THE DESIGN OF SIMPLIFIED EQUIPMENT FOR THE RAPID DETERMINATION OF THE MOISTURE CONTENT OF GRAIN AND FORAGE CROPS

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THESIS

THE DESIGN OF SIMPLIFIED EQUIPMENT FOR THE RAPID DETERMINATION OF THE MOISTURE CONTENT OF GRAIN AND FORAGE CROPS

By

Gerald William Isaacs

A THESIS

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ABSTRACT

Moisture content is commonly used as an index of the keeping quality of farm grain and forage crops. Farmers need a means of determining the moisture content of such crops in order to obtain the fullest benefit from the use of modern equipment and procedures for harvesting and curing farm crops. Equipment for determining the moisture content of farm crops on farms should be accurate, simple to operate, low in cost, and applicable to all the common hay and forage crops within a wide range of moisture contents.

Moisture content varies widely within individual lots of farm crops. This is particularly true of hay which is curing in the field. This non-uniformity in moisture content makes it important to obtain a representative sample.

Detailed studies were made of two methods of measuring moisture content, a direct oven method and an electrical resistance method.

Exhaust Oven Method. An oven which utilizes the heat from the exhaust gases of an internal combustion engine to dry samples of hay or grain was designed and tested. This oven mixes ambient air with the exhaust gases, which lowers the temperature of the gases and prevents burning of the sample. Samples of hay weighing 100 to 200 grams are dried in about seven minutes. Samples of grain are dried in about fifteen minutes.

Electrical Resistance Method. Studies were made of the effects of electrode pressure, electrode design and frequency of the

measuring current upon the electrical resistance measurement of hay and grain.

Tests of resistance-type moisture meters indicated that a single reading taken on hay or grain is not a good index of the moisture content of the whole lot. When testing hay with a resistance-type meter, at least 25 readings should be taken and the results averaged in order to obtain a reliable indication of the moisture content of the whole field.

Recognizing that most farmers would not carry out such a laborious computation, an automatic averaging device was developed which gives a single indication of the average moisture content of a large number of samples. This device measures the average electrical conductivity of the samples and thereby indicates a close approximation of their average moisture content.

Other Methods Studied. Preliminary investigations were made on several other methods of moisture determination: a method involving the measurement of the pressure of the acetylene produced in the reaction between calcium carbide and the water in the sample, a specific gravity method, an oil-distillation method, a method involving the measurement of the shearing force required to cut hay samples, and a method using wet and dry-bulb thermometers to measure the equilibrium relative humidity of grain. None of these methods were found to be as applicable to the problem as the resistance and oven methods.

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INTRODUCTION

Moisture content has long been an index of the keeping quality of grain and forage crops. Prevention of spoilage has been a great problem to mankind since he first learned to store for his future needs what he could not eat immediately. In spite of reported surpluses in certain farm commodities, the modern American farmer can no better afford waste through spoilage than his forefathers. Not only do wasted products mean wasted money to the individual concerned, but waste by spoilage means useless depletion of our nation's greatest physical asset, its natural resources.

Changes in farm harvesting and storage procedures have brought about changes in the need for moisture measuring equipment. The need for equipment for the quantitative measurement of moisture or storage quality in farm crops on the farm parallels the development of the combine and the modern crop drying and conditioning equipment.

Small grains used to be cut with a binder and placed in the shock to dry before threshing. There was no great need to rush the threshing procedure, since the grain was reasonably safe from weather damage in the shock. There was little need for a quantitative measurement of moisture content, since the grain could be dryed beyond the critical safe storage moisture content.

Today's combine harvesting methods require that the harvesting be done during a certain rather short period in the maturity of the grain. Grain which is combined too wet will obviously spoil in the granary.

Combining grain when too dry results in greater losses of grain at the cutter bar due to shattering. Furthermore, leaving the grain in the field longer than necessary increases the risk of loss through lodging and shattering due to heavy rains, wind or hail.

Some farmers prefer to harvest their grain before it has field cured to the extent that it would keep safely in an unventilated storage, thereby avoiding the risks of leaving it in the field at a time when weather losses could be great. Final curing is accomplished by artificial drying. Being able to determine the moisture content of the grain is a valuable asset in the management of a crop drier; but whether or not artificial drying is employed, a means of measuring the moisture content of small grains on the farm is needed to indicate the optimum time for harvest.

Like the combine, the corn picker has greatly alleviated the labor problem in corn harvesting, but under some conditions has created new problems in grain storage. An increasing number of farmers today are following the practice of harvesting corn before it is dry enough for safe storage, then artificially drying it to an allowable moisture content. By picking the corn at high moisture content, the picking efficiency of the picker is improved and the risk of loss through bad weather is reduced. In some years, particularly in the northerly states such as Michigan, weather conditions are such that the corn does not dry properly in the field and artificial drying becomes necessary to obtain a high grade product.

Where artificial drying of grain is practiced, some convenient means of determining the moisture content of the product is needed to

allow the most efficient management of the drying equipment. On many modern farms now practicing artificial drying of grains, moisture tests are obtained by taking samples to the local grain elevator for testing. For those farmers who are not located very close to an elevator, this practice is both inconvenient and time-consuming. Furthermore, certain types of moisture meters used in commercial elevators are not accurate when testing grain recently dried in a heated air dryer.

New practices in the harvest, curing, and storage of forage crops have also created an increasing need for a means of moisture measurement. Hay has been cured for centuries by leaving it in the field until it was adjudged dry enough to be stored without molding or excessive heating. However, farmers have long been aware of the importance of the losses of nutrients incurred by over-curing and the dangers of spoilage and heating caused by under-curing. The need for care on the part of the farmer in curing hay was indicated by Columella, a Roman who wrote as follows about 50 A.D. (1):

> "There is a measure to be observed in drying hay, that it be put together neither oven dry nor yet too green; for, in the first case, it is not a whit better than straw for it has lost its juice; and in the other, it rots in the loft if it retains too much of it; and after it is grown hot it breeds fire, and sets all in a flame. They do not put it up in mows, before that they suffer it to heat, and concoct itself, and then grow cool, after having thrown it loosely together for a few days".

Modern agricultural science has developed new curing and storage procedures which greatly retains the nutritional value of forage crops and reduce the risk of loss due to rain. These modern practices can be carried out most efficiently when a quantitative estimate of the moisture content of the crop is available to indicate when to rake, when to

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start baling or chopping, and when to start or stop the crop dryer.

Most experienced farmers have to a great extent developed a sense of judgment for determining when hay has been field cured sufficiently to keep safely in an unventilated storage. However, modern haying practices require that the farmer be able to recognize stages of curing which were not previously of specific interest to him. For example, he may now wish to rake his hay at 50% moisture content instead of 25% and he may wish to bale or chop it at 35% instead of 20% moisture content. Furthermore, if he is to realize the maximum benefit from modern haymaking practices, he should be able to determine moisture contents more accurately than when the hay was left in the field until it was "good and dry".

Most farmers now using barn dryers for mow-curing hay use rather unquantitative methods of indicating when to place the hay on the dryer. A recent survey of the experience of farmers who use barn dryers was made by Vary (2). The answers that 52 farmers gave when asked what method they used to determine moisture content are given in Table I.

TABLE I

METHODS USED BY 52 FARMERS TO DETERMINE THE MOISTURE CONTENT OF HAY (2)

Method	Number Reporting	Method	Number Reporting
None	10	Break	1
Guess	6	Rub	2
Feel	15	Oven	1
Twist	6	Leaves curl	1
Rattle	1	Experience	7
Squeeze	2		

The fact that farmers resort to such indefinite methods as those indicated in Table I reflects the unavailability of simple, inexpensive, and reliable means for quantitatively determining the moisture content of forage crops. As the acceptance of modern forage harvesting and curing practices advances, the demand for moisture measuring equipment will likewise increase.

Literature Cited

(1) Ahlgren, G. H., "Forage Crops", ed.1, Mc-Graw-Hill, New York, 1:3, 1949.

(2) Vary, Karl A., "Statistical Summary of Farmers Experience with Barn Driers". Unpublished mimeo. 11 pp. Agricultural Economics Department, Michigan State College. February 2, 1954.

REVIEW OF LITERATURE

The determination of moisture was probably one of man's earliest acts of chemical analysis. Procedures for moisture determination may be found among the oldest of scientific papers. The following review of literature is not intended to include all significant work in the subject of moisture determination, but will include some of the papers which apply most directly to the experimental work to be discussed subsequently. The author has compiled a bibliography of rapid methods of moisture determination (with abstracts) which should be of use to future investigators of this subject (1). Although this work contains 450 references, it does not necessarily include all of the research on rapid moisture determination of the last sixty years.

All methods of moisture determination may be classified generally as either direct or indirect. The direct methods include the oven methods, the distillation methods, and the methods involving drying with dessicants. They are called direct methods because they require the separation of the moisture from the dry matter and the amount of moisture removed is either measured directly or calculated from the loss in weight of the sample. The indirect methods involve the measurement of some property of the material which is dependent upon moisture content. Indirect methods require calibration with one of the direct methods.

Direct Methods

Actually all methods of moisture determination are somewhat empirical or indirect, as indicated by Zeleny (2) and other investigators. Even the so-called direct methods cannot measure with great accuracy the actual amount of water in a sample. First of all, one cannot be certain that all of the water was removed from the sample. In organic materials, some of the water is present in forms which appear to be more or less tightly "bound" by strong physical forces to proteins, high molecular weight carbohydrates, and other colloidal materials. Furthermore, when testing organic materials with the oven or distillation methods, heat must be applied which may lead to decomposition of dry matter constituents and the production of water which was not originally present as such. Volatile constituents of the dry matter may also be driven off and result in errors in the moisture measurement.

It is not the purpose of this study to discuss at great length the shortcomings of the direct methods of moisture determination. Of greater value is to point out the importance of indicating the procedure by which moisture determinations were made when presenting moisture data so that the results therefrom, may be reproduced with reasonable accuracy.

Air Oven Methods. There are several air oven procedures for the moisture determination of various materials. Standard procedures have been drawn up by organizations interested in each material. In the case of grain the U.S. Department of Agriculture has set forth air oven procedures in the Official Grain Standards of the United States (3). Basically,

this method requires heating the finely ground grain in an air oven for one hour at 130°C. Another air oven procedure has been set forth by the Association of Official Agricultural Chemists (4). This method requires heating a finely ground portion of the sample for two hours at 135°C. The latter procedure usually gives higher moisture content, as would be expected from heating the sample at a higher temperature for a longer period of time.

There have been a great number of devices developed which heat samples in air to dry them rapidly for purposes of moisture determination. These devices generally use higher temperatures in order to reduce the time required by the official methods. Heating is usually produced by electric heating coils or infrared lamps. Brabender (5) developed an oven which has a built-in scale for accurately weighing the samples while still in the oven. This removes the necessity of cooling the samples in a dessicator before weighing, which is required in the official method.

Water Oven Methods. The water oven method is recommended for corn and requires heating the whole grain at 99 to 100°C for 96 hours in a water oven (3). A water oven is essentially similar to an air oven except it is heated by circulating water which is boiling at atmospheric pressure through a water jacket in the walls of the oven. The temperatures at various points within a water oven are usually more uniform than in an air oven.

Vacuum Oven Method. The vacuum oven method for grain as set forth by the Association of Official Agricultural Chemists (4) requires heating the finely ground grain at a temperature of 98 to 100°C in a vacuum chamber

at a pressure of 25mm or less of mercury. Heating is continued until essentially constant sample weight is observed (about five hours).

Christie (6) has developed a special type of vacuum oven which uses the dielectric heating effect of a high-frequency electric field to dry samples of various organic materials. Since such heating effects occur uniformly throughout the sample, heating time is only about ten minutes. The cost of this equipment is rather high.

Drying with Dessicants. This method of drying moisture samples requires placing the sample over an efficient dessicant in a closed container. Since the dessicant maintains a very low vapor pressure within the container, the sample gradually dries to a constant weight. The Association of Official Agricultural Chemists (4) has set forth a standard procedure which requires maintaining the ground sample in a vacuum with anhydrous sulphuric acid until constant weight is attained. This method is not widely used, since it requires a great length of time to complete. However, it is sometimes used on materials containing dry matter which decomposes easily when heated.

Distillation methods. In the distillation methods, the sample is heated in some non-aqueous liquid and the moisture determined either by direct volumetric measurement of the water distilled and condensed from the grain or by determination of the weight loss of the sample during the heating process.

The official toluene distillation method for grain as described by the Association of Official Agricultural Chemists (4) requires heating the finely-ground sample of grain in toluene. An apparatus is used which

condenses the water vapor distilled from the toluene and collects it in a graduated tube for measurement.

The Brown-Duvel distillation method for grain was first described by Brown and Duvel (7) in 1907. This method is somewhat similar to the toluene distillation method except that the grain is unground and heated in oil instead of toluene. The Brown-Duvel apparatus has been standardized and marketed commercially as a rapid method moisture determination. It is still used to a limited extent.

A simple distillation method was devised by Dexter (8) for use by farmers in testing forage and grain crops. In this method, the moisture content is determined by heating the sample in vegetable oil at 190°C. and determining the weight loss of the sample and the oil. The method may be applied in the field using an alcohol stove, tractor exhaust or other means as a heat source.

Indirect Methods

Electrical resistance methods. The dependence of the electrical resistance or conductivity of materials upon their moisture content has been the basis for a number of successful moisture meters. There is some disagreement among investigators as to the exact form of the relationship between moisture content and resistance; however, it is generally agreed that resistance varies inversely with the moisture content and that relatively small changes in moisture content produce large changes in resistance. Therefore, a relatively inaccurate measurement of resistance may give a fairly accurate indication of moisture content. Moisture meters operating on the electrical resistance principle are

usually calibrated against one of the standard oven or distillation methods, as are all indirect methods.

The first report of the application of the resistance method found in the literature was by Whitney (9), who applied it to soils in 1897. Whitney used a direct measurement of the conductivity of the soil as a measure of the moisture content. Many investigators have published results on this type of measurement applied to soils during the past fifty years, but the general conclusion drawn today is that the results are too dependent upon the type of soil and its salt content.

For this reason, the modified electrical resistance method developed by Bouyoucos (10) has largely replaced methods involving direct measurement of resistance. The method developed by Bouyoucos requires the measurement of the resistance of a nylon, glass fiber, or plaster-of-Paris element which is buried in the soil. To avoid the effects of polarization, the resistance is measured with an alternating voltage source. An attempt to apply the Bouyoucos method to the moisture testing of hay in storage was attempted by Kline (11). The method was unsuccessful mainly because of poor contact between the hay and the resistance elements.

The first application of the resistance method to organic material found in the literature was reported by Briggs (12) who adapted the method for testing grain in 1908. Briggs used a Wheatstone bridge to measure the resistance between two 12-inch electrodes placed in a glass jar of wheat. He found a linear relationship between the moisture content and the logarithm of the resistance between the ranges of 11 and 16 percent moisture content. Data taken on wood by Stamm (13) (14) indicate that

the logarithm of the electrical resistance decreases in direct proportion to an increase in moisture content up to the point of fiber saturation, or about 30 percent moisture content. Above the point of fiber saturation there is very little change in resistance with increased moisture content. The variation below the fiber saturation point is such that the resistance increases 1.8 times for a decrease of one percent absolute moisture content. In other words, a decrease to 56.8 percent of the original resistance corresponds roughly to a moisture increment equal to one percent of the dry weight of the birch wood tested.

The simple logarithmic relation put forth separately by Stamm and Hasselblatt (15) indicates a linear relation when the logarithm of resistance is plotted as a function of moisture content. The degree of linearity was found in later experimentation by Suits and Dunlop (16) to be not so great and more closely approximated by a relation of the form:

$$\text{Log}_{10}\ (\text{Log}_{10}\ R) \propto (\ M\ )\ \%$$

wherein R represents resistance and M represents moisture content.

Whether or not the simple relation determined separately by Stamm and Hasselblatt or the more complicated one of Suits and Dunlop is true, the important fact is that resistance changes very rapidly with moisture content. The resistance method of moisture determination would be handicapped indeed if the same percentage of accuracy in resistance measurement were necessary to obtain a given percentage of accuracy in moisture determination.

The above empirical relations between resistance and moisture content do not rigidly hold true in all cases. Various other factors affect the relationships in varying degrees. According to Stamm (13) the

factors which affect the accuracy of the resistance method for moisture testing wood are as follows:

1. The amount of pressure applied and the type of contact between the electrodes of the device and the wood.
2. Dimensions of specimens
3. Extent of specimen beyond electrode surfaces.
4. Direction of flow of the current in the wood with respect to the grain.
5. Species and density of the wood.
6. Temperature
7. Salt content
8. Distribution of moisture in the specimens.
9. The presence of moisture on the surfaces parallel to the flow of current.
10. Polarization, electrolysis and electroendosmose.

The work by Stamm in the evaluation of these various factors was found to be very comprehensive and basic. Since the work was done on wood, which has many physical properties in common with forages and grains, an extensive review of Stamm's work follows.

Three different kinds of electrodes were used in Stamm's earlier tests (13): (a) plain copper plates 7.5cm. by 7.5cm. made from 1mm. plate, (b) 7.5cm. by 7.5cm. heavy brass plates with routings 2mm. wide and 2mm. deep cut in both directions so as to produce a cleated surface to be pressed into the surface of the sample, and (c) 5.0cm. by 5.0cm. brass plates with soft lead faces which, under pressure, conform to the surface of the board. The above electrodes were tested with a one-inch

specimen of wood. Great deviation in readings was experienced in the use of the plain copper plates held firm by a wooden screw clamp. The other two types of electrodes gave not more than a 20 percent deviation in the resistance reading. The routed electrode required tighter clamping to obtain consistent readings; therefore, the lead faced electrodes were employed in most of the subsequent experiments studying the other factors.

The tests determining the effect of thickness on resistance indicate that the resistance varies directly with the thickness. The effect of specimen cross-section was studied by using two one-inch specimens, one 5cm. square and the other 7.5cm. square. The former, when fitted with the 5cm. lead-faced electrodes, showed a resistance of 82 megohms. The 7.5cm. piece tested similarly gave a resistance of 42 megohms. The unit resistance (ohms per sq. cm. of cross-section) for the 5cm. square specimen was 2050 megohms and for the 7.5cm. specimen was 1970 megohms. These results indicate reasonable verification of the inverse law of areas for the purpose of this study. (Inverse Law of Areas -- The resistance of a mass of material is inversely proportional to the cross-sectional area).

The effect of the direction of current flow with respect to the grain of the wood was found to have a pronounced effect on the measured resistance of the sample. The resistance in the longitudinal direction (parallel to the direction of the grain) is about half of the resistance in the cross-grain direction.

Tests to determine the effects of species of wood on the resistance-moisture relation show that for the range of moisture content

determined (6 to 16 percent), the resistance-moisture relation for the six species tested was essentially the same. Again it is stressed that a rather wide variation of actual resistance is allowable to yield approximately the same calculated moisture content because of the logarithmic relation between the two quantities. At the same time the species of the samples was varied, density was necessarily changed. It is indicated that appreciable changes in density of the samples (from .336 to .584), as species were varied, failed to produce any error in determining the moisture content beyond that attributable to experimental error. The fact that a change in species does not change the resistance-moisture relation appreciably is a favorable condition indeed; however, it is certainly not to be expected that a change in the material would have the same negligible effect.

It is of interest to determine the effect of the sample extending indefinitely beyond the area actually covered by the electrodes. Experiments were conducted to indicate the amount of decrease in resistance with an increase in cross-sectional area beyond the surfaces of the electrodes.

A basswood specimen 21.5 x 19.5 x 2.7cm. gave 450 megohms with the 5cm. lead-faced electrodes, while the section from the piece 5cm. square indicated 800 megohms. Increasing the cross-section of the piece 16.4 times caused a 44 percent decrease in resistance. Further experiments showed that a decrease in thickness compared to the area will lessen the effect of cross-section on resistance. Other sections 5cm. square and 18 by 24cm., cut from 0.2cm. thick veneer, gave 1800 and 1600 megohms respectively. A decrease in resistance of only 11 percent was

experienced with an increase of 17.3 times the original cross-section. Thus it appears that for very thin sections of material, such as veneer, no correction need be made for an extension of the cross-section. However, for sections of 1 1/4-inch stock, it appears that a correction of about one percent of moisture content would be necessary. The actual relation between resistance and moisture in sections of considerable thickness and extent is an exceedingly complex one; therefore, it is suggested that a complete tabulation for any one size of stock to be tested be worked out empirically.

The effect of temperature on the moisture-resistance relation is not too damaging in practice if the ordinary range of working temperatures is maintained. Tests show that the resistance of wood falls off with an increase in temperature, producing a temperature coefficient negative to that of ordinary solid conductors. Tests show that for a decrease in temperature of 11°C., the resistance is doubled; however, this change in resistance changes the calculated moisture content only about one percent. The effect is rather small for ordinary operating conditions or may be easily compensated for when necessary.

The salt content of wood and other materials has a definite effect on the electrical resistance, being inversely proportional to the resistance. There is little variance between the salt content of species of wood; however, the salt contents of various materials differ greatly. The salt content of a specimen of wood was varied artificially by soaking in sodium chloride solution for the purpose of demonstrating the effect of the salt content. The specimen decreased in resistance from 490 to 120 megohms after it had taken on about one percent of sodium

chloride. The salt content of wood is ordinarily less than one percent. Furthermore, a large part of the natural ash in wood is insoluble. It is probable that the variations in the calculated moisture content due to variations in the natural ash content in wood are much less than one percent; however, the variations are appreciable in other materials, particularly in soils where this method of moisture determination has met with very limited success because of the large variety of salt contents in soils.

Somewhat closely related to the effect of salt content on measurements is that of polarization, or what is generally attributed to polarization. Few researchers have attempted a really rigorous explanation of the phenomenon other than to say it is present when d-c voltage is used to measure a resistance where electrolysis may operate. The effect of polarization is to build up the measured d-c resistance to as high as twice the a-c resistance. The effect is attributed to two different actions: electrolysis and electroendosmose. Electrolysis has the effect of building up an opposing emf or effective resistance in addition to the true resistance. Electroendosmose tends to create an uneven distribution of free water within the sample due to electroendosmotic motion of the water. Both of these effects are somewhat dependent on time to come into effect and are probably not very significant as long as moisture contents below that of the fiber saturation point are studied.

Surface moisture has a definite effect that cannot be denied. In extreme cases in the wood tests, where a dry specimen of 2000 megohms was streaked with a wet cloth from electrode to electrode, the resistance measurement indicated a short circuit. The resistance was reduced to

half the dry resistance when a man's breath was blown on the surface. These tests indicate that the resistance method is highly inapplicable to wood, the surfaces of which have been wet recently. However, this is a special condition and should not apply to the general case of wood specimens in storage.

The effect of unequal moisture distribution in the sample definitely limits the use of the resistance method as discussed thus far. Further research on the subject by Stamm (14) revealed that the plate-type electrodes were not suited to applications where non-uniformity in moisture content of the specimen is encountered. His research revealed that pin-type electrodes could be so arranged as to measure the average moisture content of a sample of wood containing non-uniformly distributed moisture. Electrode pins penetrating to a depth of one-fourth the thickness of the sample were found to indicate average moisture contents where normal drying gradients existed.

The effects of surface moisture and surface finish on woods were much less with the pin-type electrodes than with the plate types. Additional tests with the pin-type electrodes confirmed that the species and density of the wood had little effect on the readings of moisture content. The width and length of the board tested has no effect on readings with pin-type electrodes, as it did with the surface contact electrodes.

A number of investigators have published results of tests conducted on commercial resistance-type moisture meters for grain. Such work consisted mainly of calibrating the meters with oven determinations and determining statistically the accuracy of the meters. One of the more

comprehensive studies was made by Cook, Hopkins, and Geddes (17). In reviewing the test results of four commercial resistance-type meters for grain, it is evident that there is a linear relationship between the logarithm of the resistance of wheat and the moisture content in the range of 11 to 17% moisture content. Above 17% moisture content, the relation between moisture content and the logarithm of resistance is parabolic and is described by a relationship of the following form:

$$\text{Moisture content} = A - B(\log R) + C(\log R)^2$$

where A, B, and C are constants.

Hylnka, Mortens, and Anderson (18) made a study of ten electrical meters which operated either on the electrical resistance or the dielectric principle. The Tag-Heppenstall meter, which measures the electrical resistance of grain with an ohmmeter circuit, gave the most accurate results. This meter is still the only electrical meter approved for use in the inspection of grain under the Official Grain Standards of the United States.

Aranovsky and Sutcliffe (19) tested a commercial resistance-type meter on baled straw. A "satisfactory" comparison was reported between the average of 24 meter readings per bale and the oven-determined moisture content of the bale. The results were somewhat erratic at higher moisture contents; however, the tests were conducted on bales of straw which had been stored outdoors and were wet in spots. An increase in the reading of the moisture meter with an increase in bale density was reported.

Dielectric Methods. The dielectric constant of water is 81, while the dielectric constant of such good insulators as dry wood ranges from 2.5 to 7.7, according to data taken from the Smithsonian Physical Tables (20). Materials which contain greater amounts of moisture have higher dielectric constants. Since capacitance increases with the dielectric constant, the capacitance between two plates of condenser having a hygroscopic material as a dielectric will increase with an increase in the moisture content of the material. Thus by measuring capacitance, an indirect measurement of moisture content is obtained. This has been the operating principle of a number of moisture meters.

Lampe (21) in 1929 used the dielectric method to determine the moisture content of cereals, fruits and vegetables. The results obtained varied less than 0.5% from those obtained by regular drying methods.

Balls (22) determined the moisture content of baled cotton by measuring the capacitance between the nine iron hoops on the bales. Balls also applied the dielectric method to the measurement of soil moisture. In this work, he found that the capacitance bridge method he had used previously on cotton would not work well because of the power loss in the soil when it was used as a dielectric. By using a resonance method he avoided this difficulty.

A number of dielectric-type moisture meters have been described by various authors since the early work of Lampe and Balls. The meters described vary chiefly in the details of the capacitance measuring circuit and in the product to which the meter is applied. Variations in the meter readings due to rather small variations in sample density have been of much concern to those developing dielectric-type meters.

A patent by Stein (23), the originator of the well-known Steinlite moisture tester for grain, has as its principal feature a design for an arrangement to let the sample fall into the test chamber in such a manner that a constant density is obtained. The sample is held by a trap door at a fixed height above the test chamber. The sample is dropped *en masse* into the chamber instead of being poured in at a varying rate. Hartmann (24) is the author of a British patent for a design with essentially the same purpose as the Stein patent.

Concerning the comparative accuracy of dielectric-type meters, Zeleny (2) states the following:

> "---- it has never been demonstrated that the capacitance-type meters are capable of greater over-all accuracy in testing the normal run of commercial grain than are conductance meters. Capacitance meters should be particularly useful, however, in testing freshly dried or tempered grain, and grain of very high or low moisture content".

Zeleny further states that capacitance meters have been difficult to keep in adjustment and that the results of capacitance meters are less consistent, particularly when the results of several meters are compared.

Hart (25) and Sherwood (26) have applied the dielectric method to the determination of moisture in hay. Hart used a capacitance bridge circuit operating at 1000 cycles per second to measure capacitance of hay samples. A rigorous accuracy test was not made with this instrument; however, the accuracy was estimated at 5% moisture. Considerable drift in the indication of the meter was observed under certain conditions.

Sherwood used a capacitance substitution method to measure the capacitance of hay samples with a resonant circuit. The standard error of estimate of this meter was 3.0 moisture percentage points when testing

one pound samples of alfalfa. He avoided excessive power loss in the sample by insulating the plates of the test capacitor with sheets of plastic. Tuning the circuit for each determination is necessary with this meter.

Gas Pressure Method. This method involves mixing the material to be tested with a chemical which will react with the water in the material to produce a gas. The volume of the gas or its pressure at constant volume may be measured to determine the quantity of gas evolved and to indicate indirectly the amount of moisture in the material.

The first reference to this method found in the literature was made by Roberts and Frazer (27) in 1910. They used calcium carbide to determine the moisture content of crude petroleum. The volume of the acetylene produced was measured by a method of liquid displacement. The equation for the resulting reaction is as follows:

$$CaC_2 + 2H_2O \longrightarrow Ca(OH)_2 + C_2H_2 \quad \text{(acetylene)}$$

About 580cc. C_2H_2 (at 760mm. Hg and 0 C.) were obtained for every gram of water in the sample.

A U.S. patent on a commercial device employing this method was issued to Stanworth (28) in 1932. This device is manufactured in England and is now being sold in this country principally for use by casting foundaries for testing the moisture content of sand. The apparatus consists principally of a steel receptacle fitted with a Bourdon-tube pressure gauge and safety valve, a small scale for accurately weighing the test sample, and a quantity of reagent. This apparatus is recommended for use by farmers on hay and grain. An operating time of three minutes is claimed for grain tests when the sample is ground.

Fukunaga (29) used a steel receptacle and a steam gauge (0-30 psi range) to employ this method to soil moisture determination. The results obtained were found to be reproducible with great accuracy.

Masson (30) used this method on several organic substances and claims that there are no side reactions which would produce error. He used benzene to dissolve such fatty substances as butter and cocoa. He determined the yield of acetylene to be 10.5cc. of gas at 0 C. and 760mm. of pressure for each 18mg. of water. The theoretical yield is 11.2cc. Masson used a mercury manometer to measure the gas pressure.

Perkins and Kipping (31) state that acetylene can be spontaneously explosive above pressures of two atmospheres and should not be stored even at atmospheric pressures in metallic containers, since explosive metallic derivatives may be formed. It can be safely handled in solution with acetone.

Calcium hydride was proposed as a reagent in this method by Rosenbaum and Walton (32) in 1930. The reaction is described by the following equation:

$$CaH_2 + 2H_2O \rightarrow Ca(OH)_2 + 2H_2$$

An advantage over the use of calcium carbide is claimed, since twice the volume of hydrogen is produced as compared to the volume of acetylene produced in the carbide reaction. Rosenbaum and Walton (32) further state that hydrogen is not as soluble in other materials as acetylene; however, it cannot be used if calcium hydride reacts with some material other than water to produce hydrogen or some other gas. Notevarp (33) also used calcium hydride to determine the moisture content of various solids and high-boiling liquids.

Larson (34) reported the use of Grignard reagent (methyl magnesium iodide) to produce methane as a moisture indicator. He used this method to determine moisture in mineral oil. Dietrich (35) reported the use of the reaction of magnesium nitride with water to produce ammonia for the determination of water in alcohol.

Specific Gravity Method. A method for determining the moisture content of sand for concrete work was suggested by Waters (36). This method depends upon knowing the dry specific weight of the sand tested, which is determined previously. A two-liter cylindrical container and scale are used to take the data necessary to determine the moisture content. The wet sand sample is weighed and immersed in water inside the container. The container is filled to overflowing with water and weighed. The value of the total weight of sand and water is referred to a table which gives the moisture content for the corresponding dry specific gravity of the sand.

Bauer (37) discussed this method further and related unpublished work by the late Professor Dunagan of Iowa State College toward the development of equipment for weighing samples in air and suspended in water.

Lee (38) used a specific gravity method to determine the maturity of frozen vegetables, namely corn and peas. The method involved weighing in air and then in a solution of xylene and carbone tetrochloride of specific gravity 1.000. A weak brine solution was also used. The specific gravity of the sample is determined by the following relation:

$$\text{Specific Gravity} = \frac{\text{Weight in air} \times \text{Specific gravity of liquid}}{\text{Weight in air} - \text{Weight in liquid}}$$

Batson (39) used a specific gravity method in the determination of

moisture in sweet potato starch. The density of the dry matter was determined. Moisture content was based upon the difference in weight between five hundred ml. of water and five hundred ml. of an aqueous solution of one hundred g. of starch and water. Conversion tables were prepared. By weighing to 0.01g. accuracy, a moisture determination could be made to an accuracy of 0.7% moisture. The method is reported to be applicable to materials insoluble in water, wettable by water, and markedly denser than water when in the dry state. Materials tested should also preferrably be of a non-swelling or an non-hydrating nature, homogeneous or of constant density, and non-colloidal.

Hygrometric Methods. When grain or any other hygroscopic substance is placed in a closed container, the interstitial air becomes stabilized at a relative humidity dependent upon the moisture content of the grain. This is due to the equalization of the partial pressure of the water vapor in the air with that of the grain or other material.

Thus a measurement of the relative humidity of the interstitial air in equilibrium with a material may be used as a indication of moisture content of the material. The relation between the equilibrium relative humidity and moisture content is different for each product and has also been found to be somewhat dependent upon the history of the particular sample.

Although the hygrometric method may not be considered a highly accurate method of moisture content determination under field conditions, the measurements of relative humidity are actually better indices of storage quality than are moisture measurements. This is due to the fact that the growth of molds and other microorganisms which cause

grain spoilage is dependent largely upon the relative humidity. Milner and Geddes (40) have shown that rapid mold growth occurs at ordinary temperatures in grain when the relative humidity of the interstitial air is greater than 75%. Below 75% relative humidity, mold growth is greatly retarded.

The variations in the method of application are about as numerous as the methods of indicating relative humidity. There have been articles published and patents issued on the application of almost all known methods of humidity measurement to the indication of moisture in many different materials.

Dexter (41) has developed a simple method for use on grains which is based on wet-bulb and dry-bulb temperature readings of the air and grain inside a closed container. The wet bulb is wetted with a saturated solution of a metallic salt which maintains about the same equilibrium relative humidity as the grain tested, thereby reducing the wet-bulb depression and time to reach a stabilized temperature reading. Agitation is also used to decrease the time to come to equilibrium and to produce air movement around the wet bulb to aid vapor transfer. The experimental apparatus consists of two thermometers mounted in a rubber stopper, salts, and a container such as a milk bottle wrapped for insulation. Agitation is provided by shaking.

Gause et al. (42) developed a device which withdrew air from the center of bales of cotton and passed it over wet and dry-bulb thermometers for humidity measurement. In terms of moisture content, the standard deviation of the device was 1.45% moisture. The time required to run a sample was two to three minutes. Balls (43) employed similar methods on

baled cotton, but he indicated a standard error of 2.5% moisture. He attributed this high error to hysteresis effects caused by variations in the history of the samples with respect to past wettings from rain.

Ives (44) developed a simple device which indicates the dew-point temperature of the air inside a closed container containing the sample. The dew-point temperature is determined by observing the temperature at which a polished metal surface collects dew inside the container. The metal surface is the outside of a small tube which contains and is cooled by an evaporating liquid of low vapor pressure such as acetone. The rate of evaporation is increased by blowing air through the acetone. The dew-point temperature is assumed to be the temperature of the acetone as determined by a thermometer. Another thermometer determines the dry-bulb temperature. The relative humidity is determined in the usual manner from the dry bulb and dew-point temperatures.

Dexter (45) developed a very simple hygrometric method of determining whether hay or grain crops will keep in storage. A salt which when saturated with water has an equilibrium humidity of about 75% is mixed with the sample in a closed container. If the sample is too wet to keep (has an equilibrium humidity above 75%) the salt crystals will lump together because they are saturated. If the sample is dry enough to store, the salt will not lump.

The property of certain salts to change color when exposed to various relative humidities has been used as an indication of moisture content. Rother and Grau (46) were issued a British patent in 1926 for the application of this method to wood, textiles, and other substances, Todd and Gauger (47) describe the application of various cobalt salts to

this method. Severe color shifts with temperature were noted.

Dexter (48) used a mixture of ferric ammonium sulphate and potassium ferrocycnide in a carrier of sodium chloride as a colorimetric humidity indicator. In the dry state this mixture is blue, but in the presence of water, ferric thiocyanate which is red is formed. The use of this type of indicator eliminates the serious temperature effects encountered with the cobalt salts. The indicator is applicable in the range of 8-12% for wheat and the accuracy of observation is approximately 1% moisture.

Miloslavskii's and Palant's (49) attempts to apply the hygrometric method of moisture measurement to tobacco were unsuccessful. They attributed the failure of the method to the fact that tobacco is neither chemically or biologically definite.

Thermal Conductivity. Most organic materials when dry are relatively poor conductors of heat, but as the moisture content of such materials is increased, their thermal conductivity likewise increases. Powley and Algren (50) found that the thermal conductivity of wood varies essentially in a linear fashion with moisture content. They also found that thermal conductivity varies linearly with density.

Shaw and Baver (51) designed a soil moisture meter based on a indirect measurement of thermal conductivity of the soil. A Wheatstone bridge circuit was used to compare the electrical conductivity of two resistors having a high coefficient of thermal resistivity. One resistor was placed in the sample of unknown moisture content and the other was placed in a dry sample of the same soil. Sufficient current was passed through the resistors to cause significant temperature rise.

The temperature of the resistors at a given time after the current started to flow is a function of the ability of the resistors to dissipate heat, which is determined largely by the thermal conductivity of the materials surrounding them. The resistor in the dry soil will have a higher temperature than the resistor in the wet soil because the thermal conductivity of dry soil is less. The temperatures of the two resistors are compared by comparing their electrical conductivity with the bridge circuit.

The meter developed by Shaw and Baver gave a fairly reliable indication of moisture content; however, from 30 minutes to 2 hours were required for it to yield a stabilized reading. By taking a reading at a pre-determined time after the current flow through the resistors was started, an indication of moisture content was obtained from previous calibration for that period of time. By this procedure, a reading could be obtained in 10 to 15 minutes.

One of the greatest probable sources of error in this method is caused by the fact that when the temperature of the material is increased next to the resistor in the wet sample, the partial pressure of the water vapor at this point will be increased and water vapor will be transferred away from the resistor to the colder parts of the sample. This means that the moisture content of the sample changes at the point of measurement. This effect can be reduced by limiting the temperature of the resistors and the time of heating.

The principal advantage of the thermal conductivity method is that it is not affected by the salt content of the material tested.

Mechanical Method. Mechanical means of determining moisture content have not received a great amount of research in a formal way; however, these means are probably the oldest method man has used to estimate moisture, particularly with regard to farm forage and grain crops. The bite test on grain and the twist or thumbnail test on hay are methods which depend upon the mechanical properties of the product tested.

Nichols (52) patented a mechanical device for determining the moisture content of raisins and such materials. His apparatus consisted of a cylinder in which the sample was compressed by a known weight. The percentage of compression was determined by a suitable mechanical linkage which was calibrated to indicate the moisture content of the product.

Brough et al. were granted a British patent for a device which indicated the moisture content of webs of paper or cloth. This device transmitted sound waves on one side of the web and received them on the other. The exact variable measured was not indicated in the literature available.

Nuclear Methods. In recent years there have been two methods proposed which detect the presence of hydrogen nuclei in material as an index of moisture content, the neutron scattering method and the nuclear resonance absorption method.

Belcher et al. (54) measured the moisture content of soil by a neutron scattering method. Fast neutrons emitted from a radium-beryllium or a polonium-beryllium source are allowed to pass into the soil to be tested. In passing through the material, the neutrons collide with the atomic nuclei of the material. In these collisions, they lose some of

their energy and are scattered in all directions. When a neutron collides with a heavy neuclei such as that of silicon, much less kinetic energy is transferred from the neutron than if it hits a light nuclei such as that of hydrogen. (Analogy: A billiard ball hitting another billiard ball head-on loses all of its kinetic energy. If it hits a heavier object such as a bowling ball, it loses little of its kinetic energy).

Thus if more hydrogen nuclei are present in the material, a greater number of slow neutrons will be scattered back to the vicinity of the source. By locating a radiation counter sensitive to slow neutrons near the source, a count of slow neutrons may be obtained which is a function of moisture content. The counting rate of slow neutrons was found by Belcher to be essentially in direct proportion to the moisture content. The accuracy of the method when used on soils in situ was estimated at 1% moisture.

Non-homogeneities such as rocks in the soil, salt content, or the humus content of organic soils did not greatly effect moisture readings by this method. The radiation hazards involved in using this method are recognized by the authors. A source of about 8 millicuries activity is used in this work.

Since the cost of the apparatus is quite high and the equipment rather complex, this method does not show great promise as a field method for use by farmers. A high-quality radiation counter, including a Geiger-Muller tube, counting circuit, and scaling circuit, as well as a rather expensive radioactive source are required.

Shaw and Elsken (55) showed a linear relation between the moisture

content of several vegetable materials, viz. apple, potato, and maple wood, and measurements of the nuclear magnetic resonance absorption of the hydrogen nuclei. The sample was placed in a unidirectional field of 3500 gauss and also in a second field of constant radio frequency. With a favorable relationship between the strength of the unidirectional field and the frequency of the radio-frequency field, the hydrogen nuclei absorb energy from the radio-frequency field at a maximum rate; i.e., resonance occurs. The greater the number of hydrogen nuclei present, the greater is the absorption of energy from the field, as indicated by an increased current flow through the radio-frequency coil producing the field. Shaw used a third 60-cycle field to sweep the effective value of the unidirectional field through the resonance value and to facilitate the indication of the magnitude of the peak of the radio-frequency current on an oscilloscope.

A sample 0.3cm. by 5cm. long was used in the tests by Shaw and Elsken. The accuracy of the method as a means of moisture determination was found to be 1% moisture. Correction for shrinkage of the sample was necessary when a series of tests were conducted on a single sample which was allowed to dry between readings.

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THE PHYSICAL NATURE OF FORAGE AND GRAIN CROPS WHICH AFFECTS MOISTURE DETERMINATION

Forages

The greatest problem in the determination of the moisture content of hay curing in the field is that of the non-uniformity of its moisture content. Obtaining representative samples for moisture testing is very difficult. The moisture content of all the hay of a given variety in a field is essentially the same at the time of cutting. However, the rate of drying after cutting is dependent upon a number of factors and differs at various points in the hay mass. Some factors which affect the drying rate of cut hay plants are:

1. The parts of individual plant involved.
2. The relative opening of the stomates or pores in the leaves.
3. The atmospheric conditions to which the cut plants are exposed.
4. The species of hay.
5. The rankness of growth.
6. Topography of the field.

The rate of drying of cut plants takes place mostly through transpiration, a natural process which continues after cutting. The rate of transpiration of moisture from the leaves is much greater than from the stems. In fact, it has been shown that the leaves aid in the drying of the stems by transpiring not only the moisture which is contained in

the leaves when the plant was cut, but also part of the moisture of the stems (1). As the leaves become drier, moisture moves into the leaves from the stems by cohesive and capillary action. Transpiration from the leaves is greater because of the greater surface area exposed and the greater moisture permeability of the leaf surfaces.

The rate of transpiration from the leaves is to a great extent dependent upon the degree of contraction of the stomates, the very numerous small openings in the leaf surface through which most transpiration occurs. The stomates of uncut plants have been found to open and close periodically throughout the day. The opening of the stomates does not remain fixed after cutting. They close at a rate dependent upon the atmospheric conditions to which the cut plant is exposed. Jones and Palmer (1) found that the stomates of cut hay curing in the windrow stayed open longer than the stomates of hay in the swath. They also found that hay raked into a windrow two hours after cutting was drier at the end of the day than hay left in the mower swath.

For any given opening of the stomates, the rate of transpiration from curing hay is also dependent upon the partial pressure of the water vapor in the atmosphere. Periods of highly humid weather result in reduced rates of transpiration, since the atmospheric water vapor pressure is more nearly at equilibrium with the pressure of water vapor inside the plant.

From the standpoint of hay quality, windrowing soon after cutting is desirable. When hay is windrowed, the conditions to which individual plants are subjected are highly variable. These conditions range from extensive exposure to sunlight and wind at the top of the windrow to

rather close confinement at the bottom of the windrow. For this reason, hay at the top of the windrow dries much faster than hay at the bottom.

The species of hay also affects the drying rate to some extent. In hay mixtures, this factor contributes considerably to the non-uniformity of moisture content. For example, in alfalfa-bromegrass mixtures, the alfalfa usually dries at a slower rate than the bromegrass, due to the slow drying rate of the alfalfa stems. However, in grasses having very heavy stems, such as a rank growths of Johnson grass, the drying rate is much lower than in alfalfa (1). Rankness of growth is in turn affected by soil conditions which may vary widely in a given field and result in non-uniformity in the moisture content of the hay when curing.

Grains

Considerable non-uniformity of moisture content exists in grain, particularly in that which has been recently harvested. However, it is much more uniform in moisture content than hay and is therefore easier to test for moisture.

Soil conditions may affect the rate of maturing of grains. Since soil conditions frequently vary throughout a given field, the maturity and the moisture content of the grain may likewise vary.

Non-uniformity of moisture content within the individual kernels of grain also exists and affects the reading of some types of moisture meters. The moisture content is normally unevenly distributed within the grain kernel, the germ having the highest moisture content. Moisture may also be abnormally distributed in grain which has been recently

subjected to drying by rapid artificial means. In this case, the outer surfaces may be abnormally dry, while the inner parts are still relatively wet. Non-uniformity of moisture content is usually more pronounced in the larger grains such as corn than in the smaller grains such as wheat, since the smaller grains equalize in moisture content more rapidly.

Properties of Forages and Grains Which Vary with Moisture Content

Moisture content affects nearly all of the physical properties of forages and grains or any other hygroscopic material. Among the physical properties which are affected by moisture content are:

1. Electrical resistance or conductivity
2. Dielectric properties
3. Equilibrium relative humidity of the air in a closed vessel containing the material.
4. Mechanical strength
5. Thermal conductivity
6. Specific gravity

Each of the above factors have been used as bases for rapid indirect methods for determining the moisture content of some materials. The principal source of error in all of these methods lies in the fact that there are other factors besides moisture content which also affect the physical properties listed. For example, temperature as well as moisture content affects most of the physical properties of materials.

The rather non-exclusive effects which variations in moisture content have upon the properties of materials and the great non-uniformity of moisture content in forages and grains makes the problem of developing simple, rapid methods of moisture determination a challenging one.

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(1) Jones, T. N. and Palmer, L. O., "Field Curing of Hay as Influenced by Plant Physiological Reactions", Part I, Agr. Eng., v 13, pp. 199-200, 1932. Part II, Agr. Eng., v 14, pp. 156-158, 1933. Part III, Agr. Eng., v 15, pp. 198-201, 1934.

PRINCIPAL DESIGN REQUIREMENTS OF FARM MOISTURE METERS

Accuracy

High accuracy is one of the most obviously desirable attributes of a successful farm moisture meter or any measuring device. The accuracy required in farm applications seems quite variable with the crop tested, the range of moisture content, and the purpose for which the test is made.

It should be generally assumed that a moisture meter developed for farm use would not be used in buying and selling grain on a moisture content basis. Therefore, the accuracy required of a moisture meter in a given situation depends mainly upon the tolerances of the specified safe storage moisture contents for the products involved. No such tolerances have been found set forth in the literature available; therefore, no very sound basis can be given for estimates of the required accuracy of moisture meters. A maximum error of one moisture percentage point seems allowable for testing grain and field cured hay to determine its storage quality.

Hay which is to be partially mow-cured need not be moisture tested so accurately, since observations of the hay temperature are probably the most practical way of determining when the drying fan may be shut off. For testing hay to determine when to place it in the mow for mow curing, an error of moisture determination of three moisture percentage points should be allowable. For testing hay for silage or for determining when to start raking high moisture hay, an error of five moisture

percentage points should be allowable.

The above estimates of the allowable error in determining the moisture content of farm products are intended to include the sampling error. An exact indication of the moisture content of one sample does not necessarily tell the farmer the moisture content of the whole field of hay or the whole lot of grain.

Rapidity

Since the moisture content of agricultural products is so non-uniform, a farm moisture meter should be rapid enough to take a large number of samples within the length of time which a farmer would want to spend on moisture determination. This is particularly true of hay where non-uniformity of the moisture content is the greatest. It is doubtful that many farmers would be willing to spend longer than fifteen minutes in determining the moisture content of a field of hay; therefore, no more than one to two minutes should be required to determine the moisture content of one sample.

Simplicity of Operation

The ideal farm moisture meter might be described as a device which reads directly the average moisture content of any amount and any type of farm product when a probe is placed in the product. It is very doubtful that this ideal device will be realized for some time; however, there are number of features which may be incorporated in a farm moisture meter to keep its operation as simple as possible.

The use of loose conversion charts in the field is undesirable. Whenever possible, moisture measuring equipment should be calibrated

directly in moisture content. In order to allow for different calibrations for different products, a removable scale face made of a transparent material could be used for each product for which the meter is calibrated. Tuning or frequent standardization of electric meters is objectionable. The necessity for these operations should be avoided in the design of electric meters.

Weighing samples, although not impossible, is not a very desirable operation to be performed in the field. Arithmetic computation should not be necessary to determine the moisture content from the indication of the equipment.

Cost

The most efficient of moisture meters will contribute little to the solution of the problem if the farmer does not buy it because it costs too much.

It is very difficult to say what the typical farmer can afford to pay for a moisture meter and it is even more difficult to say what he actually will pay for one. One might consider what he can afford to pay for a moisture meter in the light of the cash value of the crops he would test with it each year. In such a consideration, the cost of the meter might be considered as insurance against spoilage of grain. In this light, a cost of a few hundred dollars might not seem unreasonable for a large farm operation.

From a more realistic viewpoint, one observes what a farmer will pay for a moisture meter. It is doubtful that a moisture meter costing the farmer more than fifty dollars would find wide acceptance in the near future. However, one small manufacturer is selling his output of

electric farm moisture meters which have a retail cost of $135.00. Since the number of these meters in use is less than 500, the success of this manufacturer does not necessarily indicate the present farm market for moisture meters. However, the success of this manufacturer does give an indication of the future market for such equipment. For this reason, it does not seem desirable to limit the work of this study to methods which would sell for less than fifty dollars.

In evaluating a method of moisture determination from the standpoint of cost, one should consider that most items of small equipment such as moisture meters have a retail price of about four times the cost of labor and materials in manufacturing them.

Versatility

A farm moisture meter should be applicable to most farm uses with a minimum of necessary changes in the apparatus. Not only should it be applicable to the principal forage and hay crops, but it should also be capable of testing each crop in the ranges of moisture content which are of interest in the various harvesting and curing procedures. A successful moisture meter should be capable of determining the storage quality of grain which has been recently dried as well as grain which has been recently harvested. A moisture meter should also be capable of giving a satisfactory test on forage crops of widely different moisture contents, from forage for silage at 60 to 75% moisture to hay for unventilated storage at less than 25% moisture content.

INVESTIGATION OF EXHAUST OVEN METHODS

A new type of exhaust oven was developed which is capable of rapidly drying forage and grain samples without detrimental burning and without special attention from the operator. The exhaust oven method was tested in the field and in the laboratory to determine the following operating characteristics:

1. Time to dry samples of various crops
2. Drying temperatures at various tractor speeds and exhaust temperatures
3. Dry matter loss of the sample
4. Collection of products of combustion by the sample
5. Drying effectiveness
6. Effect of scale accuracy

Principle of Operation of the Exhaust Oven

The first use of an engine exhaust for drying moisture determination samples was reported by Dexter (1). His oven, for which a patent was granted (2), consists of an open-ended cylinder which contains the sample as the exhaust gases are passed directly through it.

The procedure outlined by Dexter includes selecting a representative sample, weighing it in the cylinder on a platform-type spring scale, attaching the oven to the exhaust pipe, and heating the sample until a constant weight is attained. The initial and final net sample weights are used to calculate the moisture content.

The sample temperature is measured by a thermometer and controlled at about 140°C by adjusting the engine speed. To prevent burning during the heating process, the sample is turned end-for-end once per minute. Six minutes were required to dry a sample of mixed grass of 15.8% moisture content and ten minutes were required to dry a sample at 38% moisture content. Ten minutes were required to dry a sample of oats of 27.3% moisture content.

Dexter published a diagram for the construction of the exhaust oven by farmers. The oven was later manufactured and marketed commercially.

A similar design for an exhaust oven for home construction was reported by Hore and Ayers (3). They also developed plans for the home construction of a balance for use with this method.

Tests of the Dexter exhaust oven showed that a successful moisture determination can be made with this oven; however, a considerable amount of attention from the operator is required to prevent burning of the sample, especially when testing forages. Reversing the position of forage samples in the oven must be done frequently and attention must be given to the engine throttle setting in order to control the oven temperature as indicated by a thermometer. These general observations of the Dexter oven were confirmed by conferences with users of the device.

Simplification of the procedure used with the exhaust oven method seemed possible if a means could be found to reduce the temperature of the gas passing through sample and, at least to some extent, to make the temperature less dependent upon the throttle setting. The diagram of Figure 1 shows a new type of exhaust oven developed under this project. An injector pump assembly (commonly called a "jet" pump) is

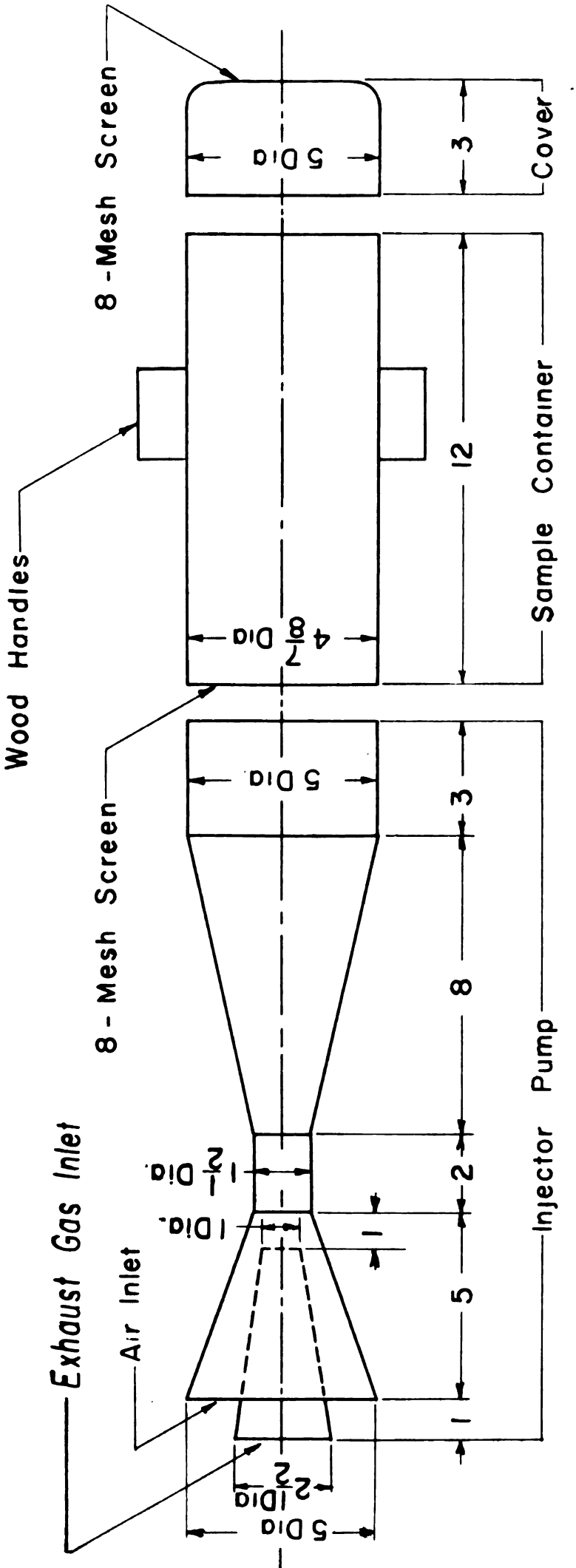


FIGURE 1. INJECTOR TYPE TRACTOR EXHAUST OVEN.

located between the engine exhaust and the sample container, which is similar to that used by the Dexter oven. The engine exhaust gas is directed into the nozzle of the injector pump where its velocity is increased by a reduction in the cross-sectional area of the passage. The high-velocity jet of exhaust gases thusly directed into the throat of the pump induces a flow of ambient air which is mixed with the exhaust gas and passed through the sample container. As a result, the mixture flowing through the sample is lower in temperature and flows at a higher rate than if the exhaust gas alone were passed through the sample. Both of these characteristics are desirable for obtaining rapid drying of the sample without burning.

Kravath (4) described applications of venturi ejectors where air under pressure is used as the primary fluid passing through the jet and the secondary fluid, the fluid to be transported, is also air or predominantly so. He presented experimental and theoretical analyses of a low pressure air ejector of the type which might be used to withdraw large volumes of air containing corrosive or errosive materials from factory space. This type of ejector is driven by outdoor air from a centrifugal fan. Since the ejector described by Kravath operates principally on air at low pressures, the analyses presented is partially applicable to the design of an injector-type exhaust oven. Further analyses and design data are presented by Keenan (5) and Kastner (6) for air ejectors with driving pressures from 20 psi. upward.

Apparatus

Figure 2 shows the injector-type exhaust oven installed on a farm tractor. The muffler of the tractor has been removed to make the sample container more accessible. Connection of the oven to the exhaust pipe was accomplished in the test model by means of a tapered fitting. This allows a degree of versatility in the application of the oven to various tractors with different exhaust pipe diameters. The oven can be attached to the tractor by placing the tapered fitting over the exhaust pipe and pushing downward firmly with a twisting motion. This arrangement is similar to that used on a commercial model of the Dexter exhaust oven.

Figure 3 is a photograph of the basic equipment necessary to determine the moisture content of hay and grain with the ejector-type exhaust oven. Shown with the ejector assembly are a long sample container for testing hay, a short container for testing grain, and a Hanson dietetic scale.

Wooden handles have been provided on the sample containers to allow handling them without the use of gloves. The sample container for hay is enclosed at either end with 8-mesh screen to confine the sample and the sample container for grain is similarly enclosed with 16-mesh screen. Both sample containers are made from sheet aluminum in order to keep their weight at a minimum and thereby maintain better weighing accuracy.

The Hanson dietetic scale was used in the field tests of this apparatus. An O'haus laboratory balance was used in some field tests and in all laboratory tests to check the accuracy of the less costly Hanson scale. The rated sensitivity of the Hanson dietetic scale is 1.0 gram. The rated sensitivity of the O'haus scale is 0.1 gram.

Fig. 2. The injector-type exhaust oven installed on a farm tractor.

Fig. 3. Left to right: The injector-type oven, the long sample container for hay, the short sample container for grain, and the Hanson dietetic scale.

Figure 4 shows the apparatus used in testing the performance of the exhaust oven in the laboratory. Iron-constantan thermocouples were used to measure temperatures at various points in the oven and sample container. These thermocouples were connected to the potentimeter by means of a manual selector switch. A tachometer was used to measure the speed of the engines.

Test Procedure

The injector-type exhaust oven was tested by two general procedures: by field tests where the operation of the method was observed under farm conditions and by laboratory tests where more complete instrumentation could be employed.

Field Test Procedure: Tests of the exhaust oven applied to forage testing were conducted using the following procedure:

1. Representative samples were selected by making up each sample from several small "pinches" of forage gathered from several locations which seemed representative of the field.

2. The empty container and lid were placed on the scale and the scale was balanced or the rotating dial was set to zero when the Hanson scale was used. The scales remained so adjusted until the conclusion of the test.

3. The samples were folded and cut with a knife into two or three lengths to fit the length of the sample container.

4. 150 to 200 grams of the sample were placed in the container and weighed. The net weight of the sample was indicated directly by placing the container and sample on the scales.

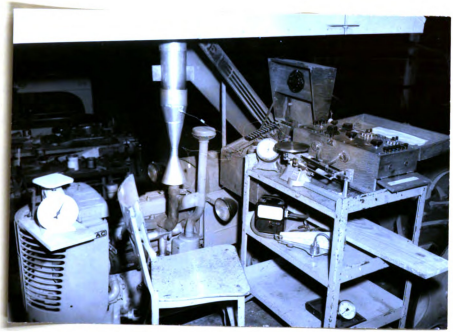


Fig. 4. Apparatus for testing the performance of the exhaust oven in the laboratory.

In the field tests of the exhaust oven, numerous recordings of heating time and oven temperature were also made. The oven was given further field trials by Mr. Bruce Hopkins who used it throughout the summer season of 1953 as a guide for his field operations in forage processing research.

Laboratory Test Procedure: Direct determination of the accuracy of this method is difficult, particularly in the case of forages. One cannot readily employ the usual methods of taking duplicate samples for testing by standardized oven methods, since two samples of forage taken simultaneously and adjacently in the field will vary considerably in moisture content as shown in other work of this project. For this reason, the evaluation of the accuracy of this method was based upon separate determinations of the effects of various factors which could conceivably bring about errors in the moisture determinations. These factors are enumerated as follows:

1. Incomplete drying of the sample
2. Loss of dry matter
3. Deposit of combustion products on the sample
4. Weighing inaccuracy

The extent to which the tractor exhaust oven is capable of drying the sample was determined by running standard laboratory oven tests on samples previously heated by the exhaust oven. Any further loss in weight in the sample during the laboratory oven test was assumed to be residual moisture content that the exhaust oven did not remove. Hay samples were heated at 220°F for 48 hours in a laboratory air oven. Grain samples were heated at 220°F for 96 hours in an air oven. One

series of hay samples was also heated in a vacuum oven for 24 hours at 212°F.

Dry matter loss could taken place through mechanical loss of leaves or kernels and by decomposition due to high temperatures. Mechanical losses can be directly observed and prevented by the proper selection of screen in the sample chamber. Forages are generally considered to be more subject to dry matter loss due to decomposition at high temperatures than are grains. To evaluate the extent of this loss, protein and sugar analyses were made on a series of forage samples which had been dried in the exhaust oven. Similar analyses were made on undried samples and the results were compared. Further qualitative evaluation of dry matter loss was made during field and laboratory tests by observations of color changes and other signs of burning the sample.

The weight of the deposit of combustion products on the sample in the exhaust oven was determined by means of a simple tests. One-hundred grams of No. 00 steel wool was placed in the long sample container, heated in the oven for three minutes and weighed. This period of heating was intended to drive off any moisture entrained in the steel wool. The steel wool and sample container were then placed in the oven and weighed again at 5, 10, and 15 minutes later. An increase in weight observed was assumed to be due to the products of combustion. To simulate an extreme condition such as a very smoky exhaust, the carburetor choke was engaged until the engine mis-fired badly and was visibly smoking at the exhaust. The steel wool was again placed in the oven and reweighed after 10 and 20 minutes.

During a large number of the above laboratory tests, duplicate

weight determinations were made, first with the Hanson dietetic scale and secondly with the Ohaus triple-beam laboratory balance. At approximately every tenth weight determination, the Hanson scale was standardized at a point within 50 grams of the weight to be measured. This was done by means of standard scale weights and was done in addition to the initial zero adjustment of the scale. The corresponding weight determinations made by the Hanson and Ohaus scales were then statistically analyzed to determine the standard error of estimate of the Hanson scale in comparison to the Ohaus scale.

Test Results

Field Tests Application of the new exhaust oven in the field demonstrated that moisture determinations could be made on forage in the field with minimal attention required of the operator during the drying process. It is possible for the operator to go about other chores such as machinery lubrication while the sample is drying.

Errors in determining the moisture content of a field of hay by this method are most likely to occur from non-representative sampling. There is a tendency for operators to select their sample from but one or two locations and not to test enough samples. Inaccuracies in weighing in the field can be caused by wind and poor adjustment and failure to level the scale.

The aforementioned application of the oven by Mr. Hopkins for guiding forage processing research required that the method be accurate and rapid enough to follow the drying progress of cut forage in the

field. Moisture data from the oven method was used as a guide for raking and baling operations. After baling, core samples of the hay were taken and tested in a laboratory oven. Agreement between the field and laboratory determinations was generally satisfactory. Use of the exhaust oven in future research on this project is anticipated.

Laboratory Tests Results of some of the laboratory tests of the exhaust oven are shown in Figures 5 to 8. In these curves, temperatures and sample weights are plotted against time from the start of drying. The points at which the temperatures were taken are shown in the inserted diagram of Figure 5. The subscript designations of temperatures are consistent through Figure 8. These tests were conducted using a Case Model VAC tractor which has a rated engine speed of 1425 r.p.m. and a displacement of 231 cubic inches.

The data of Figure 5 was taken with the engine running at 750 r.p.m., a normal idling speed. The drying was considered complete at the end of 9 minutes. The maximum sample temperature was 255°F. A temperature difference ($T_1 - T_2$) of approximately 350°F was observed between the exhaust gas temperature T_1 and the temperature T_2 of the exhaust gas and air entering the sample. This temperature difference is a measure of the effectiveness of the injector in reducing the sample temperature and increasing the air flow through the sample.

Figure 6 shows data taken with a sample similar to that of Figure 5. The tractor was run at 1250 r.p.m. or at about two-thirds of full throttle. The drying time was reduced to five minutes. The sample temperature did not exceed 310°F and the temperature difference ($T_2 - T_1$) was approximately 400°F.

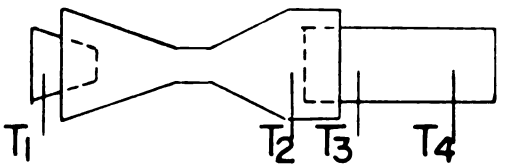
Figure 5

EXHAUST OVEN PERFORMANCE

Engine Speed - 750 R.P.M.

Second Cutting Alfalfa

M.C. 51.8%



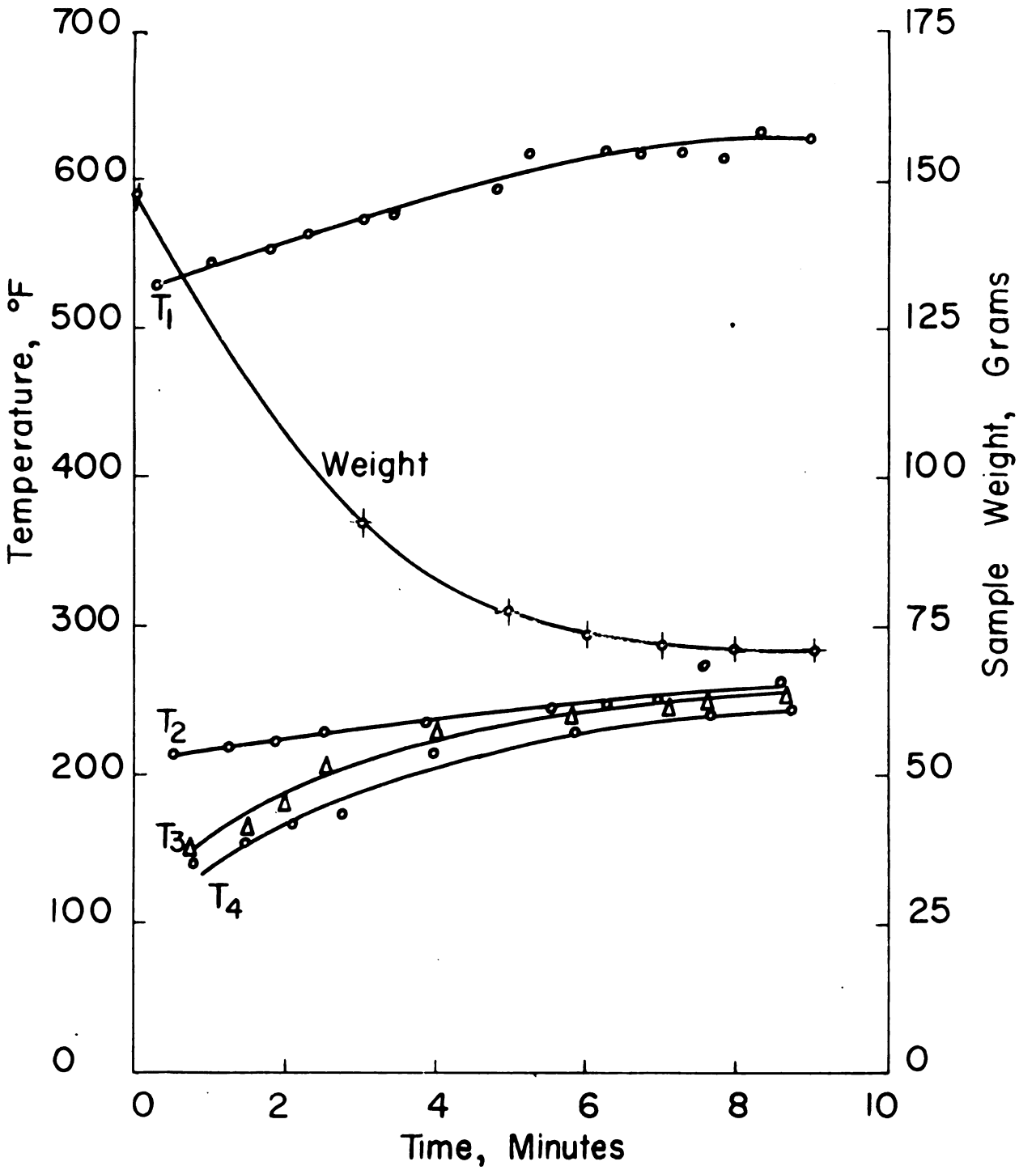
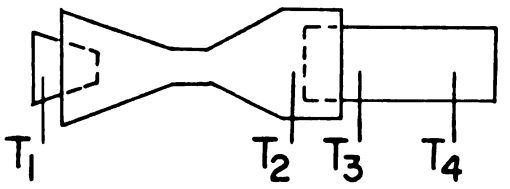


Figure 6 — EXHAUST OVEN PERFORMANCE



Engine Speed - 1250 RPM

Second Cutting Alfalfa - M.C. 51.8 %

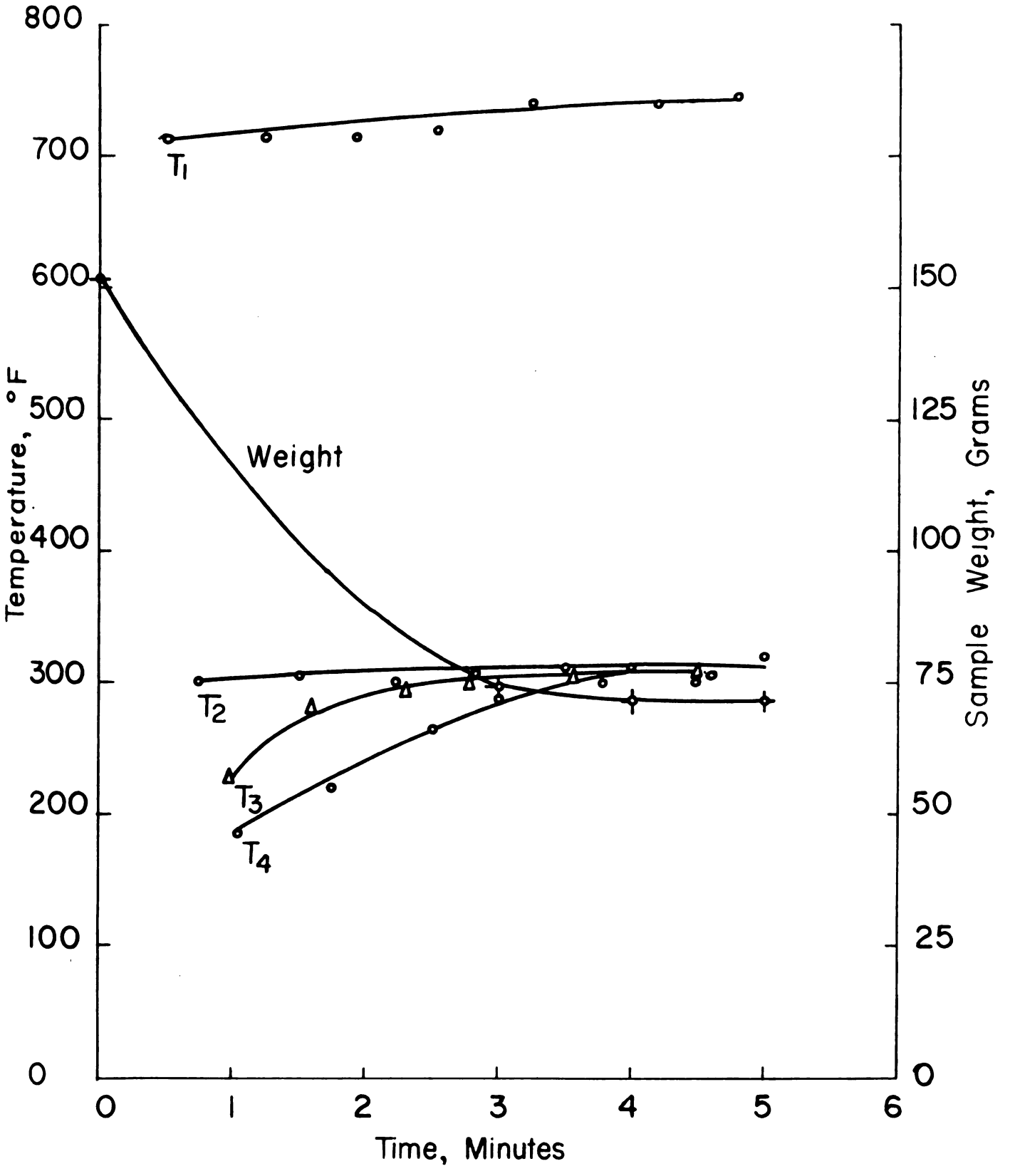
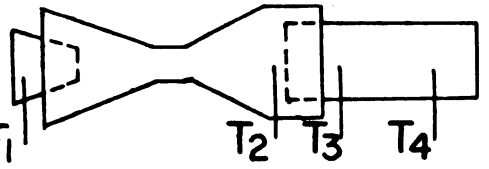


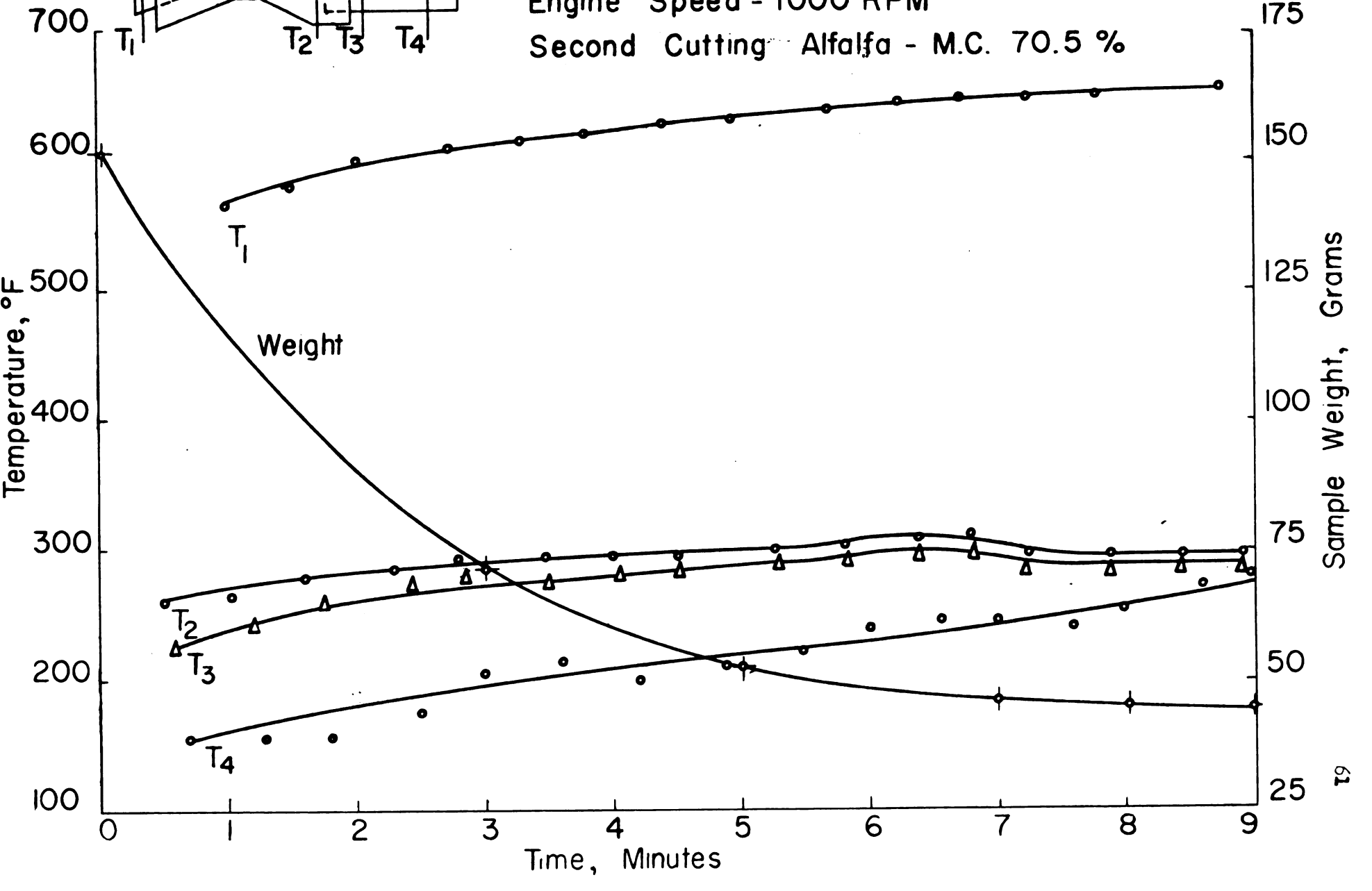
Figure 7

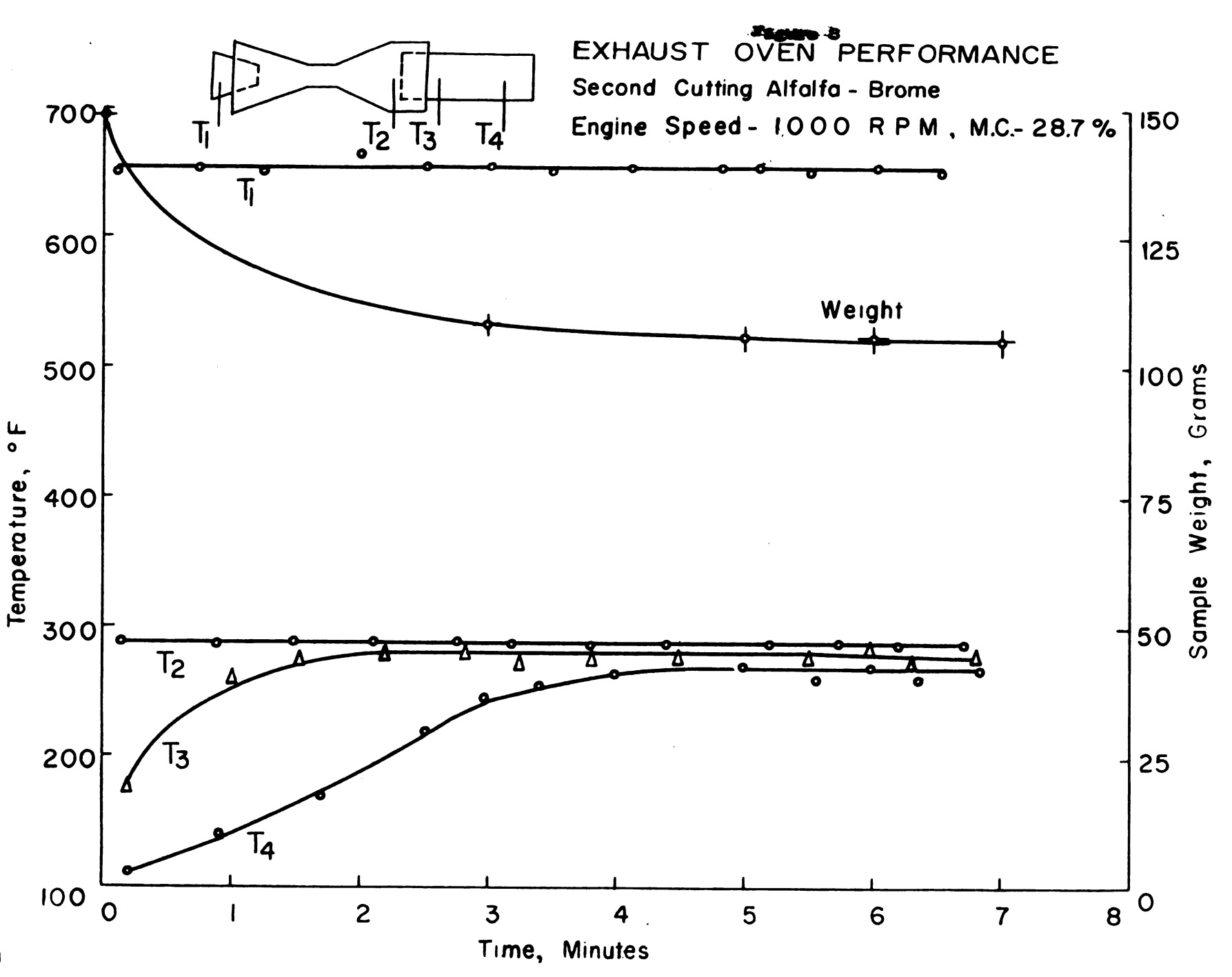
EXHAUST OVEN PERFORMANCE

Engine Speed - 1000 RPM

Second Cutting Alfalfa - M.C. 70.5 %






EXHAUST OVEN PERFORMANCE
Second Cutting Alfalfa - Brome
Engine Speed - 1,000 RPM, M.C.- 28.7 %
T1
T2
T3
T4
Weight
Temperature, °F
Sample Weight, Grams
Time, Minutes
700
600
500
400
300
200
100
150
125
100
75
50
25
0
0
1
2
3
4
5
6
7
8

The curves of Figure 7 and 8 were taken with an engine speed of 1000 r.p.m. Figure 7 shows that nine minutes were required to dry a sample of alfalfa at 70.5% moisture content. Figure 8 shows that seven minutes were required to dry a sample of alfalfa-brome mixture at 28.7% moisture content. Other tests indicated that the performance of the oven was essentially the same with alfalfa as with alfalfa-brome mixtures.

Figure 9 and 10 represent operating data from grain tests made with the exhaust oven. The drying times for the larger grains such as corn and beans are much longer than the drying times for the smaller grains such as oats and wheat. The air flow through the oven is great enough at the higher engine speeds to cause partial suspension of the sample in the air stream with good agitation resulting.

Static pressures measured with a manometer ranged from 1.0 to 1.5 inches of water in the tractor exhaust pipe, depending upon the speed of the engine. Static pressures up to 0.5 inches of water were measured at the inlet to the sample container. These static pressures depend upon the engine speed and the size of the sample being tested.

The injector-type exhaust oven was tested also on a Farmall Super C and John Deere Model 70 tractor. The performance on the Farmall was essentially the same as on the Case tractor used in previous tests; however, operation of the oven was quite different on the John Deere tractor. The exhaust temperatures (T_1) measured on the John Deere were never higher than 380°F at no-load conditions even at full throttle.

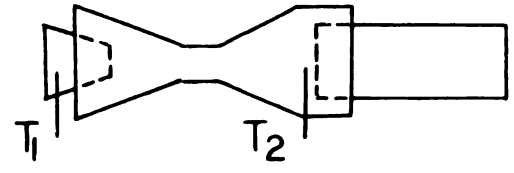
Further investigation revealed that the John Deere engines do not fire regularly on both cylinders when operating at high speed with no

Figure 9

EXHAUST OVEN PERFORMANCE

Engine Speed - 1000 R.P.M.

Corn Sample - M.C. 16.5 %



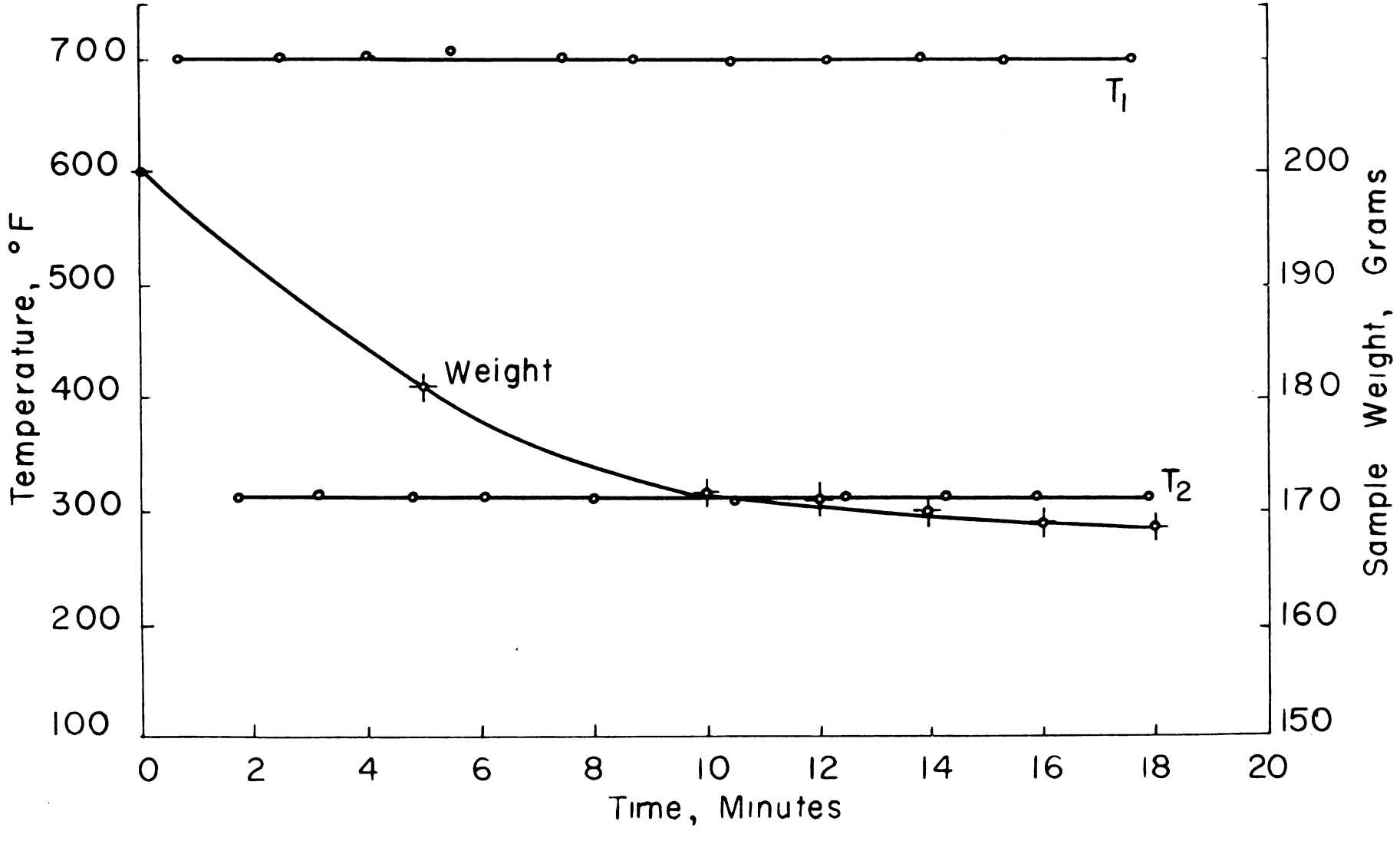
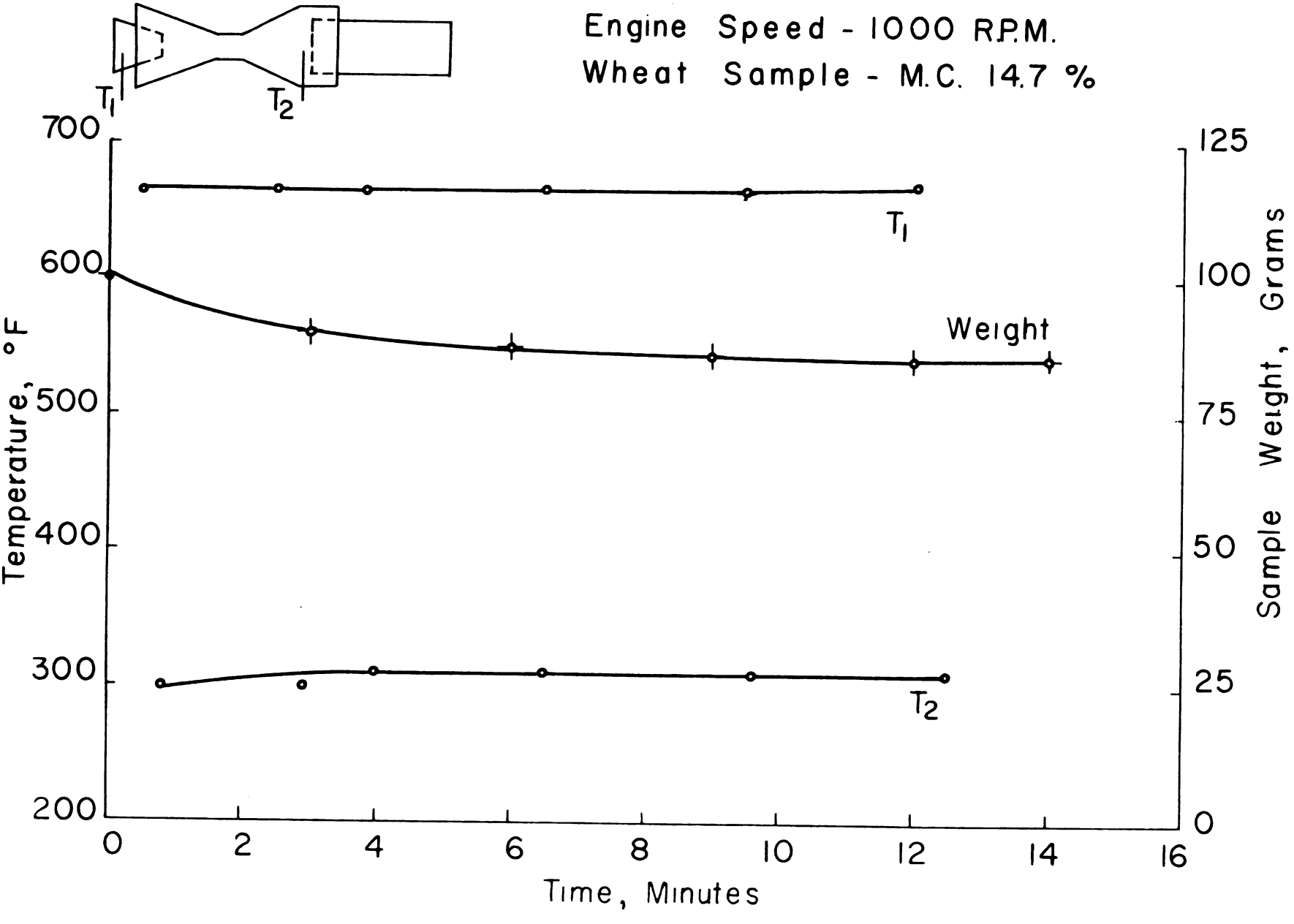


Figure 10

EXHAUST OVEN PERFORMANCE

Engine Speed - 1000 R.P.M.

Wheat Sample - M.C. 14.7 %



load on the engine. This can be demonstrated by removing one spark plug cable and noting the change, or lack of it, in the speed and sound of the engine. The low exhaust temperatures are apparently due to one cylinder exhausting an unburned mixture. The latest John Deere tractors are equipped with twin carburetors which, if properly adjusted, allow both cylinders to fire evenly under no-load conditions. The unusually low exhaust temperatures of the John Deere tractor resulted in low sample temperatures. Approximately twice the usual time was required to dry samples with the injector-type exhaust oven on the John Deere tractor.

Residual Moisture Determinations Samples dried in the above exhaust oven tests were further tested by placing them in a laboratory air oven at 220°F for a period of 48 hours for hay and 96 hours for grain. Further loss in weight was assumed to be equivalent to the moisture which the exhaust oven failed to remove, although some dry matter was probably lost in the laboratory oven. The residual moisture was expressed as a percentage of the original (wet) sample weight and calculated as follows:

$$\% \text{ Residual Moisture} = \frac{\text{Exhaust oven dry weight} - \text{Laboratory oven dry weight}}{\text{Original sample weight}}$$

Since percentage residual moisture and the wet basis moisture content are calculated on the same basis, the residual moisture content may be considered as a correction factor for the moisture content and added directly to it.

Residual moisture data for several tests of the exhaust oven on hay and grains are shown in Table XII of the Appendix. Table II summarizes

this data and presents the arithmetic mean and the standard deviations of the moisture residuals. The moisture residual values for hay and oats are for the most part negative, since a gain in weight was experienced during the laboratory oven tests. This occurance is not directly explainable from the data. A possible explanation is that moisture was re-absorbed during the time elapsed between removal from the exhaust oven and placement in the laboratory oven and the 220°F temperature of the laboratory oven may not have removed this water. Two hay samples were heated at 212°F for 24 hours in a vacuum oven after being heated in the exhaust oven and laboratory air oven. Less than 0.1% further weight loss occurred.

TABLE II

SUMMARY OF MOISTURE RESIDUAL DATA FOR HAY AND GRAIN

Crop Tested	Average Residual Moisture Content	Standard Deviation of the Average Residual Moisture Content
Alfalfa & alfalfa-brome Hay	-1.36	1.04
Oats	-0.10	0.09
Corn	1.30	0.30
Corn*	2.34	0.71
Wheat	1.12	0.92
Navy beans	0.96	0.05

*This series of samples was adjudged dry by the constant weight indication of the Hanson spring scale. All other samples in the table were adjudged dry by the Ohaus balance when two readings constant within 0.5 gram were observed.

Larger positive moisture residuals were observed from all the grain samples except oats. This is apparently due to differences in the moisture permeability of the kernel material. An attempt was made to reduce the moisture residuals in grain samples by grinding or crushing

the sample and heating it in a sample container made from fine screen. The method was unsuccessful because screens which were fine enough to stop the grain from blowing out were so fine they seriously reduced the air flow.

Dry Matter Loss

Qualitative observations of dry matter losses were made by examining the samples tested for excessive darkening in color or other signs of burning. The color photograph of Figure 11 shows a comparison in the color of several samples of alfalfa given various treatments. Sample A is a sample of freshly cut, undried alfalfa. Sample B was from the same lot of hay as Sample A, but was dried to a constant weight in the injector-type exhaust oven. Sample C was field dried to approximately 40% moisture content, then dried to a constant weight in the exhaust oven. Sample D was taken from the same lot as Sample C, but was left in the exhaust oven 15 minutes longer than necessary to obtain a constant weight. Sample E is alfalfa heated in a laboratory air oven for 48 hours at 220°F.

Sample F is alfalfa heated in an exhaust oven with no injector for inspiring ambient air. The tractor ran at the same speed (1000 r.p.m.) as for Samples B, C, & D. Sample F was not turned periodically as is recommended in the use of this type of oven. At the end of three minutes, the sample was not dry at the upper end but was burning so badly at the lower end that the test was stopped. The value of the injector is demonstrated by the obvious difference between the condition of Sample F and Samples B, C, and D; however, it should be emphasized that

Fig. 11. Samples of alfalfa hay: Sample A, freshly cut and undried; Sample B, freshly cut and dried to a constant weight in the injector-type exhaust oven; Sample C, field dried to 40% moisture content, dried to constant weight in the injector-type exhaust oven; Sample D, same treatment as Sample C with an additional 15 minutes in the exhaust oven; Sample E, heated in a laboratory oven for 48 hours at 220 F. Sample F, heated for 3 minutes in an exhaust oven with no injector (Sample was not turned).

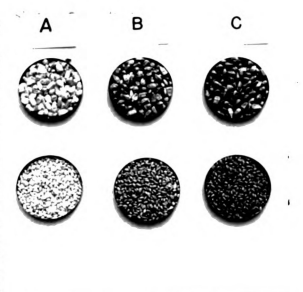


Fig. 12. A, undried grain; B, grain dried for 96 hours at 212 F in a laboratory air oven; C, grain dried in an injector-type exhaust oven.

Sample F could have been successfully dried if a lower engine speed had been used and if the sample had been turned end-for-end periodically.

The color photograph of Figure 12 allows color comparisons of undried corn and wheat (Column A), corn and wheat dried in a laboratory air oven (Column B), and corn and wheat dried in an injector-type exhaust oven (Column C). The samples dried in the exhaust oven were somewhat darker than those dried in the laboratory oven; however, the photograph exaggerates the actual color difference.

A series of protein and sugar analyses of samples of alfalfa hay were made for the purpose of comparing the effects of the exhaust and laboratory ovens on these usually unstable dry matter constituents. The results of these tests as determined by the Department of Agricultural Chemistry are shown in Table III.

TABLE III

RESULTS OF PROTEIN AND SUGAR ANALYSES OF ALFALFA SAMPLES

Sample Number	Where dryed	% Protein, dry basis	% Total sugar, dry basis
1	Not dried*	20.16	8.32
2	Exhaust oven	20.98	7.04
3	" "	21.24	6.24
4	" "	20.77	6.36
Average	" "	21.00	6.55
5	Laboratory air oven	20.65	6.34
6	" " "	21.33	6.15
7	" " "	21.16	5.93
Average	" " "	21.05	6.14

*All samples were dried in a vacuum oven just previous to the protein and sugar determinations. Sample No. 1 was not heated previous to the vacuum oven drying.

The protein content of the samples dried in the exhaust oven was essentially the same as that of the samples dried in the laboratory oven. The average sugar content of the samples dried in the exhaust oven was a little higher than that of the samples dried in the laboratory oven; however, statistical analysis showed that this difference was probably due to chance. All of the samples in this series of tests were re-dried in a vacuum oven in order that the protein and sugar values could be expressed on a common oven-dry basis.

Deposit of Combustion Products

One-hundred grams of steel wool failed to collect enough combustion products to cause a measurable increase in weight during 15 minutes of heating in the exhaust oven. The same steel wool was returned to the oven and the carburetor choke engaged to cause the engine to smoke badly. After 20 minutes under these conditions, the steel wool was blackened with soot at the end nearest the engine, but its weight had increased only 0.2 gram. The sensitivity of the scale used in the above tests was 0.1 gram.

Scale Studies One-hundred and fourteen weight determinations of grain samples ranging in weight from 38 to 200 grams were made with the Hanson Dietetic Scale and the Ohaus Triple-Beam Balance. Statistical analysis of this data showed a standard error of estimate of 1.7 gram for the Hanson scale, i.e., 68% of the weight determinations by the Hanson scale could be expected to agree within 1.7 g. with determinations of the same weights by the Ohaus balance. The Hanson scale tested was not a new scale; it had been used for exhaust oven tests in the hay field for five years and had not necessarily received special care in

handling. The above weight determinations were made in the laboratory and therefore are not subject to significant errors due to wind.

A scale for field use should be mounted inside an enclosed container which would protect both the scale and the sample container from the wind while weighing. Such a container could be made of sheet metal and so designed as to provide a convenient carrying case for the scale as well as the oven and sample container. The scale should be mounted on a rubber pad or other resilient material to reduce shock damage while carrying. A means for locking the scale platform in place while transporting should be provided.

If a spring scale such as the Hanson Dietetic Scale is used, a simple standard weight should be employed for making periodic adjustments of the scale. The dial of the scale should be adjusted first to a zero reading with the empty scale container on the platform. Then the test weight should be placed on the scale and the lever arm adjusted for the correct scale reading. A test weight of 150 grams seems satisfactory, since a great number of weight determinations are made near this value in the application of the exhaust oven. A clip should be provided for securing the test weight to the carrying case when not in use.

Several factors should be considered in the selection of a scale for use with the exhaust oven. Accuracy under the prevailing conditions is of prime importance. The effect of scale error upon the accuracy of the moisture determination can be readily shown by the following derivation of an expression for the error, E, of moisture determination due to a scale error, S.

The true wet-basis moisture content, M, of the sample is expressed by the following:

$$M = \frac{W - D}{W} \times 100 \qquad (1)$$

where W represents the true original sample weight and D represents the true dry weight of the sample.

The actual determination of W may be in error on amount S_w and the determination of D may be in error on amount S_d. Both S_w and S_d may have both positive and negative values. Using the actual determinations of W and D, the indicated moisture content is:

$$M_a = \frac{(W + S_w) - (D + S_d)}{W + S_w} \times 100 \qquad (2)$$

The error in the moisture determinations, E, is:

$$E = M - Mo = M - \frac{(W - D) - (S_w - S_d)}{W + S_w} \qquad (3)$$

If S_d and S_w are assumed to be equal in magnitude but opposite in sign,

$$|S| = |S_w| = |S_d| \qquad (4)$$

and the error, E, can have two maximum values, E_1 and E_2:

$$E_1 = M - \left(\frac{W - D + 2S}{W + S}\right) \times 100 \qquad (5)$$

$$E_2 = M - \left(\frac{W - D - 2S}{W - S}\right) \times 100 \qquad (6)$$

The units for E in Formula (3) would be moisture percentage points (wet basis) if M and Mo were calculated on exactly the same basis. This is not quite the case in Formula (3), since the basis for M is W and the basis for Mo is $W + S_w$. If S_w is small compared to W, the error in using moisture percentage points as units for E is not great.

To show the effect of the original sample weight and the true

moisture content on the error in moisture determination for a given scale error, equations (5) and (6) should be expressed in terms of M, W, and S. The true dry weight, D, may be expressed by transposing equations (1):

$$D = W\,(1 - M/100), \quad \text{then from equations (5)} \tag{7}$$

$$E_1 = M - \left(\frac{W - W\,(1 - M/100) - 2S}{W + S}\right) x\ 100$$

$$= M - \frac{WM\ \ 200\ S}{W+S} = \frac{WM\ \ MS - WM - 200S}{W + S}$$

$$= - \frac{S(200 - M)}{W+S} \tag{8}$$

A similar substitution of equation (7) into (6) yields the following relation:

$$E_2 = \frac{S\ (200 - M)}{W - S} \tag{9}$$

Equations (8) is an expression for the maximum possible moisture determination error when the error in determining the original sample weight is positive and equal in magnitude to the error in determining the dry weight, the latter error being negative. Similarly, equation (9) is an expression for the maximum moisture determination error when the error in determining the original sample weight is negative and equal to the error in determining the dry sample weight, the latter error being positive.

Inspection of equations (8) and (9) lead to a number of conclusions. E_2 is always greater than E_1, for a given moisture content and scale error; i.e., the maximum moisture determination error is always greater when the error in determining the original sample weight is negative.

For a given original sample weight and scale error, the maximum error is linearly dependent upon the true moisture content of the sample and is highest at the lower moisture contents. For a given scale error and moisture content, the moisture determination error varies inversely with the original sample weight, i.e., for a given scale error, a larger sample weight produces less error in the moisture determination.

Table IV presents calculated values of maximum errors in moisture determination for a scale error of ±1.0 gram with original sample weights of 100 and 200 grams. Actual errors in determining W and D in a given moisture determination are not neccessarily equal in magnitude and opposite in sign; therefore, the values presented in Table IV are higher than usually could be expected in practice.

Moisture Content Calculator Means should be provided for determining the percentage moisture content from the wet and dry sample weights without arithmetic computation. This can be accomplished either by using a specified sample weight with a specially calibrated scale or by using a nomograph or alignment chart.

The former method requires that the operator adjust the original (wet) weight of the sample to a specified value indicated on the scale dial. The scale is so calibrated as to indicate the moisture content directly when the sample is re-weighed after drying. The principal disadvantage in this procedure is the necessity for adjusting the sample weight to a specified value. This is not difficult with grain, but is quite tedious for forages. Special calibration of the scale would add somewhat to the cost of the weighing device.

TABLE IV

MAXIMUM EFFECTS OF A SCALE ERROR OF 1.00 g. ON THE ACCURACY OF MOISTURE DETERMINATIONS

Actual Moisture Content M % W.B.	Actual Original Sample Weight, Grams	Indicated Moisture Content M_1 % W.B.	Indicated Moisture Content M_2 % W.B.	Possible Error $E_1 = M - M_1$ Moisture % pts.	Possible Error $E_2 = M - M_2$ Moisture % pts.
10	100.00	11.881	8.081	-1.881	1.919
	200.00	10.945	9.045	- .945	.955
20	100.00	21.782	18.182	-1.782	1.818
	200.00	20.986	9.096	- .896	.904
30	100.00	31.683	28.283	-1.683	1.717
	200.00	30.846	29.146	- .846	.854
40	100.00	41.584	38.384	-1.584	1.616
	200.00	40.796	39.196	- .796	.804
50	100.00	51.485	48.485	-1.485	1.515
	200.00	50.746	49.246	- .746	.754
60	100.00	61.386	58.586	-1.386	1.414
	200.00	60.697	59.296	- .697	.704
70	100.00	71.287	68.687	-1.287	1.313
	200.00	70.647	69.347	- .647	.653
80	100.00	81.188	78.788	-1.188	1.212
	200.00	80.597	79.397	- .597	.603
90	100.00	91.089	88.889	-1.089	1.111
	200.00	90.547	89.447	- .547	.553

The application of a nomograph for the graphical computation of moisture content in the field can best be made in a form not requiring the manipulation of charts or the recording of weight values. A mechanical nomograph for computing moisture content is shown in Figure 13. The nomograph scales are placed on sheet metal. When the operator has determined the wet weight of the sample, he sets this weight on the left-hand scale of the nomograph by aligning the lower edge of the steel slider with the indicated weight on the wet weight scale. By setting the thumbscrew provided, this adjustment is held in place while the sample is drying. When the dry weight has been determined, the steel rule is positioned with its top edge over the dry weight on the right-hand scale. The moisture content is read on the center scale. The nomograph as shown in Figure 13 is set for a wet weight of 160 grams and a dry weight of 80 grams. It correctly indicates a moisture content of 50% wet basis.

This nomograph could be furnished to the farmer in paper form but it would likely soon become worn or lost in field use. It can be more permanently duplicated on the door of the sheet metal carrying case for the oven apparatus. The nomograph should be placed on the inside of the door in order to prevent mechanical damage to it in transportation.

The nomograph shown in Figure 13 is designed to be most applicable to the moisture testing of forages. If it were applied to grain moisture testing, particularly if the weighing were done to ± 0.1 gram accuracy, the readability of the nomograph would not be great enough to produce accurate results. The readability can be increased by enlarging the nomograph; however, its size must be limited to the size of the

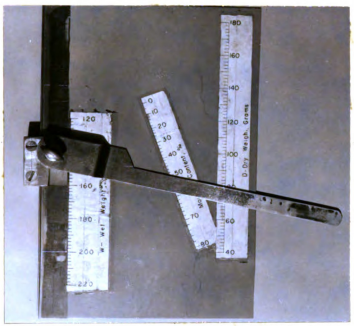


Fig. 13. **A mechanical nomograph for computing percentage wet basis moisture content.**

carrying case. Two nomographs could be made for two different ranges of moisture content and both placed on the same sheet in two different colors; however, there is more possibility of confusing the operator than if two separate nomographs were supplied.

Conclusions

The injector type exhaust oven has been found to have the following features which make it desirable for testing grains and forages on farms:

1. Simple and readily understandable operating procedures.
2. Relatively low apparatus cost.
3. Rapidity enough to follow the drying progress of products in most farm processes.
4. Accuracy not affected by secondary factors such as ambient temperature, humidity, sample species and variety, or uneven moisture distribution in the sample.
5. The operator need not tend the sample while it is drying and the length of drying time beyond constant weight is not critical.
6. Applicability over the full range of moisture contents measured in farming operations.
7. No significant dry matter losses were observed in the tests of this oven.

The following are limiting features of this method of moisture determination:

1. The method is not rapid enough to encourage the testing of several samples; therefore, the accuracy is dependent upon whether or not the samples tested represent the parent population.

2. Accuracy in testing a given sample is chiefly dependent upon the accuracy of the two weighing operations required. Accurate weight determinations must be made by unskilled operators under the adverse

conditions prevalent in the field.

3. Significant quantities of residual moisture content remain in grain samples after testing in the exhaust oven. Correction must be made for this residual moisture content.

The injector attachment is a valuable asset for reducing the drying temperatures and increasing the air flow in exhaust ovens used on most farm tractors. This attachment may not be necessary or desirable on those tractor engines operating at low exhaust temperatures under no-load conditions, such as the John Deere and most diesel tractors.

The design of the injector-type exhaust oven constructed in the course of this project was formulated to demonstrate operating principles. This design is not necessarily the most desirable from the standpoint of air injection efficiency, cost of fabrication, or convenience to the operator. Future ovens should be so designed as to lower the level of the sample container and, if possible, to remove the need for detaching the muffler from the engine.

Spring-type platform scales are sufficiently accurate to be used for testing forages if occasional checks are made with a test weight. It is very doubtful that the use of this type of scale would yield accurate enough results in testing grains. In order to obtain an accuracy of one moisture percentage point or better, a balance type of scale is probably necessary.

Residual moisture in the grain samples seems to be reasonably constant for any type of grain. Values for the average residuals listed for the various grains in Table II could be rounded off and used as a correction factor. These values could be added to the moisture percent-

ages calculated from the original and final sample weights. For example, if a value of 24% moisture content were calculated from the nomograph for a sample of corn, the true moisture content would be 24 + 1 = 25%.

It should be noted that the residual moisture correction is greater when using a scale of one gram sensitivity than when using a scale of 0.1 gram sensitivity. This is due to the difference in the ability of the two scales to indicate the true constant weights or the end point of the heating progress.

Where a scale of 0.1 gram sensitivity was used in the grain tests covered by this report, the drying was stopped when two consecutive readings were obtained which were equal within 0.5 gram. If the drying process had been continued until two consecutive readings were equal within 0.1 gram, the residual moisture contents would have been much lower, even negligible; however, the heating times would have been much longer. The constant or dry weight of drying samples of grain except oats is difficult to determine because of the reluctance of the grains to give up the last quantities of moisture. Therefore, it seem desirable to set a criterion for constant weight as two consecutive readings equal within 0.5 grams or some such significant value, since this condition is more quickly reached and more definitely recognizable than if constant weights within 0.1 gram were required. The use of correction factors seems advisable even though an operator might at any one time dry a sample completely. In this event, his error, amounting to the correction factor, would cause a moisture reading too high which is a "safe failure", i.e., he would not store his grain too wet.

Tests have shown that the venturi injector attachment is not

necessary or desirable for use on the John Deere tractor on which the exhaust oven was tested, since this tractor has unusually low exhaust temperatures. Deisel engines also have low exhaust temperatures. A commercial design of this exhaust oven might well include a simple shut-off damper for reducing or stopping the flow of secondary air when the oven is used on tractors with low exhaust temperatures. The operator could readily ascertain that his tractor operated at low exhaust temperatures if unusually long periods of time were required to dry the samples.

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INVESTIGATIONS OF THE ELECTRICAL RESISTANCE METHOD FOR HAY AND GRAIN

The electrical resistance method was selected for extensive investigation because it offers great possibilities of fulfilling most of the major design requirements for a farm moisture tester. The resistance method is very rapid, so that the testing of a great number of samples may be accomplished in a reasonable length of time. The method is versatile enough to be made applicable to all farm crops with only minor changes in the apparatus necessary. The operation of a resistance-type meter can be made simple in that it gives a direct indication of moisture content on a meter face, require no tuning of a resonant circuit, and need be adjusted for standardization only occasionally. The cost of resistance-type meters should be acceptable to the farmer, particularly if there is sufficient demand for such equipment to encourage mass production methods of manufacture.

The prime objective of the investigations of the resistance methods was to evaluate the various factors affecting the accuracy of moisture determinations of farm crops based on electrical resistance measurements.

Investigation of the Resistance Method for Hay

Resistance Measurements of Hay

Laboratory tests were conducted to evaluate the effects of the following factors on the resistance measurement of hay:

1. Electrode pressure
2. Electrode design

3. Sample size

4. Measurement frequency

Apparatus: Both a-c and d-c resistance measurements were made. Most of the d-c resistance measurements were made with a Tag-Heppenstall Model 8003-T4 resistance meter, the meter section of the Tag-Heppenstall moisture meter for grain. This instrument is a series ohmmeter, but it is not calibrated directly in resistance units. Therefore, it was necessary to calibrate it in the laboratory with standard resistors. This meter has eight ranges covering a span from 1000 ohms to 100 megohms.

D-c resistance measurements were also made with the Delmhorst Model F hay moisture meter and the Model 11E probe shown in Figure 14. This instrument was calibrated directly in hay moisture content as measured with the probe provided. The probe has one cylindrical electrode surface 0.5 by 0.3 inch in diameter and another pointed cylindrical electrode surface which is 0.6 by 0.3 inch in diameter. The two cylindrical electrode surfaces are mounted on a common axis and spaced 0.5 inch apart. The Delmhorst meter uses a d-c amplifier circuit to measure electrical resistance.

A-c resistance measurements were made with a 60-cycle impedance bridge manufactured by Clough-Brengle, Inc. (Model No. 2304). This instrument was calibrated in ohms but was rechecked with standard non-inductive resistors.

The small hydraulic press shown in Figure 15 was used to apply pressure to the hay sample contained in a 4-inch by 4-inch plastic box. A weighed sample was placed in the box between two steel plates for measurements involving plate-type electrodes. For measurements with probe-type

Fig. 14. The Delmhorst Model F hay moisture meter and the Model 11E probe.

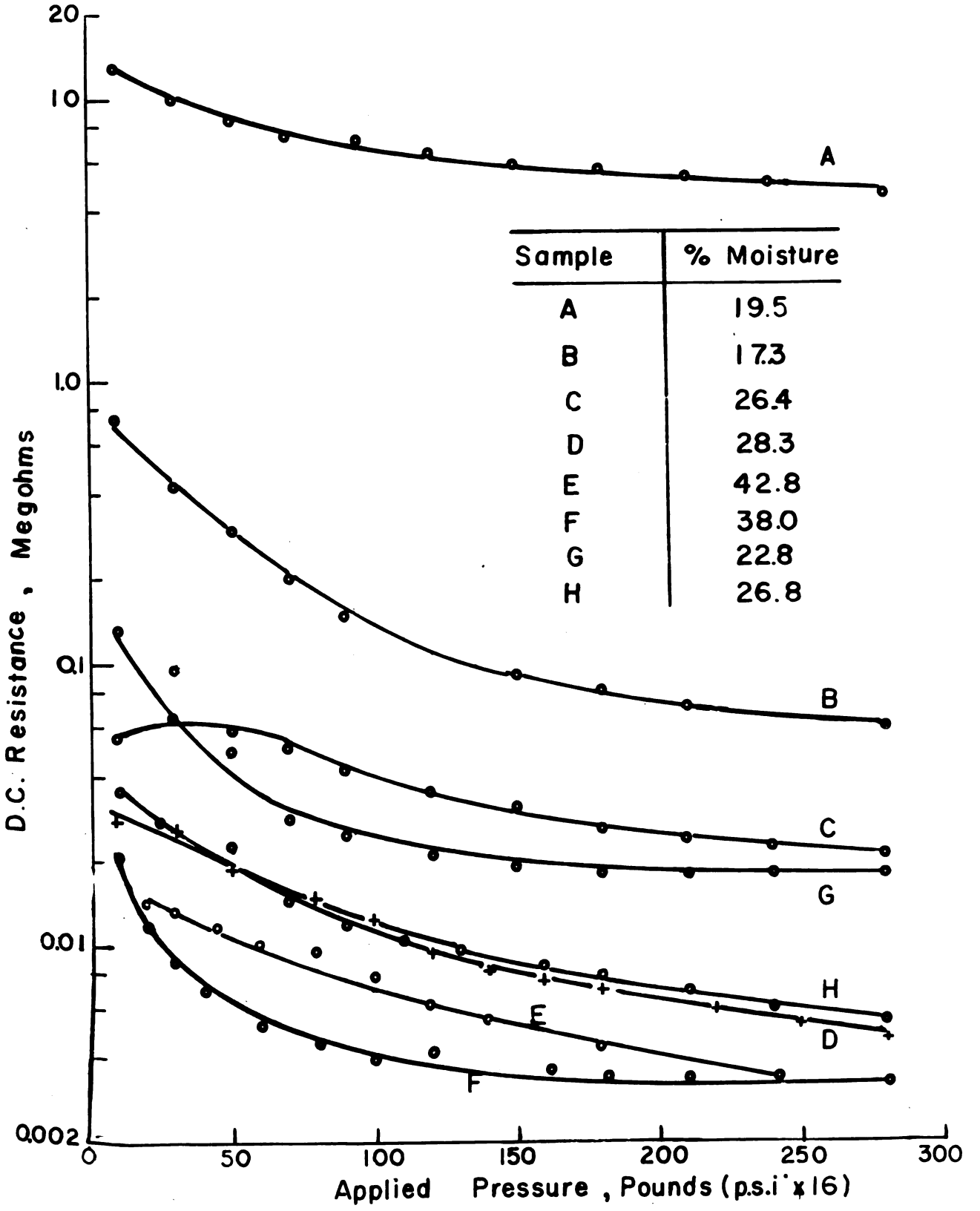
Fig. 15. The hydraulic press used to apply pressure to hay samples contained in a 4" x 4" plastic box for resistance measurements.

electrodes, the faces of the steel plates were covered by a 1/4-inch sheet of acrylic plastic and the probe was either inserted in the sample as it was installed or inserted into the sample through one of the slots in the sides of the plastic box.

The results shown in Figure 16 include resistance measurements taken between electrodes of both fixed and variable spacing. Samples B,D,F,G, and H were tested between two 4-inch by 4-inch plates which form the top and bottom of the lucite test chamber. The spacing between these electrodes decreases as the pressure applied to them increases and the sample compresses. Sample A was tested with the Delmhorst probe. Sample C was tested with a flat probe with fixed spacing. This probe consisted of two one-inch by one-inch flat pieces of steel mounted in the same plane a distance of one-half inch apart. Sample E was tested with pin-type electrodes of fixed spacing which are shown in Figure 17. The pins are made of 1/8 inch brass rod. The three longer electrodes (1 1/8-inch long) were connected to one terminal of the resistance measuring circuit and the three short electrodes (3/4-inch long) were connected to the other terminal. This electrode set is similar to that used in an experimental device to be discussed in a later chapter.

Procedure: Weighed samples of hay were placed in the test cell and pressure was applied with the calibrated hydraulic press. Readings of applied pressure, sample thickness, and electrical resistance were taken as the applied pressure was increased by increments. The pressure was maintained constant for one minute at each pressure level and the change in resistance with time observed with the Tag-Heppenstall meter (the other meters were not of sufficient sensitivity to indicate the resistance changes

Fig. 16. Resistance-pressure characteristics of several samples of alfalfa hay.



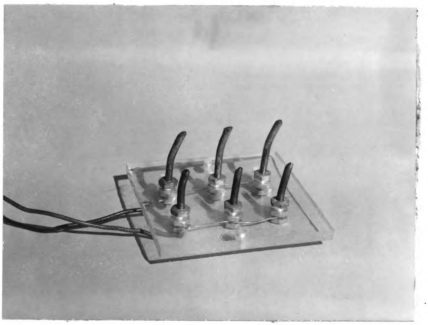


Fig. 17. Pin-type electrodes used in Test E for resistance measurements in hay.

that occurred). After the pressure was increased to a maximum value, it was released by increments and observations were made.

Results: A summary of the observations of resistance and pressure are shown in Figure 16. D-c resistance is plotted in a logarithmic scale because moisture content varies logarithmically with resistance. Therefore, the resulting curves give an indication of the decrease in the moisture content reading of a resistance-type meter with an increase in the pressure applied to the electrodes.

All of the curves of Figure 16 indicate that there is sufficient variation of resistance with electrode pressure to require the use of a known constant electrode pressure for resistance measurements of hay. The results also indicate greater variation of resistance with pressure at the lower applied pressures; however, this variation is not so rapid at the lower pressures with the electrodes of fixed spacing. This can be seen by comparing Samples A and B, Samples C and D, and Samples E and F.

The results from the electrodes of variable spacing(Samples B,D,F) indicate that constant electrode pressures in excess of 160 lbs. or 10 lbs./sq. in. would be necessary in a moisture meter using this type of electrode. The use of lower pressures would require that the pressure be applied more accurately, since small variations in the applied pressure would cause great variations in the measured resistance.

The resistance readings taken with the electrodes of variable spacing are also dependent upon the weight of the sample used, as shown by the curves for Samples B and G in Figure 16. Sample B weighed 44 grams, while Sample G weighed 28 grams. As would be expected, the smaller

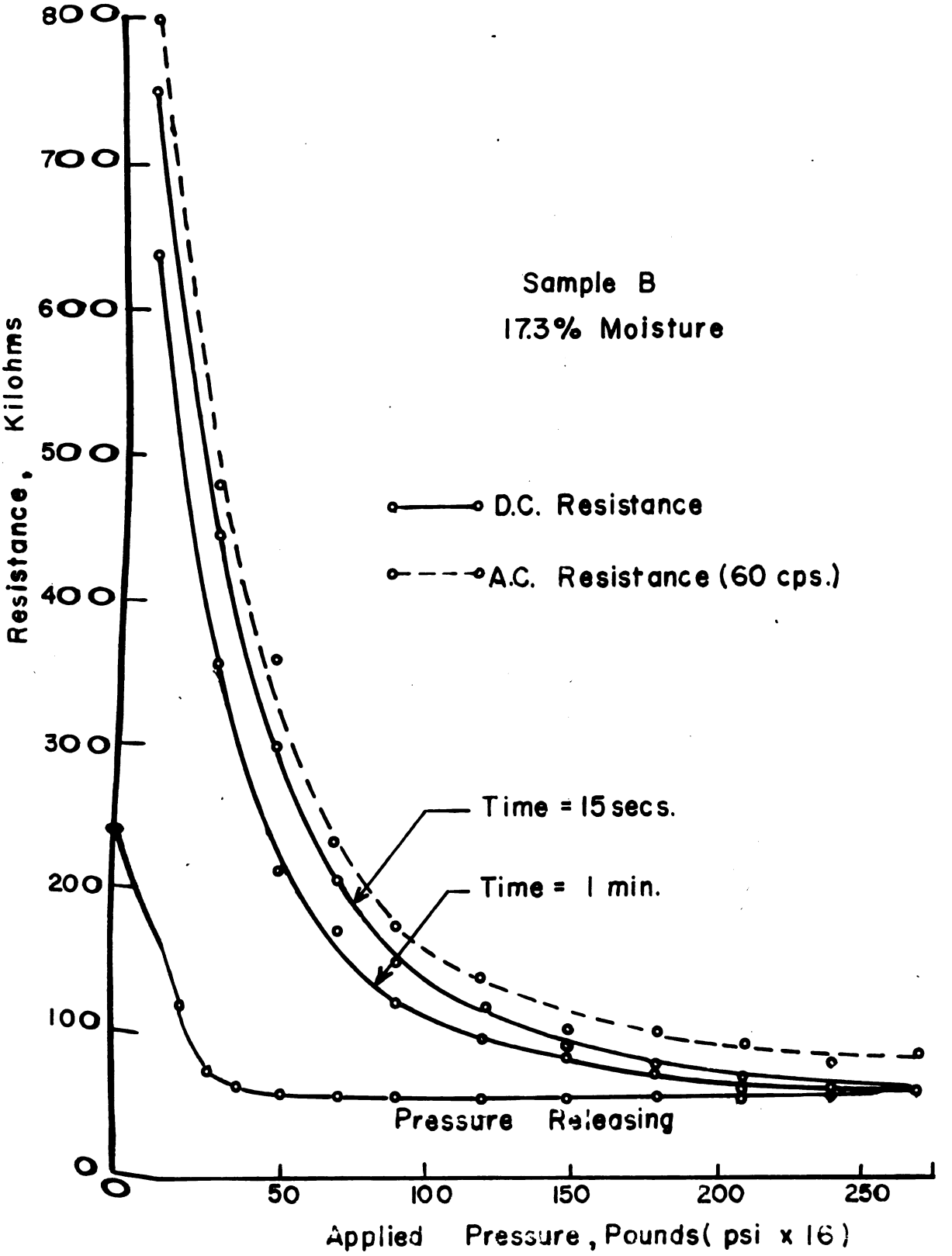
sample has a lower resistance.

The effect of electrode surface finish is shown in the results from Samples D and H. Sample D was tested with the smooth electrode plates used in other tests with variable spacing electrodes. Sample H was tested with electrode plates which were similar except that the surfaces were routed with v-shaped grooves 1/16 inch deep and spaced 1/16 inch on center. No significant difference in the results of the two samples were observed.

Figure 18 is a more detailed plot of the resistance-pressure characteristic of Sample B. Both resistance and pressure are plotted on linear scales. The upper section of the curve represents the drop in resistance as pressure was increased. The lower section shows the change in resistance as the pressure was released. As the pressure was released, the resistance remained surprisingly constant at the minimum value reached until the pressure was reduced to a value much less than half the maximum applied. This characteristic was observed in all samples. Therefore, it may be concluded that after a particular pressure has been reached, careful maintenance of the pressure while the resistance reading is being taken may not be important. This is not necessarily true at much lower electrode pressures.

A downward drift in the resistance readings at constant pressure was observed in all samples tested. Therefore, two readings were taken: one during a period less than fifteeen seconds after the pressure was increased and another one minute after the pressure change. Actually, several minutes may be required for the resistance reading to reach an apparently constant value, but one minute was chosen as the greatest

Fig. 18. Detailed resistance-pressure characteristics of a sample of alfalfa hay.



practical length of time necessary to take a reading on a resistance-type hay moisture meter. As can be seen from the plot of data taken one minute after the pressure change, the drift in the resistance reading at constant pressure is not great and is not likely to be of great consequence in the operation of a resistance-type moisture meter. This phenomenon is apparently caused by the gradual mechanical yielding of the hay stems when pressure is applied. In so yielding under compression, the stems are flattened against each and the electrodes, increasing the contact area.

No significant difference between readings of d-c and a-c resistance at 60-cycles per second could be observed in any of the samples tested. The results for d-c and a-c resistance shown in Figure 18 are typical of all the samples tested.

Further tests of the flat electrode probe was made to determine to what depth the current from the resistance measuring circuit penetrates the sample. This can be used as an index of the amount of the sample actually tested when two co-planar plate-type electrodes are applied to a sample of hay.

The arrangement of the apparatus for this test is shown in the diagram of Figure 19. The co-planar electrode plates are attached to the under side of a plastic plate to which pressure is applied by the hydraulic press. The hay sample is retained by the same 4-inch by 4-inch plastic box shown in Figure 15. Current from the measuring circuit flows from one electrode to the other.

The objective is to determine the depth to which appreciable parts of the current flow. To indicate the presence of current flow at the

bottom of the chamber, readings are taken alternately with a plastic and a steel plate at the bottom of the chamber. If appreciable current penetrates to the bottom of the chamber, the resistance reading should be decreased when the steel plate is substituted for the plastic.

A constant pressure of 1000 lbs. was used during this test and readings were taken with the Tag-Heppenstall moisture meter. The electrode plates were 1 inch x 2 inches each and were spaced 2 inches apart.

Table V summarizes the data obtained in this test. The resistance values shown are an average of three readings. The pressure was released and the bottom plate was interchanged between the plastic and steel after each reading. Two series of readings were taken, one with the stems of the alfalfa oriented perpendicular to the direction of current flow and another with the stems oriented parallel to the direction of current flow. The depth of sample was decreased by removing part of the hay. The hay used was first cutting alfalfa at about 25% moisture content.

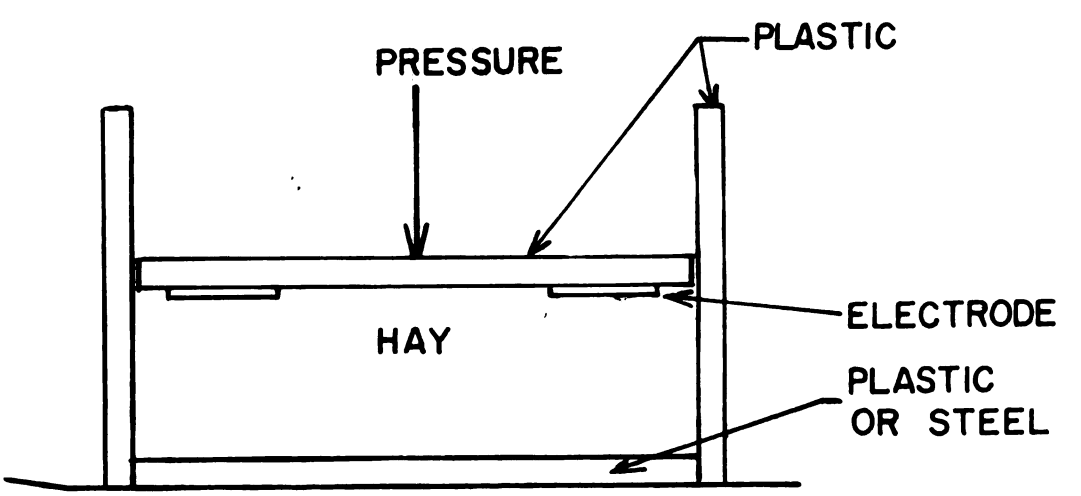


Fig. 19. Arrangement of apparatus for determining the depth of penetration of current in measuring the resistance of hay with co-planar electrodes.

TABLE V

EFFECTS OF CURRENT PENETRATION ON THE MEASUREMENT OF THE ELECTRICAL RESISTANCE OF HAY WITH CO-PLANAR ELECTRODES

Sample depth, inches	Average of Three Resistance Readings, Kilohms			
	Current Flow Perpendicular To Stems		Current Flow Parallel To Stems	
	Steel Bottom	Plastic Bottom	Steel Bottom	Plastic Bottom
0.4	800	716	265	218
0.2	733	733	253	271
0.1	193	1083	223	303

Comparison of the resistance values shown in Table V indicate that the measured resistance of the sample is not greatly affected by the presence of the bottom plate until the sample thickness is reduced to about 0.1 inch or only a few strands. Therefore, it can be concluded that most of the current is conducted between the plates by only a few strands. A moisture meter using this type of electrode would for the most part measure the moisture content of only that hay which is in actual contact with the electrodes.

Further examination of the data in Table V indicate that the electrical resistance of hay is greater to current flowing perendicular to the stems than it is to current flowing parallel to the stems.

Field Performance Tests of Two Commercial Resistance-Type Moisture Meters for Hay

Tests were conducted on two commercial resistance-type meters for hay in order to demonstrate the effectiveness of this type of meter in determining the moisture content of hay in the field. By thus observing their performance, ideas for their improvement were gained which were helpful in the design of experimental equipment. The following discussion of the work on these meters includes only the most important results of the work. For a complete presentation of the test procedure and results the reader is referred to two unpublished research reports (1) (2).

Apparatus: Two meters were tested: the Delmhorst Model RC-1 moisture meter, manufactured by the Delmhorst Instrument Company of Boonton, New Jersey and the Hart Model CU-2 moisture meter, manufactured by Hart Moisture Meters, Inc. of New York City. To the knowledge of the author these are the only commercial electric moisture meters available for use on forages.

The Delmhorst Moisture Meter (Model RC-1) used in this study is shown in Figure 20. This meter uses a type of d-c amplifier circuit to measure direct current electrical conductivity of the sample. The sample is connected to the meter circuit by means of the Model 10-E electrode probe. This probe consists of two rows of five steel pins located 1/2 inch apart. The length of the pins in contact with the sample is 9/16 inch. Pressure is applied to the probe assembly by the operator by means of a telescoping handle which contains and compresses a calibrated spring. By applying only enough pressure to compress the spring to an indicated point, the applied pressure is constant and variations in the meter

Fig. 20. Delmhorst Model RC-1 moisture meter and Model 28E probe for hay and grain.

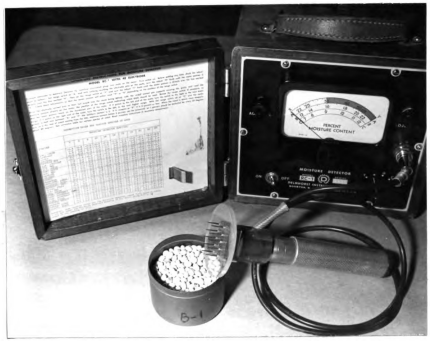


Fig. 21. Hart Model CU-2 moisture meter for use on hay.

reading due to variations in pressure are excluded.

The meter reads directly in moisture content; however, a different calibration is required for the various crops tested. Before using the meter for moisture testing, it is necessary for the operator to adjust the circuit to a standard indication at the lower and upper end of the meter scale. These settings should be checked occasionally while using the meter. The calibrated range of the meter extends from 7 to 65% moisture content on a dry basis. The use of a conversion chart for each crop tested is necessary to obtain the wet basis moisture content from the meter reading. The calibration is approximately linear except at the extreme upper end of the scale (above 30% moisture content).

The Hart Moisture Meter used in this study is shown in Figure 21. This meter also uses a d-c amplifier circuit to measure d-c conductivity. While being tested, a forage sample is pressed between two pairs of vertical plastic posts. A forage sample about one inch in diameter is selected and pressed into the space between two pairs of posts. Two parallel bars serving as electrodes are applied between the posts in a direction perpendicular to the stems of the sample. Pressure is applied to the electrodes by means of a wooden handle until the reading of the instrument does not change greatly.

Procedure on Hay Tests. All of the readings taken with the Delmhorst Meter were made on hay in the windrow. At each location in the windrow, five readings were taken along a line perpendicular to the longitudinal axis of the windrow. Two readings were taken on the periphery of the windrow and three were taken near the center of the windrow. The probe was so oriented that the measuring current flow was perpendicular to the

direction of the stems. After five meter readings were taken at each location, a section of the windrow was removed as a sample for oven testing. To facilitate removing a section of the windrow, a holding device was used which consisted of two 5/8 in. by $2\frac{1}{2}$ in. by 4 ft. boards. These boards were hinged together at one end in order to form a clamp in which the windrow could be held while a section was cut out with hedge shears. The resulting sample obtained by this procedure was a vertical section of the windrow approximately $2\frac{1}{2}$ inches thick.

Immediately after removal from the windrow the sample was placed in a paper bag and weighed immediately in the field. Weighing was done on a laboratory balance located in an enclosed trailer which provided protection from the wind during the weighing procedure.

Samples of hay were taken from the center of the windrow for testing with the Hart meter. Five meter reading were taken with each sample as the sample was rotated in the holder. Immediately after testing with the meter, the whole sample of hay used in the test was placed in a paper bag for oven testing by the same procedure used in testing the Delmhorst meter.

Results: Figure 22 presents experimental data from the tests of the Hart meter on alfalfa-brome hay. The oven-determined moisture contents for each sample are plotted against the arithmetic means of the five Hart meter readings taken from that sample. A straight line was fitted to the resulting scatter diagram by the Method of Least Squares. The equation of this line is:

$$y = 0.657x + 1.85$$

where y represents the average of the five Hart meter readings and x

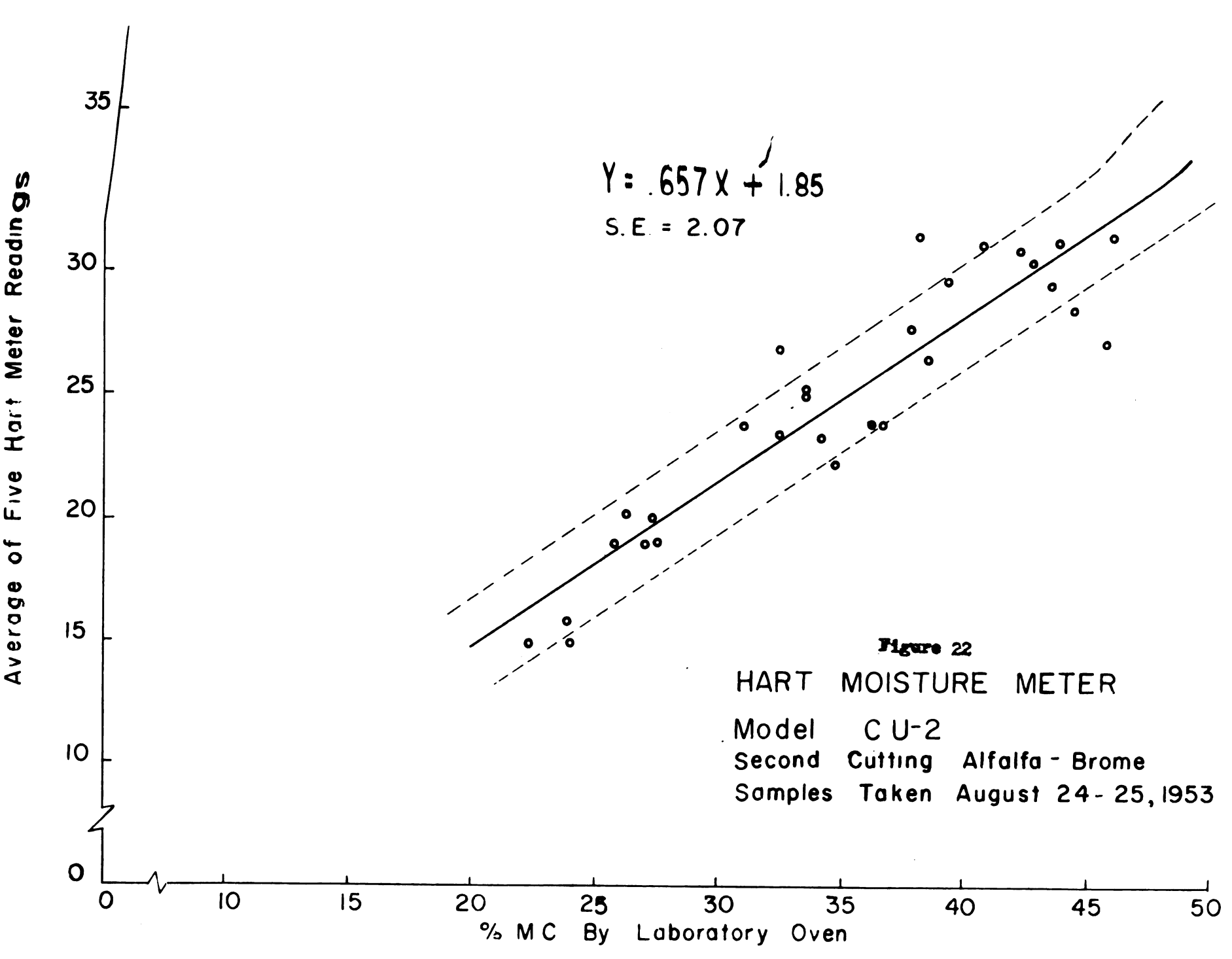


Figure 22

HART MOISTURE METER

Model C U-2

Second Cutting Alfalfa - Brome

Samples Taken August 24 - 25, 1953

represents the moisture content of the sample by oven determination. The standard error of estimate was determined for the above data and found to be 2.07 Hart meter scale units.

Figure 23 presents the same experimental data shown in Figure 22 except that all of the meter readings were plotted individually instead of the average of five readings per sample. This data was analyzed in the same manner as that in Figure 22. A straight line with the following equation was fitted to the data by the Method of Least Squares:

$$y = 0.628 + 3.0$$

The standard error of estimate for this data is 3.11 meter scale units.

Figure 24 presents data taken with the Delmhorst meter on alfalfa-brome hay. The average of five readings per sample are plotted against the oven-determined moisture content for that sample. The data is not linear throughout its full range and is probably parabolic at the upper range. In order to facilitate comparison with other data having a linear characteristic in the range below 40% moisture content, the data of Figure 24 was divided and analyzed in two sections, that above 40% and that below 40%.

From the data for samples below 40% moisture content, the following regression line was determined:

$$y = 1.17x - 8.6$$

The standard error of estimate for this data was 4.1 meter scale units. For samples above 40% moisture content, the equation of the regression line was:

$$y = 0.601x + 13.6$$

The standard error of estimate for this data was 5.0 meter scale units.

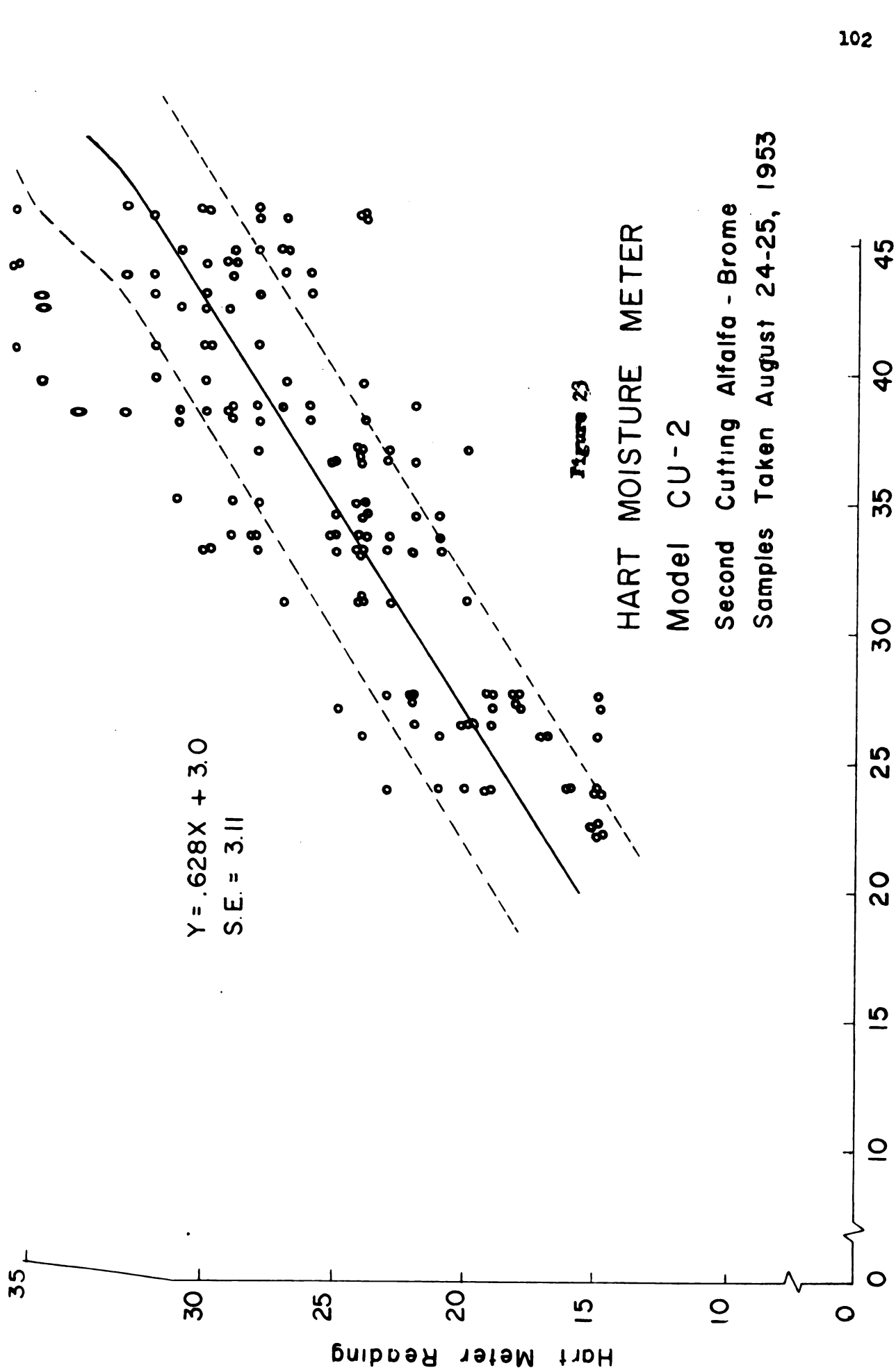
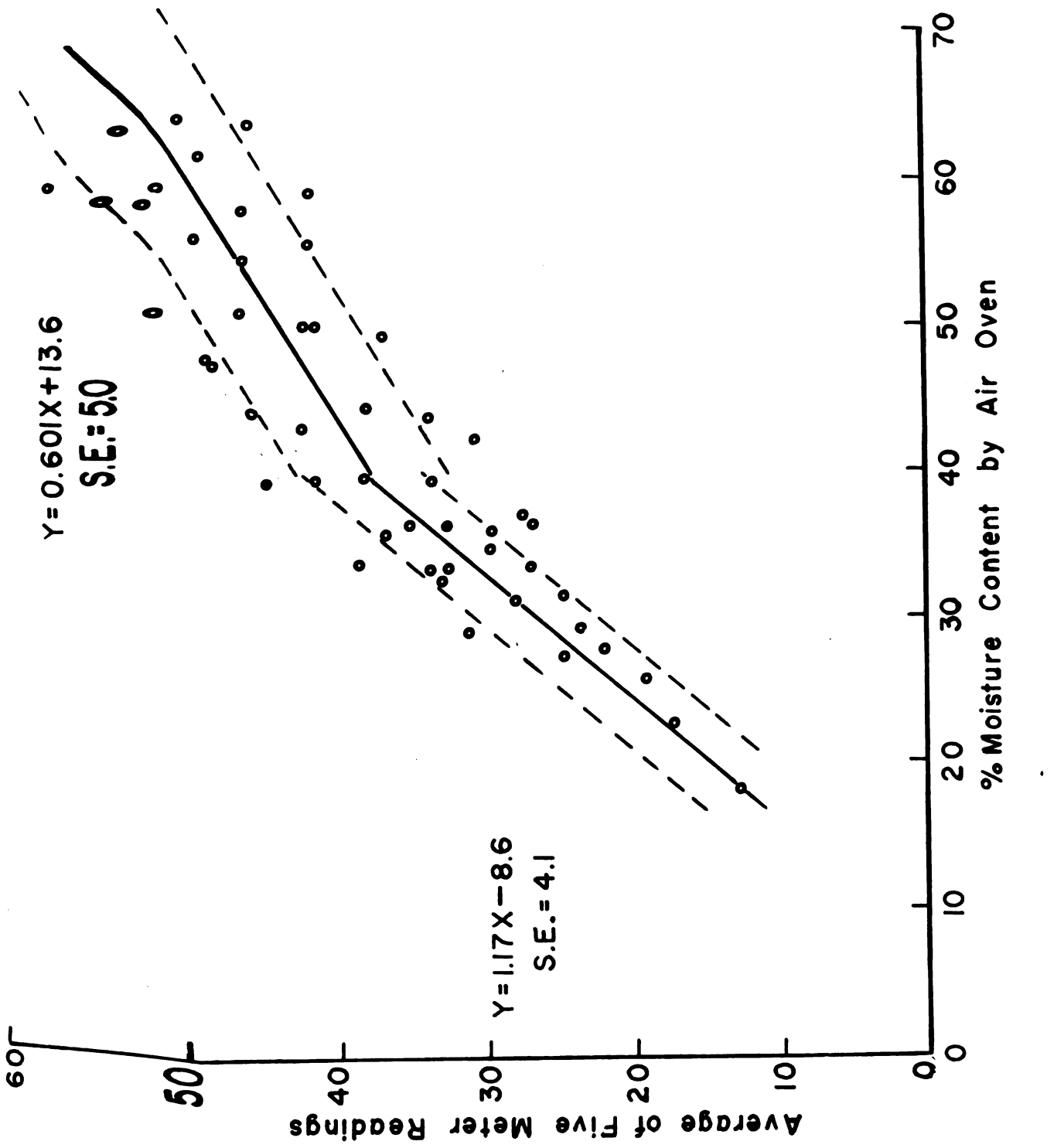


Figure 23

HART MOISTURE METER
Model CU-2
Second Cutting Alfalfa - Brome
Samples Taken August 24-25, 1953

Fig. 24. Tests of the Delmhorst meter on second-cutting alfalfa-brome hay (Test F).



An increase in the standard error of estimate at the higher moisture range is typical of resistance-type moisture measuring methods. This can by attributed to the decrease in the change of resistance with moisture content at higher moisture contents and to a greater possibility of uneven drying of the hay in the windrow in the early stages of the drying process.

A summary of the results obtained in trials of the Hart and Delmhorst meters on hay are shown in Table VI. This data indicates a generally lower standard error of estimate for the Hart meter than the Delmhorst meter; however, the methods of sampling with the two meters were very different. The sample which was oven-tested in the tests of the Hart meter was small and much of it had actually been contacted by the meter. In the Delmhorst tests, the oven samples were much larger and very little of each one had actually been contacted by the meter.

In tests of both meters, an average of five meter readings was a more accurate determination of the moisture content of the oven sample than was an individual meter reading. More than five meter readings per sample would probably give still more accurate results.

In order to evaluate the extent of the variability of the moisture content at various points in a windrow, the moisture content of hay samples which were taken in tests of the Delmhorst meter were compared with the moisture content of corresponding samples taken at the same time in tests of the Hart meter. The resulting pairs of samples originated from points less than one foot apart in the windrow. The samples from the Delmhorst tests were designated Group A and the samples from the Hart tests were designated Group B.

TABLE VI

SUMMARY OF DATA FROM COMMERCIAL MOISTURE METERS TESTED ON HAY

Meter	Hay	Moisture Range	Equation of Regression Line	Standard Error
Hart	Alfalfa-Brome	22-47%	y= 0.657x + 1.85	2.1
"	" "	22-47%	y= 0.628x + 3.0	3.1*
"	Alfalfa	17-45%	y= 0.476 + 8.65	2.8
"	"	17-45%	y= 0.396x - 11.2	3.9*
Delmhorst	Alfalfa-Brome	18-40%	y= 1.17x - 8.6	4.1
"	" "	40-65%	y= 0.601 +13.6	5.0
"	Alfalfa	11-38%	y= 0.882x + 1.8	3.3
"	"	11-38%	y= 0.968x + 0.0	5.1*

* This data was analyzed as individual meter readings against the oven-determined moisture content. All other entries were analyzed as the average of five meter readings vs. the oven-determined moisture content.

Oven-determined moisture data from pairs of hay samples taken simultaneously were compared by plotting the moisture content of each sample in Group A against the moisture content of each corresponding sample of Group B. The samples in Group A ranged from 75.1 to 344.1 grams in weight, while Group B ranged from 24.2 to 70.9 grams in weight. The Group B samples were those taken in the above tests of the Hart meter. Data from samples of alfalfa are plotted in Figure 25. The equation of the line fitted to this data is:

$$b = 1.10a + 1.2$$

The standard error of estimate between the moisture content of samples in Group B with respect to corresponding samples in Group A, is 3.38 moisture percentage points. Similar data from 25 pairs of alfalfa-brome samples has a standard error of estimate of 4.47 moisture percentage points.

The data taken in the tests of the Hart and Delmhorst meters was taken over a period of two or more days for each group of data such as that shown on each of the curves just presented. Data taking was resumed each morning as soon as most of the dew had disappeared or at a time when a farmer might reasonably expect to start baling hay. It was expected that the readings taken first in the morning might be unusually high in comparison to oven determinations due to the presence of surface moisture. However, examination of the data with regard to the time of day taken did not reveal any significant number of high meter readings which were not in accord with the oven results.

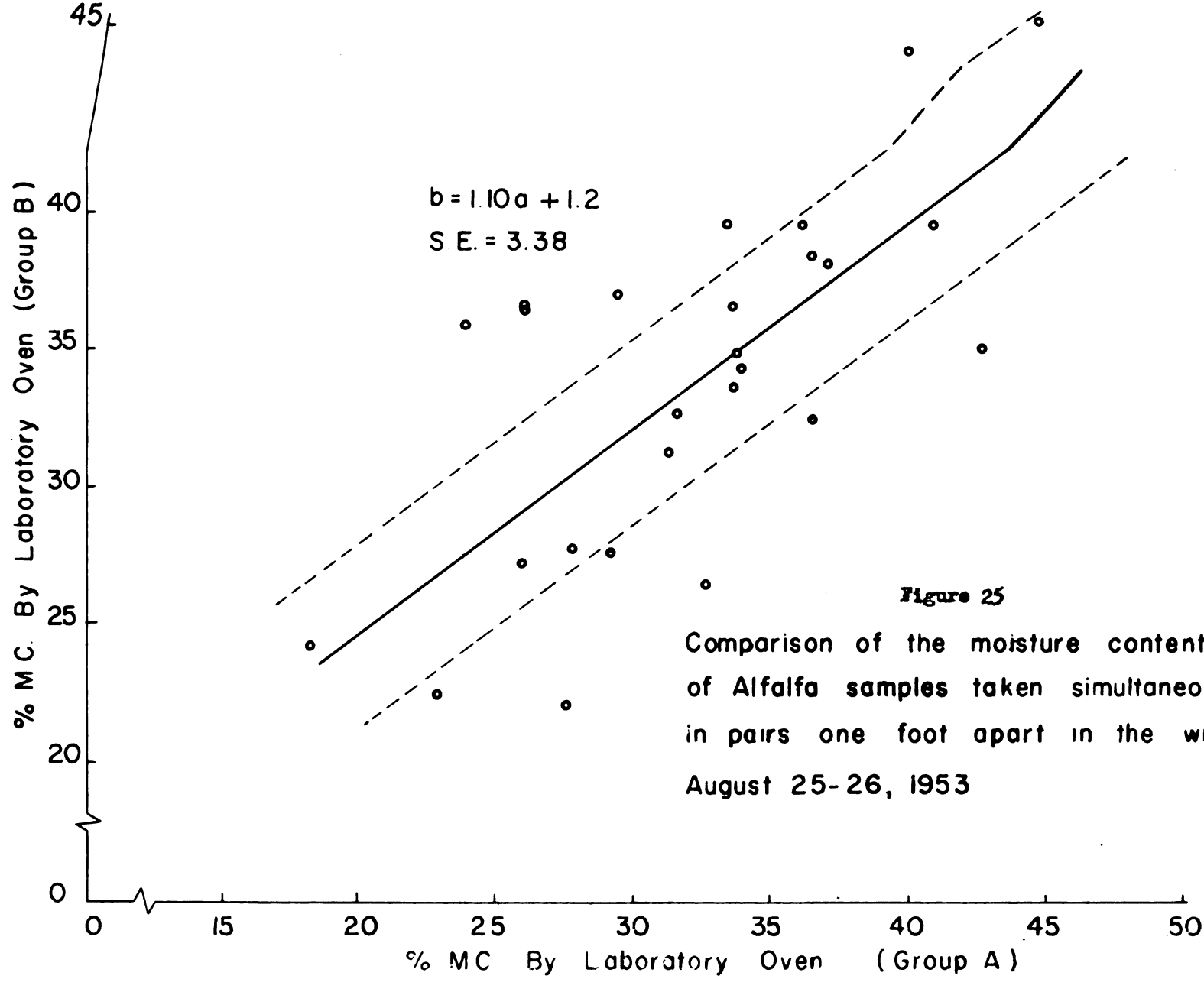


Figure 25

Comparison of the moisture content of Alfalfa samples taken simultaneously in pairs one foot apart in the windrow August 25-26, 1953

Investigation of the Resistance Method for Grain

Studies of the resistance method applied to grains included determination of the resistance-pressure characteristics of two types of electrode design, and an evaluation of the reproducibility of two types of constant-spacing electrodes. Comparison of the moisture readings of a commercial meter intended for use on farms was also made with reference to air oven determination of moisture.

Laboratory Investigations on Experimental Designs

Apparatus. A test cell, shown in Figure 26, was constructed for conducting resistance tests on grain. The cell consisted of a steel cylinder lined with acrylic plastic tubing (Lucite) for insulation. A steel plunger 1½ inches in diameter was fitted to the inside of the plastic tubing. The bottom of the plunger served as one electrode while the steel plate at the bottom of the cylinder served as the other.

The cell as shown in Figure 26 was used first for tests with variable electrode spacing. The cell was later modified for tests with constant electrode spacing. For these tests, two brass electrodes were attached to the bottom of the plunger as shown in Figure 27.

Resistance was measured with the same calibrated Tag-Heppenstall resistance meter used in the work on hay. Pressure was applied to the test cell by means of a small hydraulic press equipped with a Bourdon-tube gauge eight inches in diameter.

Tests were also conducted using the Delmhorst Model 28E electrode

Fig. 26. Test cell for resistance tests on grain.

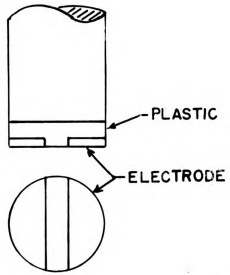


Fig. 27. Constant-spacing electrodes for grain test cell.

for hay and grain (Figure 20) and a modification of this device (Figure 28). Modification of the Model 28E probe consisted of replacement of the electrode pins with two aluminum plates as shown in Figure 28. The plates are parallel to each other and spaced 1 1/8 inches apart. Each plate is 1 inch wide and protrudes into the sample 5/8 inches.

Penetration into the sample by the electrodes is controlled by the same plastic guard plate used with the standard probe. The sample is contained in a standard No. 8 grain sample can while being tested, as shown in Figure 20. Pressure is applied to the sample by hand. The correct pressure is indicated by the compression of a spring in the handle which allows the handle to telescope to a red mark. The resulting pressure was measured and found to be 25 pounds.

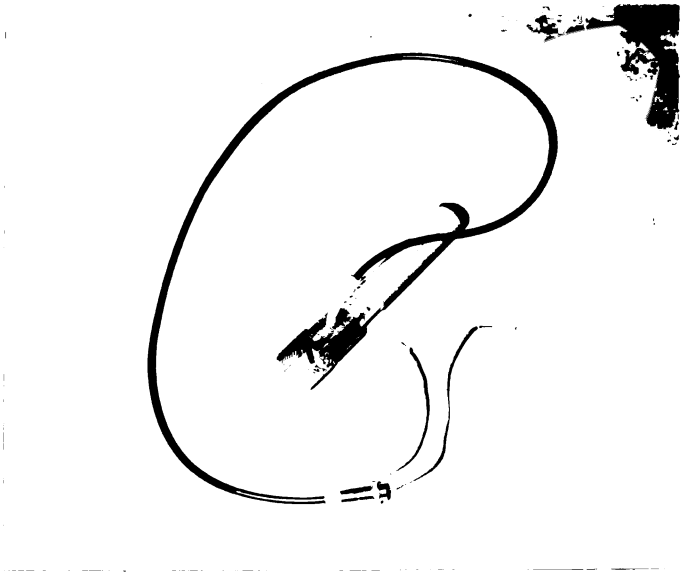


Fig. 28. Modification of the Delmhorst Model 28E probe for resistance tests on hay and grain.

Procedure. In tests with the experimental test cell, a weighed quantity of corn was placed in the cell and pressure applied with the hydraulic press. Seven gram samples were used for the tests with variable electrode spacing and 25 gram samples for the tests with constant electrode spacing. Electrical resistance readings were taken immediately after the desired pressure level was reached and one minute afterward. Constant pressure was carefully maintained during this time.

After tests with the standard probe, the samples were tested with the modified probe in a similar manner. The moisture contents of all samples was finally determined by heating for 96 hours at 212°F. in an air oven.

Results. Figure 29 shows the relation between electrical resistance and pressure applied to the experimental test cell. The electrode spacing varied as pressure was applied and the seven-gram sample was compressed. Similar data is presented in Figure 30 from tests of the experimental test cell with the constant electrode spacing.

Both sets of curves are reasonably regular and tend to level off at the higher pressures, indicating a decreasing rate of change of resistance as pressure increases. There is slightly less change in resistance with pressure with the constant-spacing electrodes.

The same data as that plotted in Figures 29 and 30 is presented in Figure 31, wherein electrical resistance is plotted against moisture content with certain pressures as parameters. Moisture-resistance characteristics with variable electrode spacing and 980 pounds pressure applied is quite linear when resistance is plotted on a logarithmic scale. This indicates that moisture content varies directly as the logarithm of resistance at a constant applied pressure. The moisture-resistance characteristics at lower constant pressures deviate more from linearity at the lower pressures. The curves plotted from data taken with constant electrode spacing are somewhat similar to those plotted for variable electrode spacing; however, the non-linearity persists to much higher applied pressures. This non-linearity could be due to differences in the areas of the two types of electrodes used. The constant-spacing electrodes were smaller and would likely be more affected by variations in the actual area of contact with the individual kernels of corn.

Table VII contains resistance data taken with the standard Delmhorst probe and with the modified probe shown in Figure 28. This data is

Fig. 29. Electrode Pressure vs. Electrical Resistance of Corn Measured in the Test Cell with Variable-spacing Electrodes.

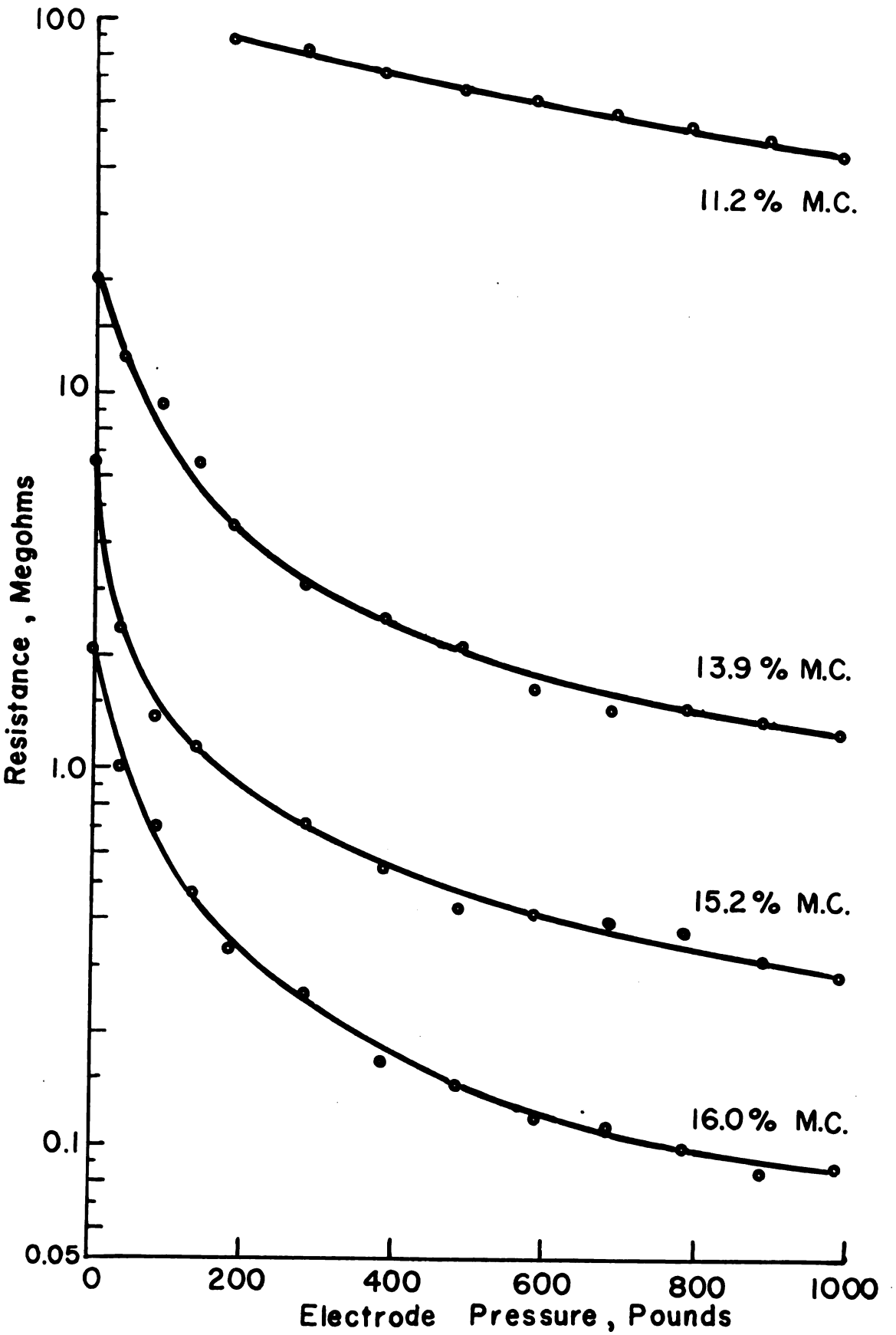


Fig. 30. Electrode pressure vs. electrical resistance of corn measured in the test cell with the constant-spacing electrodes.

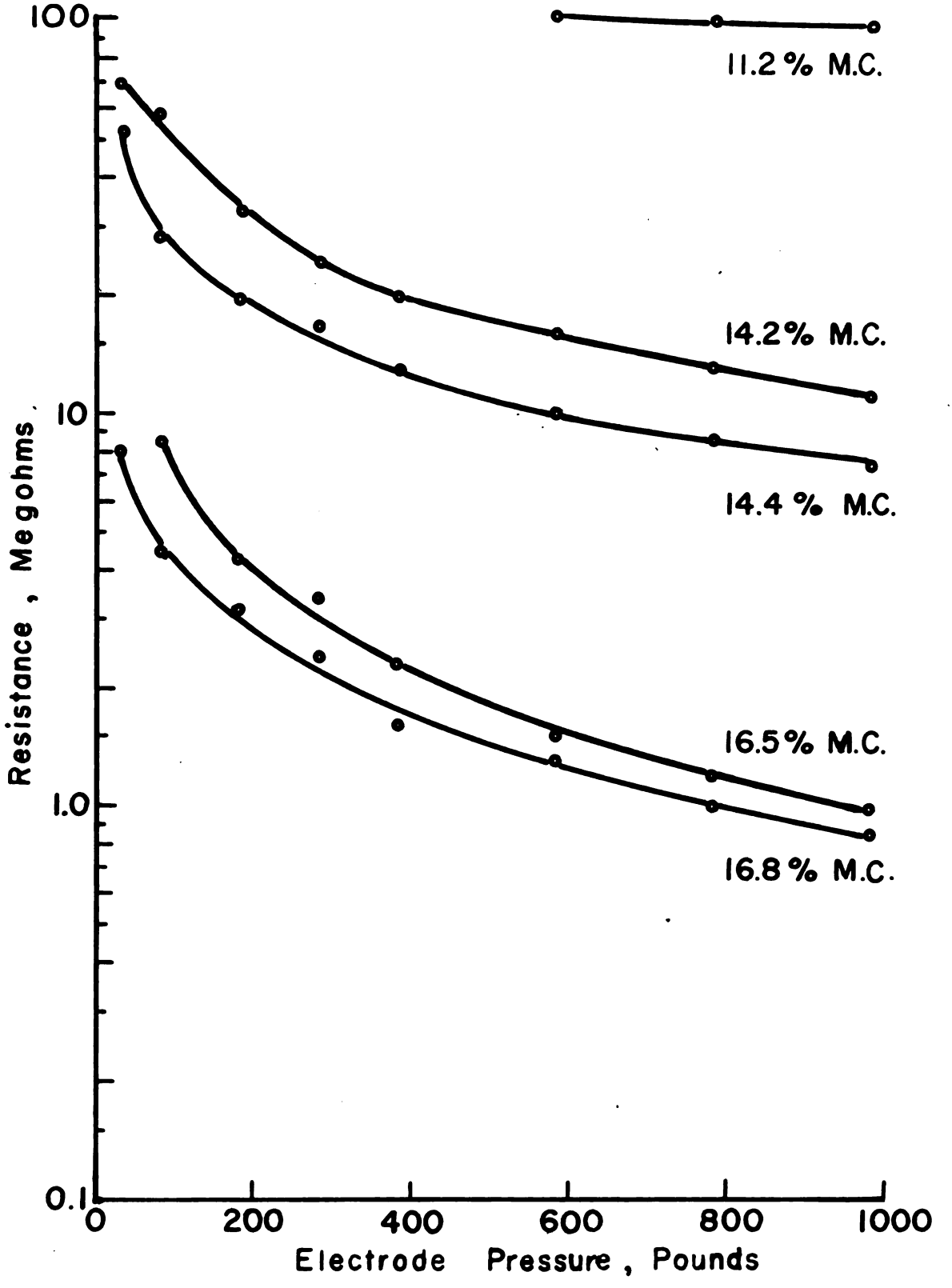


Fig. 31 Electrical resistance vs. moisture content at constant electrode pressures.

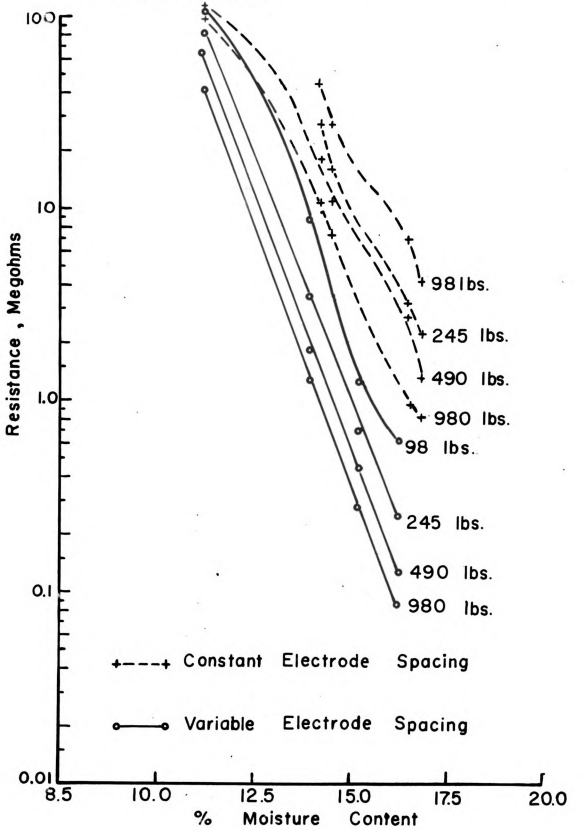


TABLE VII

REPETITIVE RESISTANCE DATA FROM CORN TAKEN WITH THE DELMHORST MODEL 28E PROBE BEFORE AND AFTER MODIFICATION

Probe	Moisture Content, %	Resistance Readings, Megohms				Mean of the Resistance	Maximum Deviation From Mean	Standard Deviation From Mean
		No. 1	No. 2	No. 3	No. 4			
Standard	15.9	3.8	2.9	3.6	3.9	3.55	-0.65	0.51
"	15.8	4.5	5.6	6.0	7.7	5.92	-1.42	1.32
"	14.0	44.0	49.0	35.0	47.0	43.8	-8.8	6.18
"	13.6	55.0	46.0	37.0	49.0	46.8	-9.8	7.49
Modified	15.5	7.5	7.3	7.5	7.0	7.32	-0.32	0.24
"	14.0	48.0	51.0	47.0	44.0	47.5	4.5	2.89
"	13.8	48.0	51.0	48.0	49.0	49.0	2.0	1.41
"	13.6	55.0	51.0	51.0	51.0	52.0	3.0	2.00

intended to compare the reproducibility of the two probes. Resistance readings for a given sample seem to be more constant with the modified probe which has the two plates as electrodes instead of the two row of pins. Standard deviations from the mean are consistently higher with the pin-type electrodes when the data are compared at similar moisture contents.

Test of a Commercial Moisture Meter on Grain

Apparatus. A Delmhorst Model RC-1 moisture meter with a Model 28E electrode assembly was tested. The meter, probe and sample container are shown in Figure 20.

Procedure for Wheat Tests. Wheat samples used in Test A were drawn at a country elevator from lots of wheat being sold by farmers. These samples varied greatly in variety, quality, and cleanliness (weed seed content). The most common weed seeds observed in these samples were cockle and quack grass seed. Records were kept of the relative amounts of foreign material in the samples. However, no significant effect of the foreign matter on the reading of the meter could be observed.

Samples were tested with the Delmhorst meter immediately after being drawn. Five readings were taken from each sample. The samples were weighed immediately after testing to determine their wet weight for the oven moisture content determination. The samples were then held in closed containers until the moisture content could be determined conveniently in a laboratory air oven.

Test B was conducted with samples held in closed containers for 40 to 48 hours. Samples in this test included the samples tested in Test A plus additional samples which had been collected from farm harvests in Huron County, Michigan. Immediately after testing with the Delmhorst meter, the samples were reweighed for determination of their moisture content by the oven method. Sample temperatures were also determined.

In Test C all of the samples of Test B were held in open containers

for six hours in an oven at 130° F. The results of these tests are intended to show the effect of artificial heated-air drying upon the indication of the meter. As in the previous tests, after the meter readings were taken, the samples were reweighed to determine their moisture content by the oven. method. Sample temperatures were again taken. The samples were tested after they had reached the approximate room temperature of 80° F.

Following Test C, the samples were dried in a laboratory air oven for 96 hours at 212° F.

Procedure for Corn Tests. Samples for the first test on corn (Test D) were drawn from approximately 1/2 bushel of corn selected at random from corn being harvested. The corn was shelled and thoroughly mixed before six samples were selected by dividing with a Boerner sampler. The samples were allowed to dry in open containers in the laboratory where the temperature was 75°F. and the relative humidity was approximately 25%. Determination of moisture by the Delmhorst meter, weight reading, and sample temperatures were determined occasionally as the samples dried from an original moisture content of 32% to 12% at the time of the meter reading.

Five separate meter readings were taken from each sample. The samples were mixed between readings by shaking. Immediately following each meter determination, the samples were weighed in order to determine their moisture contents at the time of testing by a later oven determination.

Test E was conducted to demonstrate the advisability of grinding corn samples, particularly under abnormal sample conditions. Two groups of samples were tested. Group I consisted of eight samples of corn with

an initial moisture content of approximately 22%. This corn had been rewet from an original moisture content of 14% and allowed to equalize in moisture content in a closed container for two weeks before the test. Group II consisted of five samples of corn having a moisture content of approximately 32%. This corn had a perceptible coating of mold on the kernels.

During Test E, the samples were dried at room air conditions which were approximately 80°F. and 20% relative humidity. Occasional readings with the Delmhorst meter on the whole grain were taken at intervals during the drying period. Five repetitive readings were taken on each sample with the sample being agitated by shaking between each reading. Immediately following meter readings the samples were weighed and temperatures were taken.

At intervals between the beginning and end of the drying period, one sample at a time was withdrawn from each group, tested with the meter, ground in a coffee mill, and finally retested with the meter. After grinding, the samples were weighed before placing in the oven for moisture determination. Grinding was done with a coffee mill which reduced the grain to a size of which approximately 75% would pass through a standard 8 mesh screen.

Results. The results of all tests on grain are summarized in Table VIII. which shows the equations of the regression line and the standard error of estimate for each test.

The data obtained in Test A on wheat is shown in Figure 32. The average of five meter readings per sample are plotted against oven determined moisture content. These results demonstrate the ability of the

Fig. 32. Tests of Dalmherst meter on wheat samples drawn at a country elevator (Test A).

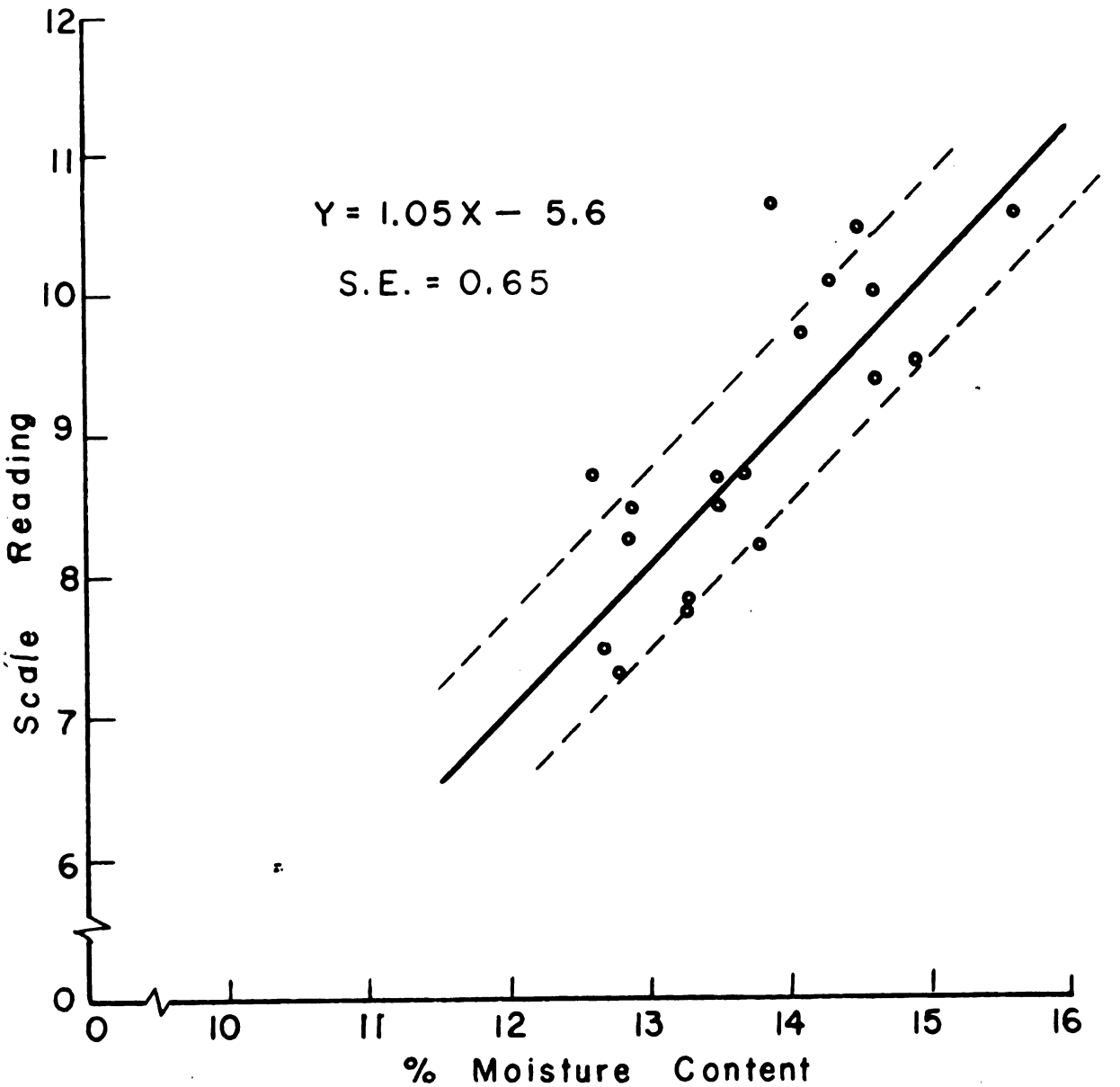


TABLE VIII

SUMMARY OF THE RESULTS OF INVESTIGATIONS OF THE DELMHORST METER IN TESTING GRAIN

Test	Crop Tested	No. of Samples	Moisture Range, Percent	Equation of the Regression line	Standard Error of Estimate	Remarks
A	Wheat	19	12-16	Y 1.05x - 5.6	0.65	Samples taken from wheat being sold at Okemos Elevator Co. Okemos, Mich.
B	Wheat	31	11-16	Y 0.706x 0.10	0.77	Samples held in closed containers for 40 to 48 hours before testing.
C	Wheat	32	8-14	Y 0.623x 1.07	0.55	Test B samples recently artificially dried.
D	Corn	46	12-32	Y 1.34x - 8.8	1.96	Corn as harvested.
E(I)	Corn	42	13-23	Y 2.22x - 22.4	0.971	Artificially conditioned samples.
E(II)	Corn	36	20-32	Y 2.59x - 35.6	2.48	Moldy samples.
E (I,II)	Corn	13	13-26	Y 2.33x - 23.0	1.54	Samples from Tests E(I) and E(II) which were ground.

meter to test "field run" samples of wheat of different varieties and grades.

The data of tests A, B, and C were also analyzed as one group to obtain an estimate of the accuracy of the meter over widely varying conditions of samples. This is admittedly a severe test of the meter. The regression line determined by this analysis is described by the following equation:

$$Y = 0.603X + 1.21$$

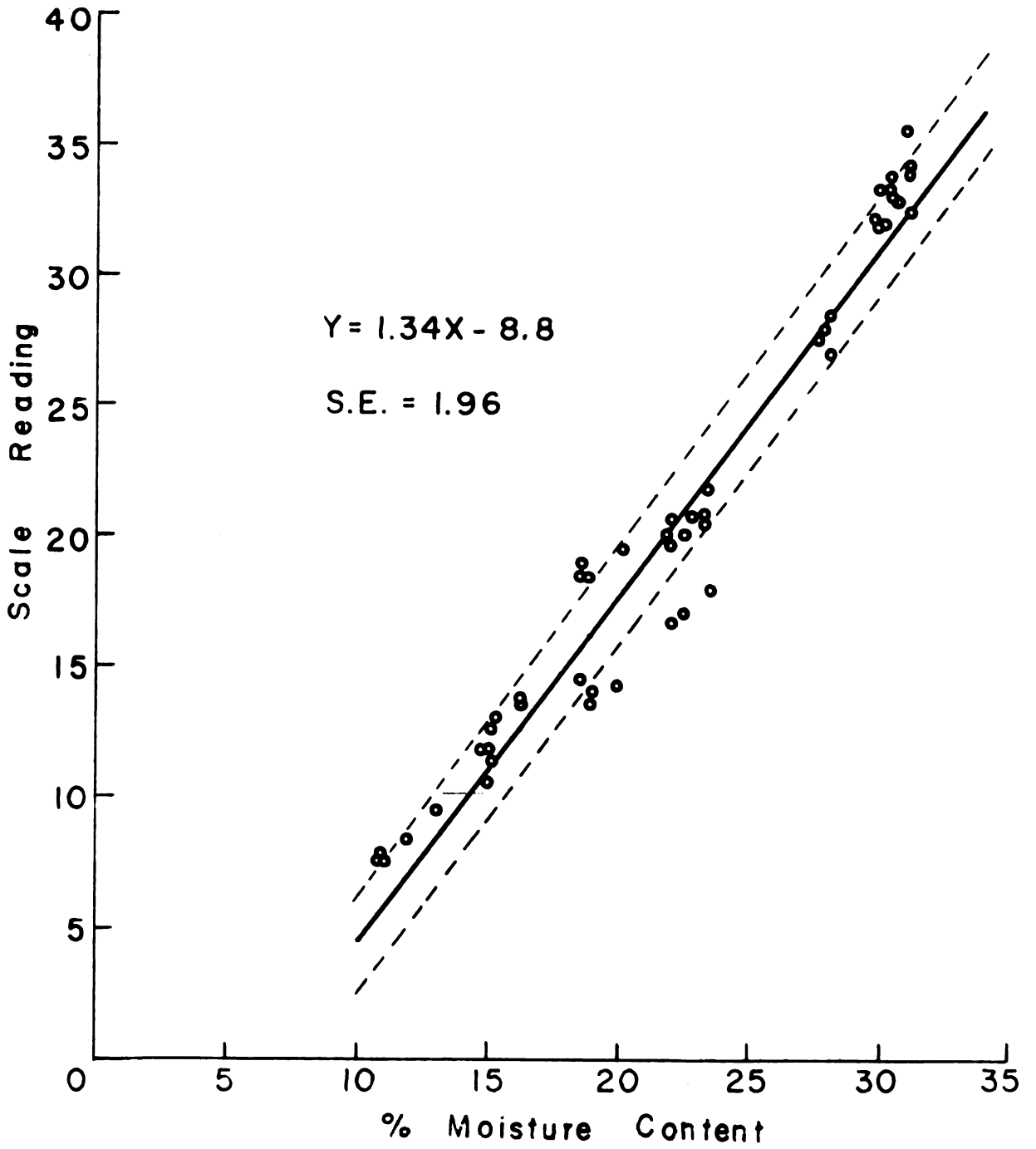
The standard error of estimate is 0.717 moisture percentage points.

In comparing the equations of the regression lines resulting from the data of Tests A, B, and C, one might expect the equations of these lines to be more similar; however, the data in these individual tests cover a rather limited range and many more points than are available would be necessary to determine the equation of the regression line more nearly accurate.

Data taken in Test D on recently-harvested corn samples is shown in Figure 33. The standard error of estimate for this data is 1.96 moisture percentage points. This indicates that the meter is not very accurate in testing whole shelled corn. Part of the lack of reproducibility in these results may be due to the variation in the area of contact which is possible between the electrode pins and the corn. This was pointed out in the previous laboratory work on the Model 28E probe.

The results of Test E indicate the value of grinding samples of whole corn before testing. The results for the Group I and Group II samples of Test E were very different, as indicated by the regression line equations for these two groups of data (See Table VIII). However,

Fig. 33. Test of Delmhorst meter on recently harvested corn samples (Test D).



the data obtained from the ground samples from both groups fall on a common regression line, as shown in Figure 34.

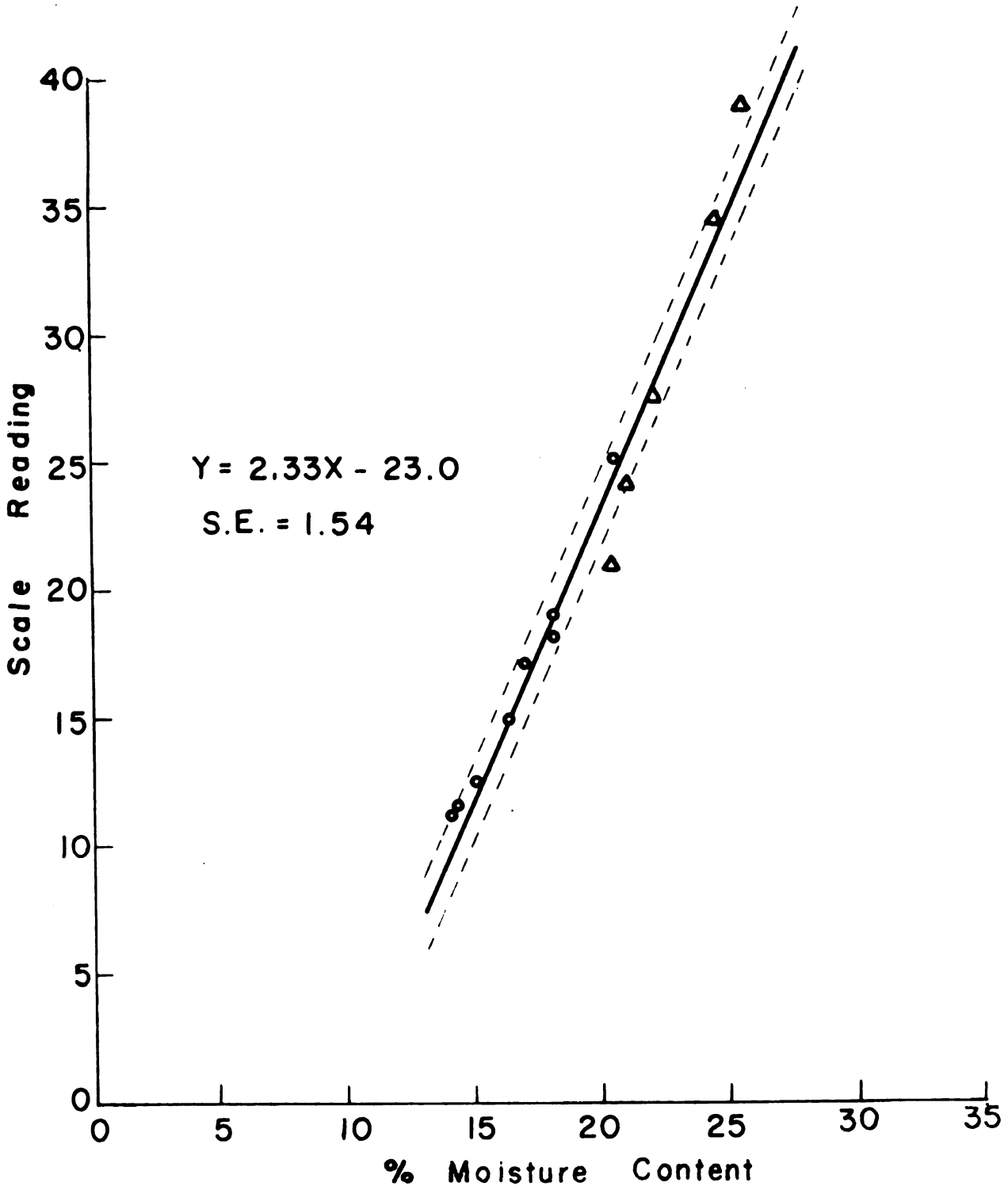
The differences in the resistance-moisture characteristics of the whole grain used in Groups I and II of Test E are probably due to differences in the condition of the kernel surfaces. Apparently, the effects of these surface conditions are greatly reduced by grinding and thereby allowing the inner parts of the kernels to come in contact with the electrodes.

Literature Cited

(1) Isaacs, G. W., Investigations of the Hart Model CU-2 Moisture Meter for Use on Hay, Unpublished research report, Agricultural Engineering Dept. Library, Michigan State College, 1954.

(2) Isaacs, G. W., Investigations of the Delmhorst Model RC-1 Moisture Meter for Use on Hay, Unpublished research report, Agricultural Engineering Dept. Library, Michigan State College, 1954.

Fig. 34. Tests of the Delmhorst meter on ground corn samples (Group I and II of Test E).



DEVELOPMENT OF AN AVERAGING MOISTURE METER

The non-uniformity of the moisture content of hay in the windrow is qualitively apparent from the visual and tactual inspection. The analysis of data, taken while field testing two commercial moisture meters for hay, indicates quantitatively the variation in the oven-determined moisture contents between paired samples of hay taken simultaneously from the windrow at points less than one foot apart. The variance of the moisture contents of the paired samples of alfalfa as represented by the standard error of one with respect to the other was 3.38%. This value compares with the standard error of estimate of the readings of the commercial moisture meters tested when compared to oven-determined moisture contents. This indicates that the greater part of the variation in simultaneous readings with the commercial resistance-type moisture meters tested is due to point-to-point variations in the moisture content of the hay tested.

The final conclusions drawn from the tests of the commercial meters were that an individual reading with these meters was of little value in determining the average moisture content of a windrow of hay. It was found that an average of five simultaneous readings was a much more reliable indication of the average moisture content of a section of windrow.

If farmers are willing to take a great number of individual readings (at least 25) and determine an average reading, they can very likely obtain a reliable indication of the moisture contents of their fields of hay. It is very likely that most farmers would not follow this tedious practice for long. Recognizing this situation, a means of automatically averaging a great number of moisture content readings was developed.

Design of the Averaging Device

One might conclude that the average moisture content of a comparatively large mass of hay could be obtained simply by using electrodes extensive enough to pass the measuring current through all of a large hay mass, thereby gaining an average with a single reading. Such an arrangement is not feasible because the value of electrical resistance measured is less than that of the lowest resistance path through the sample, since all current paths through the hay are connected in parallel. Therefore, the moisture indication is higher than that of the wettest hay forming an electrical path between the electrodes. The possible effect on the reading of one wet stem is obviously great.

Another possible arrangement to obtain an average moisture content is to connect several small electrode pairs in series. This arrangement does not have the major disadvantages of the one described in the preceeding paragraph since the measured resistance in the latter case is the sum of the individual resistances. One very low resistance in contact with one set of electrodes would not effect the overall reading greatly. However, with such an arrangement, uniform contact of the hay with every one of the electrode sets is necessary. If no contact or even a poor contact is made with one of the electrodes, the total measured resistance would be very high and the moisture indication much too low. The series arrangement of multiple electrodes would have a further disadvantage in that it would require the measurement of very high resistances, which would be more difficult under field conditions because of the greater effect of current leakage across electrical insulation.

From the previous discussion, it is apparent that a means of determining the average electrical conductivity (reciprocal of resistance) of a large number of small samples should be advantageous, since moisture content varies directly with conductivity or inversely with resistance. Since current also varies directly with conductivity, a device which would determine an average of the values of current flowing through a number of separate samples across which the same voltage is impressed should indicate an average value of moisture content. A schematic diagram of such a device is shown in Figure 55.

A continuously rotating electrical tap switch, S_1, can be made to connect any one of the n electrode sets (E_1, E_2, E_3 - - - - E_n) to the resistance measuring circuit. By this arrangement, one can conveniently take separate readings of moisture content, M, based on resistance R, and average them to determine the arithmetic average moisture content of all the samples, M_a, by the following relation:

$$M_a = \frac{M_1 + M_2 + M_3 - - - M_n}{n} \qquad (1)$$

If M is assumed proportional to 1/R, then

$$M = K_1/R \qquad (2)$$

where K_1 is a constant of proportionality. Then

$$M_a = \frac{K_1}{n} \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) \qquad (3)$$

or

$$M_a = \frac{K_1}{n} \left(Y_1 + Y_2 + Y_3 - - - - Y_n \right) \qquad (3a)$$

where Y is the reciprocal of resistance or conductance.

If a direct-reading resistance-type moisture meter such as a simple ohmmeter is used in the circuit of Figure 33, the current in the meter movement, which is either equal or directly proportional to the

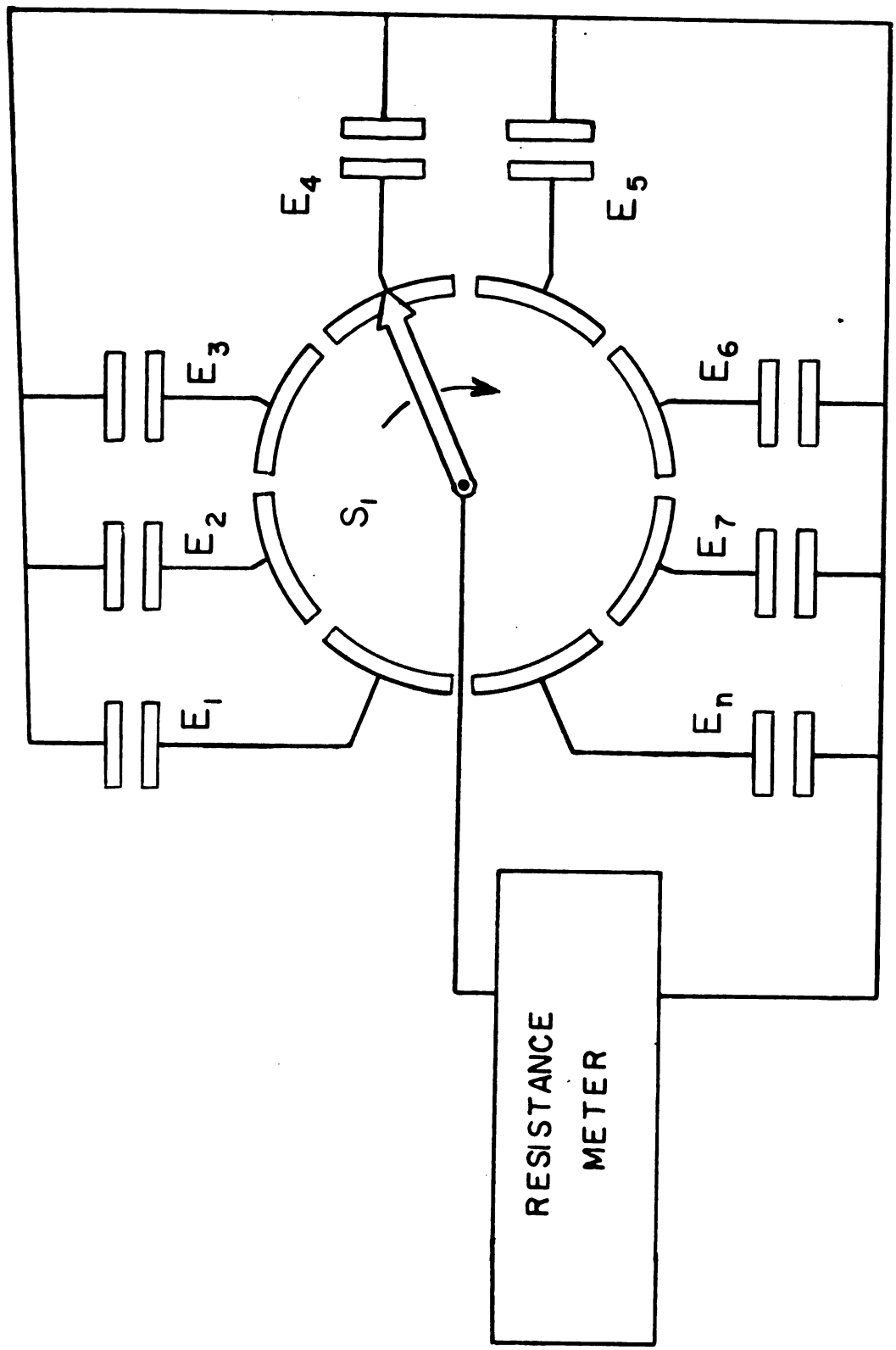


Figure 35. Schematic diagram of averaging device for use with a resistance-type moisture meter.

sample current, is actually the variable measured. The meter current, I, is related to the measured resistance, by the following relation:

$$I = \frac{K_2}{R} \quad \text{or} \quad R = \frac{K_2}{I} \tag{4}$$

where K_2 is a constant of proportionality including such circuit constants as the applied voltage and the galvanometer shunt ratio. Combining equations (3) and (4),

$$M_a = \frac{K_1}{nK_2}\left(I_1 + I_2 + I_3 - - - - I_n\right) = \frac{K_3 I_a}{n} \tag{5}$$

where $K_3 = \frac{K_1}{K_2}$. It is apparent from equation (5) that an average of the meter currents observed while testing the individual samples (I_1, I_2, I_3 - - - I_n) is a value of current proportional to the average moisture content of all the samples.

If the switch arm of the rotary switch is rotated at a constant speed, the meter movement of the resistance meter will conduct current equal or proportionate to each sample current during $\frac{1}{n}$ th of the time required per revolution. The pointer of the meter will attempt to follow the changes in the current as the switch arm contacts different samples, but because of its inertia and electrodynamic damping, it cannot do so. If the switch arm is rotated rapidly enough and the damping of the meter movement is great enough, the meter will approach a steady reading of the average current, I_a. Such meters indicate a time average of the current passing through the coil. Since the current through each sample flows an equal length of time, the meter indicated the arithmetic mean of the sample currents and therefore indirectly measures the arithmetic mean conductance of all the samples tested.

In the foregoing discussion, the assumption was made that moisture

content is proportional to the reciprocal of the resistance (See Equation 2). This means that a plot of logarithm R vs. logarithm M is linear. This may not be necessarily true over all ranges of moisture, however, the error in determining the arithmetic average moisture content is not great when the relation between logarithm R and natural M is linear if there is reasonable variation in the moisture content of the individual samples. An anlaysis of this error is presented in the Appendix II.

An arrangement similar to that shown in Figure 35 could be employed for automatically determining the average moisture content of small quantities of material, such as a single bale of hay or cotton or a bin of tobacco shredded in the manufacturing process. All of these products are usually non-uniform in moisture content. One tobacco manufacturer is at the present time, using a device similar to that shown in Figure 33. on shredded tobacco, except that readings are taken from each of several electrode pairs and the average determined manually. The addition of a hand crank or electric motor to drive the switch arm could make the averaging automatic and a single reading would yield an average moisture content.

The original objective of this work was to develop an averaging device for use in estimating the average moisture content of fields of hay in the windrow. With the arrangement of Figure 35, the operator would not be able to test a great amount of the hay in a field. The device shown in the photograph of Figure 36 was developed as a means of conveniently testing a great amount of hay in the windrow and determining a reading of its average moisture content.

Twenty-one sets of pin-type electrodes were placed radially around

Figure 36

The experimental averaging device for windrowed hay in use in the field with the Tag-Heppenstall resistance meter

the periphery of a wheel twenty inches in diameter which is to be rolled along the top of the windrow. Each set of electrodes consists of three ungrounded pins and three grounded pins, the latter being longer to minimize the effect of the electrodes touching the soil in case of a thin spot in the windrow. The three ungrounded electrodes of each electrode set are connected to a bar of a collector device, which in the experimental model, consisted of a commutator of an electric motor. The commutator bars served the same purpose as the poles of the rotary tap switch of Figure 35 and a single commutator brush served as the switch arm. A detailed description of the averaging device for windrowed hay follows with references to Figures 36, 37 and 38.

The main body of the averaging device consists of the wheel (14) fixed at its center to a shaft (12) rotating in bearing assemblies (11) and (22) which are welded to the main frame members (21). The main frame members extend upward and to the rear of the wheel to form a convenient handle for the operator to push the wheel to produce the direction of rotation indicated.

The electrical resistance of the hay is measured between groups of three of the ungrounded pin-type electrodes (2P) and the row of grounded electrodes (1N). The ungrounded electrodes (2P) are insulated from the grounded electrodes and the wheel frame by a plastic rim (15). Each set of ungrounded electrodes (2P) is connected to its respective collector bar (4). The collector bars (4) are insulated from each other by plastic segments (5) and are insulated from the frame by a plastic insulator (16). The collector assembly is attached to the plastic insulator (16) by screws (19). The plastic insulator is attached to the wheel (14) by bolts (17).

As the wheel is rolled along the windrow of hay, the set of ungrounded

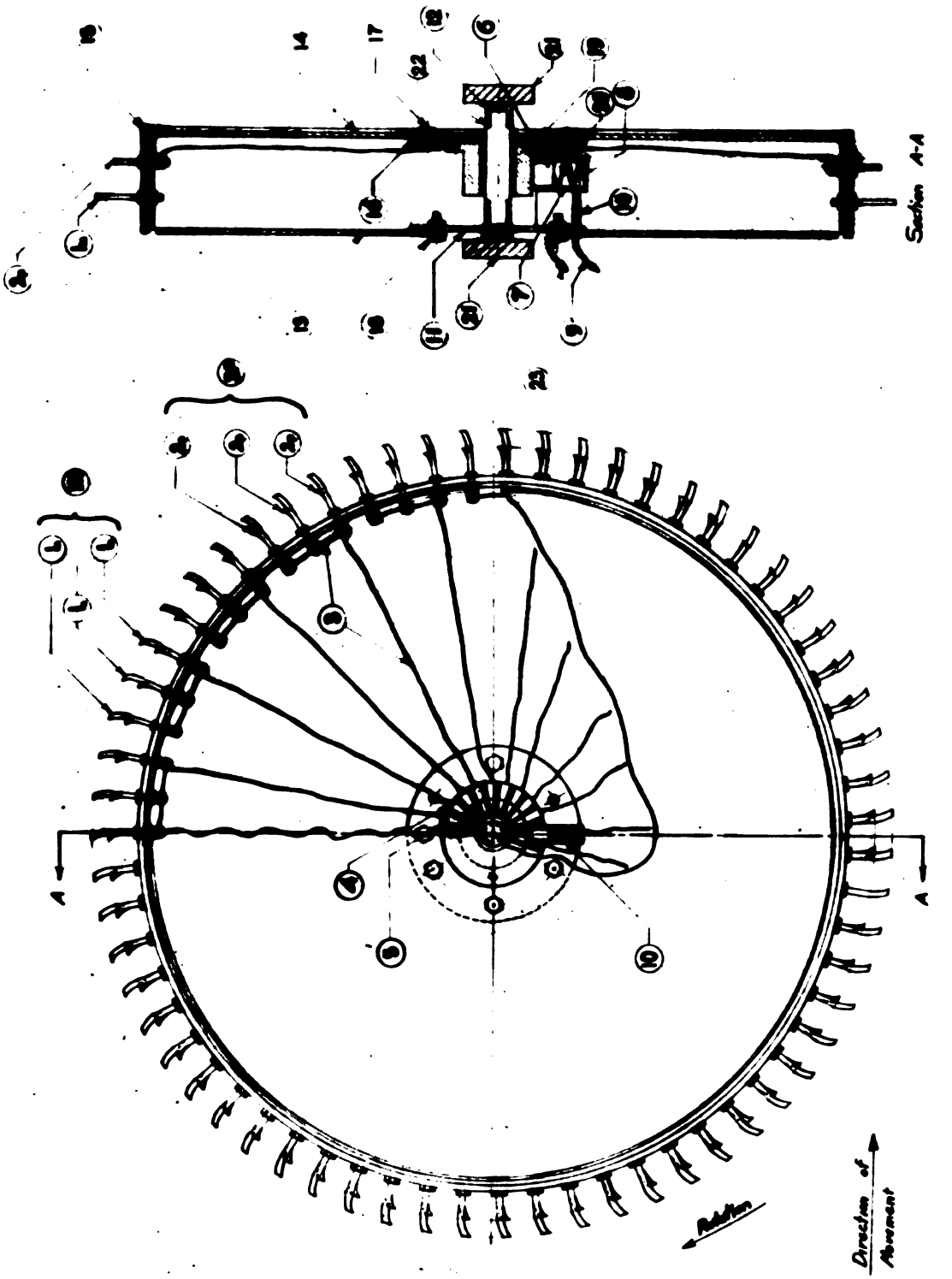


Fig. 37. Drawing of the swinging resistance-type moisture meter for hay.

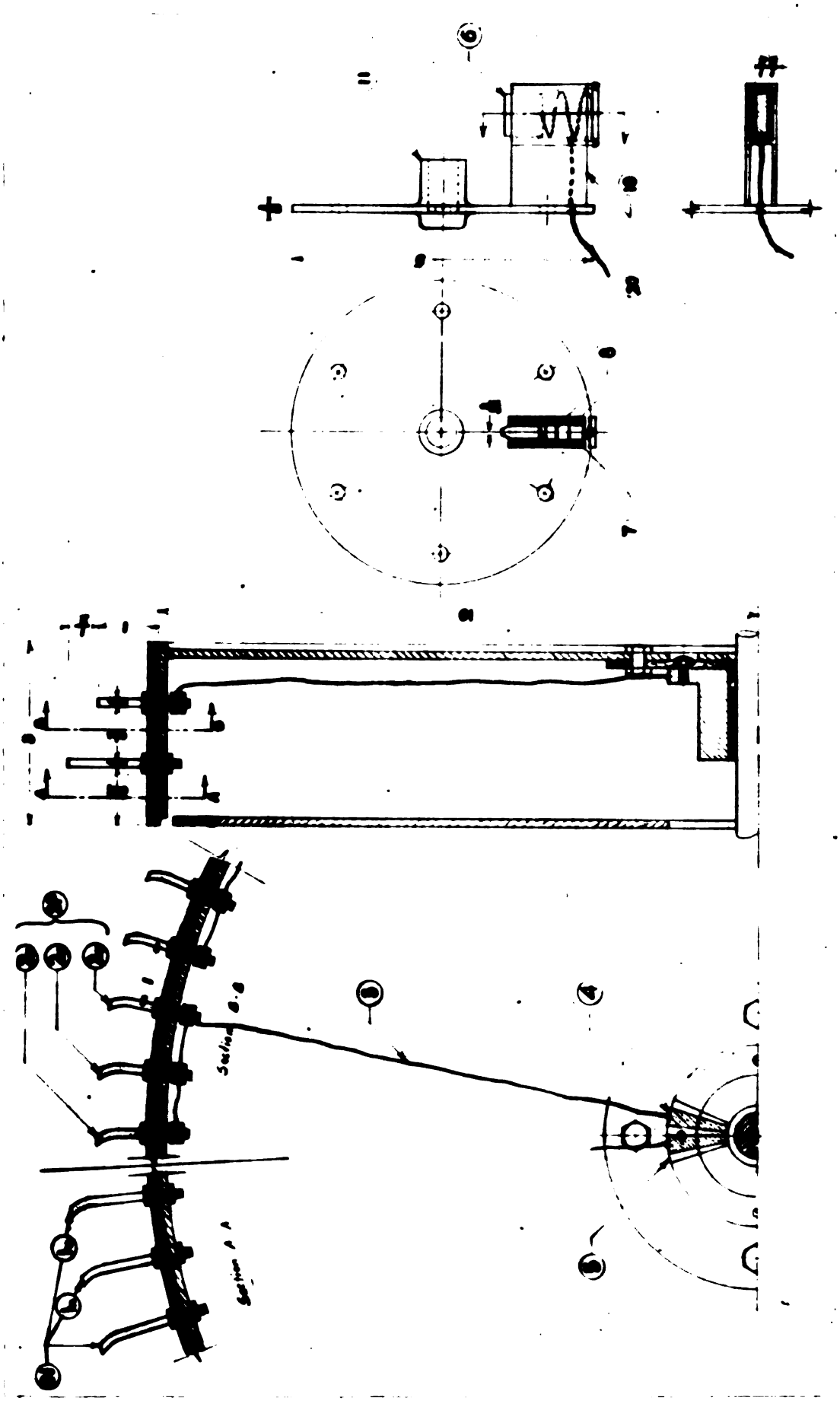


Fig. 38. Detail sections of the averaging resistance-type moisture meter for hay.

electrodes (2P) which is at the lower-most position is connected to the resistance meter by means of the following circuit: conductor (3), to collector bar (4), to brush (6), to brush holder liner (7), to conductor (9), to the meter. One terminal of the resistance meter is connected to the frame of the device by the grounded conductor (23). The brush holder liner (7) is insulated from the brush holder (10) by an insulating sleeve (20). A spring (8) holds the brush against the collector. A removable guard plate (13), attached with bolts (18) to the bearing assembly (11), is provided to protect the electrical wiring inside the wheel from mechanical damage.

Any direct-reading resistance-measuring circuit calibrated in moisture content may be used with the averaging device; however, the action of the galvanometer movement used must be heavily damped in order to maintain a reasonably steady average reading as resistances of different values are connected to it by the averaging device.

The well-known series ohmmeter circuit with its essential features is shown in Figure 39. The resistance to be measured, R_t, is connected in series with the galvanometer; an adjustable series current-limiting resistor, Ra; and the voltage source, V. A resistor, R_s, is placed in parallel with the galvanometer to produce electrodynamic damping. R_s places an electrical load on the galvanometer coil which absorbs energy from it and prevents excessive oscillation of the needle.

The current through the measured resistance, R_t, in the ohmmeter circuit of Figure 39 is expressed by the following relation.

$$I = \frac{V}{R_t + R_0} \qquad (6)$$

where R_0 is the sum of all the resistances measured from the terminals

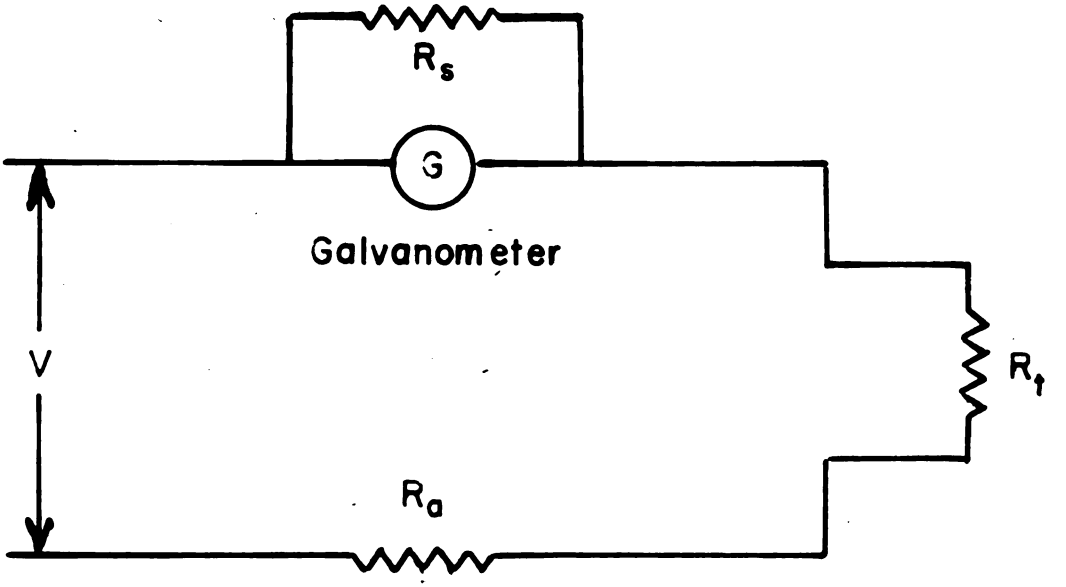


Fig. 5. Simple series ohmmeter circuit with damping resistor.

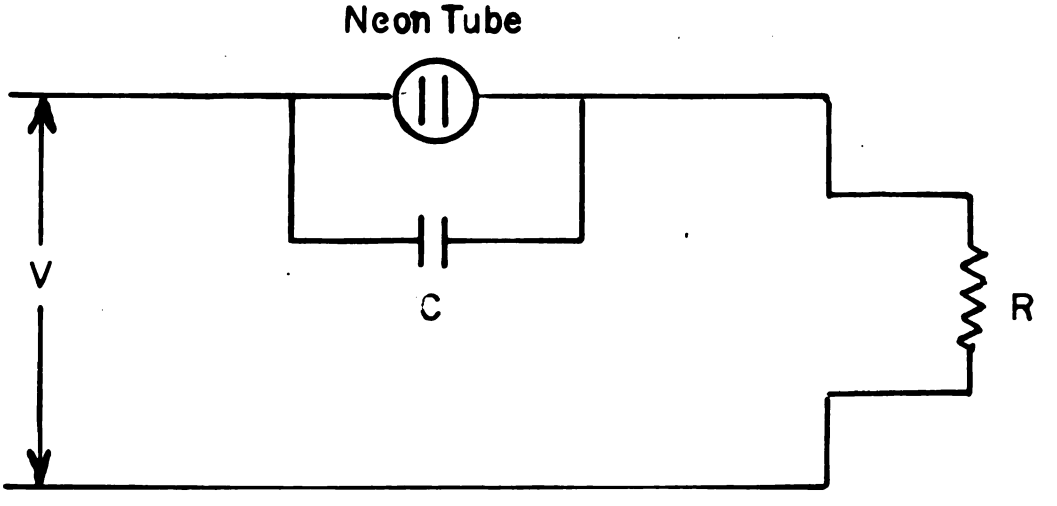


Fig. 6. Relaxation oscillator circuit for resistance measurement.

of R_t with the terminals of V shorted; i.e., the sum of R_a and the parallel combination of R_s and the galvanometer coil resistance.

In order for the relation of Equation (4) to hold true for an ohmmeter circuit, R_o must be negligibly small in comparison to R_t. This condition is not difficult to obtain in ohmmeters for high resistances such as are used for moisture measurement. However, in most of the common laboratory or portable ohmmeters, R_o is not much smaller than R_t, since the value of R_a is selected such that if the test leads are shorted ($R_t = 0$), the galvanometer deflects to full scale. This not only safeguards the galvanometer in case of accidental shorting of the test leads, but also provides a convenient means of standardizing the circuit by adjusting the value of R_a. The adjustment is frequently necessary in ohmmeter circuits in order to allow for variation in the battery voltage.

Another type of resistance measuring circuit applicable to the averaging device is the relaxation oscillator circuit which has been described fully by Suits and Dunlop (1). In the circuit of Figure 40, the resistance to be measured, R, is placed in series with a capacitor, C, and a battery voltage, E. Across the capacitor is placed a neon glow lamp which has an ignition or starting voltage, V, of about 80 volts. The battery voltage, E, is usually more than 50% greater than the ignition voltage, V. When the circuit is completed by the measured resistance, R, the voltage across the capacitor, e, increases with time, t, according to the relationship,

$$e = E\,(1 - \epsilon^{-t/RC}) \qquad (7)$$

where ϵ equals the natural logarithmic base.

The operation of the relaxation oscillator circuit is explained graphically with the aid of Figure 41. The oscillation of the voltage across the capacitor and the lamp is represented by the cycle passing through the points B_1, D_1, B_2, D_2, B_3, D_3, etc.. When the voltage across the capacitor and the neon lamp reaches the value of the ignition voltage of the lamp, V, (Point B_1), the lamp "fires" and emits light. At the same time the internal resistance of the lamp drops to a very low value and quickly drains the electrical charge from the capacitor until the capacitor voltage drops to the extinguishing voltage of the lamp, V-a (Point D_1). At this voltage the lamp ceases to glow and again becomes a very high resistance so it is again possible for the capacitor to recharge according to Equation (7) from Point D_1 to B_2. When the capacitor has charged to Point B_2 the lamp fires again and the capacitor voltage drops to D_2. The above process repeats periodically and an oscillation occurs. Each time the lamp fires, a flash of light is produced. The rate of flashing gives a visual indication of the value of the measured resistance, R.

The time elapse between flashes or the period of the oscillation is expressed by the following relation:

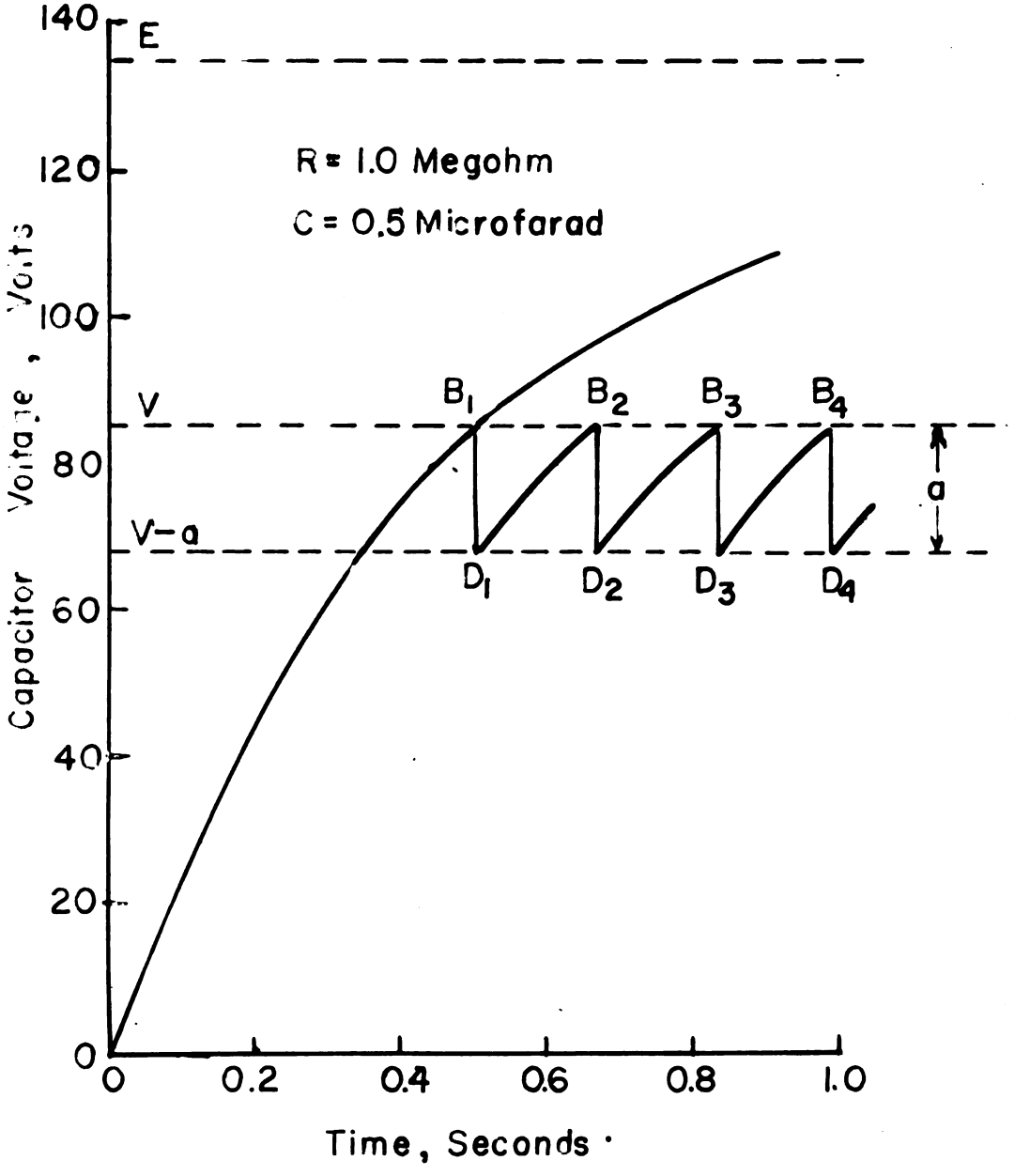
$$T = K_1RC \qquad (8)$$

Where K_1 is a constant of proportionality dependent chiefly upon the battery voltage, the ignition voltage of the lamp, and the extinguishing voltage of the lamp. The frequency of the flashing of the lamp is:

$$f = \frac{1}{T} = \frac{K_2}{R} \qquad (9)$$

where K_2 is the reciprocal of K_1C. Thus, Equation (9) indicates a response of the relaxation oscillator circuit which is similar to the

Fig. 41. Operating cycle of the relaxation oscillator circuit.



response of the ohmmeter circuit described by Equation (4). A plot of logarithm R vs. logarithm f is linear.

In the application of the relaxation oscillator circuit to the averaging device, the operator would run the averaging device continuously for a measured length of time, e.g., one minute. The number of flashes of the neon lamp observed during this time is an indication of the average moisture content of the material tested.

The operation of the circuit when connected to an averaging device can be readily explained by means of an example. A relaxation oscillator circuit having the following typical circuit constants is connected to an averaging device:

Supply voltage, E. = 135v

Starting voltage of the lamp, V = 85v

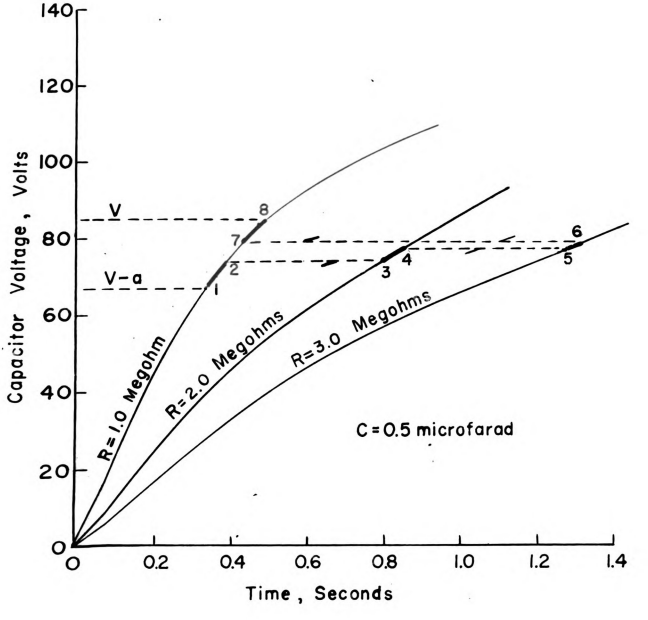
Extinguishing voltage of the lamp, V-a = 67v

Circuit capacitance = 0.5 microfarad

The circuit is connected to an averaging device such as that of Figure 35 which contacts in sequence three resistances at the rate of 0.05 second per resistance. The values of the resistances are R_1 = 1.0 megohms, R_2 = 2.0 megohms, and R_3 = 3.0 megohms.

While the circuit is in contact with any one of the resistors, the capacitor charges according to the relation of Equation (7). The relationships between capacitor voltage and time for each of the three resistances are illustrated in Figure 42. Assuming that the capacitor has already been charged to 67v, the extinguishing voltage of the lamp, and that R_1 has just been contacted, the capacitor will charge for 0.05 second along the charging curve of R_1. At the end of this time, R_2 is contacted for 0.05

Fig. 42. An operating cycle of a relaxation oscillator circuit used with the averaging device.



seconds and the capacitor is charged for the same length of time according to the curve of R_2. After R_3 has similarly been contacted, R_1 is again contacted and the capacitor charges to the firing voltage of 85 volts. At this time, the lamp fires and the capacitor discharges to 67 volts, the extinguishing voltage of the lamp. Since R_2 is the next resistance to be contacted, the second charging cycle will start with R_2 and proceed in a manner similar to the first cycle. The time required to charge the capacitor to the starting voltage of the lamp during the cycle indicated on Figure 42 is 0.1 x 4=0.4 sec.. The flashing frequency corresponding to this period is 1/0.4 = 2.5 flashes per second.

In the charging cycle just described and outlined on Figure 42, it is apparent that the rate of charging of the capacitor was not as great during the second period of time R_1 was contacted as it was during the first period of contact. This is due to a lower charging rate at higher voltages. Thus, it is apparent that whether a certain resistance is connected to the circuit early or late in the charging cycle has some bearing on its effect on the charging of the capacitor and the period of the circuit oscillation. However, it is very doubtful that this apparent source of error would be important where either a very large number of resistances of assorted values are contacted or where a small number of resistances are contacted in sequence over a period of time of one minute or more.

Of greater importance in the application the relaxation oscillator circuit is the effect of fluctuation in the supply voltage upon the accuracy of resistance measurement. According to information by Suits and

Dunlop (1), the circuit is not affected by changes in supply voltage until the supply voltage drops below about 1.5 times the starting voltage of the lamp. The current drain on batteries supplying this type of circuit is small; however, aging alone will reduce the terminal voltage of batteries. Therefore, some means should be provided in a meter of this type to indicate when the battery voltage is too low. This could readily be done by providing an accurate resistor which could be placed in the circuit for purposes of checking the accuracy by the substitution method.

It is recognized that in such applications as in testing windrowed hay in the field, the rather dim flashes of light from the neon lamp would not be clearly visible in bright sunlight. An audible indication of the flashing of the neon lamp can be obtained by connecting an earphone into the circuit in series with the neon lamp. A distant "thump" is heard each time the lamp flashes. The earphones for this purpose must be of relatively low impedance, e.g., 2000 ohms. Most of the inexpensive electromagnetic types of earphones are suitable. Laboratory experience with the relaxation oscillator circuit has shown that it is easier for the operator to count accurately at high rates from an audible signal than from a visual signal. It is also easier to watch the timing device while counting from the audible signals than to attempt to watch both the timing device and the flashing lamp simultaneously.

Tests of the Averaging Device

Both field and laboratory tests were performed on the averaging device for windrowed hay. The most desirable procedure would have been to conduct the laboratory tests before the field tests; however, the conception of the idea for the averaging device came very late in the 1953 haying season. In order to avoid delaying the field tests until another year, the laboratory tests were delayed so that the field tests could be run while field hay was available.

Field Tests

Two field tests of hay were tested with the averaging device for windrowed hay, one of alfalfa-brome mixed hay and another of practically pure alfalfa. The crop in both fields was from the second cutting and was very light in yield due to very dry weather.

Apparatus. In the field tests, the wheel-type averaging device pictured in Figure 36 was used and resistance readings were taken with a Tag-Heppenstall Model No. 8003-T4 resistance meter, the same meter which is used with the Tag-Heppenstall resistance-type moisture meter for grain. The movement of this meter is highly damped. Additional damping can be provided if needed by pressing a button on the meter face. The circuit of the Tag-Heppenstall meter is basically that of a series ohmmeter with a low internal meter resistance, R_0. (See Equation 6). Therefore, the response of the meter to changes in resistance is hyperbolic; i.e., logarithm of the meter deflection vs. logarithm of the measured resistance is linear. Eight ranges of resistance measurement are available on the meter. The overall range of the meter as determined from a previous

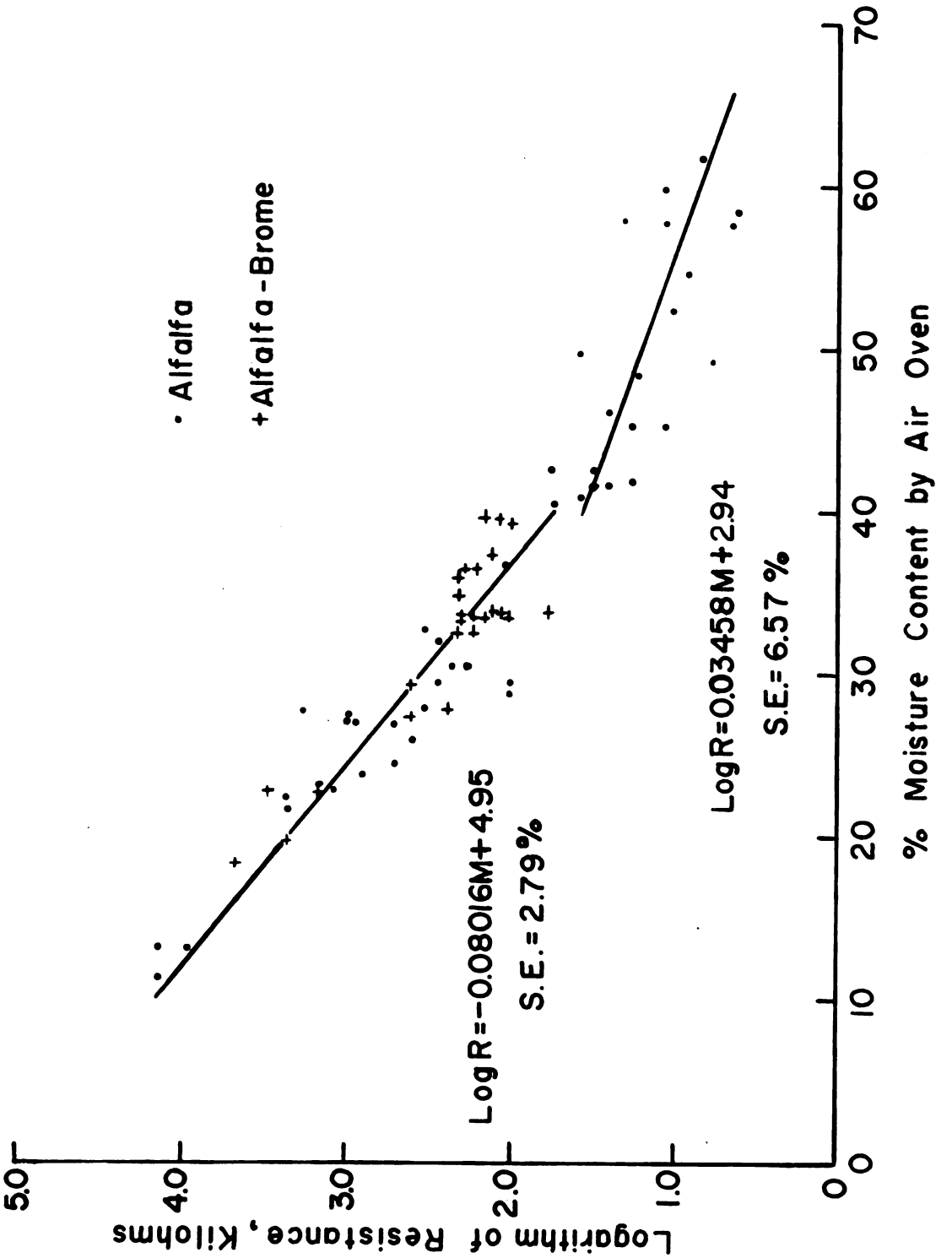
laboratory calibration is 1500 ohms to 100 megohms.

Procedure. Approximately 75 feet of windrow was used for each test run of the apparatus. Three marker stakes were layed out at points approximately 1/4, 1/2, and 3/4 of the length of windrow to be tested. While running the wheel over the windrow, the operator read off aloud the meter reading as the wheel passed the marker stakes. These readings were recorded by an assistant. Immediately after each test run, the operator also recorded an estimate of the average meter reading during all of the test run.

As soon as possible after each test run with the wheel, cross-sections were cut out of the windrow at the location of the marker stakes to serve as samples for moisture determinations by air oven methods (212°F for 48 hours). While cutting the cross-sections, the windrow was clamped between two 5/8 x 2-1/2 x 4' boards which were hinged together at one end. A vertical cross-section of the windrow about 2-1/2 inches thick was cut with a hedge shears. The samples so obtained were placed in paper bags and weighed immediately in the field on a laboratory balance. Weighing was done in an enclosed trailer to avoid scale errors due to wind, leveling, and other factors.

Results. Oven-determined moisture contents of the samples cut from the windrow have been plotted in Figure 43 against the logarithm of resistance readings recorded as the wheel passed the point where the samples were taken. The data from the alfalfa and alfalfa-brome are plotted together and identified. It is apparent from the data of Figure 43 that the relation between moisture content and logarithm of resistance is not linear throughout the range of moisture contents tested. The direction

Fig. 43. Field data from the averaging resistance-type moisture meter for hay.



of the curvature of the relation at the higher moisture contents suggests that it might be linear if plotted as logarithm moisture content vs. logarithm resistance. A plot of this sort was made in analyzing the data and a somewhat greater degree of curvature in the opposite direction was found in the relation. Therefore, it was decided to divide the data in two groups, that above 40% and that below 40%, assuming linearity within these two ranges.

The equation of the regression line for the data below 40% moisture content was determined by the Method of Least Squares and found to be as follows:

$$\log R = 0.08016\ M + 4.955 \qquad (10)$$

The standard error of estimate of the logarithm of resistance was 0.237. In terms of moisture content, the standard error was 2.79 moisture percentage points (0.237/0.08016 = 2.79).

The equation of the regression line for the data above 40% moisture content is as follows:

$$\log R = 0.03458\ M + 2.936 \qquad (11)$$

The standard error of estimate for this data is 6.57 moisture percentage points.

The error of the moisture measurement with the wheel-type meter seems to be much greater in the higher moisture range. This is to be expected from all resistance-type meters, since the variation of the logarithm of the resistance with moisture content is less at higher moisture contents. It is also possible that in the early stages of drying in the windrow, the moisture content may be more non-uniform than in the later stages of drying, thereby increasing the sampling error involved in

Figure 44 shows the average of the oven-determined moisture contents of the groups of samples taken following each run of the wheel plotted against the estimated average reading of the meter recorded by the operator after the corresponding run. The average of the moisture contents of the samples taken after each run probably better represents the moisture content of the windrow and the hay tested by the meter than do the single sample moisture contents of Figure 43 represent the hay from which the individual meter readings were taken.

The equation of the regression line for the data below 40% moisture is:

$$\log R = 0.0929 M + 5.38 \qquad (12)$$

The standard error of estimate for this data is 2.11 in terms of oven-determined moisture percentage points. The equation of the regression line for the data above 40% moisture content is:

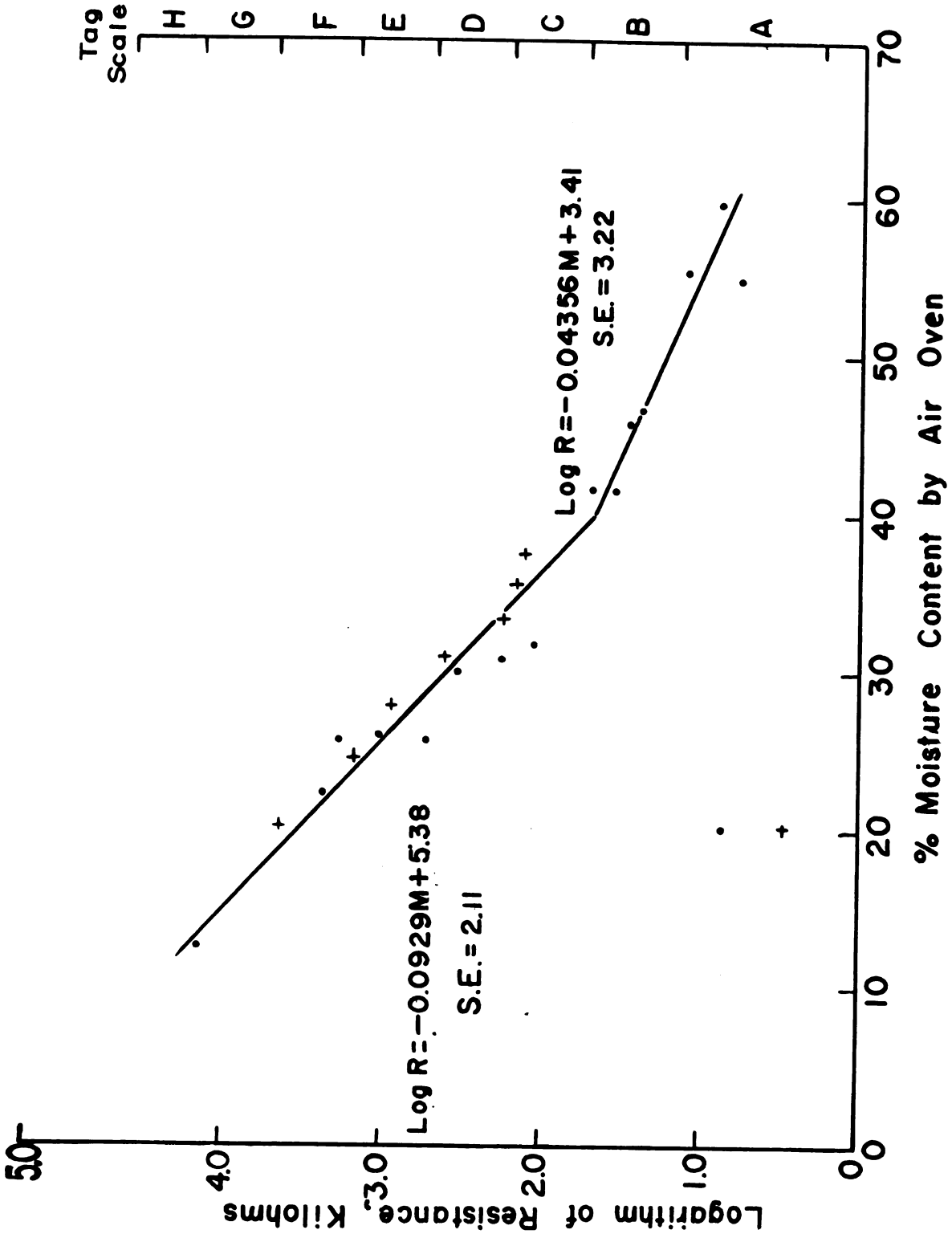
$$\log R = 0.04356 M + 3.41 \qquad (13)$$

The standard error of estimate for this data was 3.22 moisture percentage points.

Indicated in the right-hand scale of Figure 44 are the ranges of the eight scales on the Tag-Heppenstall meter. Since all of the scales overlap below 20 scale divisions, only the ranges from 20 to 60 scale divisions are shown for each scale. The span of the meter is sixty scale divisions.

Comparisons of the data plotted in Figure 43 and Figure 44 show that the error of estimate of the meter is much less when the meter readings are plotted against the average of three simultaneously-determined samples.

Fig. 44. Field data from averaging resistance-type moisture meter for hay. Logarithm resistance vs. the average moisture content of three oven samples.



This suggests that much of the apparent error of the meter is due to sampling error in obtaining the oven samples. The standard deviation of the average of the moisture contents of each group of samples was determined. The average of these standard deviations was found to be 4.75 moisture percentage points for all the alfalfa-brome samples, 2.77 for the alfalfa samples below 40% moisture content, and 3.15 for the alfalfa samples above 40% moisture content. These values are not intended to show quantitatively the extent of the sampling error in these tests; however, the need is indicated for taking a much greater number of samples per run of the wheel in future tests of this device.

Laboratory Tests

Laboratory tests of the averaging device were conducted to demonstrate its effectiveness in determining the average conductivity of known resistances and to substantiate the theoretical analysis of its operation. Apparatus and Procedure. The averaging device for windrowed hay was mounted in a fixed position as shown in Figure 43. The wheel was belt-driven by an electric motor operating through a hydraulic speed regulator. By adjusting the speed of the drive, a complete range of practical ground speeds could be similated. Resistors of assorted values were attached to the electrode sets to similate the testing of hay samples of various moisture contents with the averaging device. During all of the tests, the same Tag-Heppenstall resistance meter used in the field tests was connected in the usual manner to the averaging device. On some of the tests, resistance readings were also taken with the ohmmeter section of a Simpson Model 260 portable ohmmeter and with a relaxation oscillator circuit manufactured by the Shafer Instrument Company of Loudonville,

Fig. 45. Arrangement of equipment for the laboratory tests of the averaging device.

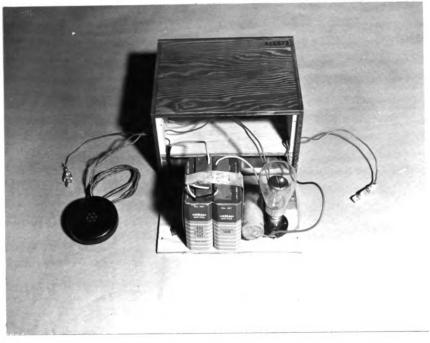


Fig. 46. Components of the relaxation oscillator circuit of the Shafer moisture meter. The earphone and the test leads with clips were added to the meter by this project.

Ohio. The circuit of the Shafer meter is similar to that shown in Figure 40. The voltage supply is 135v (battery source); the value of the capacitor is 0.5 microfarad; and the neon-tube is a General Electric Type NE-36 with a starting voltage of 84 volts. An inside view of the relaxation oscillator resistance meter is shown in Figure 56. This meter is marketed commercially for use by farmers for the moisture testing of grains.

Results. Table IX shows the arrangement of resistances connected to the 21 electrode sets on the wheel during Test A. The resistance values shown were determined with the Tag-Heppenstall resistance meter after the resistances were connected to the electrodes. Conductance values have been calculated and are shown in Table IX. Also shown in Table IX are mutual conductance values which are the values of conductance connected to the meter during the time of transition between one collector bar and another when the brush is in contact with two electrode sets simultaneously. The mutual conductance is calculated as the sum of the conductances of adjacent resistors. Entries of mutual conductance in Table IX are for a parallel combination of the resistor connected to the indicated electrode number and that of the next electrode; e.g., the mutual conductance opposite No. 4 is equal to the sum of the conductances of No. 4 and No. 5.

The width of the brush contact area was about 25% of the center to center distance between the collector bars. Therefore, in determining average conductances which the meter should indicate, the conductances of the connected resistors should be given a weighted value of three and the mutual conductances should be given a weighted value of unity. The average conductance, Y_a, is a follows:

TABLE IX

LOCATION AND VALUES OF TEST RESISTANCES (TEST A)

Electrode Set No.	Connected Resistance ohms x 10^3	Connected Conductance mhos x 10^{-3}	Mutual Conductance mhos x 10^{-3}
1	7.8	133.3	141.4
2	128	8.1	38.4
3	32.5	30.3	32.0
4	620	1.7	13.3
5	92	11.6	12.3
6	1750	0.7	5.0
7	260	4.3	4.4
8	10,000	0.1	166.8
9	5.8	166.7	173.6
10	150	6.9	36.3
11	36	29.4	31.0
12	740	1.6	11.8
13	108	10.2	10.8
14	2400	0.6	5.1
15	250	4.5	4.6
16	10,000	0.1	1.4
17	950	1.3	12.9
18	90	11.6	12.2
19	2000	0.6	6.2
20	192	5.6	5.7
21	10,000	0.1	133.4
		$429.3 = \Sigma Y$	$859.6 = \Sigma Y_m$

$$Y_a = \frac{1}{4n}\left(3\Sigma Y + \Sigma Y_m \right) = \frac{1}{R_a} \qquad (14)$$

$$= \frac{1}{4 \times 21}\left(3 \times 429.3 + 859.6 \right) = 25.56 \times 10^{-3} \text{ mhos}$$

$$R_a = \frac{1}{25.56 \times 10^{-3} \text{ mhos}} = 39.12 \text{ Kilohms}$$ or an indication of 26 on the "B" range of the Tag-Heppenstall meter.

A summary of the data from Test A is given in Table X. Two observations were made with the Tag-Heppenstall meter, one with the normal damping in the meter movement (designated "undamped") and one observation with extra damping introduced by depressing the "damp" button on the face of the meter. This button introduces additional resistance in parallel with the microammeter. The meter readings are given in meter scale units with the meter range designation indicated as a prefix to the scale readings; e.g., an indication of 26 scale units on the "B" range is indicated as B26. The scale units are proportional to the current through the sample.

The predicted meter reading as calculated using Equation (14) is also shown in Table X for comparison with the observed values. The observed values indicated are a range of readings, representing the lowermost and uppermost travel of the needle during the test. As should be expected, the range of the observed readings is less with the additional damping than with only normal damping. The range of the readings also decreases with an increase in the speed of the wheel or the number of resistances contacted per unit of time.

Comparison of the calculated and observed values of Table X is most favorable at the highest speed and with the greatest damping. A somewhat erroneous conclusion might be drawn that the average of the

TABLE X

SUMMARY OF DATA FROM TEST A OF THE AVERAGING DEVICE

Peripheral Wheel Speed m.p.h.	Tag-Heppenstall Meter Readings in Scale Units			Simpson Ohmmeter Readings, Kilohms		
	Observed		Calculated	Observed		Calculated
	Undamped	Damped			Average	Average
1	B3-38	B13-33	B26	45-1500	87	151
1.5	B12-36	B19-31		60-1200	113	
2	B13-33	B21-28		60-450	106	
2.5	B17-31	B23-27		70-700	127	
3	B18-28	B24-27		120-420	187	

uppermost and lowermost readings of the meter at a given speed should agree closely with the predicted reading and that the average of these two observed scale readings should not vary with the speed of the wheel. This is not true, since the average of the uppermost and lowermost readings of the meter at a given speed is not a time average, as is the calculated value. The observations do not reveal the proportionate length of time the meter needle dwelled on the highest or lowest reading. Comparison of the observed and calculated values is most favorable at high speeds because the needle is steadier at higher speeds and does not indicate readings of short time duration which are widely variant from the average.

The observed readings taken with the Simpson ohmmeter were taken immediately after the readings with the Tag-Heppenstall meter. Since the Simpson meter is not highly damped, the ranges of the observed readings are much greater. The averages of the observed readings with the Simpson meter shown in Table X are not arithmetic means of the resistances but are the reciprocals of the average of the conductances indicated. For example, the average of the observed readings at 3 m.p.h. are indicated as follows:

$$\text{Average conductance} = \frac{1}{2}\left(\frac{1}{120} + \frac{1}{420}\right) = 0.00535 \times 10^{-3} \text{ mhos.}$$

$$\text{Observed average resistance} = \frac{1}{0.00535} = 187 \text{ kilohms.}$$

The calculated average resistance value was determined by a procedure similar to that used for the Tag-Heppenstall readings and explained previously except that the internal resistance of the meter was taken into consideration. This was not necessary with the Tag-Heppenstall meter because its internal resistance is negligibly low in comparison

to the measure resistances. This is not the case with the Simpson meter since its internal resistance is 118 kilohms. In calculating the average indicated resistance, the internal resistance is added to the observed value of the individual resistors before the values of connected conductance and mutual conductance are determined by the same procedure used with the Tag-Heppenstall meter. The average resistance as calculated by Equation (14) must be adjusted to the indicated average resistance by subtracting the internal resistance of the meter.

The special procedure indicated above for analyzing the operation of the Simpson meter on the averaging device is necessary because the meter movement indicates the average conductance in the whole meter circuit and not just that of the resistances connected to its terminals. Also for this reason the indicated values of average resistance of Table X are not the same for the Simpson meter as they are for the Tag-Heppenstall meter, even though they were operating on the same resistors. The Simpson meter does not indicate a value of resistance corresponding to the average conductivity of the resistances tested. However, it is possible by the above procedures to predict within experimental error the reading of either of the meters on a given set of resistances.

Further laboratory testing of the averaging device was conducted in Test B using the resistance values indicated in Table XI. In previous tests of the averaging device, a copper-impregnated carbon brush was used. In Test B, a brush was made from a piece of 5/16 in. x 3/4 in. aluminum flat bar stock. In order to reduce the shorting effect as the brush passes from one collector bar to another, a blunt edge was ground on the brush so that the width of the area contacted on the collector

TABLE XI

LOCATION AND VALUES OF TEST RESISTANCES IN TEST B
ODD-NUMBERED RESISTANCES WERE DISCONNECTED FOR TEST C

Electrode Set No.	Connected Resistors ohms x 10^3	Connected Conductance mhos x 10^{-6}	Mutual Conductance mhos x 10^{-3}
1	510	1.960	35.858
2	29.5	33.898	37.898
3	250	4.000	5.613
4	620	1.613	31.025
5	34	29.412	34.967
6	180	5.555	6.963
7	710	1.408	30.820
8	34	29.412	34.620
9	192	5.208	6.712
10	665	1.504	31.807
11	33	30.303	34.651
12	230	4.348	5.776
13	700	1.428	31.731
14	33	30.303	34.470
15	240	4.167	5.575
16	710	1.408	30.820
17	34	29.412	33.288
18	258	3.876	5.837
19	510	1.961	31.373
20	34	29.412	35.294
21	170	5.882	7.842
		256.470 = ΣY	512.940 = ΣY_m

TABLE XII

SUMMARY OF DATA FOR TEST B AND C OF THE EXPERIMENTAL AVERAGING DEVICE

Test	Peripheral Speed, m.p.h.	Tag-Heppenstall Meter Readings in Scale Units		
		Observed		Calculated Average
		Undamped	Damped	
B	1	B14-22	B16-21	C41
"	1.5	C45-60	C49-57	
"	2	C37-41	C39-40	
"	2.5	C36-38	C37	
"	3	C36.5 -C37.5	C37	
C	1	C14-32	C18.5-26	C22.5
"	1.5	C18-29	C20.5-24	
"	2	C19-26	C21-23	
"	2.5	C19-23	C20.5-21.5	
"	3	C19.5-20.5	C20.5-21.5	
"	3.5	C20.5-22	C21.5	

was approximately 10% of the center-to-center spacing of the bars. The aluminum was hard enough not to wear badly when ground to so sharp a point, but was not so hard enough to cut the copper collector bars.

Calculation of the predicted meter readings was done by the same method used in Test A except that 10% brush coverage was assumed instead of 25%. The test data and the calculated results are shown in Table VI

Agreement between the calculated and experimentally determined results is somewhat more favorable at the 2 m.p.h. than at 3 m.p.h., which could be due to "jumping" of the brush as it passed over the groove between the collector bars. The sharp aluminum brush would be more apt to do this than the flat-faced carbon brush. If this phenomenon did occur, it would mean that contact with the collector bars was not continuous and would explain the lower indicated conductivities which resulted.

In Test C, the resistors were disconnected from the odd-numbered electrode sets, so only ten resistors remained connected to the averaging device. Since there were no two adjacent commutator bars to which resistors were connected, there was no mutual conductance entering into the circuit when the brush passed between bars. Therefore, the predicted average reading was calculated as follows:

$$Y_a = 1/R_a = \frac{1}{n} \quad (Y_2 + Y_4 + Y_6 \text{ - - - } Y_{20}) \qquad (15)$$

$$= \frac{1}{21} \quad (141.329) \quad = 6.730 \text{ micro-mhos.}$$

$$R_a = \frac{10^3}{6.730 \times 10^{-6}} = 148.6 \text{ kilohms}$$

This is a reading of C22.5 on the Tag-Heppenstall meter and it agrees favorably with the experimental results shown in Table XI.

In Tests D and E, a relaxation oscillator circuit for resistance

measurement was utilized as well as the Tag-Heppenstall meter. The calibration of the relaxation oscillator circuit is described by the following relation:

$$R = \frac{320}{f} \qquad (16)$$

where R is the measured resistance in megohms and f is the number of the flashes observed per minute.

Resistors were connected for Tests D and E as indicated in Table XIII. The calculation of the predicted meter readings was carried out as in Test C. The observed meter readings at various speeds of the averaging device are tabulated in Table XIV.

The data observed from the Shafer meter shows that there is little or no dependence on speed of the reading of this meter when used with the averaging device. This is a reasonable result, since there is no inertia involved in the indications of this meter as there is with a D'Arsonval galvanometer movement. Each resistance contacted provides a current path for charging the capacitor. The amount of charge passing to the capacitor is irrespective of the value of the resistors just previously contacted. With the D'Arsonval galvanometer, if a single resistance of a value much different from the value of those resistances just preceeding it is contacted, the effect on the galvanometer reading will be much greater at low speeds than at high speeds.

TABLE XIII

LOCATION AND VALUES OF THE TEST RESISTANCES
IN TEST D AND E OF THE AVERAGING DEVICE

Electrode Set No.	Test D		Test E	
	Connected Resistance, Megohms	Connected Conductance, Micro-mhos	Connected Resistance Megohms	Connected Conductance, Micro-mhos
2	1.7	0.612	1.7	0.612
4	10.1	0.099	10.1	0.099
6	14.5	0.069	1.48	0.677
8	1.55	0.645	1.55	0.645
10	9.2	0.109	9.20	0.109
12	13.8	0.073	1.44	0.694
14	1.64	0.610	1.64	0.610
16	10.1	0.099	10.1	0.099
18	12.5	0.080	1.50	0.667
20	1.64	0.610	1.64	0.610
		$\Sigma Y = 3.006$		$\Sigma Y = 4.822$

TABLE XIV

SUMMARY OF DATA FOR TESTS D AND E OF AVERAGING DEVICE

Test	Peripheral Speed m.p.h.	Tag-Heppenstall Meter Reading				Shafer Relaxation Oscillator Circuit Reading			
		Observed		Calculated		Observed		Calculated	
		Scale Units	Megohms	Scale Units	Megohms	Flash/min.	Megohms	Flash/min.	Megohms
D	1	G26-53	10.6-5.2	G39	7.0	43.0	7.45	45.7	7.0
"	2	G34-43	8.0-6.3	"	"	43.5	7.35	"	"
"	3	G37-41	7.4-6.6	"	"	43.5	7.35	"	"
E	1	F14-34	6.8-2.7	F21.5	4.37	77	4.17	73.3	4.37
"	2	F20-29	4.7-3.2	"	"	77	4.17	"	"
"	3	F22-26	4.3-3.5	"	"	78	4.11	"	"

Conclusions

The field test data of Figure 44 indicate that a standard error of estimate of 2.11 moisture percentage points applies to the averaging meter when testing windrowed hay between 20 and 40% moisture content. The standard error of estimate of the average of five readings per sample with the Delmhorst moisture meter was 4.10 moisture percentage points when testing hay from the same field at the same time. The standard error of estimate of five readings for sample with the Hart moisture meter was 2.8 moisture percentage points when testing hay from the same field at the same time.

In comparing the above results, one should examine the sampling procedures in the tests of each meter in regard to what degree the oven samples taken were representative of the hay actually tested. The Hart meter tested only a small bunch of hay about one inch in diameter and this hay was used as the oven sample. This procedure is probably more favorable to the meter than either of the procedures used on the other meters, but it does not indicate the ability of the meter to determine the average moisture content of the field or the windrow.

Tests of the Delmhorst meter involved taking a cross-section of the windrow where five readings had been taken with the probe. This procedure is certainly less favorable in indicating the accuracy of the meter than that used with the Hart meter, since only a very small percentage of the oven samples had actually been contacted by the probe.

The procedure for obtaining oven samples used in testing the averaging meter was probably the least favorable of all to the meter. Considering

the high standard deviation of the average moisture content of simultaneously drawn samples, the number of samples taken was inadequate to supply reliable information as to the average moisture content of the hay tested in one run by the averaging meter. Future tests of the averaging meter should be conducted taking at least ten samples from the windrow per pass of the wheel.

Laboratory tests of the averaging meter substantiate the initial theory that it indicates the average conductivity of the resistances connected to it. However, this is strictly true only if the internal resistance of the measuring circuit is negligible in comparison to the measured resistance. Therefore, ohmmeters of the most common portable type cannot be used, since they have very high internal resistances.

The relaxation oscillator circuit has been found quite applicable to the averaging device. This circuit is inexpensive in comparison to other resistance measuring circuits. Its methods of operation would probably be as acceptable to farmers as a direct-reading ohmmeter. Use of the relaxation oscillator circuit requires the counting of flashes or audible signals during a reasonably accurately determined period of time; however, operation of the ohmmeter circuit requires taking a meter reading from a pointer which fluctuates considerably during a run of the averaging device. This variation in reading is of the order of the variation encountered in the Tag-Heppenstall resistance-type moisture meter for grain. This meter is widely accepted for testing grain for market purposes, but a degree of judgment is usually required to decide upon the exact indication of the meter. When the relaxation oscillator circuit is used on the averaging device for windrowed hay, the reading taken

is dependent upon the moisture content of all the hay contacted during perhaps a minute of time. A reading taken with the ohmmeter circuit is either a judgement of the average reading of the meter during the test period or a single reading taken on only a few feet of windrow.

The mechanical design of the averaging device for windrowed hay was generally acceptable, except for one feature. The insulating segment between the collector bars should be wider than the brush width so that shorting together of adjacent collector bars is avoided.

The immediate practical value of the averaging meter for windrowed hay as a tool for farmers is somewhat open to question, principally because of its high cost of construction. A less elaborate simplification of this device might include a crank-operated rotary switch connected to several electrode sets attached to a fixed member, the arrangement which is shown schematically in Figure 35. An averaging device in this form could readily find application on baled hay and in testing other materials of non-uniform moisture content. The application of the averaging device to the process industries such as paper making (from straw), cotton milling, and tobacco manufacturing should be investigated. In these industries where cost is not such an important consideration, the instrument would probably find more immediate application.

Literature Cited

(1) Suits, C. G. and Dunlop, N. E., Determination of the Moisture Content of Wood by Electrical Means, General Electric Review, v 34, pp. 706-13 (1931)

PRELIMINARY INVESTIGATIONS OF OTHER METHODS OF MOISTURE MEASURMENT

Investigations discussed in this chapter are those which were conducted in the early stages of the project to gain general information on the applicability of several methods of moisture measurement to the problem. The information and experience obtained were used as a guide in selecting the methods on which to concentrate attention.

Gas Pressure Method

Apparatus. Figure 47 shows the steel receptable and gauge for testing the moisture content of grain in relation to the amount of gas released when mixed with a chemical such as calcium carbide or calcium hydride.

The receptacle was constructed from standard 1½ inch pipe fittings. A gasket union with a neoprene gasket was used. A small rubber disc of the type used as a safety valve on pressure cookers was installed in the end of the receptacle to reduce the danger of explosions. A small piece of steel wool was installed in the gauge port to prevent dust from entering the gauge. The total displacement of the receptacle was approximately nine cubic inches.

The Bourdon-tube gauge shown has a pressure range of 0 to 60 psi. Another gauge of similar size which has a range of 0 to 15 psi. and a minimum scale subdivision of 0.25 psi. was also used in these tests.

Procedure. A weighed sample of grain was placed in one half of the receptacle and a weighed quantity of chemical in the other. (Weighing the chemical is not altogether necessary if an excess is used). The two

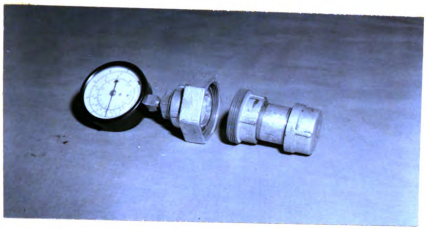


Fig. 47. Test cell for trials of the gas pressure method on grains

halves of the receptacle were then closed tightly as quickly as possible with the aid of a pipe vise and a wrench. Care was taken to prevent the sample and the chemical from mixing before the receptacle was tightly closed.

In the early tests, shaking was continued throughout the test to mix the grain and the chemical, but it was found that continuous agitation did not aid the reaction after the first minute. Later samples were shaken only occasionally after the first minute.

Frequent checks of the tightness of the seal on the receptacle were made by immersing the test cell excepting the gauge in water and watching for gas bubbles. This could be done only at the conclusion of a test because the water would affect the temperature of the receptacle and consequently change the pressure of the gas. Data from the tests in which

leaks were encountered were discarded.

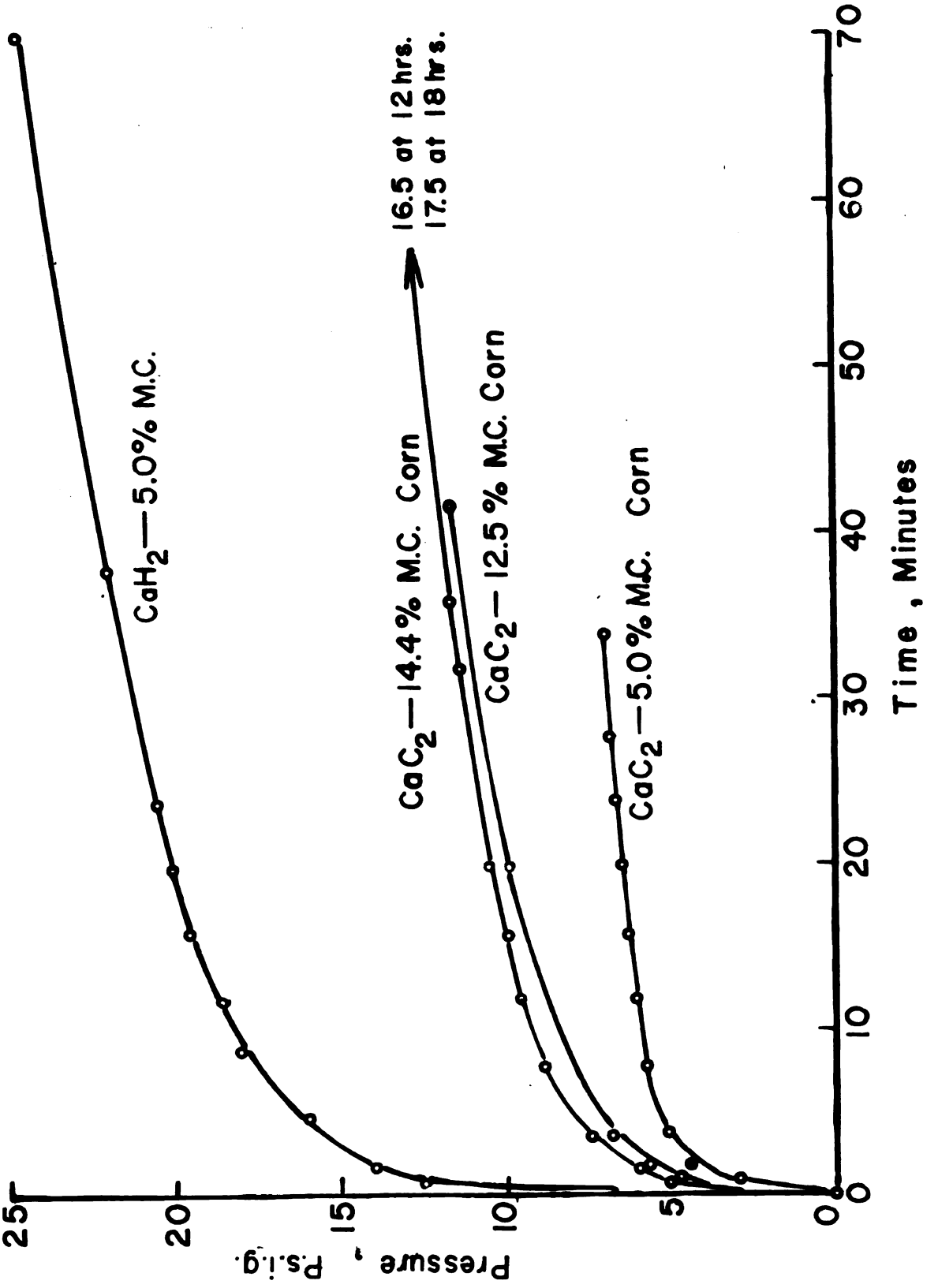
The corn used in these tests was ground to the consistency of commercial corn meal in a burr mill. The lots of corn at each moisture content were divided after grinding by means of a Boerner sampler. One portion was used in the tests and the other was moisture tested in an air oven.

Results. Representative data from these tests are plotted in Figure 48 Data are plotted for three different moisture levels for 3.0 gram samples of corn and 3.0 grams of calcium carbide. A curve is also plotted from data taken from a 3.0 gram sample of corn at 5.2% moisture content tested with 3.0 grams of calcium hydride. These data were also plotted on a logarithmic time scale and the relation between pressure and the logarithm of time was found to be linear within the range of the data.

Although the rate of pressure rise decreased, no true equilibrium point could be definitely indicated. During the extended time test run at 14.0% moisture content, the pressure increased one pound per square inch between 12 and 18 hours after the test was started. This pressure data was taken on a four-inch gauge with $\frac{1}{4}$ pound divisions and a range of 0 to 15 psi.

As was indicated in the literature, the pressure of the hydrogen produced by the calcium hydride was much greater than the pressure of acetylene produced by calcium carbide under similar conditions. The relative danger of handling hydrogen and acetylene in the quantities involved is about the same according to consultations with chemists. No explosions were experienced with either chemical in these tests.

Fig. 48. Rate of pressure rise in a receptacle containing ground corn and calcium carbide or calcium hydride.



Conclusions. The gas pressure method as applied in these tests is not very suitable as a method of moisture determination for grain because of the following disadvantages:

1. Excessive time required to reach an equilibrium point.
2. Possible hazard from fire and explosion.
3. Very accurate weighing of a small sample is required.
4. Maintenance of a gas-tight seal on the receptacle would probably be difficult for a farmer under field conditions.
5. The equipment cost of the method is rather high because an accurate scale and pressure gauge are required.

Oil Distillation Method

Apparatus. The first of these tests was intended to determine the weight loss of corn oil (Mazola) during extended periods of heating. For this purpose an ordinary porcelain enameled cooking pan was heated over a gas flame manually regulated to maintain the desired temperature. Five hundred grams of oil were used in this test. Temperature was measured with a mercury thermometer.

The oil distillation tests on hay and grain were conducted using a four-quart pressure cooker over the gas flame. The cooker was loosely covered during the tests at atmospheric pressure. During the tests under vacuum, the cooker was closed and attached to a vacuum pump as shown in Figure 49. Pressure was measured with a Bourdon-type gauge and regulated manually by an air bleed valve. Temperatures were measured by a mercury thermometer. A weighted screen was required to keep the hay submerged in the oil.

Fig. 49. Apparatus for dehydration tests in oil at below-atmospheric pressures.

Procedure. The stability test on corn oil was conducted by heating the oil at 212°F. for thirty minutes, 300°F. for thirty minutes, and 350°F. for thirty minutes. The oil was weighed occasionally during these tests.

In the oil distillation tests on hay and grain, the container, oil, and thermometer were weighed at the beginning of each test. The oil was then heated to 325°F. and a weighed sample was introduced. The apparatus and the sample were weighed at intervals until the weight became constant. The loss in weight of the apparatus and the sample was assumed to be the moisture loss of the sample. A vacuum of twenty inches of mercury was maintained during the vacuum tests. This degree of vacuum was selected because it is normally available at the exhaust manifold of a tractor.

Results. The weight loss of the five-hundred gram sample of oil during the entire stability test was 0.4 grams or 0.008%. This apparent loss is well within the range of expected experimental error in weighing the oil and container.

Observation of the rate of weight loss of alfalfa and corn samples when heated in oil are shown in Figure 50. The corn samples reached the equilibrium condition much more slowly than alfalfa hay. This cannot necessarily be considered typical of alfalfa in the field, since these samples were of rather light-stemmed hay and had been frozen in storage. The freezing may have damaged the cell structure of the hay so as to make it more easily dried.

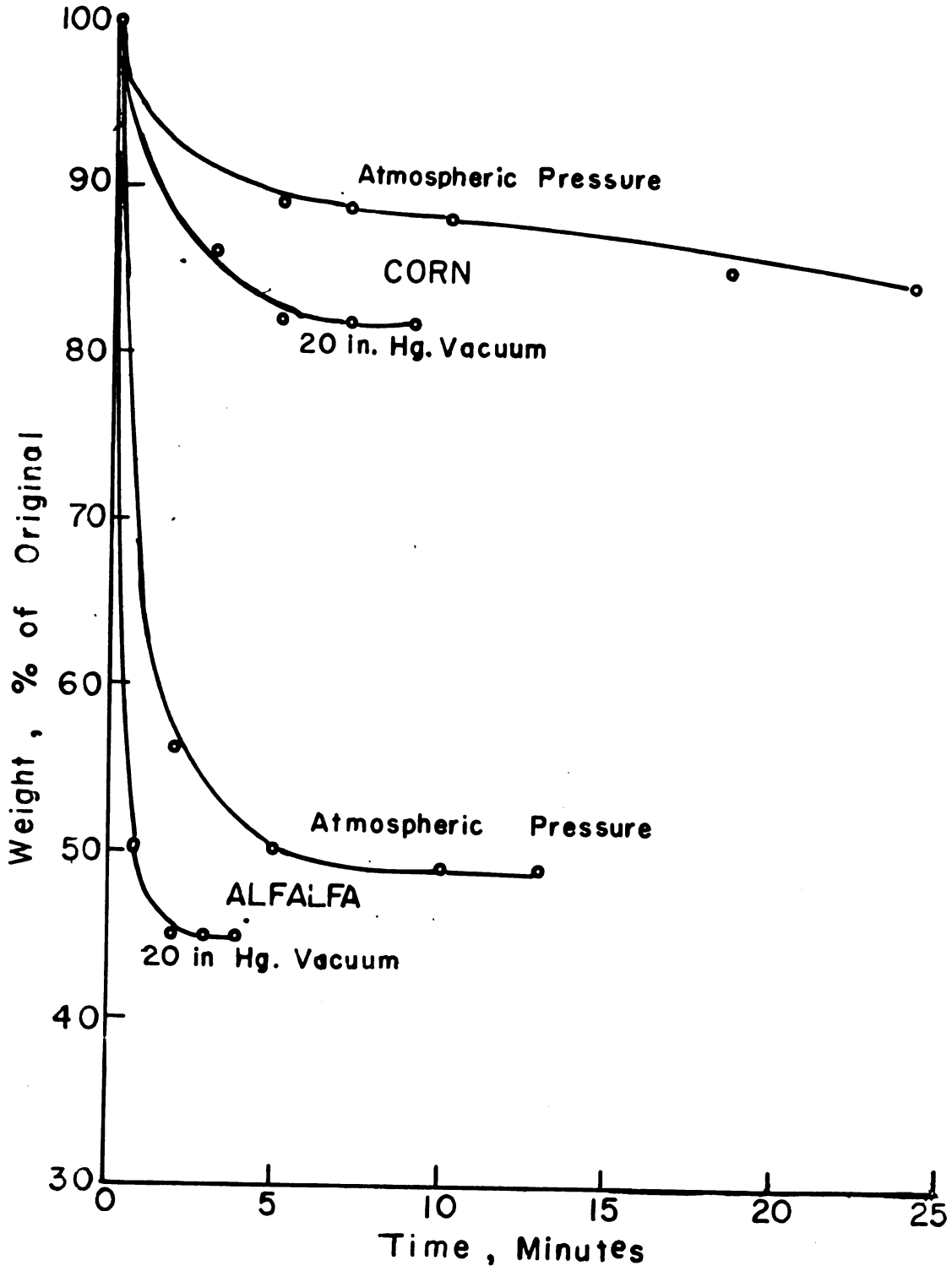
The use of vacuum pressures in the heating increased the drying rate as indicated by the curves of Figure 50.

Conclusions. Stability tests on Mazola oil indicate that a negligible weight loss of the oil occurs during the usual periods of heating which are required in the moisture testing of farm products by this method. Therefore, this method for moisture testing, which requires the assumption that the weight loss of sample, container, and oil is equivalent to the absolute moisture content, is not subject to errors due to weight loss of the oil.

Drying grain and hay samples in oil is much faster than drying in air as in the exhaust oven. The drying process can be further hastened by the use of vacuum pressures. No further work was conducted on the method because of the following disadvantages in comparision to the exhaust oven method:

1. This method requires the weighing of a considerable quantity of

Fig. 50. Rate of weight loss of corn and alfalfa samples heated in corn oil at 325 F.



oil in addition to the sample and the sample container. Since the accuracy of most scales decreases with the mass weighed, the net weight of the sample is determined less accurately by the distillation method than with the exhaust oven method.

2. Working with the distillation method is objectionable to the operator, since the handling of hot oil is necessary. However, the equipment can be design to reduce this objection.

3. The distillation method requires essentially the same equipment as the exhaust oven plus a supply of oil.

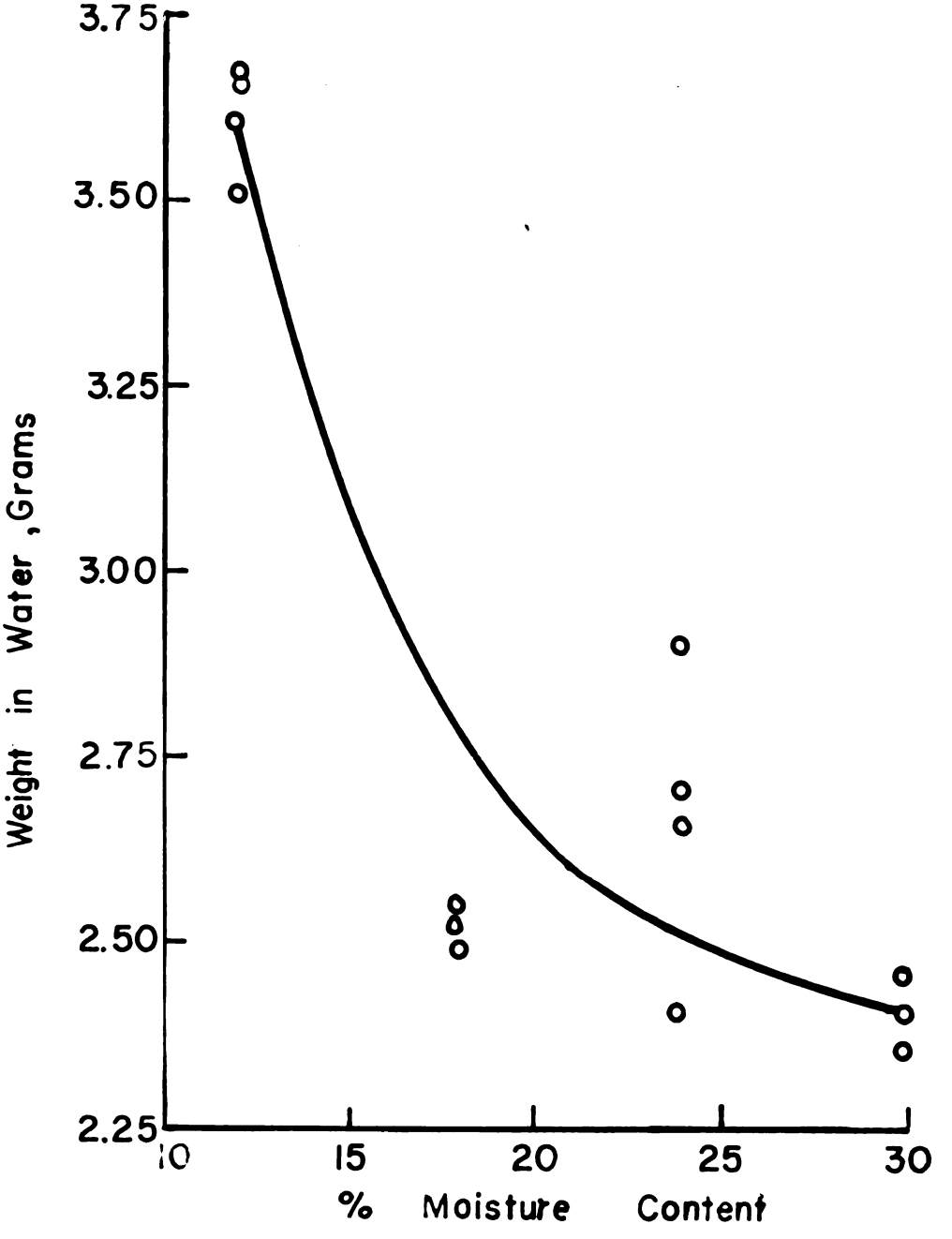
Specific Gravity Tests

Apparatus. A small brass wire basket was constructed for weighing a 25 gram sample under water. Weighing was done with a balance with a minimum scale division of 0.01 gram.

Procedure. The 25 gram corn samples were first weighed in air, then immersed in water and reweighed. The samples were divided by means of a Boerner sampler. Half of each sample was used in the specific gravity tests and the other half was tested for moisture in an air oven.

Results. Weight in water of a 25 gram sample of corn is plotted against moisture content in Figure 51. The water temperature was 70°F. A relationship between moisture content and weight in water (or specific gravity) was indicated; however, it does not seem very reproducible. The change in weight while the samples were suspended in water was observed and found to be negligible.

Fig. 51. Weight in water vs. moisture content of 25 gram samples of corn.



Conclusions. The observations of this test indicate that the specific gravity method does not show great promise as a method of moisture determination for grain due to its lack of reproducibility. The method also requires very accurate weighing and would not be applicable to hay or to some of the small grains such as oats which would absorb water rapidly.

Mechanical Shear Studies on Hay

The objective of this work was to evaluate the relation between moisture content and the shearing force required to cut alfalfa stems with a Tenderometer. This machine, shown in Figure 52, is a commercial device used in the canning industry for the numerical evaluation of the tenderness of meats, fruits, and vegetables in terms of the force required to shear them.

Apparatus. The test cell in the Tenderometer consists of two sets of parallel plates of 1/8-inch in thickness and spaced 1/8-inch apart. When the two sets of plates are brought together they mesh and cut the contents of the test cell into 1/8-inch pieces. The force to shear the sample is automatically applied and registered on a dial in terms of numbers proportional to the actual shearing force.

Procedure. The hay used in these tests were stripped of leaves and cut to 4-inch lengths to fit the Tenderometer test cell. The moisture content of the test samples was assumed equal to the oven-determined moisture contents of the hay mass from which they were taken. The samples were divided into three size classifications.

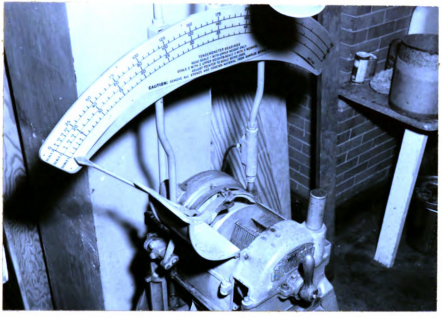


Fig. 52. The Tenderometer used in the mechanical shear studies on hay.

Results. The data obtained from this test are indicated in Table XV. Although certain trends are indicated by the data, it is doubtful that this sort of measurement could be made a reliable indication of the moisture content of hay. Generally, the data indicate that the higher the moisture content, the lower the force required to shear hay stems. However, other variables such as stem size seem to affect the data greatly.

Past experience of the Department of Horticulture with this machine in testing snapdragon stems, has indicated a very definite effect of the origin of the sample with respect to height on the growing plant, regardless of stalk size. There were also indications of the effect of this variable in this test on hay.

Conclusions. The shearing force required to cut hay stalks is affected by other factors besides moisture content. A moisture meter operating on this principle would have to be designed to take into consideration stem size and location of the test point along the stem. Maturity of the crop would also very likely affect the shearing force-moisture relationship.

TABLE XV

DATA FROM TENDEROMETER TESTS ON ALFALFA STEMS

Moisture Content (Percent)	No. of Stalks Tested	Relative Stalk Size	Tenderometer Scale Reading
61.2	2	Small	57
61.2	2	Small	53
61.2	2	Medium	77
61.2	2	Large	175
43.7	2	Small	105
43.7	2	Medium	105
43.7	2	Medium	97
43.7	2	Large	142
43.7	2	Large	88
14.3	2	Small	150
14.3	2	Medium	158
14.3	4	Small	Over 250*
14.3	2	Medium	Over 250*

* Maximum reading of the machine was exceeded.

Wet and Dry-bulb Thermometer Method

The modified wet and dry-bulb thermometer technique developed by Dexter for determining the moisture content or storage quality of grains was investigated. The operating principles of this method were discussed in the Review of Literature. Dexter has shown that this method works satisfactorily on laboratory samples of grain, i.e., samples of grain which have been held in a closed containers for extended periods of time. Additional work was undertaken by the author with the purpose of investigating the effects of recent drying and foreign matter content of the sample upon the accuracy of the method. A commercial device operating on the wet and dry-bulb principle was also investigated to determine its applicability to testing grains on the farm.

Apparatus. The apparatus for employing the Dexter wet and dry-bulb thermometer technique included an ordinary square-type glass milk bottle wrapped with an inner layer of $\frac{1}{2}$ inch of glass wool insulation and an outer wrap of paper. Two mercury thermometers with a mimimum scale division of 1^{o}F. were used and read with the aid of a reading glass. The wick on the wet-bulb thermometer was made of cotton tubing available commercially for this purpose. The thermometers were mounted in a rubber stopper. A saturated sodium chloride solution was used in the wet bulb.

The Master Moisture Meter, manufactured by the C. H. Baldwin Company of Lansing, Michigan, is shown in Figure 53. The base of the device, shown at left in the photograph, contains an electric motor with a rated speed of 1550 r.p.m. The sample container (center) fits on top of the

Fig. 53. The Master Moisture Meter, a commercial moisture meter operating on the wet and dry-bulb principle.

base and stirrer blades in the bottom of the container are connected directly to the motor. A dry-bulb and a wet-bulb thermometer are attached to the lid of the sample container by means of rubber grommets.

Results. Early trials of the Baldwin tester revealed that the temperatures of the two thermometers did not reach a definite equilibrium point. This is apparently due to the fact that the electric motor continuously imparts considerable energy to the sample in the form of mechanical work and heat. The power input to the motor was found to be 100 watts. Table XVI shows temperature data from a typical test run with wheat at 13.1% moisture content. Both the wet and dry-bulb temperatures increase steadily, but the wet bulb depression, which is the index of the moisture content or storage quality of the grain, does not stay constant. The observed decrease in temperature difference with time can be partially explained by the fact that equilibrium relative humidity of grain increases with temperature at a given moisture content, which causes a lower wet bulb depression as the dry-bulb temperature increases. However, the observed wet bulb depression is much greater than that observed in the original work by Dexter for similar changes in dry-bulb temperature. A greater contributing factor to the decrease in dry-bulb temperature seems to be the grain dust which is produced in considerable quantities by the high speed stirring blades. After approximately two minutes of operation, the wet bulb becomes noticably coasted with this dust, which no doubt reduces the rate of evaporation from the bulb and thereby reduces the wet bulb depression.

The milk bottle apparatus was used in tests on samples taken from lots of wheat being sold by farmers to the elevator company at Okemos,

TABLE XVI

DATA FROM BALDWIN MOISTURE TESTER

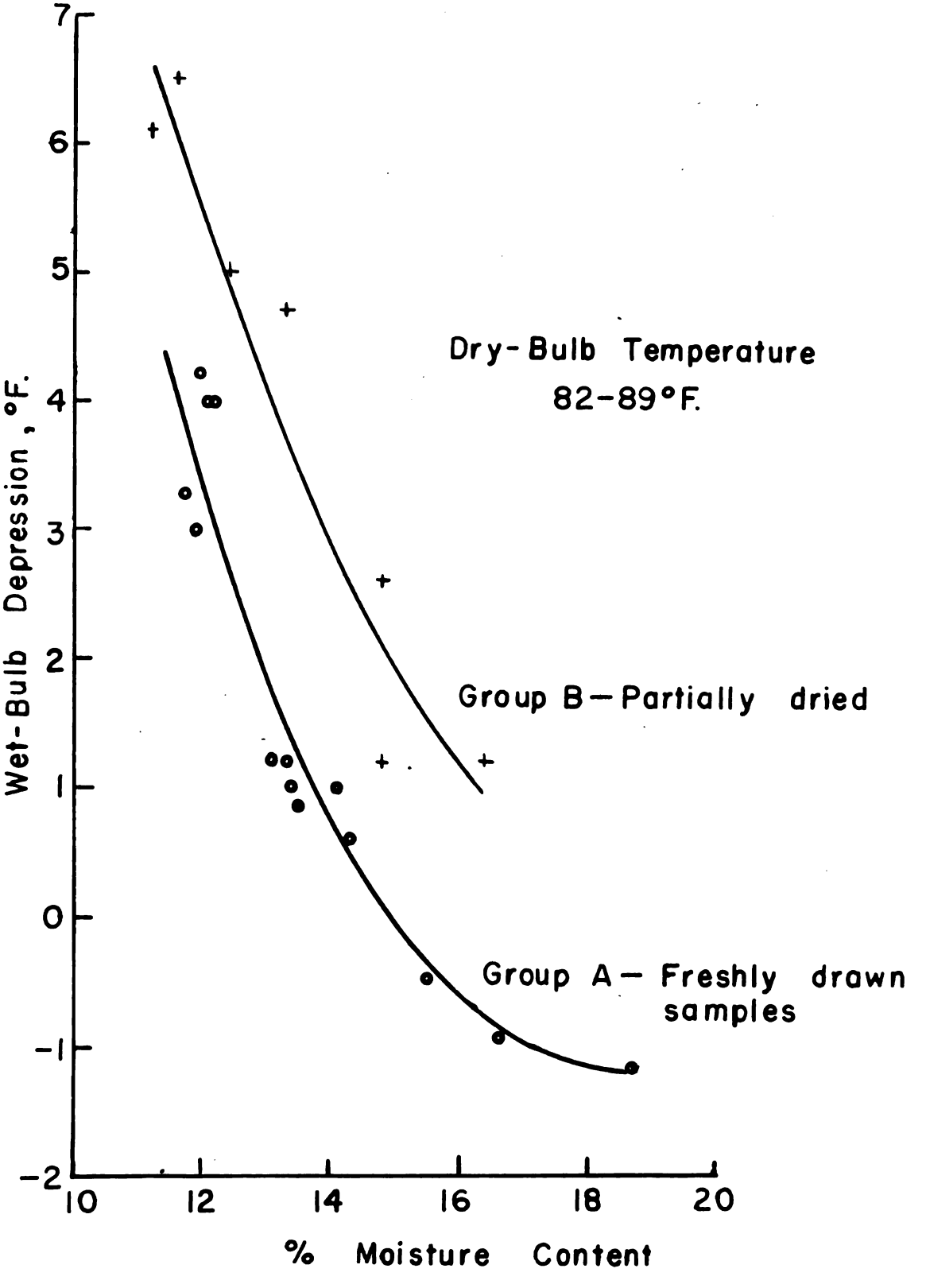
Time, Minutes	Dry-Bulb Temperature, °F.	Wet-Bulb Temperature, °F.	Wet-Bulb Depression, °F.
0	72.5	72.5	0.0
1	74.2	73.0	1.2
2	75.2	74.2	1.0
3	76.6	75.6	1.0
5	79.2	78.4	0.8
7	80.4	81.0	0.6
9	82.2	82.6	0.4

Michigan. The samples were drawn from within the grain masses in the wagons and tested immediately. The wheat was of different varieties and contained different amounts of foreign matter.

Wet bulb depression plotted against moisture content in Figure 54 (Group A) indicates a reproducible relationship between the wet bulb depression and the moisture content of the samples by an oven determination. The variations in the results which did occur can be attributed largely to experimental error in reading the temperatures. No effect of foreign matter in the wheat was observed. The data observed in this test agrees well with that presented by Dexter, particulary at moisture contents above 13%.

The data designated as Group B in Figure 54 was obtained from wheat samples which were spread in a thin layer and exposed to the air in the laboratory for a period of one hour before testing. The temperature in the laboratory was 85°F. and the relative humidity was 40%. This data indicates a greater wet-bulb depression at a given moisture

Fig. 52. Data from tests of the wet and dry-bulb thermometer method on wheat.



content in comparison to the data from Group A. This is very likely due to the drying experienced by the samples of Group B. Drying of the individual kernels occurs first in the outer layers; therefore, air which is in moisture equilibrium with the outer layers will be lower in humidity than if it were in contact with the inner parts of the kernels. A wet bulb depression is indicated which is too high and not an accurate measurement of the moisture content or storage quality of the grain.

Grain samples which have abnormally dry kernel surfaces, such as might be drawn from a crop drying system, could be allowed to equalize in a closed container before testing, but this procedure requires several hours. Grinding the sample seems to be a solution to the problem; however, when the samples were shaken in the milk bottle it was found that dust from the ground grain collected on the wet-bulb thermometer and reduced the evaporation from it.

A design intended to allow the testing of ground grain without appreciable dust collection on the wet-bulb thermometer is shown in Figure 55. The objective in this design is to pass air through the grain at low enough velocity that no appreciable dust is entrained and yet to pass the air over the wet bulb at a sufficiently high velocity to encourage evaporation. In the design presented, air is recirculated through the grain by means of an aspirator bulb. The air is injected into the grain mass at the bottom of the container through a perforated tube. The air passes through the grain at a very low velocity because of the large area of the cross-section of the can. The tube through which the air leaves the can surrounds the wet bulb so that the velocity of the air passing over the salt solution on the wet bulb is high.

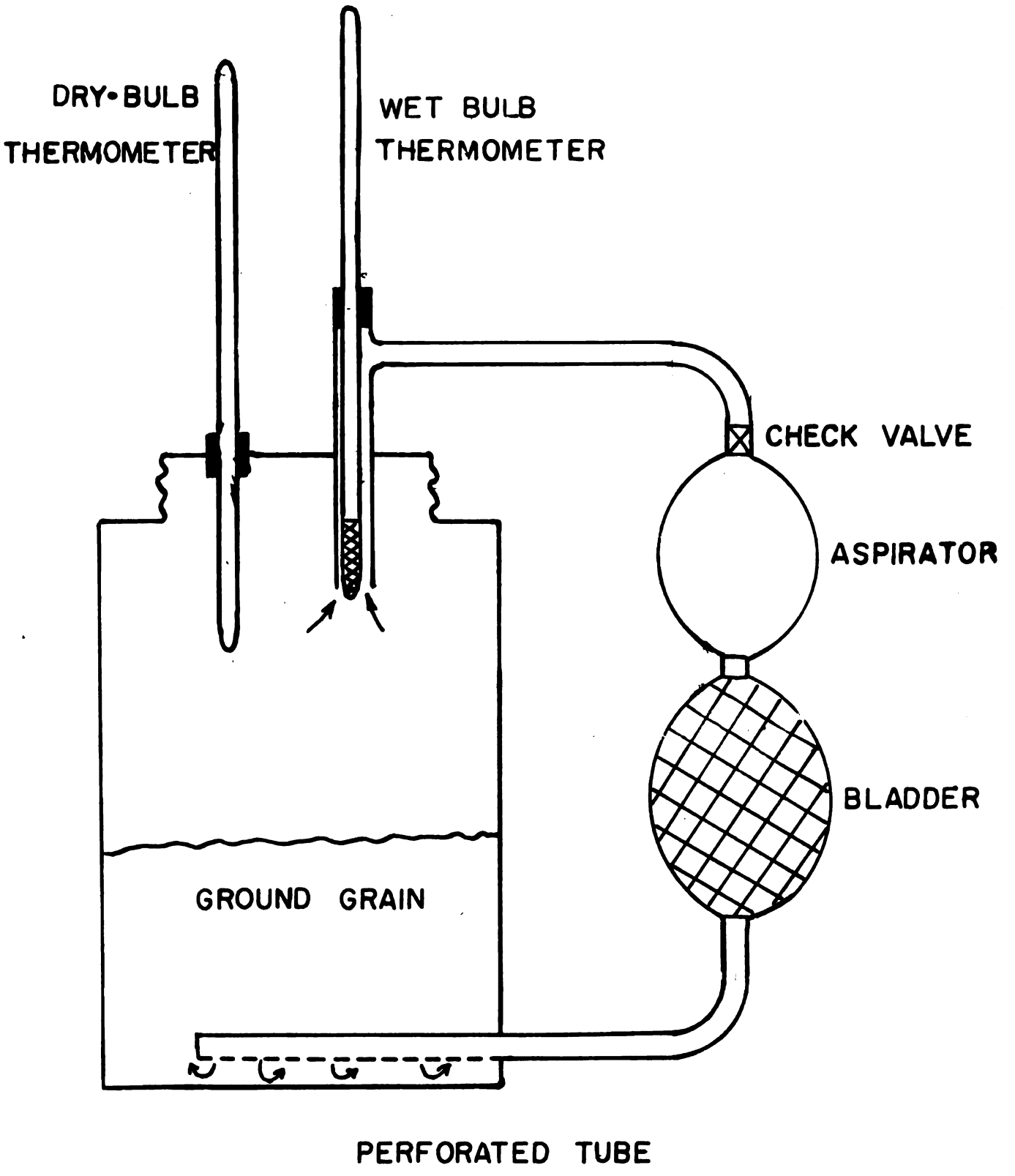


Fig. 55. Experimental wet and dry-bulb thermometer apparatus for testing ground grain.

Tests with this device indicate that it reaches an equilibrium temperature much faster on both whole and ground grain than the milk bottle apparatus, particularly when high wet-bulb depressions are encountered. Equilibrium has been reached in two minutes with wet-bulb depressions of 8°F. Since the wet-bulb temperature changes more rapidly, the equilibrium point is more easily determined. This feature would be important to a non-skilled operator.

There was no noticeable amount of dust in the air in the can or collection of dust on the wet bulb when testing ground grain. This was true even for very finely ground wheat.

As in the case of the milk bottle apparatus, no measurable rise in dry-bulb temperature occurred during tests with the experimental apparatus. Apparently the transfer of heat from the operator's hand on the aspirator bulb to the air was not significant under the conditions of the test.

Table XVI shows data from a test with the experimental dry and wet-bulb device of Figure 55. A sample of wheat at 11.1% moisture content (determined by oven at the conclusion of the test) was tested the first time immediately after being removed from a tight can where it had been stored for several months. The sample was then spread in a thin layer and allowed to dry at room conditions for a period of 20 minutes. The data for this test indicates a much higher wet-bulb depression than was observed before the grain was dried. The sample was then finely ground and tested again. The wet-bulb depression decreased to 6.5°F., which is comparable to that observed before the sample was dried. Dexter also observed that the wet-bulb depression of ground grain was slightly lower with ground grain than with whole grain, particularly at lower moisture

TABLE XVI

DATA FROM TEST OF THE EXPERIMENTAL WET AND DRY-BULB APPARATUS OF FIGURE 53 USING A SINGLE SAMPLE OF WHEAT AT 11.1% MOISTURE CONTENT

Time, minutes	Dry-bulb Temperature, °F	Wet-bulb Temperature, °F	Wet-bulb Depression °F	Remarks
0	82	77.5	4.5	Whole wheat
0.5	82	74.5	7.5	
1	82	74.5	7.5	
2	82	74.5	7.5	
0	80	77.5	2.5	Whole wheat
0.5	80	72.5	7.5	dryed in room
1	80	70.5	9.5	air for 30 min.
2	80	69.5	10.5	
3	80	69.5	10.5	
0	78	75.5	2.5	Ground fine
0.5	78	73	5	
1	78	72	6	
2	78	71.5	6.5	
3	78	71.5	6.5	

contents.

Conclusions. The equilibrium wet-bulb depression when using the Baldwin tester is difficult to observe. If an equilibrium condition does exist, it is not maintained for long. Furthermore, the fact that both wet and dry-bulb temperatures are changing continually makes the equilibrium depression difficult to observe.

The wet and dry-bulb method in general does not seem to be greatly affected by the presence of reasonable quantities of foreign matter in the sample.

The method appears to be accurate for whole grain which has not been recently subjected to drying air. Under such conditions grinding the sample seems very desirable. The experimental apparatus successfully tests ground grain without depositing dust on the wet bulb. Since the air velocity over the wet bulb is higher, this apparatus reaches temperature equilibrium more rapidly than the more simple milk bottle apparatus.

SUMMARY AND CONCLUSIONS

Exhaust Oven Method

The exhaust oven method of moisture determination is the most versatile of all the methods studied. It is applicable to all crops in any condition and at practically any moisture content. Since the results of this method are not greatly affected by factors other than moisture content, conversion charts are not necessary. The principle of the method can be readily understood by non-technical personnel; therefore, errors caused by mis-use or misunderstanding of the method should not ordinarily occur.

The cost of the equipment for the exhaust oven method should not be prohibitive. The complete apparatus as previously described should certainly sell at retail for less than $50.00, including the injector-type oven, the moisture calculator, a scale, and a carrying case.

The principal disadvantage of the method lies in the fact that the time required to test a single sample is so great that testing many repetitive samples is not feasible. Experimental data indicate that the moisture content of hay curing in the field is highly variable at any given time. Therefore, the validity of one or two samples as an indication of the moisture content of the crop is very questionable.

An injector-type tractor exhasut oven has been developed which is capable of drying samples of alfalfa hay in approximately 7 minutes and samples of grain in approximately 15 minutes. The injector principle

employed limits the temperature of the exhaust gas and air passing through the sample so that serious burning does not ordinarily occur. The operator need not tend the sample while it is heating in the oven. Leaving the sample in the oven as long as twice the time necessary to reach constant weight does not appreciably affect the moisture determination.

A simple calculator has been designed for use in the field to determine the moisture content from the wet and dry weights without arithmetic computation.

Electrical Resistance Method

Laboratory studies of the resistance method indicated the importance of electrode pressure on the resistance measurement of hay and grain. This demonstrates the need for standardizing the electrode pressure for such measurements. Electrode configurations of constant spacing were found most desirable, since weighing of the sample is not required and the resistance reading is less dependent upon pressure. Of the types of constant-spacing electrodes tested, the pin-type electrode configuration seems most desirable, since it is applicable to both hay and grain and it applies the measuring current to a greater definite sample volume than the coplanar plate-type electrodes.

Field investigations of the resistance method indicated that single moisture determinations made with resistance-type meters do not reliably indicate moisture content of the lot, particularly when applied to hay. A reasonably accurate measurement of quantities of hay or grain can be obtained if the average of a number of readings is taken.

Since it was anticipated that most farmers would not care to take many readings and average them arithmetically, an automatic averaging device was designed to give a single reading of the average moisture content of a large number of samples. The averaging device actually determines the average conductivity and a close approximation of the arithmetic mean moisture content of a large number of samples.

The principal advantage of the resistance method is in its great rapidity and versatility. The use of this method with the averaging device appears to be the best solution to the problem of sampling error which is so prevalent in the moisture testing of hay.

The cost of the equipment for the electrical resistance method is the highest of the methods studies, particularly if the averaging device is employed. This factor may delay the broad acceptance of this equipment until such time as it can be economically produced or the demand for moisture measuring equipment becomes well developed among farmers.

The averaging resistance-type moisture meter for hay should find immediate application as a research tool. The rapid determination of the average moisture content of large lots of hay has always been a serious problem to those engaged in research on hay harvesting and curing methods.

Wet and Dry Bulb Thermometer Method

The wet and dry-bulb thermometer method of determining the moisture content or storage quality of grain was found to give an accurate indication of the moisture content of wheat which had not been subjected to drying air. However, when samples were tested which had been exposed to

drying air for short periods of time, the method consistently indicated moisture contents too low. This is due to abnormally dry surfaces of the kernels which cause humidity readings that are too low.

When testing grain from a dryer, grinding the sample is necessary in order to expose to the air surfaces of the grain which are more representative of the moisture content of the mass. A wet and dry-bulb thermometer apparatus was developed which is capable of testing ground grain without the collection of grain dust on the wet bulb. Dust on the wet bulb prevents accurate determination of the wet-bulb temperature.

The wet and dry-bulb thermometer method requires less costly equipment than any of the methods tested. No weighing is required. The method is not as versatile as the resistance and exhaust oven methods, since it is applicable only to moisture contents in a narrow range above and below the safe storage moisture content. It is applicable to testing grain in most of the moisture range of interest to farmers. It would not be applicable to the testing of hay in the field for silage or mow curing. Its applicability to testing hay for any purpose is somewhat limited by the fact that a large number of samples cannot be tested rapidly.

TABLE XVII

DATA FROM TESTS OF INJECTOR-TYPE TRACTOR EXHAUST OVEN

Crop Tested	Initial Sample Weight, Grams	Final Sample Weight by Exhaust Oven, Grams	Final Sample Weight by Lab. Oven, Grams	% M. C. by Exhaust Oven	% M. C. by Lab. Oven	% Residual Moisture Content	Max. Tractor Exhaust Temp., F.	Max. Sample Temp., F.	Drying Time in Exhaust Oven Minutes
Alfalfa	148.9	80.2	80.3	46.2	46.1	-0.07	603	280	15
"	152.1	67.2	69.5	55.9	54.3	-1.51	720	345	9
"	144.8	104.0	103.8	28.2	28.3	0.14	715	365	6
"	148.0	71.3	73.2	51.8	50.6	-1.28	635	275	9
"	151.1	71.3	72.6	52.9	51.9	-0.86	745	320	5
"	149.9	110.1	112.4	26.6	25.0	-1.53	760	350	5
"	99.8	53.2	55.3	46.7	44.6	-2.11	650	275	8
"	97.3	55.0	56.8	43.5	41.6	-1.85	655	285	8
"	101.2	59.1	61.8	41.6	39.0	-2.67	780	340	6
"	98.0	64.3	67.2	29.1	31.8	-2.96	765	335	10
"	193.8	136.5	139.8	29.6	27.9	-1.70	715	340	7
Alfalfa-brome	156.2	127.4	129.2	18.5	17.3	-1.15	655	302	6
"	148.7	106.0	108.3	28.7	27.2	-1.55	667	285	7
"	149.6	107.6	109.1	28.1	27.1	-1.00	655	290	6
Alfalfa	149.4	109.0	111.0	27.1	25.7	-1.34	655	275	7
"	158.7	105.1	106.7	33.8	32.8	-1.01	650	282	8
"	152.6	86.1	86.9	43.3	43.7	-0.52	655	280	7
"	151.3	44.7	46.9	70.5	69.1	-1.45	650	255	9
Wheat	200.0	180.4	180.1	9.8	10.0	0.15	685	330	16
"	180.4	155.5	153.7	13.8	14.8	0.99	740	340	17
"	100.0	87.1	85.3	12.9	14.7	1.80	620	290	17
"	100.0	85.3	83.2	14.7	16.8	2.1	665	310	14
"	100.0	84.0	83.3	16.0	16.7	0.7	700	310	10
"	100.0	85.4	84.4	14.6	15.6	1.0	765	340	14
Oats	149.2	131.2	129.3	12.1	13.3	1.27	725	315	16
"	149.9	128.5	128.8	14.3	14.1	-0.20	780	375	14
"	150.3	102.8	102.5	31.6	31.8	0.19	835	425	14
"	150.6	128.1	127.7	14.9	15.2	0.26	825	425	12
"	199.7	128.9	129.1	35.5	35.1	-0.10	685	340	20
"	150.8	103.8	104.2	31.2	30.9	-0.26	710	350	18
"	149.5	103.8	103.0	30.6	31.1	0.53	650	315	20
"	99.3	68.3	68.0	31.2	31.5	0.30	660	315	18

TABLE XVII Continued

Crop Tested	Initial Sample Weight Grams	Final Sample Weight by Exhaust Oven, Grams	Final Sample Weight by Lab. Oven Grams	% M. C. by Exhaust Oven	% M. C. by Lab. Oven	% Residual Moisture Content	Max. Tractor Exhaust Temp., F.	Max. Sample Temp., F.	Drying Time in Exhaust Oven Minutes
Corn	200.0	166.9	162.6	16.6	18.7	2.15	545	310	28
"	200.3	140.4	137.3	29.9	31.4	1.54	750	320	20
"	203.0	165.6	163.4	18.4	19.5	1.08	700	320	26
"	199.6	138.5	135.8	30.6	32.0	1.35	790	335	20
"	200.2	160.3	159.8	19.9	20.2	0.24	790	340	20
"	149.0	120.5	118.4	19.1	20.5	1.40	810	340	18
"	96.2	80.6	79.0	16.2	17.9	1.66	720	300	14
"	200.0	164.0	161.5	18.0	19.3	1.25	710	325	20
"	201.1	164.8	162.2	18.1	19.3	1.29	755	325	18
"	149.3	124.2	121.1	16.8	18.9	2.08	720	310	18
"	99.0	82.7	81.7	16.5	17.5	1.01	705	290	18
"	199.5	162.0	160.9	18.8	19.3	0.55	795	325	20
Soya Beans	200.0	182.6	180.2	8.7	9.9	1.20	665	330	17
"	200.0	181.9	180.4	9.1	9.8	0.75	660	345	19
Navy Beans	200.0	150.4	149.2	24.8	25.4	0.60	650	340	19
"	200.0	150.1	149.5	25.0	25.3	0.30	620	350	16
"	200.0	151.0	150.0	24.5	25.0	0.50	565	330	19
"	150.0	113.9	111.8	24.1	25.5	1.40	555	320	19
"	200.0	159.9	157.4	20.1	21.3	1.25	560	335	15
"	149.8	120.5	118.0	19.6	21.2	1.67	555	325	23
"	200.0	150.5	148.5	24.7	25.8	1.00	565	330	19

APPENDIX II

ANALYSIS OF THE AVERAGE INDICATED BY THE AVERAGING DEVICE

The averaging device was found by analysis and experimention to indicate the average conductivity of n samples of resistance R_1, R_2, R_3, --- R_n and moisture content M_1, M_2, M_3, --- M_n. The indication of the meter in terms of resistance is expressed by the following:

$$\frac{1}{R_a} = \frac{1}{n}\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots \frac{1}{R_n}\right) \qquad (1)$$

If the moisture content is assumed to be inversely proportional to the logarithm of resistance, any sample of moisture content, M_i, has a resistance which may be expressed by the following exponential relation:

$$R_i = b10^{-aM_i} \qquad (2)$$

where a and b are calibration constants of the meter.

Substituting Equation (2) into Equation (1) and simplifying:

$$10^{aM_a} = \frac{1}{n}\left(10^{aM_1} + 10^{aM_2} + 10^{aM_3} + \cdots 10^{aM_n}\right) \qquad (3)$$

Taking the logarithm of both sides of Equation (3) and simplifying:

$$M_a = \frac{\log\left[\frac{1}{n}\left(10^{aM_1} + 10^{aM_2} + 10^{aM_3} + \cdots 10^{aM_n}\right)\right]}{a} \qquad (4)$$

Thus an expression is obtained for the average moisture content indicated by the meter in the terms of the moisture contents of the individual samples and a calibration constant, a. The calibration constant, a, is equal to the rate of change of the logarithm of resistance with the moisture content.

The true arithmetic mean moisture content, M_e, of n samples is

expressed by the following relation:

$$M_e = \frac{M_1 + M_2 + M_3 + \cdots M_n}{n} \qquad (5)$$

M_e and M_a are equal only when the moisture contents of the individual samples are equal. It can be easily shown by substitution of moisture values into Equations (4) and (5) that the greater the variation of the moisture values, the greater is the difference between M_e and M_a.

Of concern in the application of the averaging device is the magnitude of the difference between M_e and M_a for a given standard deviation of the moisture contents of a large number of samples. The standard deviation of the moisture contents of hay samples in the field was found to be approximately three moisture percentage points. In order to demonstrate the magnitude of the inherent error of the averaging device in indicating the arithmetic mean of a number of samples, a hypothetical group of 20 samples, were averaged by Equations (4) and (5) and the results compared. The moisture contents of the 20 samples were normally distributed about an arithmetic mean of 30% moisture content with a standard deviation of 3.2%. A typical value of 0.1 was assumed for the calibration constant, a. The average, M_a, calculated by Equation (4) was 30.7% moisture. Thus the inherent error of the device in determining the arithmetic mean is 0.7% moisture. The averaging device will always indicate an average higher than the arithmetic mean , since the rate of change of conductivity with moisture content decreases as moisture content increases.

By assuming a constant standard deviation for all hay, most of the inherent error of the averaging device could be removed by calibration.

However, there is little reason to believe that the arithmetic mean moisture content is any better index of storage quality of hay than the slightly higher value which is indicated by the averaging device.

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