent moisture to 1.05 at sixteen percent moisture content when the density of the wood was 37 pounds per cubic foot. These same authors found that thermal conductivity varies approximately in a straight line ratio with density for any given species. This fact presents an important problem in adapting this method to measuring the moisture content of hay; provided, of course, that the same relationship is true for hay.

Shaw and Eaver (33) used this method in measuring the moisture content of soils by passing a current through two resistances, one in moist soil and the other in dry soil. By using resistances having a large coefficient of thermal resistivity, the investigators measured the moisture content of the soil as a function of the resistance which varied with the thermal conductivity of the soil. The following conclusions were made:

(a) The change in conductivity of soils at various moisture contents can be measured.

(b) The thermal conductivity of soils gave a reliable index of the soil moisture content.

(c) Changes in salt concentration of the soil did not materially affect the heat conductivity.

The only known application of this method to hay was made by Schoenleber (27) who reported preliminary investigations conducted by inserting a thermally sensitive resistor (Thermistor) in a bale of hay and heating the resistor by passing a current through it for a short period. The magnitude of the change in resistance was measured by the bridge circuit shown in Figure 1. Since resistance changes varied with the amount of heat conducted away from the thermistor or with the thermal conductivity of the hay, the method offered a means for the determination of hay moisture content.

Since it has received limited attention, the determination of hay moisture content by measuring its thermal conductivity offers possibilities for research.

3. Capacitance methods. The dielectric constant of any insulating material will increase as the water content becomes greater due to the many polar molecules contained in water. Since an increase in the dielectric constant produces an increase in capacitance, an increase in moisture content will produce an increase in capacitance of a parallel plate capacitor having the material as the dielectric. This fact has been used as the operating principle for a number of moisture testing devices.

Brockelsby (9) describes an electrical moisture meter for wheat developed by Larceni Instruments, Ltd., London, which can detect moisture changes of 0.2 percent in grain.

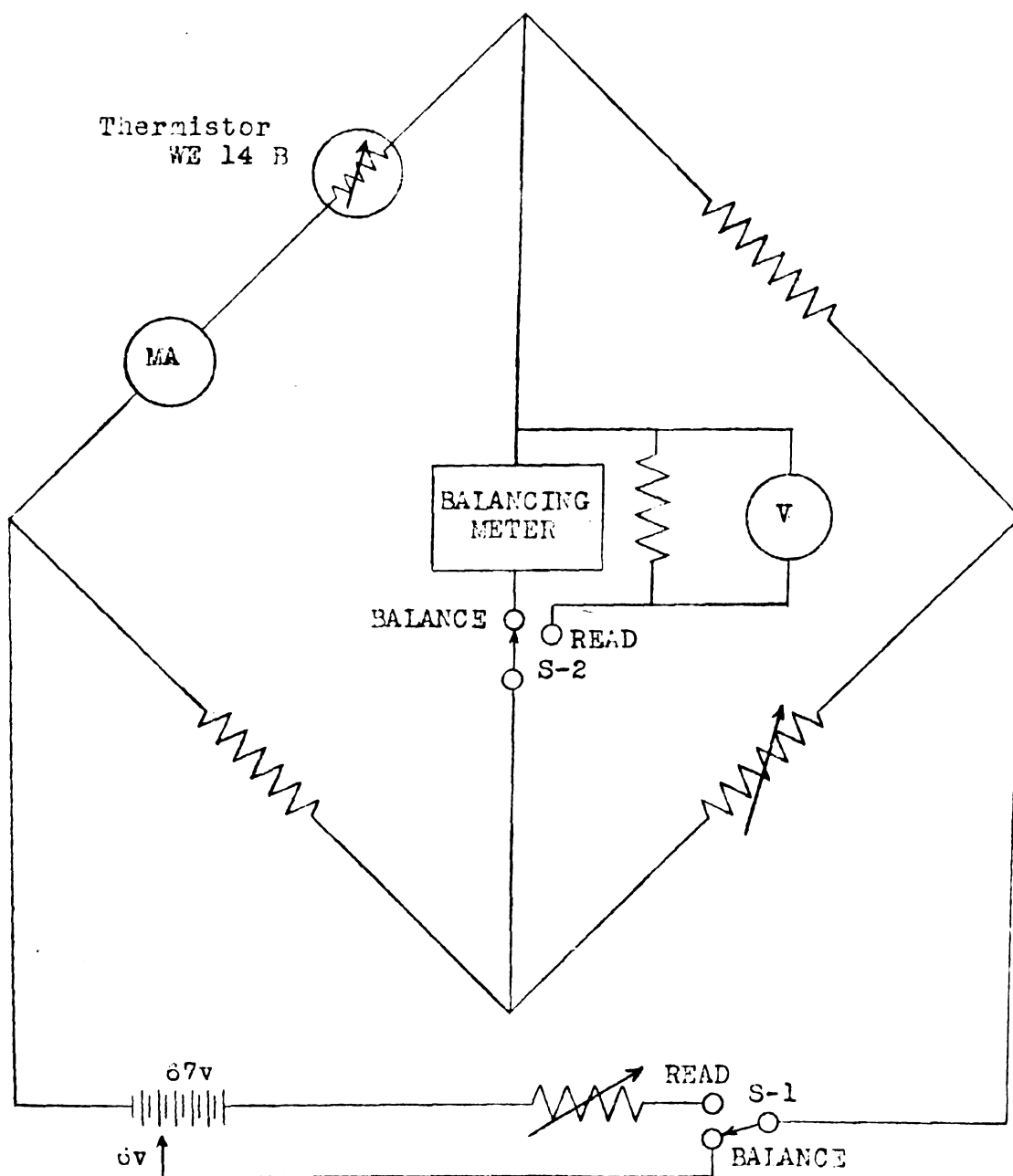


Figure 1. Bridge circuit for measuring moisture content of hay with a thermistor.

Designed for a direct reading range of eight to twenty-eight percent moisture content, the manufacturers claim a probable error of plus or minus 0.4 percent over the entire range. Readings of capacitance are made by applying a low radio frequency voltage to a guarded parallel plate capacitor having the wheat as a dielectric.

Rasmussen and Anderson developed another dielectric meter for estimating the moisture content of grain. (33) This meter accommodates a 150 gram sample which forms the dielectric of a condenser in the plate circuit of a triode crystal oscillator. (See Figure 2) Changes in capacity due to the sample are compensated for by varying the capacity of a variable condenser. Both with and without the sample in the capacitor, the variable condenser is adjusted so that the capacitance of the tuned circuit is of the correct value for oscillations to occur in the triode section of the tube. This oscillating state is indicated by the change in the shadow angle of the indicating eye of the 6E5 tube. This meter was calibrated with 159 samples of Canadian hard red spring wheat and the standard error of estimate found to be 0.36 over the range of ten to seventeen percent moisture.

Gerdel and others at the Central Sierra Snow Laboratory, Sacramento, California, (21) developed meters to measure the free water content of snow using the dielectric principle. He stated that the change in dielectric constant is a logical

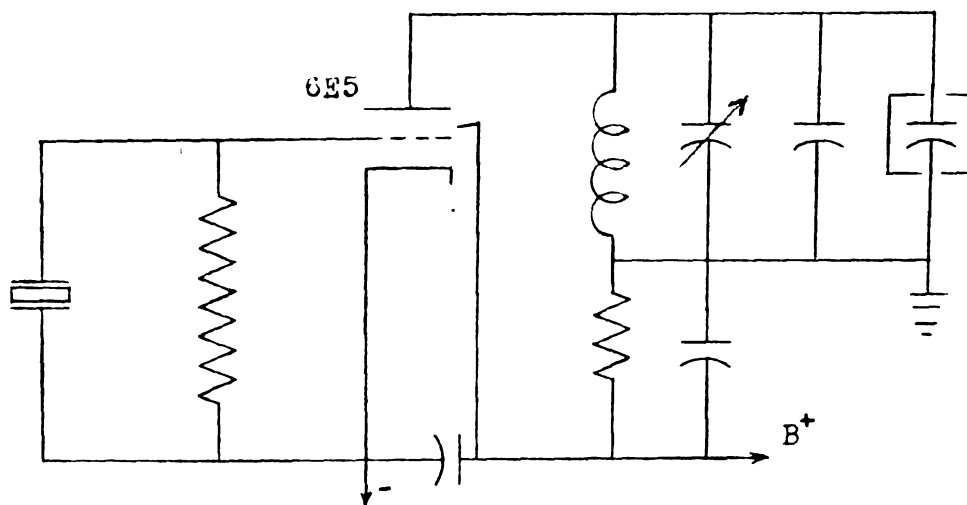


Figure 2. Schematic diagram of dielectric type moisture meter for wheat.

basis for the development of any moisture measuring instrument unless there are excessive losses involved. With snow, crystal size and density had a marked effect on power factor but were difficult to measure.

A moisture tester for cattle foods, seeds, dehydrated foods, straw, tobacco and other materials described by Jupe (24) was developed by Hartshorn at the National Physical Laboratory, England. A sixty-cycle voltage is applied to the capacitor cell and either the conduction current or the capacitance current which is in quadrature is measured. (See Figure 3) Therefore, the circuit responds to either capacitance or a-c conductance changes or to any combination of the two. Since a rise in temperature produces a decrease in dielectric constant and an increase in conductivity, the combined method of measurement enables over-all temperature variations to be minimized.

In 1932, Balls (4) measured the moisture content of baled cotton by measuring the change in capacitance between the nine iron hoops on the bale. This method enabled him to be certain that the moisture content of bales coming from the presses was between eight and nine percent as required by international agreement at that time. Balls also investigated the measurement of soil moisture content and found that a capacity bridge method of measuring capacitance changes in a buried condenser was impractical on account of power

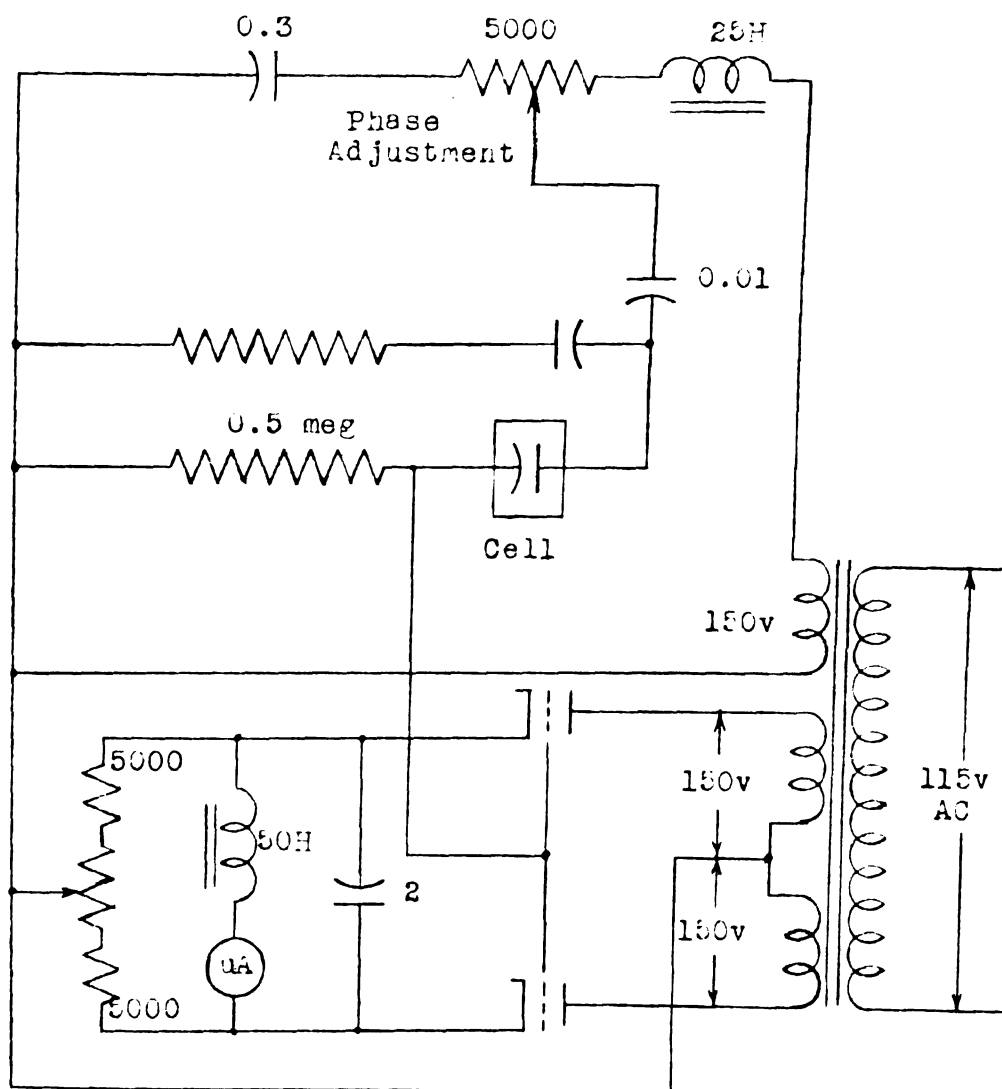


Figure 3. Schematic diagram of dielectric type moisture meter developed at the National Physical Laboratory, England.

losses to the earth. By the use of a resonance method the effect of this loss was evaded.

Fletcher (20) was another of the many investigators who conducted tests of soil moisture content based on dielectric methods. The results of his work seemed to indicate that the method was a reliable indication of soil moisture and offered possibilities for soils "in situ". Measurements were made by a resonance method to avoid effects of power factor changes. (See Figure 4)

The application of the capacitance method to the problem of hay has received limited attention. Schoenleber (37) conducted some investigations using capacitor plates six by eight inches. Between the plates was a plywood box with a space for hay two inches thick, four inches wide and about thirteen inches long. Using a frequency of 3.5 megacycles, he found that moisture contents of forages up to 35 percent gave readings of measurable differences. Schoenleber commented that it was quite possible that other arrangements and frequencies for a capacitance meter might be a better indication of moisture content.

Another use of this method was made by Hart in 1947. (32) Using a frequency of one thousand cycles per second and the simple bridge circuit shown in Figure 5 to measure changes in capacitance, he obtained readings accurate to five percent moisture content. Some difficulties were

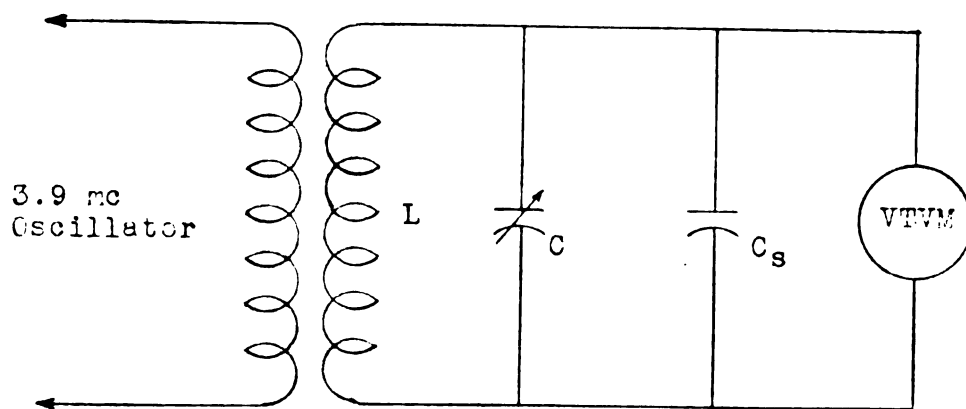


Figure 4. Diagram of method used by Fletcher to measure soil moisture content.

Portable Oscillator
1000 cycles

22

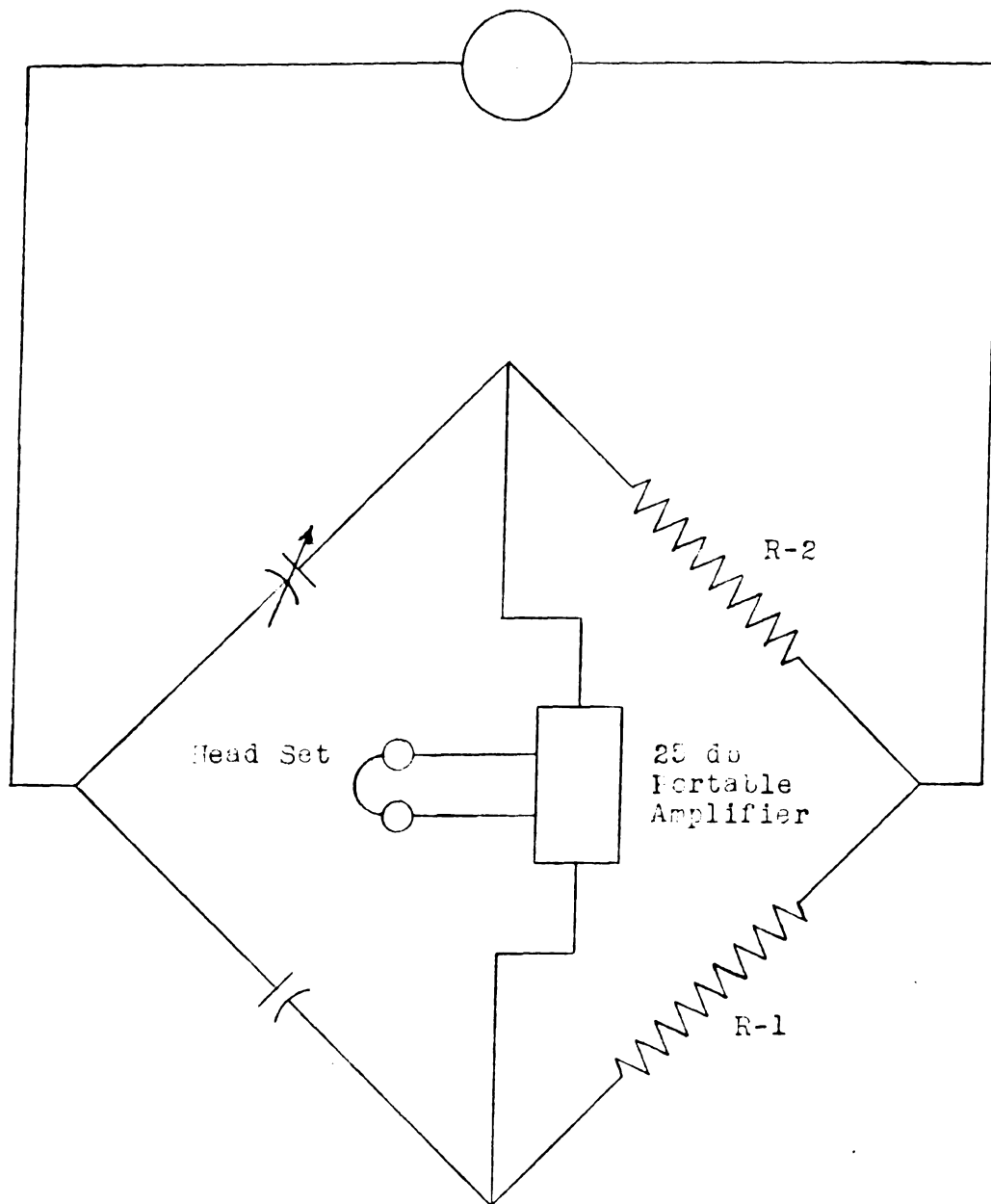


Figure 8. Bridge circuit used by Hart to measure capacitance.

encountered in obtaining a sharp null point at balance and with drift readings of capacitance. No provision was made for compensation of the variable resistance of the pick-up unit. The amount of equipment needed to measure capacitance was cumbersome and hardly portable. After one season of use in conjunction with hay research work, the apparatus was not developed or used further.

Reports were received of development work on a moisture tester using the dielectric method having been conducted at the University of Nebraska. No results have been presented or published at this date.

Due to the nature of dielectrics and the fact that the principle is widely used in grain testing, the capacitance method appeared to offer possibilities as a hay moisture testing device although few applications have been made in the past.

4. Other indirect methods. Dexter (16) presented a method whereby one could estimate whether hay or grain would keep in storage. The absorption of moisture by a salt such as ammonium chloride is used as the basis for this test. If the moisture content of the hay or grain sample is above a certain value (about 25 percent for hay and 12 percent for grain), enough moisture will be absorbed to dampen the salt and cause it to gather in clumps. This test is only suitable for the lower limits of moisture content.

In 1929 Burton and Pitt (13) developed a moisture tester for wheat depending on the change in circuit inductance caused by placing the wheat in the core of a coil contained in the tuned plate circuit of a vacuum tube. (See Figure 6) In 1932 Davies (14) commented that the changes produced by the insertion of the seed in the core of the coil could be caused by either of two reasons. (a) The change in the effective inductance and resistance of the coil due to eddy currents induced in the seeds, or (b) a change in the self-capacity of the coil due to a change in the dielectric constant of part of the surroundings. He contended that Belz (5) showed that this eddy current effect is negligible even at radio frequencies for a highly conducting liquid such as concentrated sulfuric acid. Davies therefore believed that this method actually depended on the change in self-capacity of the coil or dielectric constant of the core. Before reviewing the analysis by Davies, this author conducted some preliminary investigations noting the change in coil inductance with moisture content of hay. These results are presented in another section of this thesis.

This review of literature revealed that no known portable instrument existed for the rapid and accurate determination of hay moisture content. Although a great amount of work has been conducted in developing apparatus to measure the moisture content of soil, wood, seeds and similar materials,

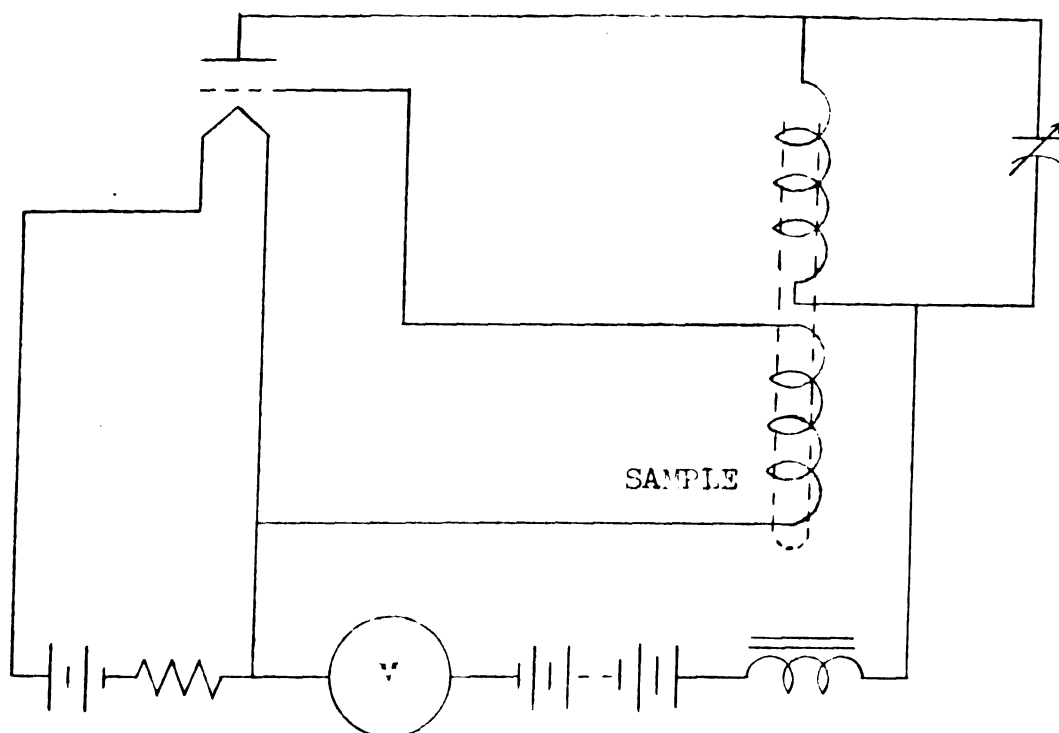


Figure 6. Schematic diagram of wheat moisture tester based on change in coil inductance with the sample in the core.

little attention has been paid to the measurement of the moisture content of hay. The present need for a solution to this problem suggested the research to determine basic relationships and the design of suitable apparatus..

III. THEORY OF CAPACITANCE METHOD

In order to apply the capacitance method to the measurement of hay moisture content, the nature and behavior of dielectric materials must be fully understood. Since the development of the electrical power and communication industries, a great number of investigators have been concerned with the dielectric properties of insulating materials. The purpose of this section is to correlate this information with the problem of measuring moisture content.

A. Dielectric Constant

Dielectric or insulating materials can be considered as an assemblage of bound charges or an assemblage of charged particles which are bound together so that they cannot drift from one electrode to another. This condition contrasts with that in conductors, which contain free electrons or ions. When a voltage is applied to a dielectric, the electric field causes a systematic displacement of the bound charges from their normal position of equilibrium or the position they occupy when the applied voltage is zero. This effect is termed dielectric polarization. On removal of the voltage the charges return to their normal positions. If two metal plates are attached to opposite sides of the dielectric to form a capacitor, the charge stored in the

capacitor will be proportional to the amount of polarization of the dielectric. The capacitance, C , of the capacitor is directly proportional to the charge stored, Q , and inversely proportional to the voltage, E , producing the polarizations in the dielectric. Or:

$$C \text{ equals } \frac{Q}{E} \quad (\text{Equation 3})$$

Polarizations may be classified into two groups according to the length of time required to form: (a) Rapidly forming or instantaneous and (b) slowly forming or absorptive. The time required for a polarization to form or disappear is known as the relaxation time.

Four different types of polarizations can occur in a dielectric: (a) Electronic; (b) Atomic; (c) Molecular or Dipole; and (d) Interfacial or Ionic. Electronic polarizations consist of the displacement of electrons with respect to the positive nuclei of the atom and occur in about 10^{-15} seconds or almost instantaneously. Atomic polarizations are the result of the displacement of atoms with respect to each other in the molecule and also occur almost instantaneously. Dipole polarizations are the effect of the applied field on the orientation of molecules with permanent dipole moments and are usually slow forming. Interfacial polarizations are caused by the accumulation of free ions at the interfaces between materials having different conductivities and dielectric constants. This type of polarization is always slow forming.

The dielectric constant of a material is determined by the sum of the products of amplitude and charge extended over all of the bound charges in the material. The dielectric constant of a substance is also defined as the ratio of the capacitance of a capacitor having that substance as a dielectric to the capacitance of the capacitor with a vacuum as the dielectric. The dielectric constant of air is 1.000590 and of a vacuum is exactly one. For all practical purposes the dielectric constant of air may be taken as one.

Since different times are required for the various types of polarizations to occur, the application of an alternating voltage to a dielectric will allow only those polarizations to occur which require a time less than the period of the applied voltage. This fact leads to the phenomena of anomalous dispersion, or a decrease in dielectric constant with increasing frequency.

In 1939, Debye (15) stated that the relaxation time of water dipoles at ordinary temperature was $0.95 (10)^{-10}$ seconds. A frequency of less than ten thousand megacycles per second would allow all polarizations to occur. Murphy and Morgan (39) in 1947 stated that the relaxation time of water dipolar molecules (the major source of polarization in water) was $(10)^{-10}$ seconds corresponding to a relaxation frequency of 1,600 megacycles per second. The variation

between these two values is probably due to additional investigations. Applying this information to hay moisture determination, the use of any frequency below these values would permit the polarization of the water dipole molecules to occur and hence give readings of dielectric constant that would vary with moisture content. Since these are very high frequencies, the upper frequency limit is more dependent on the ease and accuracy of measurement.

The lower limit of frequency for measuring the dielectric constant of hay should be high enough so that the interfacial polarizations do not contribute to the dielectric constant. This type of polarization could be expected to vary with the chemical and cellular composition of the hay and hence may vary from sample to sample producing erratic results. The drift readings reported by Hart (12) who used a frequency of one thousand cycles per second may have been due to the variation in the amount of interfacial polarizations which occurred. Brockelsby (9) reported that the use of a low radio frequency eliminated the drift readings encountered when an audio frequency was used to measure the dielectric constant of wheat. Apparently, the use of a frequency high enough to eliminate drift readings and low enough to permit ease and accuracy of measurement is essential to the successful measurement of hay moisture content by the dielectric method.

1. Effect of temperature on dielectric constant. The major effect of temperature on dielectric constant is produced by the changes in the amount of polarization caused by the orientation of the dipole molecules. A liquid or gas contains many molecules which are continuously undergoing translational and rotational motion. The effect of an increase in temperature is to increase this motion and to result in a random orientation of molecules. When the material is subjected to an electric field, the dipole molecules tend to be aligned by the field. An increase in temperature will oppose this tendency and, hence, result in a decrease in the amount of polarizations. A decrease in temperature will produce a decrease in the thermal energy resulting in less random orientations of the molecules and an increase in the amount of polarizations and dielectric constant. Most materials have, therefore, a negative coefficient of dielectric constant with temperature.

2. Dielectric constant of granular materials. The dielectric constant of solid sheet materials is easily determined by constructing a capacitor having the material for a dielectric. If a granular material such as wheat, hay or flour is placed between the plates of a capacitor, the measured capacitance will be the result of the dielectric constant of the material and the dielectric constant of the air in the spaces between the particles. Yevstigneyev

determined the variation of the absolute dielectric constant of biscuits, flour and sugar using the relationship presented by Liehtenecker. (40) The development of this formula is as follows:

The dielectric constant of a mixture is related to the dielectric constant of the two components by the expression,

$$k_m \text{ equals } k_1^x k_2^y$$

where k_m is the dielectric constant of the mixture;

k_1 and k_2 are the dielectric constants of the two component parts;

x and y are the fractions of volume occupied by the component parts.

If one material is air, then k_2 equals one and,

$$k_m \text{ equals } k_1^x$$

$$\text{or, } \log k_m \text{ equals } x \log k_1$$

$$\text{and, } \log k_1 \text{ equals } \frac{\log k_m}{x}$$

$$\text{But, } x \text{ equals } \frac{a}{vd}$$

where a is the weight of the substance

v is the volume of the mixture

d is the specific gravity of the substance

Therefore,

$$\log k_1 \text{ equals } \frac{vd}{a} \log k_m$$

(Equation 5)

Analysis of this equation with reference to hwy indicates that if the weight of the substance (hwy) and the volume of

the mixture are kept constant, the capacitance of a capacitor containing hay will vary only with the specific gravity of the hay. Therefore, the variation in the specific gravity of wet and dry hay would be an indication of the change in capacitance with moisture content..

B. Dielectric Losses

Dielectric losses in practical insulators are due to both absorption and conduction. Absorption losses are the result of the dissipation of the energy of the field as heat because of the friction experienced by the bound charges or dipoles in their motion in the applied field when forming polarizations. Conduction or Joule heat losses are caused by the presence of free ions in the dielectric and are proportional to the direct current conductivity of the material. Both types of losses result in the heating of the dielectric.

The total current flowing through a capacitor is composed of a dissipative and a non-dissipative part. The power factor of a capacitor represents the fraction of the input voltamperes that is dissipated in the condenser.. Using the equivalent series circuit notation, the phase angle is the angle between the voltage across the capacitor and the current flowing into the capacitor.

(See Figure 7)² In a perfect capacitor, the losses would be zero and the phase angle would be ninety degrees or the voltage across the capacitor would be ninety degrees out of phase with the current. The loss factor of a material is the product of the dielectric constant and power factor. Dielectric power loss is proportional to the loss factor.

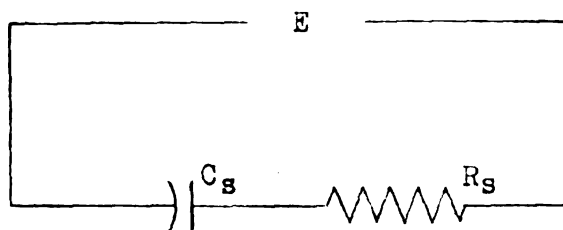
Another indication of the losses in a capacitor is the Q or quality factor.³ By definition, Q is the ratio of the energy stored in the capacitor to the energy dissipated per cycle of the applied voltage. An expression for Q is

² Any capacitor can be represented as an equivalent series circuit or an equivalent parallel circuit. The equivalent parallel circuit and the corresponding vector relationship are shown in Figure 8. If the actual capacitance has been determined in a series circuit, the equivalent parallel capacitance may be calculated from the following equation:

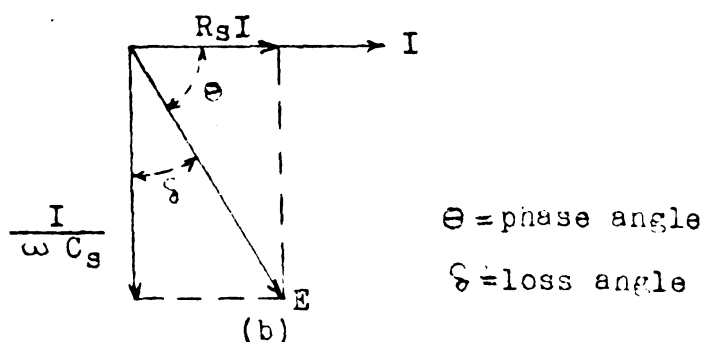
$$C_p = \frac{C_s}{1 \mp \frac{1}{Q^2}}$$

If Q is greater than 10, the two capacitances are alike to within one percent.

³ The losses in a capacitor are also expressed in terms of dissipation factor, D, which is the reciprocal of Q.

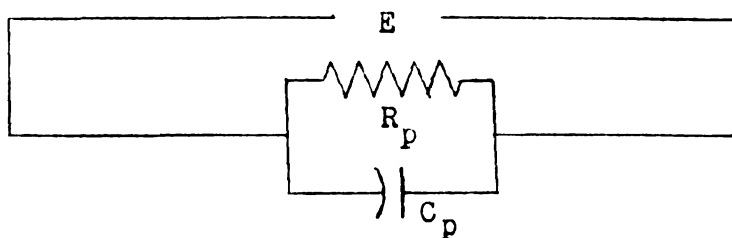


(a)

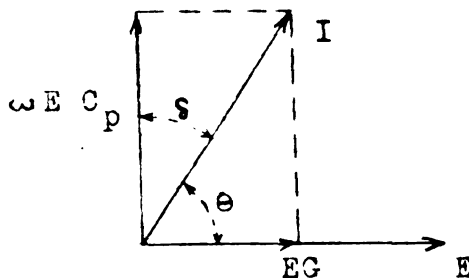


(b)

Figure 7. (a) Equivalent series circuit of a capacitor
 (b) Vector relations for equivalent series circuit



(a)



(b)

Figure 8. (a) Equivalent parallel circuit of a capacitor
 (b) Vector diagram of equivalent parallel circuit

obtained from the following relationships:

$$Q \text{ equals } \frac{\text{Energy Stored}}{\text{Energy Dissipated}} \text{ equals } \frac{\text{Reactance}}{\text{Losses}} \text{ equals } \frac{1}{w C R_s}$$

(Equation 4)

where w equals 2π times the frequency of the applied voltage

C equals the capacitance

R_s equals the equivalent series resistance of the capacitor.⁴

Both power factor and Q are used to indicate the merit of capacitors and other circuit elements. As Q increases, the reciprocal of Q approaches the power factor, and for capacitances having a Q greater than ten, power factor is equal to the reciprocal of Q with an error of less than one percent.

As the water content of a dielectric material is increased, the dielectric losses and hence the power factor will also be increased. The increase in losses with moisture content is due in part to the increased friction of the heavy polar molecules of water resulting in more dielectric absorption and in part to the increased direct current conductivity due to the presence of free ions in water. If they were to comprise the dielectric material of a capacitor,

⁴ If the losses in the capacitor are represented by an equivalent parallel resistance, the expression for Q is as follows:

$$Q = w C_p R_p$$

the change in power factor might be used as an indication of changes in moisture content. Experimental investigations described later indicate that this is not a practical method for determining the moisture content of hay.

IV. EXPERIMENTAL INVESTIGATIONS

A. Objectives

Since the review of literature and study of dielectric theory indicated that the capacitance method offered possibilities for the determination of hay moisture content, investigations were conducted to determine the basic relationships between hay moisture, frequency, power-factor and capacitance. The specific objectives of this study were as follows:

- (a) To determine the value of capacitance and power-factor of a capacitor using hay of varying moisture content as a dielectric;
- (b) To determine the effect of frequency on capacitance and power factor;
- (c) To determine the change in the capacitance - hay moisture content relationship with method of packing the hay..

An initial objective of the program was to determine the minimum size of sample which would give a true indication of average moisture content. Subsequent design permitted the use of a hay sample larger than that used in most present methods. Therefore, no work was undertaken to meet this objective..

Preliminary investigations were conducted to determine the effect of moist hay on coil Q when the hay was placed in the core of the coil. No exhaustive tests were conducted after analysis indicated that this was essentially a dielectric method.

B. Q -Meter Measurements

In the following tests all measurements of capacitance and Q were made with the Boonton-type 160A Q -meter shown in Figure 9. The simplified schematic diagram of this meter is shown in Figure 10. The meter operates on the resonant circuit, resonant rise principle which is based on the fact that when a known radio frequency voltage is introduced into a resonant circuit, the ratio of this voltage to the voltage appearing across the capacitor is approximately the dissipation factor of the circuit. The known radio frequency voltage is introduced into the circuit by passing a known current through the 0.04 ohm resistance, R . Capacitance measurements are obtained by noting the amount that the standard air capacitor, C , must be decreased in order to resonant the circuit when the unknown capacitor, C_x , is connected. (6)

The inductance, L , is not an integral part of the Q -meter, but is attached externally when making measurements of capacitance. The size of the inductance must be such that it will resonate with the combination of known and

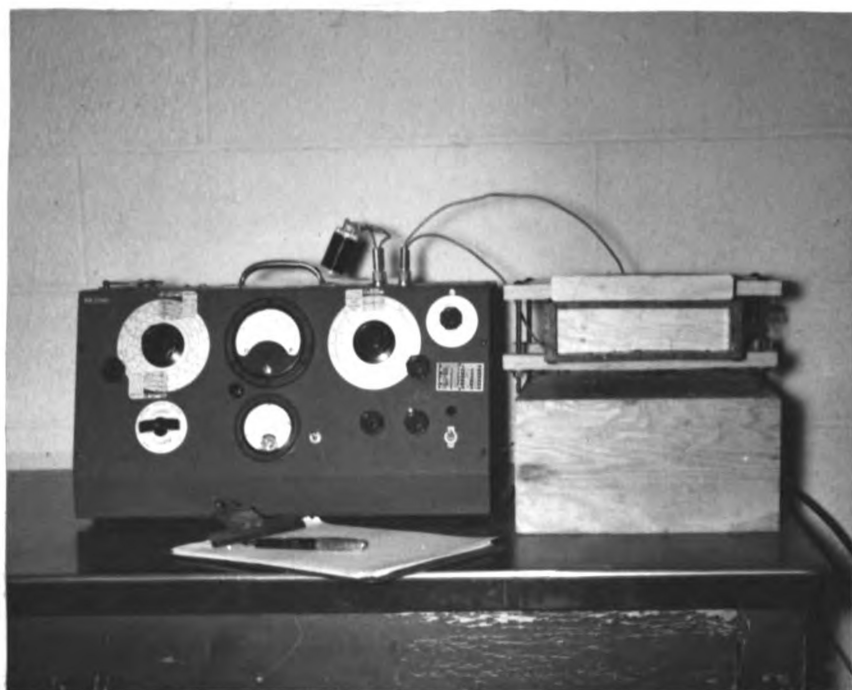


Figure 9. Doonton Type 160A Q-meter used in measurements of capacitance and Q . Capacitor cell used in Test IIB is attached to meter.

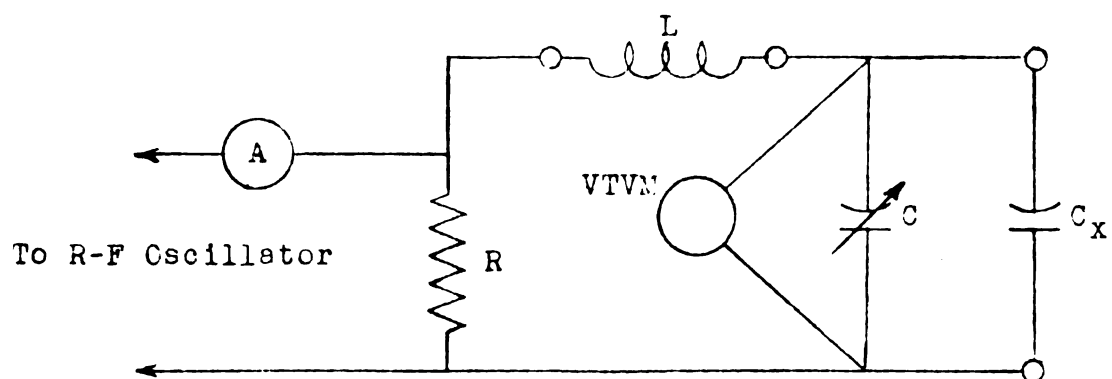


Figure 10. Simplified schematic diagram of Boonton Type 160A Q-meter.

unknown capacitance at the desired frequency of measurements. Coils used in these measurements are shown in Figure 11.

The figure of merit of a coil may be read directly from the calibrated vacuum tube volt meter when the coil is the inductor L and the circuit resonated by adjusting the standard air capacitor. When measuring the Q-factor and capacitance of a capacitor, the circuit must first be resonated with a high Q coil and the standard air capacitor. Readings of the capacitance and the Q volt meter must be taken and are designated C_1 and Q_1 , respectively. Next the unknown capacitor is attached in parallel to C and the circuit re-resonated. The readings of capacitance and Q for this second resonant setting are then designated C_2 and Q_2 . The unknown capacitance, C_x is then calculated from the expression:

$$C_x = C_1 - C_2 \quad (\text{Equation 6})$$

The figure of merit of the unknown capacitor is calculated from the formula:

$$Q_x = \frac{(C_1 - C_2) (Q_1) (Q_2)}{C_1 (Q_1 - Q_2)} \quad (\text{Equation 7})$$

The equivalent series resistance of the capacitor is calculated from the expression:

$$R_s = \frac{1.59 (10)^8}{f^2 C_s Q_x} \quad (\text{Equation 8})$$



Figure 11. Inductances used with the Q-meter in making capacitance measurements.

Where f is the frequency in kilocycles.

C_s is the equivalent series capacitance of the capacitor and is equal to C_x if Q_x is greater than 10.

C. Test I: Effect of Inserting Hay in Core of Coil

1. Apparatus and procedure. In order to determine the effect of moist hay on coil Q , the figure of merit of the coil was measured with the Boonton-type 100A Q -meter. Hay was placed in the 1 7/8-inch diameter core of a coil wound on a glass form. The coil used in Test IA had a Q of 349 at 2.5 megacycles and an inductance of 2.48 mh when empty. The number of turns on the coil used in Test IB was reduced in order to place it in a device which maintained a constant pressure on the hay. As used in this test, the coil had a Q of 261 and an inductance of 1.48 mh.

In Test IA the hay was placed in the core and tamped with a one-half by six-inch plastic bar. No particular attention was paid to obtaining either constant pressure on the sample or a constant weight of sample. In Test IB a spring loaded plunger was used to place the hay under an approximately uniform pressure. (See Figure 12) By filling the cell so that the compressed length of the spring was the same for all tests, the force exerted by the plunger was also constant. The compression force was 45

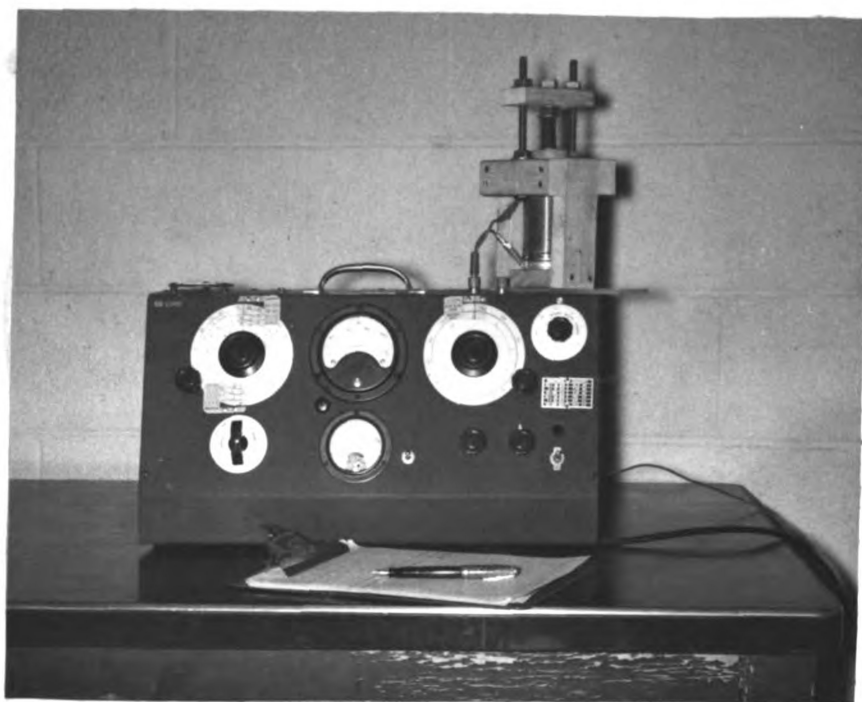


Figure 12. Coil cell with spring loaded plunger attached to Q-meter.

pounds. The area of the plunger was 2.4 square inches resulting in a plunger pressure of 19 psi.

In all tests the hay was cut to an approximate length of one-half inch in order to make packing easier. The average weight of sample was 55 grams. The hay used was second-crop alfalfa.

The test procedure was as follows:

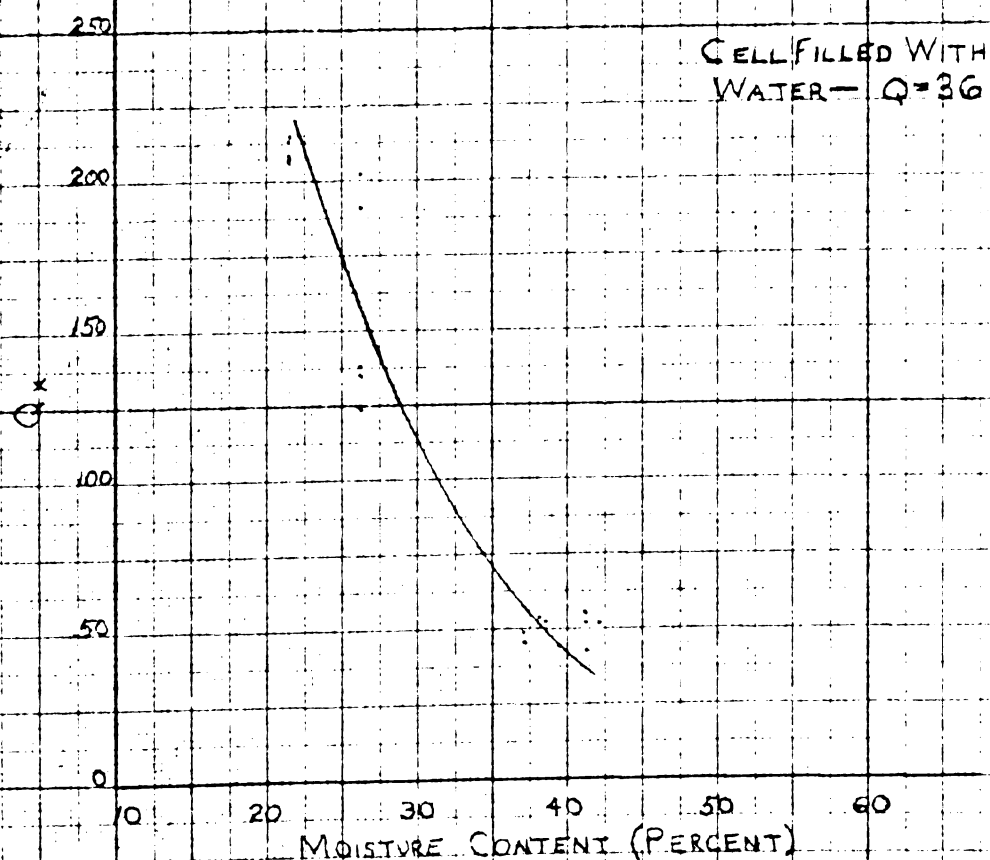
- (a) Sample selected and cut to one-half inch lengths.
- (b) Hay inserted in core of coil and tamped. (Hand tamped in test IA and mechanically tamped in test IB.)
- (c) Coil was connected to Q-meter and capacitance dial adjusted to measure Q. (This operation usually took less than one minute.)
- (d) Sample removed from coil and weighed for moisture determination by oven drying method.

2. Results: Test IA. The relationship between moisture content and coil Q for hand packing of the sample is presented in Graph I. Over the range of moisture contents measured (21 to 42 percent) the relationship between the moisture content and Q departed slightly from a straight line.

3. Results: Test IB. The relationship between moisture content and coil Q for a plunger pressure of 19 psi on the sample is presented in Graph II. Only three different moisture contents were included in this test so that the results are probably not significant. A trend toward

GRAPH I

COIL Q AS A FUNCTION OF THE
MOISTURE CONTENT OF
HAY PLACED IN
THE CORE



GRAPH II

COIL Q AS A FUNCTION OF MOISTURE
CONTENT WITH HAY PLACED
UNDER A CONSTANT
PRESSURE

250

PLUNGER PRESSURE - 19 psi

200

150

100

50

0

10

20

30

40

50

60

70

MOISTURE CONTENT (PERCENT)

x

8

8

8

8

8

a leveling off of the curve at the higher moisture contents was indicated.

4. Analysis and results. Actual coils can be represented by the combination of pure inductance and series resistance in parallel with the distributed capacity of the coil as shown in Figure 13. This distributed capacitance is the result of the electrostatic field in the core material and the air near the coil produced by the voltage difference between turns. Terman (39) stated that the presence of distributed capacity introduces losses in the coil because some of the electrostatic storage involves solid dielectrics which are never perfect. These dielectric losses account for part of the series resistance of the actual coil. Since an added series resistance will lower the Q of the coil, the insertion of the imperfect dielectric, moist hay, will cause a decrease in the Q -factor..

Hay moisture determination by the coil method is essentially therefore, a measurement of the hay power factor. This method was not investigated further for the following reasons:

(a) Later tests with capacitors indicated no consistent relationship between hay power factor and moisture content.

(b) The Q factor measurement would require complex and expensive instruments for field use.

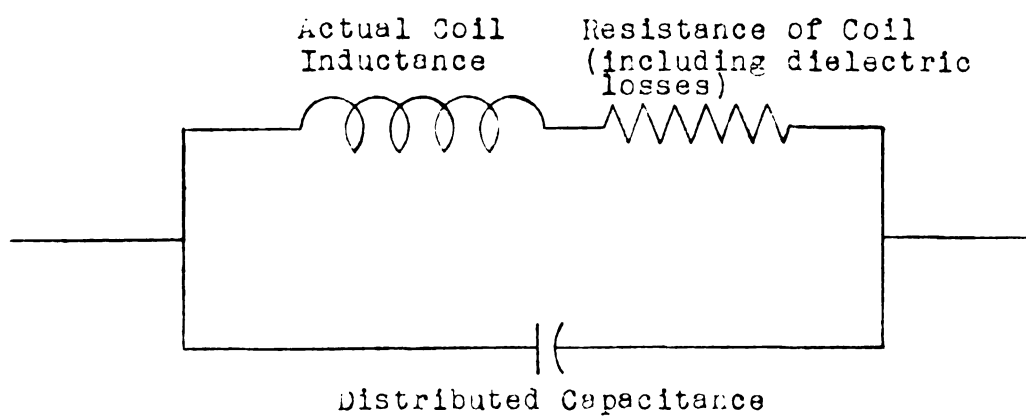


Figure 13. Equivalent circuit of an actual coil.

(c) The physical size of a practical cell limits the sample size so that the accuracy of the measurement when applied to the entire field of hay is decreased.

D. Test II: Variation of Capacitance and Power Factor in the Low Radio Frequency Range

The general procedure for tests described in this section was to place hay of varying moisture contents in a capacitor consisting of two metal plates supported by plywood. The Beerton-type RCA meter was used for all measurements of capacitance and Q.

1. Test IIA: Approximate Procedure. The capacitor used in this test was constructed as shown in Figure 14. Two 6 x 10 inch aluminum plates were attached to two 9 x 12 5/8 inch pieces of one-half inch plywood. The lower section of plywood, and hence the lower plate, was fixed permanently to the frame of the box. The upper plywood section together with the attached plate could be moved to vary the distance between electrodes. For this test the spacing between electrodes was 1.45 inches. First crop alfalfa hay of 18 percent moisture content was used in this test. The hay was placed by hand to two different densities, 5.50 and 7.50 pounds per cubic foot.

Readings of capacitance and circuit Q were obtained for each density at the selected frequency. The hay was not removed from the capacitor until all readings at one frequency had been obtained.

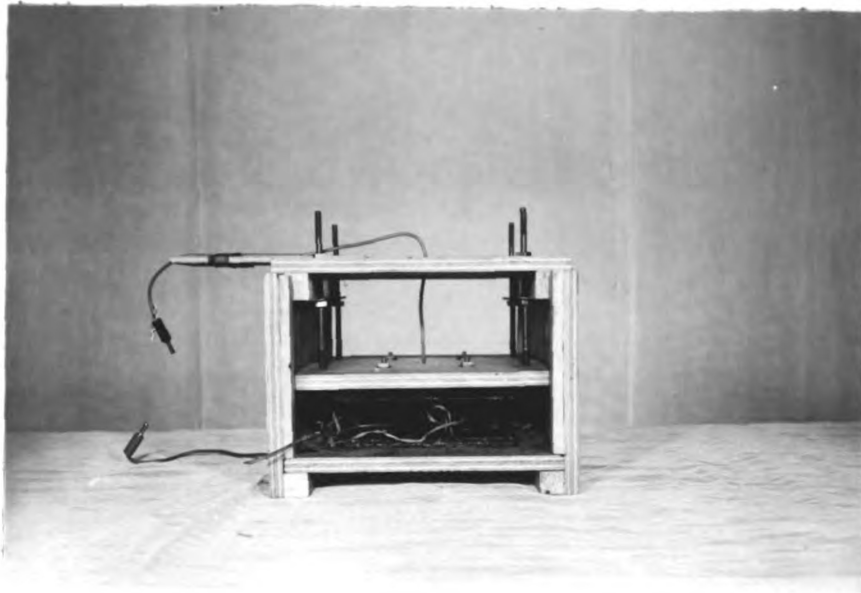
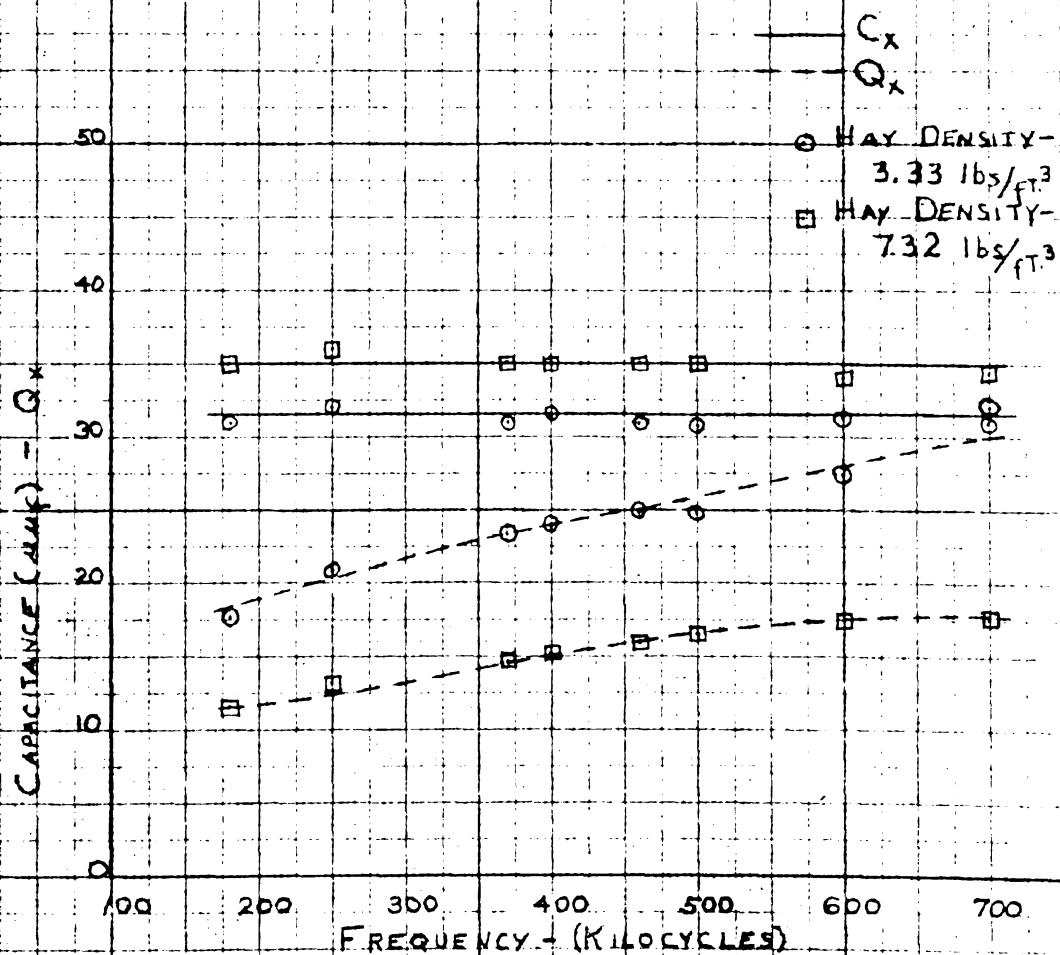


Figure 14. Capacitor with movable plates used in Test IIA.

2. Results. Graph III presents the relationship between capacitance and calculated Q of the capacitor and frequency. Values of capacitance have not been corrected for edge effect or stray capacitances. The value of lead capacitance was not considered but was kept approximately constant each time by keeping the leads in about the same position for each reading.

3. Analysis. This test indicated that there was very little change in capacitance between frequencies of 130 and 700 kc., using hay at 12 percent moisture content. Considering that the relaxation frequency of the water polar molecules is about 1,600 megacycles, anomalous dispersion due to these molecules at these frequencies would not be expected nor was it encountered. Any anomalous dispersion in this frequency range would probably be due to the effect of variations in ionic or interracial polarizations. Since capacitance did not decrease with frequency, the effect of these polarizations in this frequency range may be considered constant. Evidently this frequency range is not near the relaxation frequency of interracial polarizations. Therefore, the capacitance due to these polarizations should remain constant and not affect the readings of a moisture meter based on the dielectric method. Although this hypothesis is based on only one test, later tests showed no appreciable change in capacitance with frequency.

GRAPH III

VARIATION OF CAPACITANCE AND Q_x
WITH FREQUENCY

4. Test IIB: General variation of capacitance and power factor. When hay with a moisture content of thirty percent was placed between the plates of the capacitor unit used in this test, only a slight or, in the case of higher moisture content hay, zero deflection of the Q volt meter was observed at the point of resonance. This effect indicated that the conductivity of the hay together with the dielectric absorption was so great that the capacitor Q was reduced to an unmeasurable value. Attempts to insulate the plates with an insulating varnish did not prove successful for the radio frequency voltages being used.

The primary reason for using a capacitor with plates in direct contact with the hay had been to eliminate the effect of another unknown and perhaps varying dielectric material between the plates. Since the conductivity of the hay prevented this approach, all other capacitors used in the work were of a type used by Hart and Schoenleber (22) (37) in their preliminary work. The capacitors used by these investigators had the metal plates attached to the outside of a plywood box which served as the insulating medium.

(See Figure 9)

In order to determine the general properties of this type of device, a number of random measurements at various moisture contents, frequencies, and conditions of packing were made. These experiments comprise Test IIB of the investigations.

5. Apparatus and procedure. In these tests, hay was placed in a varnished plywood box having inner dimensions of $2 \times 7 \frac{3}{4} \times 13 \frac{1}{2}$ inches. Two sheet steel plates, $1/16 \times 6 \times 10$ inches, were held in place on the outside of the box by means of two wooden strips on each side bolted together. One end of the box was open. The other end had a removable gate to allow the hay to be pushed through and out of the box when a test had been completed. Moisture contents were determined by the oven method immediately after the readings were taken.

The hay was packed by hand with a one pound hammer as it was placed in the capacitor unit. This procedure was not intended to give reproducible results although some tests were repeated by merely removing the hay and replacing to note the change in C_x and G_x .

6. Results. The results of the test are tabulated in TABLES II and III. Corrections have not been made for edge effects, stray capacitances, or lead capacitances. Since these factors remained approximately constant, the values give a relative indication of the effect of moisture content, length and amount of hay on capacitances and power factor.

A variation of capacitance from 34 to 76 uuf in the moisture range of about 19 to 70 percent was indicated. The values of Q were between 4.79 and 18.76 over the same range of moisture contents.

TABLE II
CAPACITANCE OBTAINED WITH VARYING AMOUNTS
AND MOISTURE CONTENTS OF RAY

Condition of Ray and Method of Packing	Moisture Content	Freq. Kc.	C_x uuf	Freq. Kc.	C_x uuf	Freq. Kc.	C_x
Long, tightly packed	20.8%	130	43	250	41	350	38
" " (Repeat)	20.8		42		41		37
3/4" lengths, packed	20.8		42		40		36
" " , 2/3 Full	20.8		44		41		38
Capacitor Empty	----		20		21		20
Long, packed	13.8		34		30		31
Long, packed	70.3		71		70		69
" " (Repeat)	70.3		73		73		72
3/4" lengths, packed	70.3		73		73		71
Long, packed	68.6		76		75		75
Long, packed	44.0		68		68		68
" " (Repeat)	44.0		68		69		68
3/4" lengths, not packed	44.0		67		68		68
3/4" lengths, not packed	43.3		54		52		54

TABLE III

Q_X OF CABLE WITH VARYING AMOUNTS AND
MOISTURE CONTENTS OF HAY

Condition of Hay and Method of Packing	Moisture Content	Freq. Kc.	Q_X	Freq. Kc.	Q_X	Freq. Kc.
Long, tightly packed	20.0%	130	4.79	250	5.08	350 ¹
" " " (Repeat)	20.8		4.07		5.07	
3/4" lengths, packed	20.8		5.50		5.75	
" " , 2/3 Full	20.8		5.54		5.34	
Capacitor Empty	----		49.1		50.3	
Long, packed	13.8		5.01		5.94	
Long, packed	70.3		12.6		12.6	
" " (Repeat)	70.3		11.6		11.5	
3/4" lengths, packed	70.3		10.7		11.0	
Long, packed	62.6		9.95		9.75	
Long, packed	44.0		11.7		11.3	
" " (Repeat)	44.0		11.7		11.5	
3/4" lengths, not packed	44.0		10.7		10.3	
3/4" lengths, not packed	43.3		7.99		7.52	

¹ Values of Q_X were not measured at 350 Kc.

In three tests, long hay was first placed in the capacitor and the capacitances recorded and then the hay was cut to three-quarter inch lengths and the capacitances noted. In no case did the change in length of the hay cause the capacitances to vary more than one μf .

7. Analysis. This test was conducted to obtain qualitative data on the performance of a capacitor unit with the plates attached to the outside of the box. The results showed that an appreciable change in capacitance with moisture content did occur and that the Q of the condenser was high enough to be measured by the Q meter method.

In general, the Q of the unit increased with increasing moisture content. This phenomenon is the exact opposite expected of dielectric materials. Moisture in the dielectric causes increased losses due to both increased direct current conductivity (resulting in greater Joule heat losses) and an increase in the amount of absorption by the water dipole molecules. In this capacitor, however, the effect of the plywood insulation between the hay and the plates was to reduce or eliminate the losses in the dielectric (hay) due to direct current conductivity. The added polarizations of the water molecules caused the increased capacitance of the unit as would be expected. Since coil or condenser Q is defined as energy stored per cycle of the applied voltage divided by the energy dissipated per cycle of the applied

voltage, Q will increase with increasing capacitance. With the moist material insulated from the capacitor plates, the capacitance increases at a faster rate than resistance with increasing moisture content to result in an actual increase in Q . This effect was observed in all tests using this type of capacitor construction.

E. Test III: The Dielectric Properties of Capacitor Materials

In order to investigate the dielectric properties of hay, attention was given to the design of a low loss capacitor unit with dimensions in accordance with standard practice in testing dielectric materials. To select materials for this unit, the dielectric properties of common, cheap building materials were investigated.

1. Apparatus and procedure. The dielectric constant and power factor of the following materials were determined in this test: (a) 1/2 inch plywood; (b) 1/4 inch plywood; (c) 1/4 inch Masonite wallboard; (d) 1/8 inch Masonite wallboard; (e) 1/8 inch plastic.

Tests were made by constructing a capacitor having the material as the dielectric and measuring the capacitance and Q . Actually, therefore, the calculated power factor is the power factor of the capacitor and not of the material. The power factor of the material is considered as the power factor of a condenser containing the dielectric and having

no losses other than those in the dielectric. Terman (39) states that the power factor of dielectric materials tends to be independent of the size and shape of the material and the magnitude of the applied voltage.

The capacitor containing the dielectric consisted of two aluminum sheets held in close contact with the dielectric by means of Vaseline. Leads were attached to the Q meter and the capacitor placed between the leads after the initial resonance setting had been made. Spring action in the leads held them in contact with the foil plates.

The dimensions of the capacitors conformed to the tentative recommendations of the American Society for Testing Materials for tests of power factor and dielectric constant of electrical insulating materials. (1) The specifications for measurements where a guard ring cannot be used are summarized as follows:

(a) For most accurate measurements, one electrode shall be appreciably smaller than the other. (The larger electrode shall extend at least five times the thickness of the dielectric beyond the edge of the smaller electrode.)

(b) Petrolatum (Vaseline) shall be used as the adhesive for foil electrodes. The electrodes shall be applied so as to eliminate all wrinkles.

(c) The width of the smaller electrode shall be at least ten times the thickness of the specimen.

(d) The capacitance of the specimen shall be preferably not less than seventy uuf.

(e) The ratio of the smaller electrode area to specimen thickness, should be at least equal to eighty.

2. Results. The result of the test is presented in TABLE IV. Although measurements were made at several frequencies, only the results for a frequency of 450 kilocycles are presented since there was little change with frequency. These values of dielectric constants have been corrected for edge effects by use of the following formula:

$$K = \frac{C_x - 1.2P}{C_a + 0.103P} \quad (\text{Equation 9})$$

where K is the dielectric constant.

M is $0.195 \log_{10} \frac{1.5}{t}$ (where t is the thickness of the dielectric).

C_x is the capacitance indicated on the meter.

C_a is the capacitance of the capacitor with air as the dielectric.

P is the distance around the perimeter of the smaller electrode.

(Dimensions are in inches and uuf.)

3. Analysis. The desirability of a material for use as the insulating medium between the capacitor plates and the lug is determined primarily by the losses in the material as represented by the effective series resistance. On this basis plastic would be most suitable and plywood the least

TABLE IV

DIELECTRIC PROPERTIES OF CAPACITOR MATERIALS

(Large Electrode 12"x12" - Small Electrode 7"x7" f = 450 Kc)

Material	Dielectric Constant (K)	Power Factor (%)	Effective Series Resistance (ohms)
1/2" Plywood	3.01	3.14	189
1/4" Plywood	2.51	3.20	93
1/4" Masonite wallboard	3.37	3.04	84
1/8" Masonite wallboard	3.45	3.17	35
1/8" Plastic	2.79	2.47	32

suitable. The increased losses in plywood are probably the result of the glue and other compounds which contain many complex and absorptive molecules.

The dielectric constant of the capacitor material would only result in a higher capacitance value for the material. As long as there is a substantial difference between the dielectric constant of the moist hay and the capacitor materials, the insertion of the hay will produce a large change in capacitance. The actual value of the dielectric constant is not too important as long as it is small. Any of the materials tested would be suitable from this standpoint..

F. Test IV: The Dielectric Constant of Dry Hay

If the method of packing dry hay in a capacitor unit causes the capacitance to change, the capacitance would be expected to change with the method of packing moist hay. The purpose of this test was to determine the effect of packing on capacitance when using dry hay and to obtain some information on the actual dielectric constant of hay.

1. Apparatus and procedure. In this test, a capacitor was constructed which conformed with the recommendations of the American Society for Testing Materials for testing insulating materials. In order to keep the dimensions of the unit as small as possible, a thickness of hay between plates of 1.25 inches was selected. Even with this thickness, the

cell was so large that one-eighth inch Masonite was used as the insulating material between the hay and plates in order to reduce costs. The outside dimensions were $1\frac{1}{2}$ x 28 x 31 inches and the inside dimensions or space for hay were $1\frac{1}{4}$ x $26\frac{3}{8}$ x $29\frac{1}{2}$ inches. The completed unit is shown in Figure 15. Aluminum foil electrodes were held in place with Vaseline. In order to obtain structural strength, braces were attached to the side when using the cell. These braces increased the capacitance only five uuf, but introduced considerable losses to lower the Q from 323 to 132.

Test procedure consisted of packing random amounts of air dry hay (eight percent moisture content) into the unit and measuring the capacitance and Q. Measurements were made in a range of frequencies from 75 to 700 kc..

2. Results. Since there was no appreciable change in capacitance with frequency, values for capacitance and Q at only one frequency, 170 kc., are shown in TABLE V. Due to the low specific gravity of hay, the amount of hay in the unit did not vary considerably with the amount of packing. Values for capacitance were practically constant and averaged 63.3 uuf. The capacitance of the unit without any hay between the plates was 62 uuf..

3. Analysis. The dielectric constant of one material of a two-layer capacitor such as used here may be calculated as follows: The capacitor used in this test may be



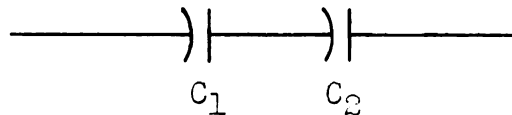
Figure 15. Large capacitor unit used to measure the dielectric constant of hay.

TABLE V

VALUES OF CAPACITANCE AND Q OBTAINED WITH VARYING AMOUNTS
OF DRY HAY IN LARGE CAPACITOR ($f = 170 \text{ Kc}$)

Sample Number	Density of Hay (lbs. / ft. ³)	Capacitance C_x (uuf)	Q_x
1	4.45	63	115
2	4.89	63	105
3	5.77	63	93
4	5.53	64	99
5	5.53	63	105

represented as two capacitors in series as shown in the following diagram:



Where C_1 represents the capacitance due to the Masonite dielectric.

C_2 represents the capacitance due to the hay.

Since capacitances in series are added,

$$C_T = C_1 + C_2$$

Where C_T is the total capacitance.

However,

$$C = \frac{KA}{4.45t} \quad \text{or} \quad C \propto \frac{K}{t}$$

Where A is the area of the plates (inches).

t is the thickness (inches).

Therefore,

$$\frac{K_T}{t_T} = \frac{K_1}{t_1} + \frac{K_2}{t_2}$$

Solving for K_2 , the dielectric constant of hay,

$$K_2 = \frac{-K_T t_2 K_1}{2t_1 K_T - K_1 t_T} \quad (\text{Equation 10})$$

Where K_T is the dielectric constant of the total unit.

t_2 is the thickness of hay.

K_1 is the dielectric constant of 1/8 inch Masonite.

t_1 is the total thickness of Masonite.

t_T is the total thickness of the unit.

K_T may be calculated from Equation (9) with the additional consideration of the stray capacitance, C_s , due to the large condenser size, or,

$$K_T = \frac{C_{11} - 1P - C_s}{C_{11} + 0.100(P)} \quad (\text{Equation 11})$$

Substituting,

$$K_T = \frac{33.3 - 0.100(36) - 7.6}{33.7 + 0.100(36)} = 1.63$$

Using this value in Equation 10, the value of K_2 or the dielectric constant of dry hay is 1.61.

The value of dielectric constant calculated is not the actual dielectric constant of the hay itself. Instead, it is the dielectric constant of the mass of hay and air in the capacitor. The absolute value of dielectric constant can be obtained from Equation 8, if the specific gravity of the hay is known. Using an estimated specific gravity value of 31.2 lbs/ft³, the absolute dielectric constant is calculated to be 1.6.

When hay of 85 percent moisture content was placed in this cell, power losses were so great that only a slight deflection of the C-voltmeter was observed. For this reason, the cell was not used for further testing.

G. Test V: Variation of Capacitance and Power Factor with weight of Hay Sample

The objective of this test was to determine the relationship between weight of the hay sample and the capacitance and power factor of a capacitor containing the hay. With moisture content expressed on the wet basis, a straight-line relationship exists between the moisture content of the hay and the actual water content for a constant initial weight of sample. If capacitance varied only with the weight of water in the sample, a straight-line relationship would be expected between capacitance and moisture content when a constant initial weight of sample is used.

1. Apparatus and procedure. The cell used in this test was constructed of 3/8 inch plywood with inner dimensions of 1 3/4 x 9 x 13 inches. Plywood was used since it is relatively inexpensive and would lower the cost of a production unit.

Two aluminum foil electrodes were held in place on each side of the cell with Vaseline. The large electrode was 9 x 13 inches and the small electrode was 7 x 12 inches. The capacitor was attached to the Q-meter by means of long heavy wires which pressed against the foil electrodes as shown in Figure 10.

In order to vary moisture content, cured alfalfa hay was sprayed with water and placed in a cardboard box for

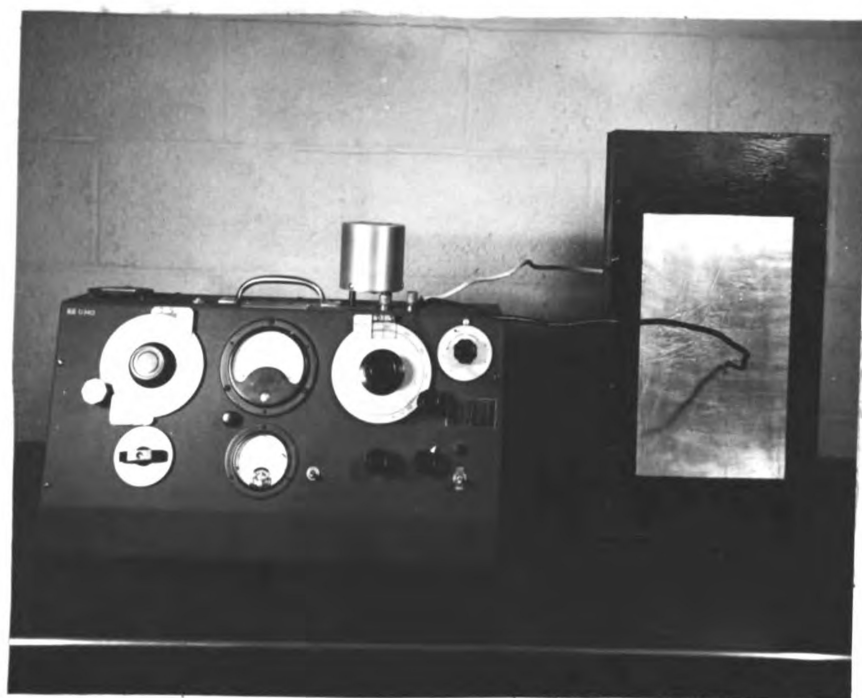


Figure 16. Capacitor cell used in Test V attached to Q-meter.

about twelve hours to allow the moisture to be absorbed by the stems and leaves. The moisture content of the hay was determined by the oven method from two random samples taken from each box. The first sample was taken at the beginning of each experiment while the second sample was selected at the end of each experiment. The percent moisture of the hay for each experiment was taken as the average of these two values in order to compensate for any drying which occurred during the testing period of about twenty minutes.

In conducting each test random amounts of hay were selected from the box of treated hay and packed into the capacitor unit. The cell was weighed to determine the net weight of hay. After readings of capacitance and Q had been taken, the hay was removed from the unit and mixed with the hay in the box before taking another sample. The hay was packed to varying degrees in the cell in order to obtain different weights of samples.

2. Results. The values of capacitance and Q for varying weights of hay at seven moisture contents are presented in TABLE VI. The linear regression lines of capacitance with weight of sample are plotted in Graph IV. From these lines, the values of capacitance at varying moisture content for constant sample weights of one and one and one-half pounds have been obtained and plotted in Graphs V and VI, respectively.

TABLE VI
CAPACITANCE AND Q OF CAPACITOR UNIT
WITH VARYING WEIGHT OF SAMPLE

Moisture Content Percent	Weight of Sample Pounds	Capacitance C_x --unf	Q_x
	Cell empty	20	30.9
11.4	0.640	30	3.90
11.4 Av. 11.4	0.935	31	3.44
	1.015	30	3.75
	1.015	33	3.11
15.5	0.730	36	4.68
15.3 Av. 15.4	0.875	47	4.19
	1.030	39	4.57
	1.140	42	4.37
	1.310	43	4.12
27.0	0.750	49	5.31
18.3 Av. 18	0.935	50	4.99
	0.950	50	4.57
	1.160	55	4.80
	1.315	55	4.30
31.8	0.870	59	5.64
28.9 Av. 30	0.940	60	5.74
	0.970	65	6.50
	1.000	65	6.21

TABLE VI (CONTINUED)

Moisture Content Percent	Weight of Sample Pounds	Capacitance C_X --uuf	Q_X
	1.455	71	7.10
	1.455	71	7.10
33.0	0.797	62	5.93
35.0 Av. 33.5	0.830	65	7.90
	0.909	64	6.65
	1.202	71	8.63
	1.265	72	8.75
	1.295	73	10.22
	1.330	75	9.45
	1.433	75	8.54
41.9	0.890	69	8.10
40.5 Av. 41	1.000	70	8.84
	1.070	74	8.67
	1.080	72	9.76
	1.160	74	9.00
	1.270	75	9.46
	1.230	77	10.81
42.4	0.780	66	7.74
40.7 Av. 41.5	0.870	66	8.03

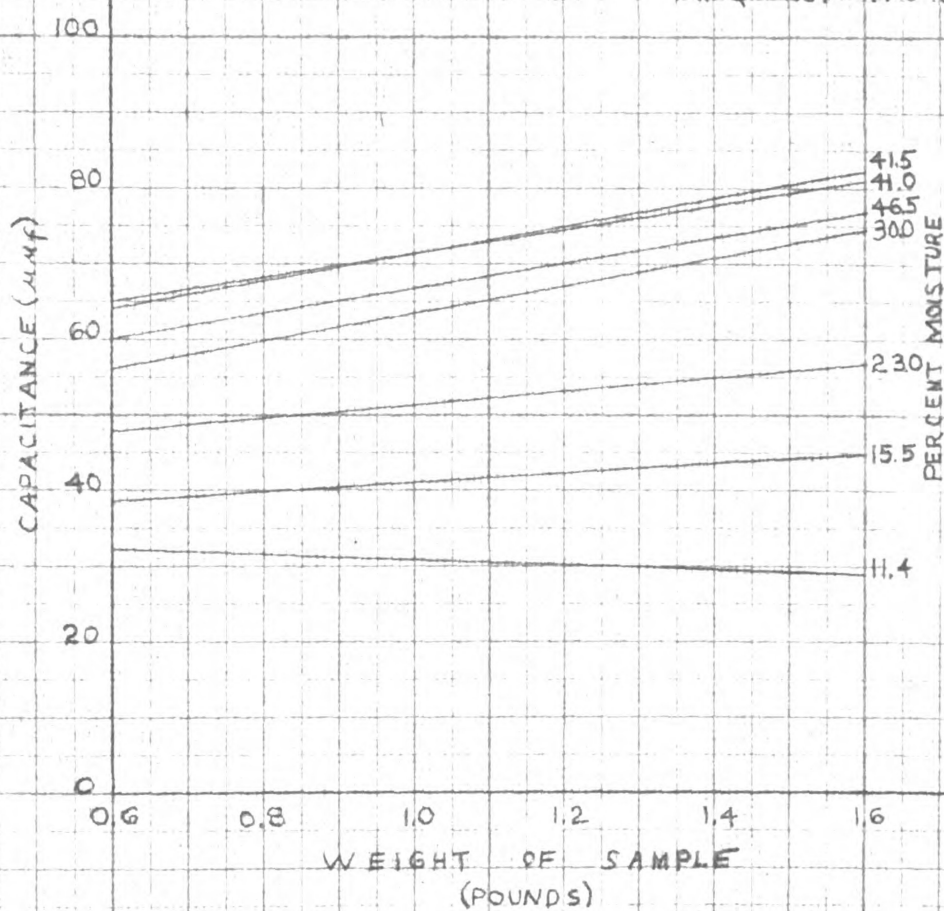
TABLE VI (CONTINUED)

Moisture Content Percent	Weight of Sample Pounds	Capacitance C_X --uuf	C_X
	1.000	73	8.88
	1.110	75	9.13
	1.220	76	13.76
	1.423	80	11.82

GRAPH IV

RELATIONSHIP BETWEEN CAPACITANCE
AND SAMPLE WEIGHT AT
VARYING MOISTURE CONTENTS

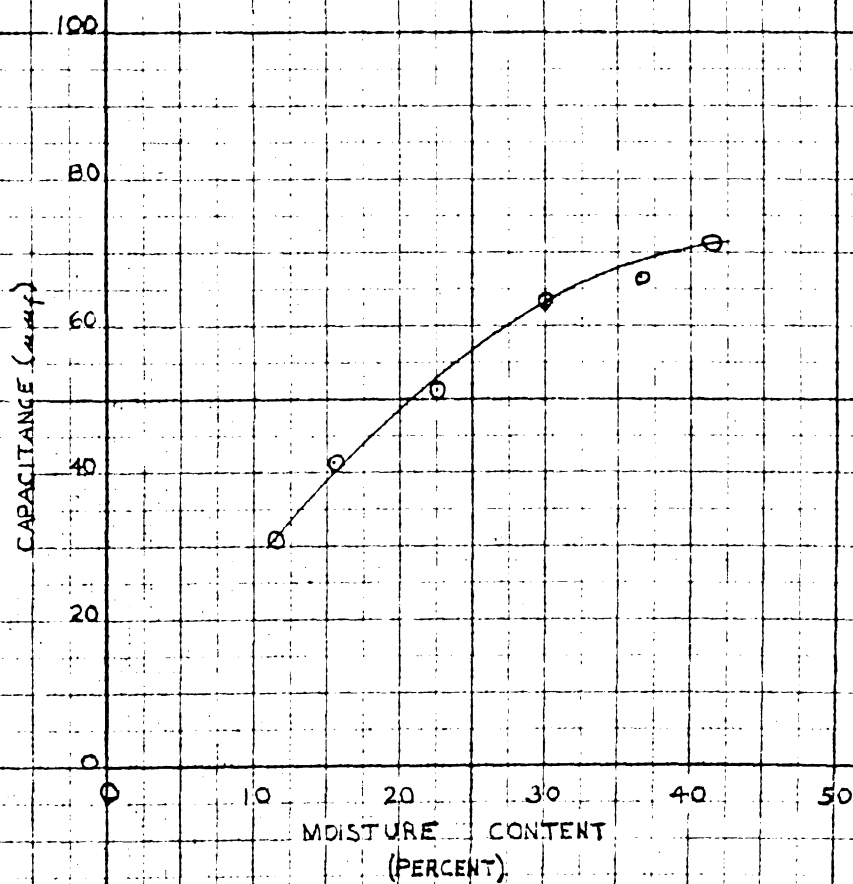
VOLUME OF HAY - 0.164 ft.³
FREQUENCY - 170 Kc.



GRAPH V

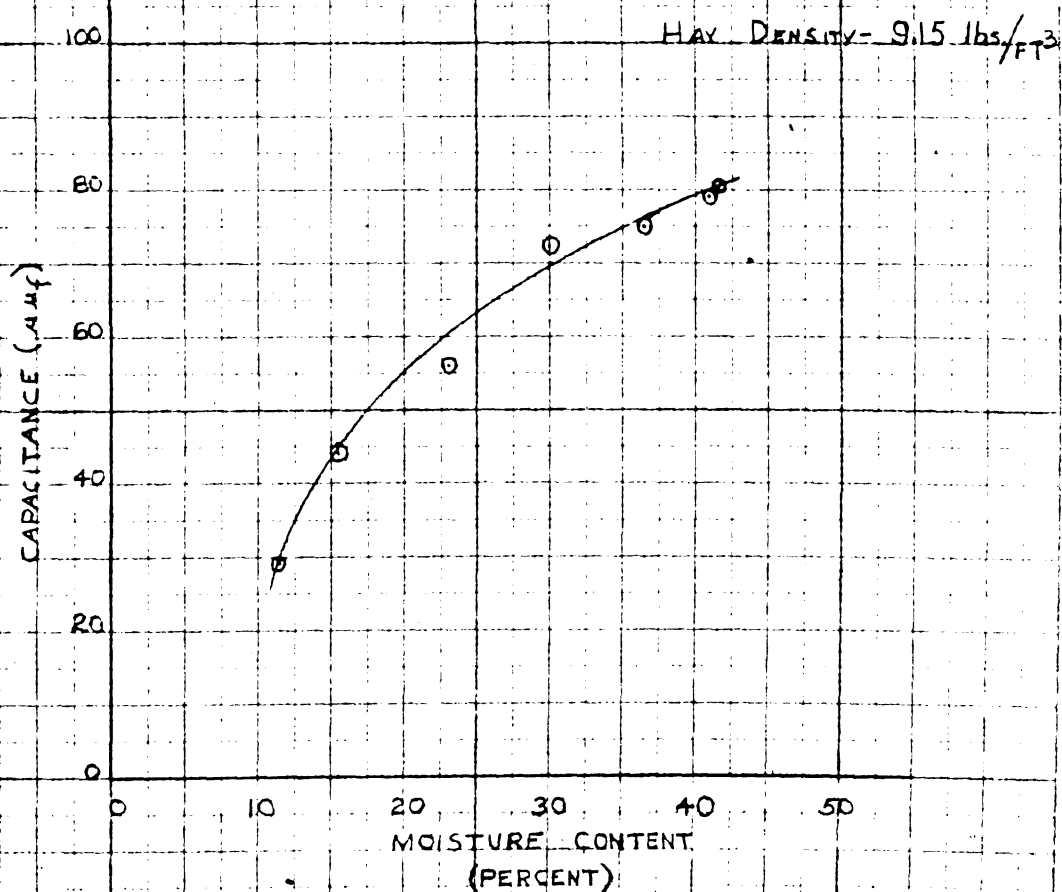
INDICATED CAPACITANCE WITH A
SAMPLE WEIGHT OF
ONE POUND

HAY DENSITY - 6.10 lbs/ft³



GRAPH VI

INDICATED CAPACITANCE WITH
A SAMPLE WEIGHT OF
ONE AND ONE-HALF
POUNDS



Errors in these results may have been introduced as a result of the sampling methods used. Some drying of the hay between the first and last reading took place as evidenced in the difference between the two moisture contents. A question may also be raised as to whether these two samples were representative of the entire amount of hay used in each experiment. Some error in the values of Q may have resulted from the lack of poor contact between the leads and the foil although both were maintained reasonably clean.

The fact that these samples were conditioned hay and not taken directly from the field may have altered the relationship of moisture content vs capacitance. The condition of the samples seemed to approximate hay freshly cut.

Due to the many variations involved, the data of TABLE VI and the associated graphs are presented as an indication of the relationship that exists and not as values to be used in the calibration of a dielectric moisture meter.

3. Analysis. The lines of Graph IV indicate an appreciable change in capacitance with weight of sample with the change increasing with moisture content as evidenced by the increasing slopes. This indicates that any moisture meter using this principle would necessarily require the use of a constant weight of sample.

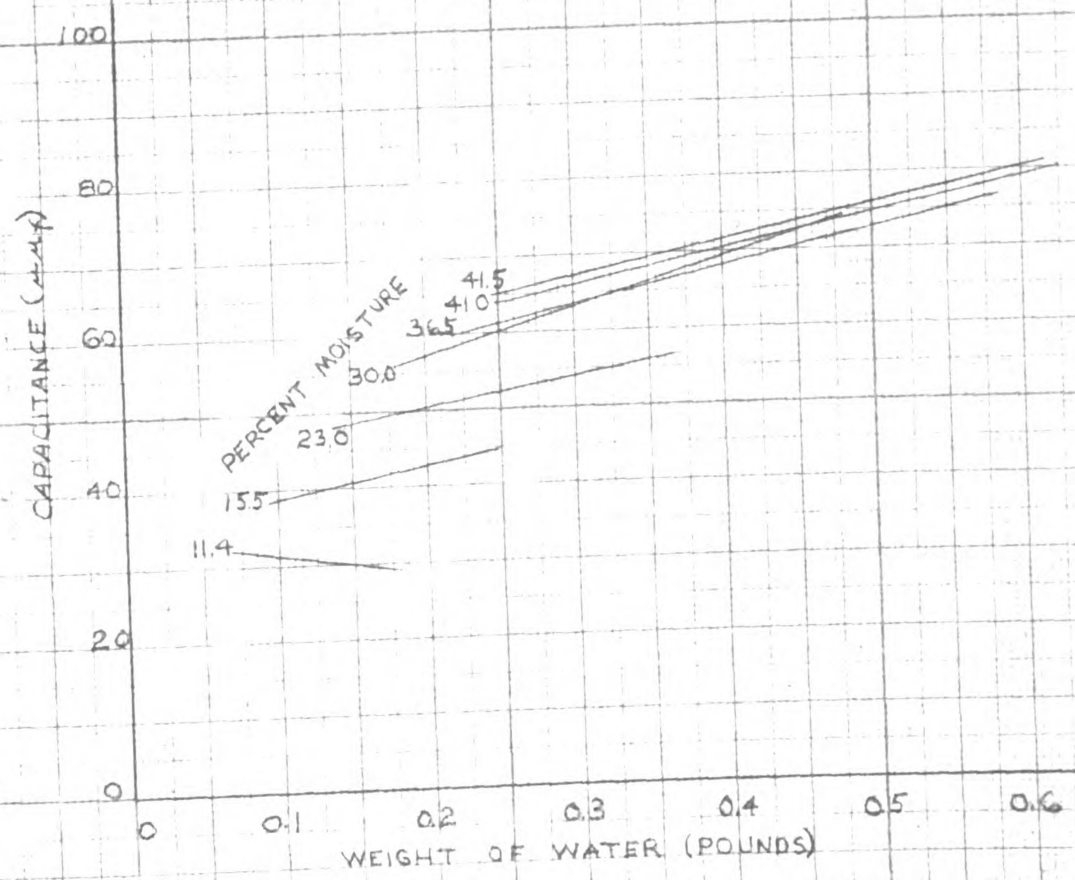
For a constant weight of sample, the change in capacitance and moisture content tends to decrease as the moisture content increases. As the fiber saturation point of the hay is approached, more moisture appears as free water. The decrease in the amount of water held in the hay cells may produce a decrease in the number of polar molecules with the resultant decline in polarization and capacitance. The effect of this phenomena would be to reduce the accuracy of a capacitance-type meter at the higher moisture contents.

Capacitance did not vary directly with the absolute weight of water between the plates as shown by the line for each moisture content in Graph VII. This graph shows that capacitance is influenced not only by the weight of water, but also by the proportion of water to dry hay. For a constant weight of water, capacitance increases with moisture content or with an increase in the proportion of water to weight of dry hay. This effect would be expected due to the interfacial polarizations which occur as the result of the absorbed water molecules in the intercellular passages of the hay.

Variation of capacitor Q with weight and moisture content does not follow any definite pattern as shown by the results in TABLE VI. The general increase in Q with moisture content confirms results obtained in Test III.

GRAPH VII

RELATIONSHIP BETWEEN ABSOLUTE
WEIGHT OF WATER IN
CELL AND CAPACITANCE



II. Summary

The experimental investigations may be summarized as follows:

1. The determination of hay moisture content by insertion of the hay sample in the core of a coil, while appearing to yield a consistent relationship, is not practical due to the limitations imposed on the size of the sample. The method is also essentially a dielectric method.

2. The capacitance of a capacitor containing hay was found to be practically constant in the radio frequency range of 170 to 700 kc.. Anomalous dispersion would not appear to affect the readings of a dielectric meter operating in this range.

3. Insertion of moist hay in a 1/4 inch plywood box having capacitor plates attached to the sides caused about one uuf change in capacitance for each one percent change in moisture content up to forty percent moisture content. (Area of each plate was sixty square inches with a distance between plates of 2 1/2 inches.)

4. Insertion of moist hay in a 3/8 inch plywood box having foil electrodes attached to the sides caused about a five uuf change in capacitance for each three percent change in moisture content up to forty percent moisture. (Area of active electrode was 84 square inches with a distance between electrodes of 2 1/2 inches.)

5. The Q of the capacitor coil described in Items 3 and 4 increased from about four to fourteen with increasing moisture content but did not vary consistently.

6. Capacitance varied directly with the weight of the hay sample..

7. The absolute dielectric constant of dry hay was calculated to be 1.3 assuming a specific gravity of 31.2 lbs/ft³.

These investigations were conducted to determine basic information necessary in the design of a dielectric moisture meter. After this meter had been designed and constructed, field investigations were conducted to test and calibrate the instrument. The report of these trials is presented in another section of this thesis.

V. DESIGN AND CONSTRUCTION OF THE PORTABLE METER

Experimental investigations described in the previous section showed that a definite moisture content-capacitance relationship existed when a constant weight of sample was used. In order to obtain information on the effect of the type of hay and condition of maturity of the hay on the moisture content-capacitance relationship and to further establish this method of moisture detection, a relatively large number of samples would have to be tested under actual field conditions and a curve plotted by drying the samples in the oven. The extent of the deviations of the samples from this curve would determine the value of this method. In order to facilitate measurements in the field, attention was given at this point to the design and construction of a direct reading, portable capacitance meter.

A. Method of Measurement

Three common methods of measuring capacitance using radio frequency voltages are: (1) resonance method; (2) heterodyne tone method; and (3) bridge method. The resonance method was selected for the following reasons:

(1) Equipment needed for this method is relatively inexpensive. Cost was considered in the design of this

instrument since the aim of the research was to provide a simple meter for farm use.

(2) The resonance method provides the minimum number of controls to be adjusted in making measurements. Readings can be obtained quickly.

(3) By using the resonance method, capacitance measurements can be made practically independent of capacitor losses. Experimental investigations showed appreciable changes in power factor with hay moisture content.

When an alternating voltage is applied to a series circuit consisting of inductance, resistance, and capacitance, maximum current is obtained when the circuit constants are adjusted to resonate at the frequency of the applied voltage. The values of circuit inductance and capacitance required for resonance at the frequency, f , are obtained from the following equation:

$$f = \frac{1}{2 \pi \sqrt{LC}} \quad (\text{Equation 12})$$

This relationship is true when the circuit is excited by an undamped wave as ordinarily produced by a vacuum tube oscillator. If the circuit is excited by a damped wave, the circuit resistance, R , affects the resonant frequency as indicated by the following equation:

$$f = \frac{1}{2 \pi} \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \quad (\text{Equation 13})$$

The method of measurement selected is shown schematically in Figure 17. A radio frequency voltage, produced by a vacuum tube oscillator, is introduced into a series R, L, C circuit. (The resistance of this circuit consists only of the losses in the inductance and capacitor.) By adjustment of a standard variable capacitor, C, the circuit can be tuned to resonance. When the capacitor unit containing the hay sample is connected in parallel with C, the circuit must be re-tuned to resonance by adjustment of C. The amount of change in capacitance of the standard, C, is a measure of the capacitance of the test capacitor. The condition of resonance is indicated by maximum voltage developed across the combination of capacitors. Actually, maximum voltage does not appear at resonance, but rather at a value of capacitance away from resonance determined by the following equation:

$$C_{\text{max}} = \frac{1}{\omega^2 L} - \frac{R^2}{L} \quad (\text{Equation 14})$$

Reed (35) presents curves indicating the relationships in a series R, L, C circuit resonated by varying C. The values of capacitance obtained from the setting of variable condenser, C, will depend, therefore, to some extent on the resistance of the circuit and hence on the power factor of the capacitor unit containing hay. Since a general relationship between power factor and moisture content was noted in

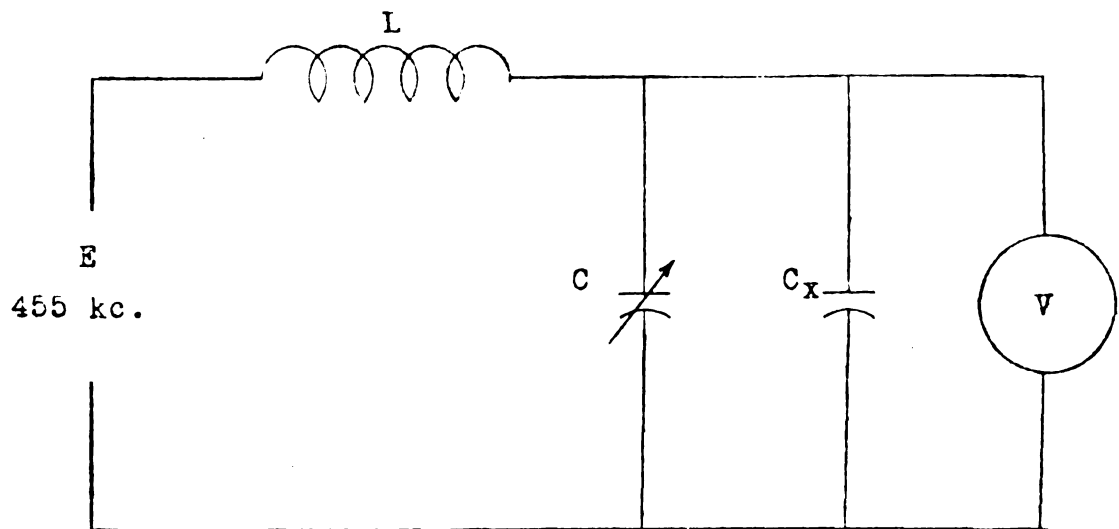


Figure 17. Schematic diagram of method of measurement.

laboratory tests, this effect should not affect the accuracy of the readings.

In order to make the point of circuit resonance entirely independent of capacitor losses, the variable capacitor could be tuned for maximum circuit current as indicated by maximum induced voltage in a coil loosely coupled to the series inductor, L. This method was tried by winding about 15 turns on the core form as used for L. The resultant output voltage was so small that further amplification was necessary in order to measure it. The more convenient method of measuring the voltage across the capacitor was selected for present purposes.

This method of measurement is similar to the principle of operation of the Q-meter previously described. The meter is designed to measure capacitance only, although as constructed it could easily be calibrated to give an estimate of circuit Q.

D. Power Supply

Due to the portability requirement of the meter, dry batteries were selected for the source of power. Anticipating a relatively short operating period for the meter, only one ordinary flashlight cell was selected as the 1.5 volt "A" supply. In order to obtain high plate supply voltage with a minimum battery weight, one 90 volt, portable radio "B" battery (Eveready #430 or equivalent) was selected.

These two batteries comprising the power supply are contained in the chassis of the meter. (See Figure 18)

C. Oscillator

Experimental investigations showed little variation in test cell capacitance with frequency. An oscillator frequency of 485 kc. was selected so that ordinary intermediate frequency transformers used in A 1 broadcast receivers could be used both for the oscillator coils and for the tuned circuit of the following amplifier. In order to reduce the effects of loading on the oscillator frequency, an electron-coupled type of oscillator was selected. As shown in the circuit of Figure 19, the oscillator consists essentially of a tuned-plate, tuned grid oscillator with the screen grid of V-1 serving as the oscillator plate. The radio frequency voltages produced are electron coupled into the plate circuit of the oscillator tube and appear across the tuned circuit consisting of the primary of a conventional intermediate frequency transformer (T-2). Both the primary and secondary of this transformer are tuned to 485 kc. An r-f voltage is developed across the one ohm resistor (R-2) in series with the capacitor in the secondary circuit. This voltage is a small part of the oscillator output voltage since the ratio of reactance to resistance is about 4850 providing further protection against loading



Figure 13. Chassis of capacitance meter showing location of parts.

of the oscillator by insertion of the leaky dielectric material, hay.

The voltage developed across resistor R-2 causes a current to flow in the series circuit consisting of L-1 and the parallel combination of C-5, C-6, and C_x together with either C-3 and C-4 depending on the position of selector switch, S-2. C-5 serves to resonate the circuit with C-6, the standard variable, set at maximum capacity and with C_x , the test cell, empty. After moist hay is placed in C_x , C-6 is adjusted to re-establish the resonant condition. Values indicated on the dial of C-6 can be plotted against the moisture content of the hay sample determined by the oven method to obtain the capacitance-hay moisture content relationship. The three position selector switch, S-2, varies the amount of capacitance in the series circuit in fixed steps to provide low, medium and high moisture content ranges on the meter.

D. Amplifier and Detector

Resonance of the series L, C circuit is indicated by maximum voltage across the capacitor. This voltage is amplified by a radio frequency amplifier stage consisting of V-2 and output transformer T-3. The radio frequency output current is rectified by the diode section of V-2. The direct current output of the rectifier is measured by the C-20 d-c microammeter. Maximum current through the

meter occurs when maximum voltage is impressed on the grid of V-2. Variable resistor, R-4, provides a means to adjust the current through the meter compensating for changes in voltage produced by changes in Q of the series L, C circuit. Values of all component parts are listed in TABLE VII.

E. Test Capacitor Cell

1. Dimensions. In order to eliminate errors due to a small size of sample, the capacitor unit was constructed to hold one or one and one-half pounds of hay. This was the same size of samples used in laboratory tests. To reduce the time necessary to pack the sample in the box and to eliminate the need for a packing device, the capacitor was constructed in the form of a square box with a removable top plate. The top plate of the capacitor is designed to be forced into place after the hay sample is weighed. This operation compresses the hay in the box and, with a weighed sample, provides for a constant hay density.

The inner dimensions of the box for hay are $12\frac{1}{2}$ x $12\frac{1}{2}$ x 6 inches high. The actual space occupied by the hay when the top capacitor plate is in place is $12\frac{1}{2}$ x $12\frac{1}{2}$ x $1\frac{3}{4}$ inches. The sides of the box were extended in order to provide a space for the hay before compression.

The capacitance meter is attached to the upper side of the top plate forming a compact unit, as shown in Figure 20.

TABLE VII

VALUES OF COMPONENT PARTS USED IN CAPACITANCE METER
SHOWN IN FIGURE 19

V-1, 105 GT
V-2, 1S5
R-1, 100k ohm
R-2, 1 ohm
R-3, 500 ohm
R-4, C-1/3 meg variable
C-1, 100 uuf, mica
C-2, 33 uuf, ceramic
C-3, 225 uuf, mica
C-4, 75 uuf, mica
C-5, 10-190 uuf, air
C-6, 10-145 uuf, air
C _x , test capacitor
C-7, 0.005 uuf paper
C-8, 0.005 uuf paper
C-9, 8 uuf, electrolytic, 150v
T-1, T-2, and T-3, 455 kc i-f transformers
L-1, 0.31 mh, air core
ua, C-50 d-c microammeter



Figure 20. Complete instrument consisting of capacitance instrument and test cell. (An external meter was attached to lead shown at left but could be placed on instrument panel)

2. Materials. Three-quarter inch plywood was selected for the side walls of the box and one-half inch plywood for the other wooden parts. These materials offer strength and durability for field use.

Galvanized sheet steel was used for the capacitor plates. The dimensions of the upper or active electrode were 10 1/4 x 10 1/4 inches or an area of 108 square inches. The lower electrode covered the entire bottom and sides of the compartment for hay.

3. Prevention of losses. Losses or power factor of the cell were kept low in order to improve the sensitivity of measurements by providing sharp resonance peaks. This was accomplished by constructing an insulated plate type of capacitor similar to those used in laboratory tests. The purpose of the insulated plates was to reduce the losses due to the d-c conductivity of the hay at high moisture contents. This method reduces the effect of the dielectric constant of the hay on the total capacitance of the cell depending on the thickness of the insulating medium. For example, if the mixture of moist hay and air is assumed to have a dielectric constant of 70 (as indicated by laboratory measurements) and one-quarter inch of insulating medium having a dielectric constant of 3.33 is used, the resulting dielectric constant of the unit will be 19.9 for a total thickness of two inches. If the thickness of the insulating medium is reduced to

1/16 inch, all other factors remaining the same, the dielectric constant of the unit will be increased to 42.8. These examples have been calculated by solving Equation 10 for K_T , the dielectric constant of the unit.

The first cell designed had two 1/16 inch sheets of plastic serving as the insulation on the capacitor plates. Plastic sheets 1/16 inch thick were also used to line the sides of the box giving a plastic-lined container for holding the hay. In order to simplify construction, and to eliminate edge effects, the design was modified so that only the top or "above ground potential" plate was insulated from the hay. For insulation the plate was painted with coil dope and also covered with 1/16 inch plastic. The plate at ground potential was made in the form of a sheet steel pan with no insulation from the hay. The sides of the pan were about 2 1/8 inches high and extended above the top capacitor plate. The interior of the completed unit is shown in Figure 21.

F. Operational Procedure

The following steps are necessary to determine the capacitance of a hay sample using this type of meter:

- (1) With the cell empty and with dial D set to zero, adjust knob A for maximum meter deflection. (Refer to Figure 20)
- (2) This adjustment needs to be repeated only occasionally.



Figure 21. View showing interior of test capacitor cell and top electrode.

(3) Remove top part of instrument and place lower part on scale.

(3) Place desired weight of hay in lower part.

(4) Remove from scale, distribute evenly and compress hay by replacing top part of unit. Fasten the two parts together with the two clamps on the side.

(5) Adjust knob B controlling C-5 till meter reads a minimum. Meter range may have to be changed by moving selector switch S-2 depending on the sample. Current through the meter can be increased by adjusting Knob C controlling R-4. For meter protection, always turn knob in extreme counter-clockwise direction after completing the reading. Never allow the needle to be driven off-scale.

(6) Observe reading on dial D. This reading can be used to plot a calibration curve for the instrument or, if this curve has been plotted, it can be used to read the moisture content of the sample.

VI. TEST OF INSTRUMENT

A. Capacitance Calibration

In order to obtain the value of test cell capacitance for any dial reading, a calibrated variable capacitor (40-640 uuf) was connected in parallel with the empty test cell. Capacitor C-5 of the meter was varied in steps of ten dial divisions and the variable capacitor adjusted to resonate the circuit as indicated by maximum deflection of the microammeter. Values of external capacitance in addition to the empty test cell capacitance are shown in Graph VIII. Each division of the dial represented about 1.9 uuf. The capacitance of the empty test cell was 50 uuf and the Q was 46.

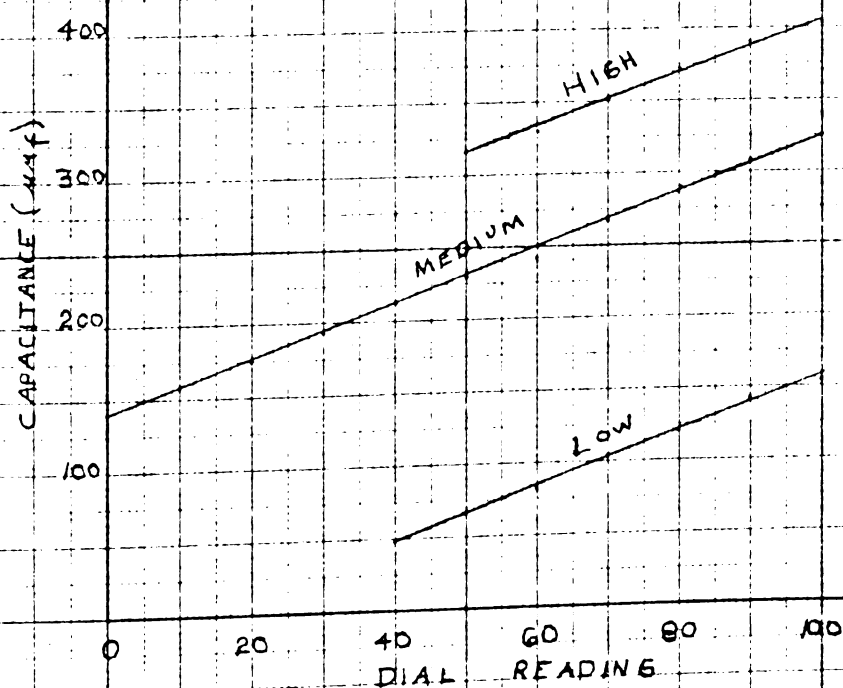
B. Moisture Content Calibration

Three tests were conducted in order to obtain preliminary information on the dial reading-moisture content relationship and the value of this instrument in estimating moisture content.

1. Test #1: 81 to 86 percent moisture alfalfa and grass hay. (83 samples). The test procedure consisted of placing one pound of hay in the test cell and taking at least two readings of dial "D" for each sample. The sample was weighed with a simple household scale which had been made

GRAPH VIII

CAPACITANCE CALIBRATION OF METER WITH
TEST CELL (50 μmf) CONNECTED



more sensitive by using a lighter spring. With this conversion, three one-pound divisions on the dial equaled one pound, thus making measurements more accurate and quicker to obtain.

After the first reading had been taken, the sample was removed and turned over before taking the second reading. Some variation between readings was observed as indicated by the data presented in TABLE VIII. This was attributed to two factors: (1) Variations in moisture contents within the samples, and (2) A decrease in the amount of contact with the top plate in the second reading due to the sample being already compressed. The moisture contents as determined by the oven method for the samples, A and B, for each trial varied considerably as shown in TABLE VIII. Observations indicated that moist hay near the top plate resulted in a higher dial reading than did moist hay near the bottom plate. This fact was probably due to the extended sides on the bottom plate giving a shorter path for the electrostatic flux lines causing the hay in the top of the unit to have more effect on the dial reading than the hay in the bottom. Another factor producing different readings with non-uniform samples may have been the uninsulated bottom plate. The conductivity of the hay may have produced a series of small plates on the surface of the hay itself at varying distances from the top electrode.

TABLE VIII

DIAL READINGS OBTAINED WITH 20 SAMPLES OF IMITATED ALFALFA
AND GLASS BALL HAVING A MOISTURE CONTENTS BETWEEN 21 AND
58 PERCENT (ONE POUND SAMPLE)

Sample #	Moisture Content (percent)			Dial Reading	
	A	B	Average	First	Second
1	26.4	14.6	21	35	21
2	24.5	23.0	24	26	24
3	24.9	25.6	24	32	26
4	24.3	24.7	25	34	34
5	25.1	21.2	25	27	24
6	25.1	23.7	25	38	25
7	25.6	27.4	25	20	31
8	26.5	16.0	23	43	22
9	27.0	23.4	26	35	26
10	26.2	26.5	26	33	25
11	26.4	26.6	26	25	23
12	23.3	23.0	23	46	41
13	26.3	29.3	23	40	33
14	30.9	20.7	21	36	26
15	30.3	30.7	34	49	45
16	33.0	34.4	36	47	53
17	35.6	43.3	39	57	59
18	35.0	43.7	39	60	60
19	40.4	40.2	42	71	65
20	42.8	42.0	43	65	59

TABLE VIII (CONTINUED)

Sample #	Moisture Content (percent)			Dial Reading	
	A	B	Average	First	Second
21	45.1	43.4	47	67	79
22	46.0	49.0	48	65	63
23	43.5	49.3	49	75	72
24	50.7	46.3	49	76	70
25	50.2	51.0	51	73	66
26	53.4	----	53	87	85
27	57.3	53.7	55	82	82
28	50.0	----	50	90	80

Since the primary purpose of the instrument is to provide a means of obtaining average moisture content of a sample with one reading, the linear regression line of the first dial reading on moisture content was calculated and is shown plotted together with the observed values in Graph IX. A summary of the values obtained in the statistical analysis is presented in TABLE IX. The calculated value of b was 1.83 indicating that for a one percent change in moisture content the dial reading would change approximately two divisions. The standard deviation from regression ($s_{x.y^2}$) was three percent of the moisture content of a sample as obtained from the regression line for an observed dial reading would be plus or minus three percent at least 66 percent of the time. Between 21 and 33 percent moisture, the standard deviation was 2.6 percent. This accuracy may be sufficient for farm use but might be improved by eliminating the influence of factor (1) previously mentioned.

B. Test #3: 44 to 75 percent moisture alfalfa and grass hay. (14 samples). Although the knowledge of the water content of high moisture hay is not as important as that of low moisture hay, a preliminary test was conducted to determine the performance of the instrument for this purpose. Using a one and one-half pound sample, the values of dial reading for various high moisture contents presented in TABLE X were obtained.

GRAPH IX

REGRESSION OF DIAL READING ON MOISTURE CONTENT

FOR A ONE POUND

SAMPLE

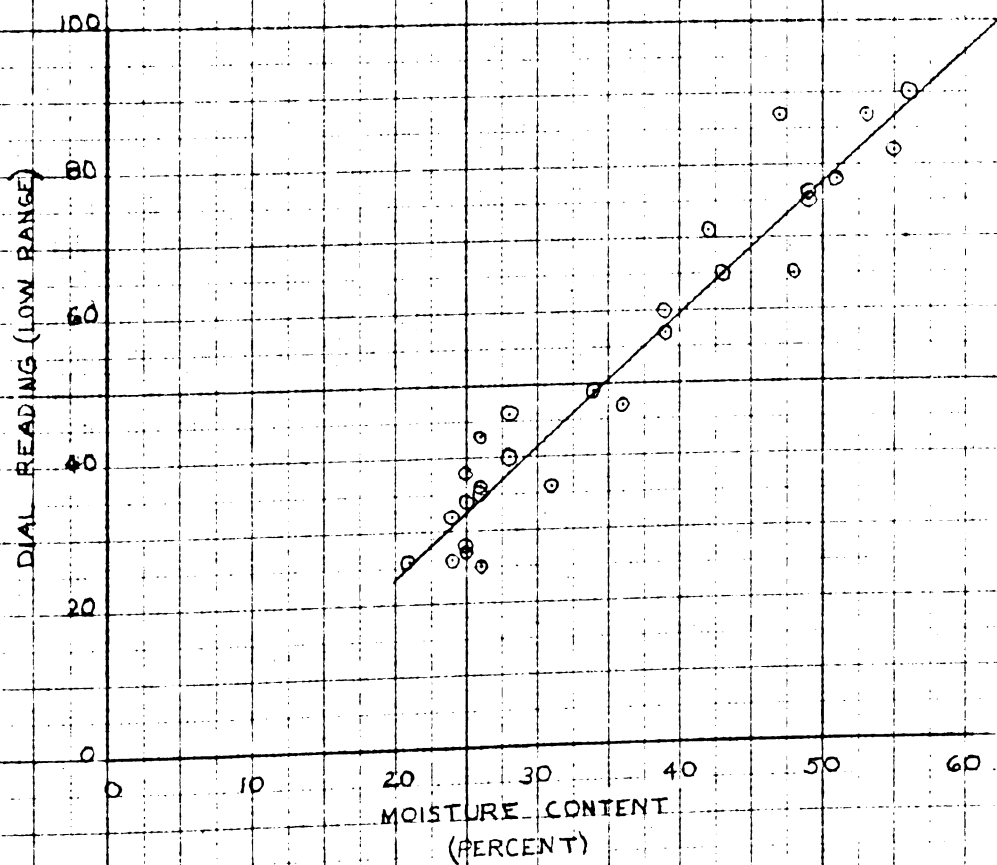


TABLE IX

SUMMARY OF REGRESSION CALCULATIONS¹

(x equals moisture content, y equals dial reading)

$$S x^2 = 3538.2 \qquad S y^2 = 12,600.1 \quad S xy = 6465.2$$

$$b = \frac{S xy}{S x^2} = 1.830$$

$$S d_{y.x}^2 = S y^2 - \frac{(S xy)^2}{S x^2} = 889.3$$

$$s_{y.x}^2 = S d_{y.x}^2 / n-2 = 51.99 \quad s_{y.x} = 5.6 \text{ dial divisions}$$

$$s_{x.y}^2 = S d_{x.y}^2 / n-2 = 3.91 \quad s_{x.y} = 3.0 \text{ percent moisture}$$

$$s_b = 0.0901 \qquad t = \frac{b}{s_b} = 19.25$$

¹ For explanation of symbols, see Snedecor, G. W., Statistical Methods, The Iowa State College Press, Ames, Iowa, 1946, p. 121.

TABLE X

DIAL READINGS OBTAINED WITH 14 SAMPLES OF IMMATURE ALFALFA
AND GRASS MAY HAVE A MOISTURE CONTENTS BETWEEN 44 AND
79 PERCENT (ONE AND ONE-HALF POUND SAMPLE)

Sample #	Moisture Content (percent)			Meter Range	Dial Reading
	A	B	Average		
1	47.4	40.3	44	Low	75
2	50.6	50.2	50	Med	15
3	51.3	49.3	51	Low	86
4	54.6	53.6	57	Med	83
5	57.1	53.6	55	Med	50
6	58.7	59.2	59	Med	40
7	58.2	59.0	59	Med	53
8	59.7	60.7	60	Med	40
9	58.1	63.0	60	Med	17
10	61.8	63.2	65	Med	40
11	69.0	62.5	66	Med	40
12	73.5	74.0	74	Med	40
13	77.5	73.0	75	Med	69
14	77.3	80.4	79	Med	66

The same factors that tended to cause deviations between readings in Test #1 were present in this test. Due to the higher moisture contents, their influence was increased. Whether the changes listed later will make the meter suitable for high moisture content may can only be determined by further tests.

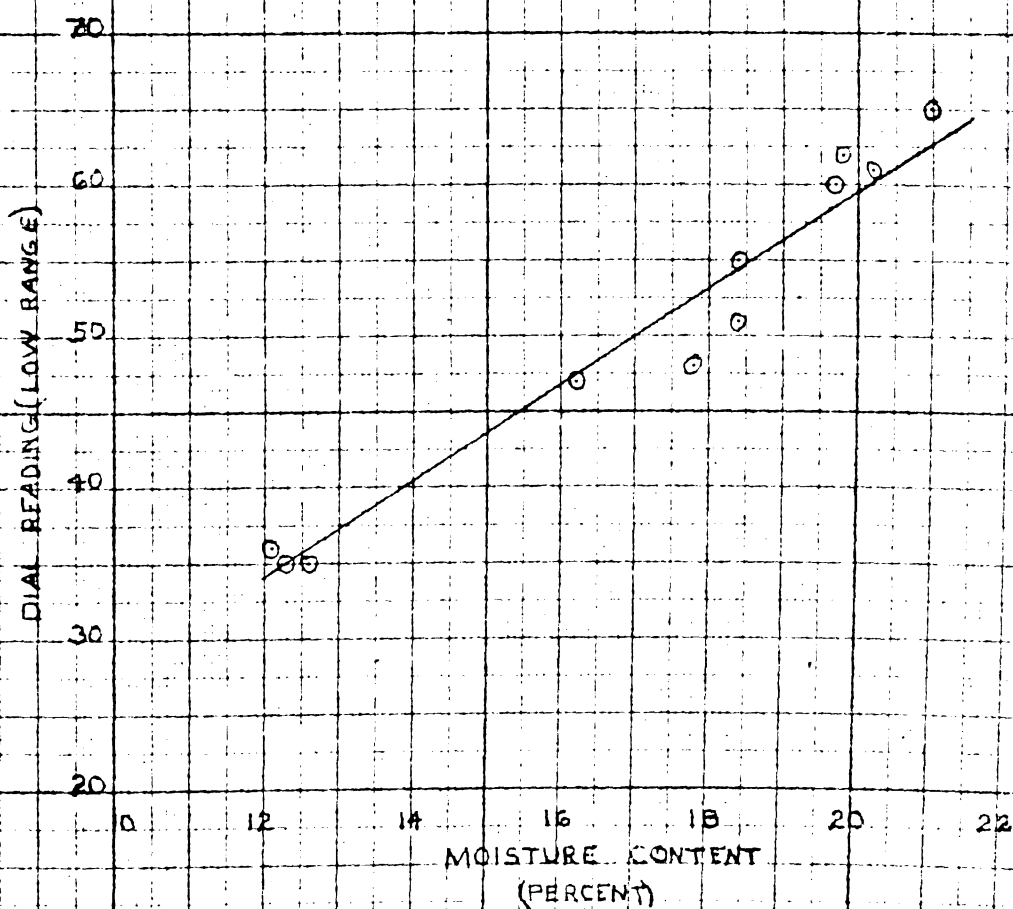
In this test, the effect of packing appeared to have much more influence on the readings than it did at the lower moisture contents. The use of a chopped sample may eliminate this factor.

3. Test #3: 18.1 to 31.0 percent Cornbelt wheat. (11 samples). A knowledge of the moisture content of small grains is often desired on the farm and may be obtained from commercial indirect meters described in the review of literature. In order to investigate the possibility of using this meter, without any changes, for the determination of wheat moisture content, this test was conducted.

To measure wheat moisture content an unweighed conditioned sample (about eight pounds) was placed in the test cell and leveled with a sample scraper so that the top of the wheat was in contact with the plastic insulation over the top plate. Dial readings were taken and are shown plotted against wheat moisture content in Graph X. The moisture content of the sample was determined by a Steinlite Moisture Tester. The fact that one indirect method was

GRAPH X
DIAL READING FOR VARIOUS MOISTURE CONTENTS
OF CORNELL WHEAT

SAMPLE SIZE - APPROX. 8 lbs



used to check another indirect method was recognized as poor testing procedure but was considered adequate for this preliminary test. The use of a special test capacitor would probably further extend the accuracy.

C. Design Changes

1. Capacitance meter. During the tests, the operation of the capacitance meter proved satisfactory. Since no panel-type microammeter was available, an external 0-100 ua meter was used. This made determination of the resonance point somewhat less accurate than if a smaller range meter had been used. In order to correct this and to make the instrument more easily portable, a panel-type microammeter with a range of about 0-50 ua should be installed. No other changes are proposed for this part of the instrument.

2. Test capacitor cell. In order to obtain better correlation between the dial reading and the average moisture content of a sample, the vertical sides on the bottom plate were removed and a flat, 11 1/2 x 11 1/2 inch bottom plate substituted. A sheet of one sixteenth plastic was placed over the electrode in order to insulate both electrodes from the hay and improve the Q of the unit. In order to obtain good contact between the plastic and the electrode, the plastic sheets were heated until soft and pressure applied so as to press the plastic into the plate.

The effect of these changes will be to reduce the amount of increase in capacitance due to any moisture content as indicated by Equation 10. Random tests indicated that the average reading characteristics of the meter were improved by the changes, but proof can only be obtained by conducting another test and calculating the standard deviation from the regression line.

D. Suggestions for Further Tests

With the changes cited above, further tests should be conducted using a large number of samples and the regression line and standard deviation calculated. At the same time, samples of various kinds of hay should be tested and a statistical analysis completed to determine differences in the moisture content-capacitance relationship with varieties.

Further testing could also be carried out to determine the usefulness of the meter in determining the moisture content of wheat and other materials.

VII. SUMMARY

Since a review of literature indicated that there was no means for the rapid determination of hay moisture content in the field, investigations were conducted to find a method for this measurement. The capacitance method was selected as the indirect method offering the greatest possibilities. A study of dielectric theory with reference to the measurement of hay moisture content indicated that capacitor losses and anomalous dispersion would be the two main factors affecting the operation of a capacitance indicating moisture tester.

Experimental investigations of the basic relationships of the method indicated that capacitance did not change with frequency in the low radio-frequency range. These tests also showed that there was a definite moisture content-capacitance relationship which was dependent on the initial weight of sample but that the power factor-capacitance relationship was not consistent. In all measurements, an insulated plate-type of capacitor was used to reduce losses due to d-c conductivity.

A portable capacitance meter and test capacitor cell was designed and constructed. Preliminary tests of this instrument indicated the following results:

(1) The standard deviation from the regression line for 23 samples having a moisture content between 21 and 56 percent was three percent. Considering only the hay samples between 21 and 39 percent, the standard deviation was 2.6 percent.

(2) Some variations in readings were encountered depending on the placement of non-uniform samples in the cell.

(3) At higher moisture contents (between 44 and 79 percent) the capacitance-moisture content relationship was less consistent.

(4) Limited measurements (11 samples) of soft winter wheat moisture content indicated a standard deviation from regression of 1.5 percent in the range of 18.1 to 21.0 percent moisture.

Changes in the test capacitor cell have been made which may improve the accuracy of the meter. In order to prove the final value of the instrument as an indicator of hay moisture content, further tests will have to be conducted.

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