SOME EFFECTS OF CHEMICAL AND MECHANICAL TREATMENTS IN HAYMAKING

By

R. BRUCE HOPKINS

A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

1955

ACKNOWLEDGMENTS

The author wishes to express his appreciation for the helpful suggestions and guidance of Professor D. E. Wiant of the Department of Agricultural Engineering of Michigan State College.

Acknowledgment is due the J. I. Case Company of Racine, Wisconsin for providing the hay storage facilities, the machinery used in the field experiments, and part of the funds to finance the studies.

Valuable assistance in the work with mold inhibitors was rendered by Dr. E. E. Dunn of the Biochemical Research Department, Dow Chemical Company. Professor H. R. Pettigrove judged the hay for quality and the presence of molds. Chemical analyses were made by the staff of the Agricultural Chemistry Department.

L. Bruce Horrall, Nguyen Tu Ban, Anandrao P. Deshmunkh, and Donald B. Churchill, students at Michigan State College, assisted in various aspects of the studies.

Appreciation is extended to Dr. Ingram Olkin for assistance with statistical analyses of data and to the author's wife, Betty, for typing the manuscript.

Richard Bruce Hopkins

candidate for the degree of

Doctor of Philosophy

Final examination, May 11, 1955, 1:00 p. m., Room 218, Agricultural Engineering Building

Dissertation: Some Effects of Chemical and Mechanical Treatments in Haymaking

Outline of Studies

Major subject: Agricultural Engineering
Minor subject: Physics

Biographical Items

Born, January 8, 1920, Clark's Summit, Pennsylvania

Undergraduate Studies, The Pennsylvania State University, 1937-41

Graduate Studies, Illinois Institute of Technology, 1948-50, University of Maine, 1950-52, Michigan State College, 1953-55.

Experience: Research Technician, Draftsman, Designer, Assistant Engineer, Allis-Chalmers Manufacturing Company, 1941-50, Assistant Agricultural Engineer, University of Maine 1950-53, Assistant Professor of Agricultural Engineering, University of Maine, 1952-53, Graduate Research Assistant, Michigan State College, 1953-55.

Member of American Society of Agricultural Engineers; Society of Automotive Engineers; Sigma Pi Sigma, Physics Honor Society; Society of Sigma Xi.

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INTRODUCTION

Since ancient times man has made hay from grasses and legumes as a method of providing food for livestock during the winter period. At the present time hay is an important source of food for dairy and beef animals, sheep, and draft animals. In 1949 (2), some 65,635,943 acres from a total cropland acreage in the United States (other than that devoted to pasture) of 408,506,094 acres (1950 census) was utilized in the production of 90,050,799 tons of hay with a value of $1,884,072,277. Thus approximately 16 percent of the total cropland in our nation is devoted to hay production.

With a steadily mounting population and a limited area of farmland it is becoming necessary that better use be made of the available cropland. This can be partially realized by the harvest of more nutrients per acre of hay through better handling and curing methods. In this regard Bender (1) wrote:

> It can be stated axiomatically that we can grow excellent hay crops but that we fail miserably in curing them as hay. The losses in protein, nutrients and minerals in the normal haying processes are too high. The greatest losses are due to leaching, bleaching, heating, and overhandling. These losses are too well known to spend any time on them, except to state that they run 20 to 50 percent of the nutrient content of the plant. This increases production costs and affects the health and well-being of our livestock. These losses must be reduced by improvements in hay-making operations.

A broad objective of research on hay-making methods is to find methods of reducing nutrient losses and make hay of good quality. What is quality hay? Bender (ibid.) stated:

> Quality hay is any legume or grass of economic value to livestock, grown on well-limed fertile soils, cut in the early bloom stage, and cured rapidly with a minimum loss of nutrients and minerals. This hay is green in color, the leaves are intact upon the stems, has a pleasant aroma, and is free of dust.

Bender (ibid) stated further:

> The greatest enemies of quality hay production are low soil fertility, the cutting of plants for hay when they are overmature, overcuring in the swath and windrow which causes bleaching, leaching due to rain, and the shattering of leaves due to overhandling. Nutrient losses from any one or a combination of these sources may total 20 to 50 percent.

The engineering aspects of making quality hay lie in the curing, handling, and storage of hay. A matter of particular concern is the conservation of nutrients through the reduction of field-curing time and reduction of the loss of leaves from handling the hay.

The traditional method of making hay is to completely field-cure the hay and store it in the long, loose form. In this method the farmer is completely dependent upon the weather for suitable drying conditions and must have available sufficient labor to handle the hay when it is ready to store.

During World War II, when protein supplements became scarce, interest was aroused in making better hay. As a consequence, numerous installations of barn hay finishers have been made which are used to complete the curing of partially field-cured hay. Through reduction of the field-curing time the weather hazards are reduced, and by storing the hay at moisture contents of 35 to 40 percent (wet basis) leaf shattering is lowered considerably. This method is satisfactory for long or chopped hay but is not completely satisfactory for baled hay since it is difficult to force air through dense bales.

In recent years the pickup baler has found wide acceptance. Vary (3) reported that the percentage of hay which is baled in Michigan has increased from 38 percent of the total in 1948 to 60 percent in 1952. The wide use of the pickup baler is probably due to the reduced peak labor requirements of this hay handling method. In making long or chopped hay, the hay must be hauled and stored as it is picked up from the windrow. This is not the case with a pickup baler. The bales can be dropped onto the ground and picked up for storage at a later time when help is available.

It is difficult to completely field-cure hay in humid areas such as Michigan. From the standpoint of making quality hay in humid areas the use of the pickup baler is not desirable. The hay is subjected to all the weather hazards of making long hay with the attendant loss of nutrients and, in addition, in many cases the hay is not adequately cured before baling. It then heats in storage and becomes musty or moldy.

Since the pickup baler has found wide acceptance, it is desirable that methods be found whereby better quality baled hay may be realized. The study discussed here was preceded by six years' research on curing, handling, and storage of baled hay. The purpose of this study was to further investigate possible methods of making high-quality baled hay. The investigation consisted of three general phases:

1. The use of chemical additives as a method of preserving partially-cured hay.
2. A study of the relation of bale density and moisture content to baled hay quality.
3. An investigation of the effects of hay crushing on: the drying rates of plant parts, absorption of rain and subsequent drying rates, losses of nutrients due to rain, losses of leaves from raking and baling, and the drying rates of bales when cured with forced air.

All field tests were conducted in the vicinity of East Lansing, Michigan during the 1953 and 1954 haying seasons with alfalfa or alfalfa-brome grass mixtures. The hay was made with conventional J. I. Case Company hay-making equipment consisting of a 7-foot cut tractor-mounted mower, a No. 170 left-hand side-delivery rake, a Model NT pickup automatic twine-tie baler, and rubber-tired wagons to haul the hay. Hay crushing was done with a John Bean "Haymaker" provided by the College Farms.

Storage tests were conducted in the J. I. Case Hay Laboratory which contains closed bins with forced draft drying facilities, open bins with raised mesh floors for natural drying, and thermocouples for measuring temperatures in the stored hay.

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THE PROBLEM OF HAY PRESERVATION

Haymaking is a task in food preservation. Drying, the traditional method of making hay, is also used to preserve foods for human consumption. In drying, the salts and sugars normally found in the hay become sufficiently concentrated that the microorganisms are desiccated by osmosis and are consequently inactivated. Foods such as jams and jellies, which are preserved by the addition of sugar, are protected by the same mechanism of desiccation.

The use of refrigeration, which prevents the reproduction of organisms with the resulting decomposition of the host material, is hardly economical for forages. Likewise, canning is unsuitable for preserving hay, although it destroys microrganisms and halts enzyme action.

Chemical action is the mechanism which preserves ensiled forages by means of the decomposition of carbohydrates. This decomposition produces carbon dioxide which displaces oxygen and thus inactivates aerobic microorganisms. In addition, lactic acid, which possesses some germicidal properties, is produced.

Terry (12) suggested the possibility of preserving hay by pasteurization. He stated that temperatures greater than 120° F kill most molds, but to accomplish pasteurization with heated air requires a considerably higher air temperature. However, Baumgartner (1) stated that the growth of two mucor species was observed at 131° F. His statement that most species are destroyed by 30 minutes heating at 149° F suggests that to attain pasteurization in a short period of time would require a considerably higher surface temperature of the hay. In order to raise the surface temperature to a high level it would be necessary to evaporate considerable moisture since the surface of the hay would be cooled by evaporation. In addition, there is the prospect of the hay later becoming reinfested by mold spores from the atmosphere. Altogether, the prospect of preserving high moisture content hay through pasteurization is not promising.

Sources of Molds on Hay

Lewis (6) isolated and identified the fungi found on 30 hay samples obtained in the vicinity of East Lansing, Michigan. He found the predominant groups to be the mucors, aspergilli, and penicillia which are commonly found in the soil. He concluded that the types of fungi which cause mold on hay are the types predominating in the soil in which hay is grown.

Factors Influencing Mold Development in Hay

Terry (op. cit.) showed graphically the relationship between storage temperature and the time required for visible mold development on hay, indicating that the optimum temperature is approximately 85° F. The period of time required for mold development increases at temperatures either above or below the optimum. However, the actual period of time required at a particular temperature depends to some extent upon the genera present. Baumgartner (op. cit.) stated that the optimum temperatures for growth of most fungi lie in the range of 77° to 86° F. Lewis (op. cit.) found that in cultures obtained from hay the mucors developed most rapidly and masked the slower growing organisms. Mallman and Michael (7) studied the development of molds on cold storage eggs and cited work in which molds were observed on meats in cold storage. This slow development of mold growth in cold storage presents another reason why refrigeration would be unsuitable as a method of preserving hay. The author (4) observed the development of mold on hay of about 50 percent moisture content (wet basis) after storage at 40° F for approximately three weeks.

In dry materials, the concentration of sugars and salts causes desiccation of microorganisms. As moist organic materials become drier there is less moisture available for mold growth and fewer of the molds can be active. Since a high relative humidity in the storage atmosphere leads to a higher equilibrium moisture content of organic materials, more rapid mold development results. Snow, et al. (11) reported that mold growth took place quickly on materials stored at 75 to 100 percent relative humidity while at lower humidities mold growth appeared only after a prolonged storage period. They stated that the relative humidity of the atmosphere rather than moisture content of the host is a factor controlling mold growth while Wright (13) reported that the rate of molding of hay is related to the moisture content.

Dawson and Musgrave (2) stated that moisture content is not a reliable indication of the likelihood of mold development in hay although at moisture contents above 25 percent (wet basis) mold populations will develop in all hays. They argued that moisture potential is a better measure of the ability to support mold growth. Moisture potential, the change in potential energy of one gram of pure liquid water from being absorbed by an infinite mass of hay at constant temperature, is a function of relative humidity under equilibrium conditions. It is also a function of osmotic pressure and freezing point depressions of solutions which would exist at vapor pressure equilibrium with hay. The conclusion was reached that the moisture potential or relative humidity which is low enough to prevent mold growth is approximately the same for all hays. It was also concluded that the moisture potential or relative humidity low enough to prevent mold development decreases as the length of storage time increases.

Wright (op. cit.) reported that mold growth occurred on hay at moisture contents down to 13 percent (wet basis) although it is generally considered that hay can be stored at moisture contents on the order of 20 percent without danger of spoilage.

There is evidence that fungi have varying critical moisture contents at which they can develop. Koehler (5) found that the lowest moisture content at which various species of molds developed on corn varied from 14.3 to 23.4 percent (wet basis).

The length of storage period also influences the development of molds. Wright (op. cit.) stated that it is necessary to extend storage trials over a long period of time. In one case, 300 days was required for mold growth to appear.

Snow, et al. (op. cit.) reported that the balance and type of nutrients provided by the host influence the latent period as well as the extent of mold development. It was found that molds develop most rapidly in materials which provide a supply of readily available nutrients. Mixtures of starches and protein provide the most rapid mold growth. At low storage humidities a readily available source of soluble carbohydrates was found necessary to support mold development.

For an organic material such as hay, which contains the carbohydrates and proteins required to support mold development, the time required for mold growth to appear is a function of the fungi present, the temperature, and the moisture content of the material or the relative humidity of storage.

Importance of Preventing Mold Development

According to Miller (8), when mold growth takes place on hay the starches and water combine with the aid of molds and enzymes to produce glucose. The glucose then is oxidized with the aid of microorganisms to produce carbon dioxide and water, a condition which is commonly referred to as sweating. At the same time proteins and water combine with the aid of microorganisms to produce amino acids which are utilized by bacteria for reproduction.

In the decomposition of hay by molds and bacteria, heat is produced from the consumption of dry matter. If the temperature of the hay remains fairly low, profuse mold growth appears and the hay is unpalatable. Morrison (9) stated that if temperatures on the order of 150° F to 170° F occur the molds and bacteria are killed or inactivated but the oxidation processes continue. This results in a brown or black hay which, while palatable, is lower in feeding value because of the loss of nutrients. Roethe (10) found a maximum loss of dry matter of 22 percent with an average loss of 14 percent in hay which was stored at an average moisture content of 30 percent (wet basis). Hodgson, et al. (3) cited a case in which the digestible protein in normal hay was 14.4 percent, it was reduced to 3.4 percent in brown hay, and to 0.6 percent in black hay. The total digestible nutrients were reduced from 55.8 percent to 37.3 percent and 23.4 percent respectively.

According to Morrison (op. cit.), when the temperature rises above 160° F there is danger of spontaneous combustion. At temperatures of 175° to 185° F fire pockets may be expected, which if ignored will burst into flame.

It is evident that the key to the preservation of partially-cured hay is the prevention of mold growth, the initial step in the decomposition process. The prevention of mold development should lead to the safe storage of partially-cured hay. This should result in less loss of nutrients from exposure to the elements, shattering of leaves from handling the hay, and from decomposition in storage.

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CHEMICAL PRESERVATION OF HAY

The preservation of partially-cured hay by chemical means has been attempted for many years. Common salt was probably the first compound used. In later years compounds which release carbon dioxide have been sold to the unsuspecting. During the last few years there have been serious attempts to find suitable fungicidal compounds, which are frequently referred to as "mold inhibitors".

The Use of Salt for Hay Preservation

Salt (sodium chloride) is still used by some farmers to prevent heating and spoilage of damp hay in spite of published research results which are generally negative. Henson (10) reported that no beneficial results were obtained in six of eight trials in which salt was added in amounts of $\frac{1}{2}$ to 2 percent of the weight of the hay. In one case markedly beneficial results were reported and in another case slightly beneficial results obtained. However, Roethe (20) compared lots of alfalfa hay stored at 35 percent moisture content (wet basis). One lot was unsalted, and $1\frac{1}{2}$ percent salt was added to the other. He reported that there were no differences in the two lots with regard to color or mold, and the salt had no appreciable effect in preventing or retarding heating.

Hartwig (9) reported that in tests at Cornell University in which salt was added to hay at rates of about 0.6 to 1.2 percent there was no improvement of the salted hay over unsalted hay from the same field.

Stuart and James (22) performed laboratory tests to evaluate the effect of salt on heating of hay. They found that the addition of salt delays, but does not prevent heating or mold development. The application of 5 percent of salt to hay of 30 percent moisture content was not sufficient to prevent molding.

Shutt (21) reported that the addition of one percent of salt to hay produced no adverse effects on animals whereas the addition of $1\frac{1}{2}$ percent produced undesirable physiological effects. Bolin (3) discussed some cases and experiments in which animals died as a result of overconsumption of salt. Pistor _et al_ (17) performed tests in which cattle and goats were fed excessive quantities of salt and found that the consumption of excess salt with a limited quantity of water was fatal. However, when the animals consumed sufficient water so that the kidneys could eliminate the excess, the symptoms of salt poisoning were not present. They concluded that the kidneys of ruminants cannot eliminate sodium chloride in the urine at a higher concentration than about 2.4 percent.

According to the studies of Pistor _et al_ (ibid), animals can safely consume larger quantities of salt than they need for health if they are permitted to drink sufficient water. In fact, it has become common practice to feed range animals a mixture of 30 percent salt and 70 percent cottonseed meal or grain supplement. The excess salt is used to limit the consumption of concentrate. Accordingly, higher concentrations of salt might be used if it would prevent mold growth in hay. However, it appears that the application rate might have to be so high that it would limit the hay consumption of the animals to which it is fed.

The Use of Carbon Dioxide and Carbon Dioxide Producing Materials

Compounds which release carbon dioxide when placed in hay are being marketed as mold inhibitors. Superficially, there appears to be a sound basis for their use. According to Baumgartner (2) the majority of common molds are aerobes. Although some species are capable of growth under reduced oxygen concentrations, in general, inhibition of molds can be obtained through storage under anerobic conditions. He stated further that in an atmosphere containing 20 percent carbon dioxide the rate of spore development was reduced to one-half to one-fifth of the rate in air at comparable temperatures.

Kleis (13) performed several tests in which carbon dioxide was used as a mold inhibitor for hay. He found the treatment to be effective when the air in and around the hay was displaced by the carbon dioxide for the duration of the test. In a simulated mow test in which a small mow was constructed of plywood and all joints calked, it was necessary to refill the mow with carbon dioxide twice daily. Even then heating and mold development were not prevented.

Carbon dioxide lacks fungicidal properties and can inhibit mold growth only when oxygen is displaced. To maintain the carbon dioxide atmosphere requires that either the hay be stored in a sealed container or that the supply of gas be continually replenished. If a sealed container were used, the moisture in the hay could not escape and the hay would be subject to spoilage if removed and exposed to the atmosphere.

Kleis and Wiant (14) tested a commercial preservative of the carbon dioxide producing type which was ineffective when used at rates up to 9.5 lb per ton of approximately 30 percent moisture content (wet basis) hay. The substance was composed of 86.8 percent sodium bicarbonate (ordinary baking soda), 12.4 percent calcium bicarbonate, 0.5 percent magnesium bicarbonate, and 0.2 percent inert ingredients. Of these compounds only sodium bicarbonate may be expected to release carbon dioxide at ordinary temperatures. For the release of carbon dioxide there must be an acid present. An example of the reaction is that which occurs when water is added to the cream-of-tartar type of baking soda as given by Hopkins (11):

$$NaHCO_3 + KHC_4H_4O_6 \rightarrow KNaC_4H_4O_6 + H_2O + CO_2$$

Thus one mole of sodium bicarbonate yields one mole of carbon dioxide if the reaction goes to completion. If the commercial preparation is applied at the rate of 10 lb per ton of hay, 8.86 lb of sodium bicarbonate is used which can yield a maximum of 4.64 lb of carbon dioxide. At standard atmospheric pressure and a temperature of 85° F this weight of carbon dioxide will occupy 41.7 cubic feet.

In view of the experience of Kleis (op. cit.) in trying to protect hay with carbon dioxide in a tightly constructed bin one could hardly expect such a small quantity of carbon dioxide to protect a ton of hay for the long period of time which is required for high moisture content hay to dry. If the carbon dioxide were to remain in the hay, protection would be possible, but since it is heavier than air, it flows to the bottom and thence to the outside atmosphere under the usual storage methods. In addition, the oxidation of glucose equal to 0.2 percent of the weight of the hay will produce more carbon dioxide than the commercial preservative at a rate of 10 pounds per ton of hay. Respiration losses in stored hay are known to occur at a considerably higher rate than 0.2 percent.

Lewis (15) applied the same compound in laboratory tests at a rate equal to one-sixth of the weight of the hay and found it to be ineffective.

Potential Benefits from the Use of Mold Inhibitors

In regions, such as Michigan, where it is difficult to field cure hay because of high relative humidities and frequent rains, the use of a mold inhibitor might offer many benefits. If hay could be baled at moisture contents of 30 to 35 percent (wet basis) the field-curing time would be reduced considerably. The lessening of weather hazards should result in lower nutrient losses from bleaching by the sun and leaching by rain and dew. It is generally considered that handling the hay at the higher moisture contents would result in less leaf shattering.

The application of a mold inhibitor could eliminate the need for forced-air curing of hay which is frequently done to overcome weather difficulties. In cases where forced-air curing is not done it would reduce the loss of nutrients from molding in storage and also greatly reduce the danger of spontaneous combustion.

Requirements of a Mold Inhibitor

Since hay is low in cash value as compared to other crops, it is necessary that an inhibitor be low in cost. It would be difficult to justify its use if the cost exceeded the value of the nutrients conserved. An inhibitor must be easily applied because it is necessary to make hay when the weather is favorable and unnecessary delays cannot be tolerated. Preferably, it should be applied during one of the normal haying operations. An inhibitor must protect the hay against mold growth until either the hay is fed to livestock or it dries to a level which will not support mold growth.

Certainly, a mold inhibitor should not seriously reduce the palatability or digestibility of the forage or be toxic to animals in the amounts consumed. Any residues that remain in the flesh of the animals or in milk produced for human consumption must be within acceptable limits in order to protect the consumers.

Some Inhibitors and Their Limitations

There is extensive literature on the subject of fungicides and fungistatic agents. Wolf and Wolf (23) reviewed the literature on the use of chemicals to control molds in meats. Brunner and Mallman (4) discussed the subject of mold prevention on dairy products. Great numbers of references are cited in a book edited by Reddish (18).

Compounds of the heavy metals, especially mercury, silver, and copper, possess fungistatic and fungicidal properties. Copper compounds are frequently used to control fungus diseases on plants. However, since residues of many heavy metal compounds are toxic to animals they are unsuitable for use on foods.

A series of fatty acids including propionic, valeric, and butyric acids possess fungistatic properties. Propionic acid and its compounds are used in the food industry. Sodium propionate is used particularly in the baking industry to inhibit molds and bacteria. Lewis (15) tested a series of fatty acids on hay in the laboratory and found acetic, propionic, butyric, and valeric acids to be effective mycostatic agents. Butyric acid is unsuitable for use because of its objectionable odor; it is the agent which causes the unpleasant odor of rancid butter. Lewis (ibid) applied propionic acid to hay before mowing and Eggleton (8) applied it during the baling operation without beneficial results. The failure to protect baled hay may have been due to its volatility since it would have to be present in adequate concentration for some period of time.

A group of phenol compounds known by the general name of bis-phenols are effective fungicides and fungistats. According to Cade and Gump (5) only the bis-phenols "which contain a halogen and which are linked in the positions adjacent to the hydroxyl group are effective against bacteria and fungi." Some of these compounds are used for mildew- and rot-proofing of materials such as canvas.

Dawson, et al (7) reported that Dowicide 2 (2,4,5-trichlorophenol), Dowicide 2S (2,4,6- trichlorophenol), and mycotox no. 1 (2,4,5- trichlorophenol acetate) controlled mold growth in laboratory tests when applied at rates of six to eight pounds per ton of hay. Some additional compounds,mycotox no. 12 (tetrachlorophenyl acetate), mycotox no. 20 (tetrachlorophenyl propionate), and Dowicide 1 (orthophenylphenol) were considered to warrant further study. Richards (19) reported that Dowicide A (sodium o-phenylphenate) and Dowicide B (sodium trichlorophenate) were effective when applied to hay which was baled at approximately 30 percent (wet basis) moisture content. Eggleton (op. cit.) concluded that Dowicide 2S was more effective than Dowicide A or Dowicide B.

Mallman and Michael (16) tested Dowicide A, Dowicide B, Dowicide C (2,4,5,6- tetrachlorophenate), Dowicide F (tetrachlorophenate), and Dowicide G (sodium pentachlorophenate) as agents to prevent mold on eggs, cases, fillers, and flats in cold storage. They found that Dowicides B, F, and G were the most effective compounds. They concluded that the effectiveness of these compounds is related to their vapor pressures, compounds with higher vapor pressures being more effective.

Anderson, et al (1) conducted cattle feeding trials with derivatives of 2,4,5- trichlorophenol which are used to treat cottonseed intended for planting. When steers were fed up to nine times the quantity they would be likely to consume and later slaughtered, no traces of phenol or abnormalities were found in the organs or tissues.

Kennedy and Shenk (12) reported that when 2,4,6- trichlorophenol (Dowicide 2S) was fed to lactating dairy cattle a trace of the trichlorophenol was present in the milk. The quantity present was not sufficient to materially affect the odor or flavor of the milk. However, the effect on people consuming the milk must be studied before the compound can be used on hay which is to be fed to lactating cattle. The digestibility of hay was found to be unaffected by the application of Dowicide 2S at a rate of 10 pounds per ton of hay.

Field Methods of Application

Richards (op. cit.) applied inhibitors to standing hay by spraying aqueous solutions immediately ahead of the mower. Some difficulty was encountered in securing good coverage due to wind drift of the spray, especially under gusty conditions. The greatest difficulty was encountered when rain fell between the times of inhibitor application and baling of the hay. As a result, the inhibitor was washed off the hay by rain.

Eggleton (op. cit.) applied inhibitors in the form of dust in the bale chamber. When it was fed by gravity the dust was not evenly distributed throughout the hay. Blowing the dust into the bale chamber produced better distribution in the bale but caused an unpleasant cloud of dust around the baler. Kennedy and Shenk (op. cit.) reported that Dowicide 2S could not be applied satisfactorily as a dust because of caking and sticking in the dusting equipment. They reported greater success when inhibitor solutions were sprayed on the swath just before raking and on the windrow after raking. However, unless the hay is baled soon after the application, there is the possibility of its being washed off by rain.

Eggleton (op. cit.) in 1952, also applied inhibitor solutions through a single nozzle located in the top of the baling chamber but did not obtain adequate coverage of the hay. In the 1953 trials a test with three nozzles in the top of the chamber was equally unsuccessful. In the same season, a solution of Dowicide 2S in mineral oil was applied through two low-pressure nozzles located in the face of the plunger. Several intervals of application during the plunger cycle were tried but in no case was the coverage of the hay satisfactory. Regardless of where nozzles are located in the chamber the spray is intercepted by hay which is pressed closely around the nozzles. This results in a concentration of spray on the hay which is immediately in front of the nozzles. With the baler on which the tests were conducted, hay continues to enter the baling chamber during most of the compression stroke. At the time the last hay enters, the available space in the chamber is filled with partially compressed hay. In order to apply inhibitor to the last hay which enters, it would be necessary to force spray through some of the hay. Since it is difficult to force a spray through compressed hay, there does not appear to be an easy method of applying inhibitor in the baling chamber.

The most satisfactory results in the application of inhibitor at the time of baling were obtained by Eggleton (op. cit.) in 1952 with a three-nozzle spray boom placed over the baler apron to apply the chemical after the hay was picked up from the ground and before it entered the baling chamber. Good coverage of the hay was obtained except for one edge of the bale where the knife on the plunger cut off each charge of hay. This resulted in mold on the cut edge which from the feeding standpoint is not sufficient to be objectionable. However, if hay is marketed according to the U. S. Grading Standards, the presence of any must or mold requires that the hay be classed as U. S. Sample, the lowest grade. It was reported that this method of application also possessed the disadvantage of spray drift which was unpleasant for the tractor operator.

One might speculate that some movement or migration of the inhibitor should occur after application. The experience with mold growth occurring on the cut edge of the bale indicates that such an event does not take place. Mallman and Michael (op. cit.) concluded that the effectiveness of the phenol compounds is related to the vapor pressure. This is undoubtedly true under cold storage conditions where the molds develop slowly and are surrounded by inhibitor vapor before development begins. However, molds frequently appear on high moisture content hay within 48 hours after baling under the usual summer atmospheric conditions. If the vapor pressure of the inhibitor were high enough to envelope the hay in a fungistatic vapor in time to prevent mold growth, the inhibitor would be so volatile that it would soon be entirely evaporated.

Further tests were made in the 1954 season with a spray boom similar to that used by Eggleton (op. cit.) Fig. 1 is a sketch which shows the nozzle locations with respect to the baler apron. Fig. 2 is a photograph showing the boom mounted on the baler while Fig. 3 shows the spray boom covered by a canvas. This hood reduced the spray drift considerably and made driving the tractor which pulled the baler, and loading bales on a wagon at the rear of the machine, considerably more pleasant tasks.

Dowicide 2S was applied in a mineral oil solution supplied to the nozzles by a pump driven from the crankshaft of the baler power unit. The pressure, and consequently the rate of delivery, was controlled by a pressure control valve. Before the field trials, the nozzles were calibrated individually by collecting the discharge from each during timed intervals at several pressure settings.

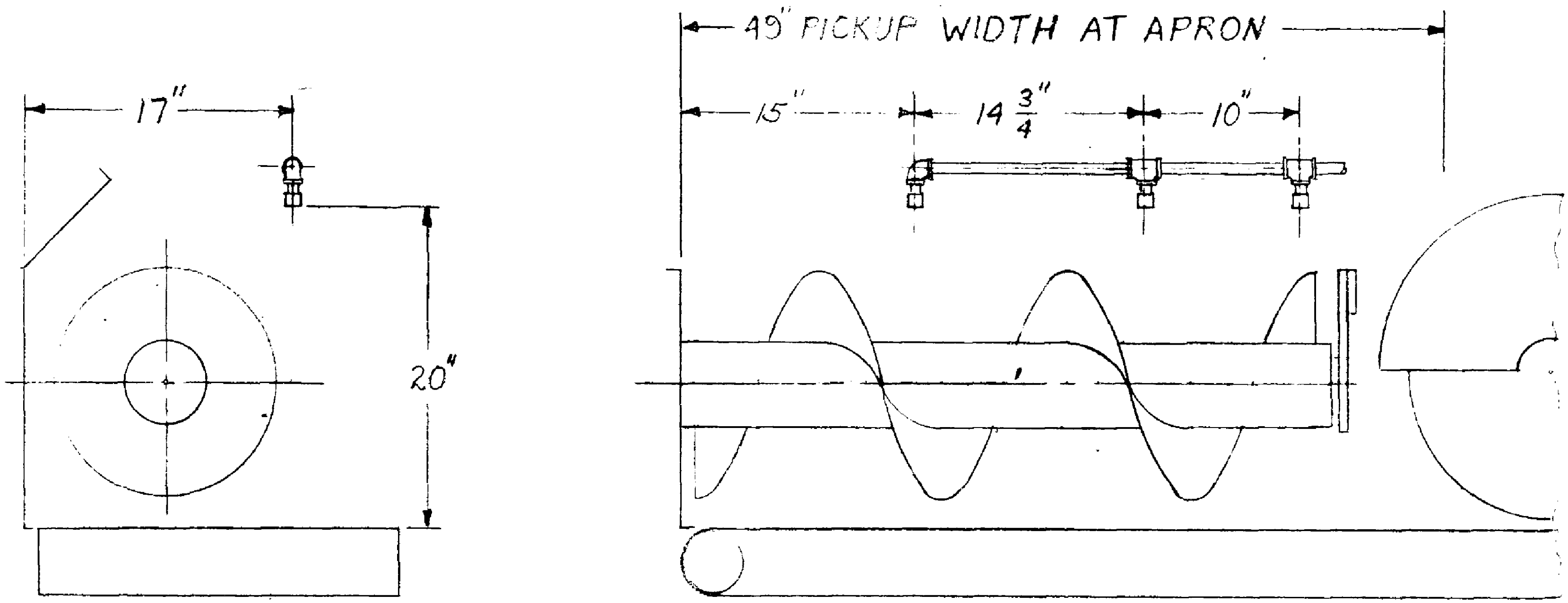

FIG. 1. SKETCH OF NOZZLE LOCATIONS FOR APRON SPRAY BOOM

Fig. 2 Two-nozzle spray boom mounted on the baler

Fig. 3 Canvas hood over the spray boom

In the field the weight of inhibitor applied to each bale was determined from the pressure setting and by stopwatch measurement of the time required to form each bale. From the bale weights the rates of application per ton of hay were determined. The moisture contents of the individual bales were determined by removing a core sample from each bale with the device constructed by Eggleton (op. cit.), and oven-drying the samples at 220° F.

Part of the hay was crushed. The mowing, crushing, and raking were performed on August 23 and the hay was baled the following day. Since the crop was rather light (approximately 1.2 tons of field-dried hay per acre) and the hay had been raked into single windrows, the nozzle was removed from the outer end of the boom and the inhibitor applied through the remaining two nozzles. Otherwise, much of the spray from the third nozzle did not strike the hay as it moved over the baler apron.

After baling, the bales were sampled, weighed, and stacked in a closed bin of the Case Hay Laboratory. On December 30 the bales were re-sampled for moisture content and inspected for the presence of must and mold.

Relation of Application Rate to Period of Protection

Some results of the 1954 test are presented in TABLE I. Bale nos. 1 through 4 contained crushed hay, and the remaining bales consisted of uncrushed hay. Because of favorable drying conditions in the field, the crushed hay became somewhat drier than the desired range of 30 to 35 percent (wet basis). It is evident that the crushed hay underwent very little change in moisture content in storage while the uncrushed hay dried to some extent. This probably occurred because all the bales were placed in a single stack where the crushed hay absorbed moisture from the uncrushed until they attained a mutual equilibrium.

TABLE I

RESULTS OF MOLD INHIBITOR TEST

Bale No.	Moisture Content (Wet Basis) Percent		Inhibitor Application Rate		Condition After Storage
	When Stored	After Storage	Lb/Ton of Wet Hay	Lb/Ton of Oven-Dry Hay	
1	25	24	6	8	No must or mold
2	25	23	7	9	Slightly musty and moldy
3	25	25	10	13	No must or mold
4	24	25	12	16	Slightly musty and moldy
5	33	-	9	14	Slightly moldy
6	34	23	15	23	Musty
7	36	27	19	30	Slightly moldy
8	32	28	35	51	Slightly moldy
9	29	28	32	45	Slightly moldy
10	30	25	35	49	Slightly moldy

In all bales, except one in which small masses of mold were found, the mold consisted of very small spots which would not be noticed in casual observation. Although the hay was in good condition after 4 months' storage it was not completely free of mold growth even though inhibitor was applied at rates as high as 51 pounds per ton of oven-dry hay.

Inspection of the bales indicated that the inhibitor was reasonably well distributed throughout the bale cross-section since there were no masses of mold such as develop on areas which are not covered with inhibitor.

Kennedy and Shenk (op. cit.) reported that the application of Dowicide 2S in the laboratory at a rate of 5 pounds per ton of oven-dry hay in some cases delayed mold growth which eventually covered the surface of the hay. At a rate of 10 pounds per ton, only small colonies of mold were present on some samples after prolonged incubation. They further reported that storage of baled hay with initial moisture contents of 24 to 28 percent for a period of 33 weeks resulted in considerable mold growth in untreated hay and in hay treated at a rate of 7 pounds per ton. At rates of 11 to 25 pounds per ton there were occasional spots of luxuriant mold growth but on most of the hay the mold was confined to very small spots.

The data in TABLE I together with the results of tests by Kennedy and Shenk (ibid) show that Dowicide 2S even at high rates of application is not capable of <u>completely</u> preventing mold growth in high moisture content hay which is stored indoors for a period of months.

In order to determine if there is a relation between the rate of inhibitor application and the time required for mold development some laboratory tests were made with Dowicide 2S in the spring of 1954. Hay samples consisting of 275 grams of 15 to 16 percent moisture content alfalfa hay, which had been run through a hammermill, were used. Sufficient cold water was added to raise the moisture content to 40 percent (wet basis). The inhibitor was used in the form of CE-121 solution, which was supplied by the Dow Chemical Company, and is miscible with water. To secure good coverage of the inhibitor it was mixed with the water before the water was added to the hay. The hay was stirred until it was uniformly wet. All samples were placed in closed, but not sealed, 2-quart fruit jars and stored at 85° F. where they were examined daily for the presence of visible mold. Tests were made with rates of application up to 9 pounds per ton of 30 percent moisture content hay.

The results of the test are shown graphically in Fig. 4 which indicates that there is practically no inhibiting effect at rates below 3 pounds per ton. At higher rates the period of time for which protection is provided

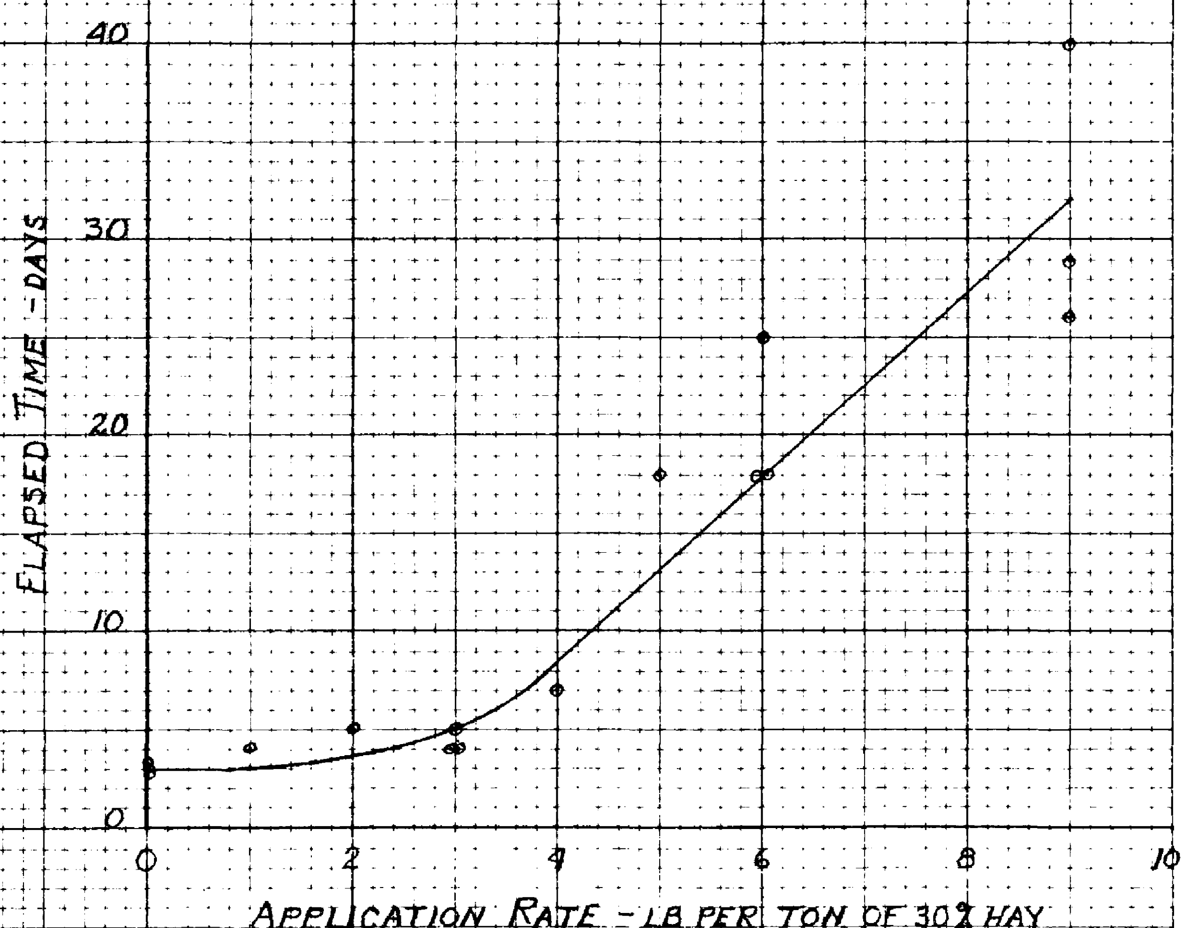

FIG. 4 RELATION OF APPLICATION RATE OF DOWICIDE 25 TO TIME REQUIRED FOR VISIBLE MOLD DEVELOPMENT

increases with the rate of application. This clearly indicates that the required rate of application of a mold inhibitor is dependent upon the period of time for which protection is required. The length of time for which protection is necessary depends upon the initial moisture content and the rate at which the hay dries. The rate of drying is, in turn, determined by the characteristics of the hay, the storage conditions and atmospheric conditions of temperature, humidity, and air movement.

Drying Rates of Stored Hay

Since the required rate of inhibitor application depends upon the period of time for which protection is required, a test was made in the fall of 1953 to determine the rate of drying of stored bales of hay.

In this test two lots of second cutting alfalfa hay were used. One lot of bales had moisture contents ranging from 25 to 35 percent (wet basis) with an average moisture content of 30 percent. The moisture content of the bales in the second lot ranged from 17 to 26 percent with an average moisture content of 21 percent. Each lot consisted of 18 bales so that 3 bales from each lot could be sampled each month for a period of 6 months.

The high moisture content lot was baled on August 26, 1953. Dowicide 2S (2,4,6- trichlorophenol) was applied through nozzles in the face of the plunger at an average rate of 6.2 pounds per ton of hay. The bale densities ranged from 9.1 to 12.0 pounds per cubic foot with an average density of 10.7 pounds per cubic foot. The low moisture content group was baled from the same field on the following day. No mold inhibitor was applied. The density of these bales varied from 5.2 to 7.9 pounds per cubic foot with an average density of 6.5 pounds per cubic foot.

The bale density was determined by weighing the bales; the moisture content was determined by removing a core sample. The bales were stored in a closed bin in the Case Hay Laboratory where they were placed on the floor of the bin with several inches of free space between bales.

Three bales were selected from each lot at four-week intervals. These bales were separated into approximately 10 sections, and each section was weighed to the nearest ounce. The center portion of each section was removed with a device which cut out a 5¼ inch diameter core. This sample was weighed to the nearest one-tenth gram and dried in order to determine the moisture content. The sampling device was constructed to take samples concentric with the hole made by sampling when the bales were placed in storage. This was done in order to determine if the hole had any appreciable effect on the drying of that end of the bale.

The weight of dry matter in each section of the bale was computed from the weight and moisture content of the section. This weight of dry matter in each section was used to compute the percentage of the total dry matter in the bale which each slice contained. From this information the moisture content longitudinally through the center of each bale was plotted.

Because the bales varied in moisture content, a graph of the final variation of moisture content throughout a bale without reference to the initial moisture content, does not indicate the change which occurred. For this reason the change in moisture content between the time of storage and the time of sampling is a better measure of the change which took place. In Fig. 5 the curves represent the average change in moisture content during the storage period of the high moisture content bales sampled at the end of each interval. Fig. 6 presents similar data for the low moisture content lot. In each case the curves are arranged so that the end of the bale which was sampled at the time of storage falls on the left side of the graph.

The outside of a bale of hay can be expected to dry more rapidly than the interior. According to the laws of diffusion there will be a movement of moisture from a region of high moisture content to the region of low moisture content and thence to the atmosphere. If the moisture is uniformly distributed throughout the bale, the surface will dry most rapidly. With a gradient in moisture content between the surface and interior of the bale, the

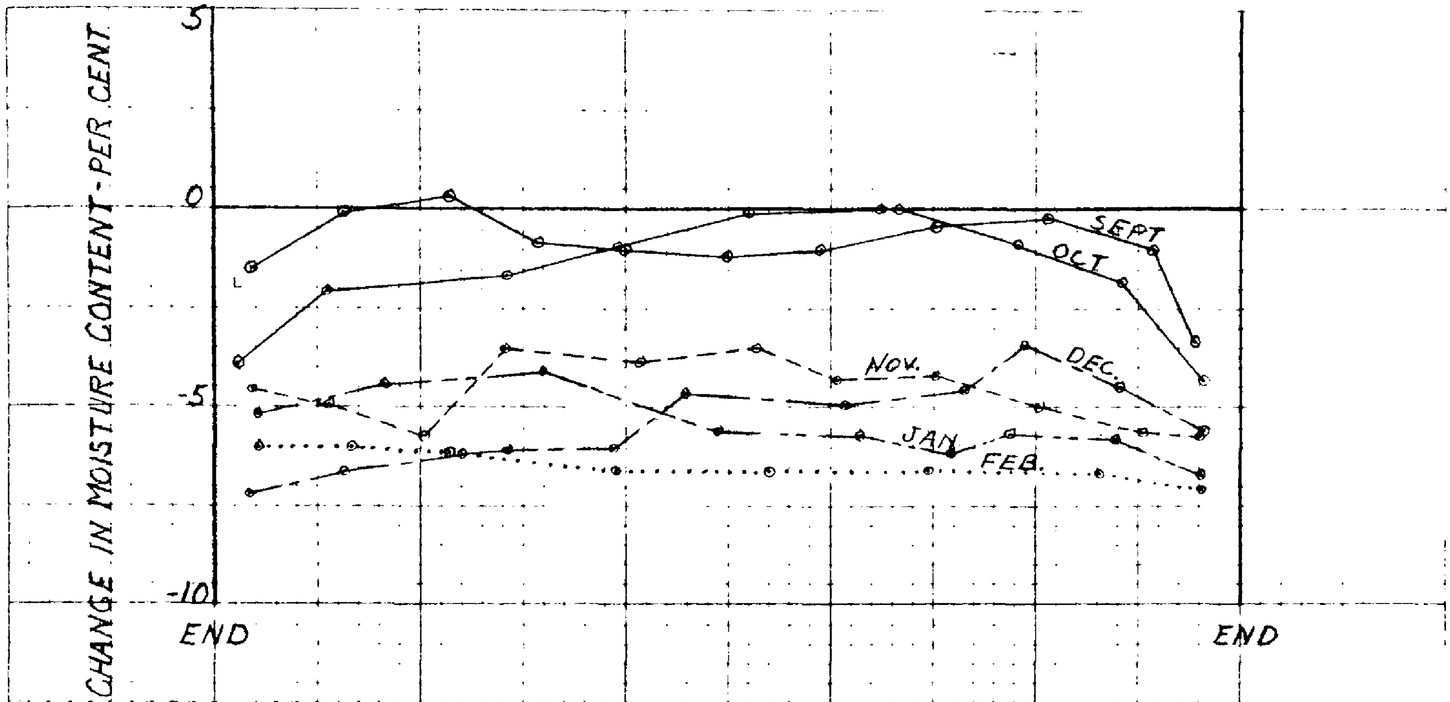

FIG. 6. CHANGE IN MOISTURE CONTENT OF LOW MOISTURE CONTENT BALES

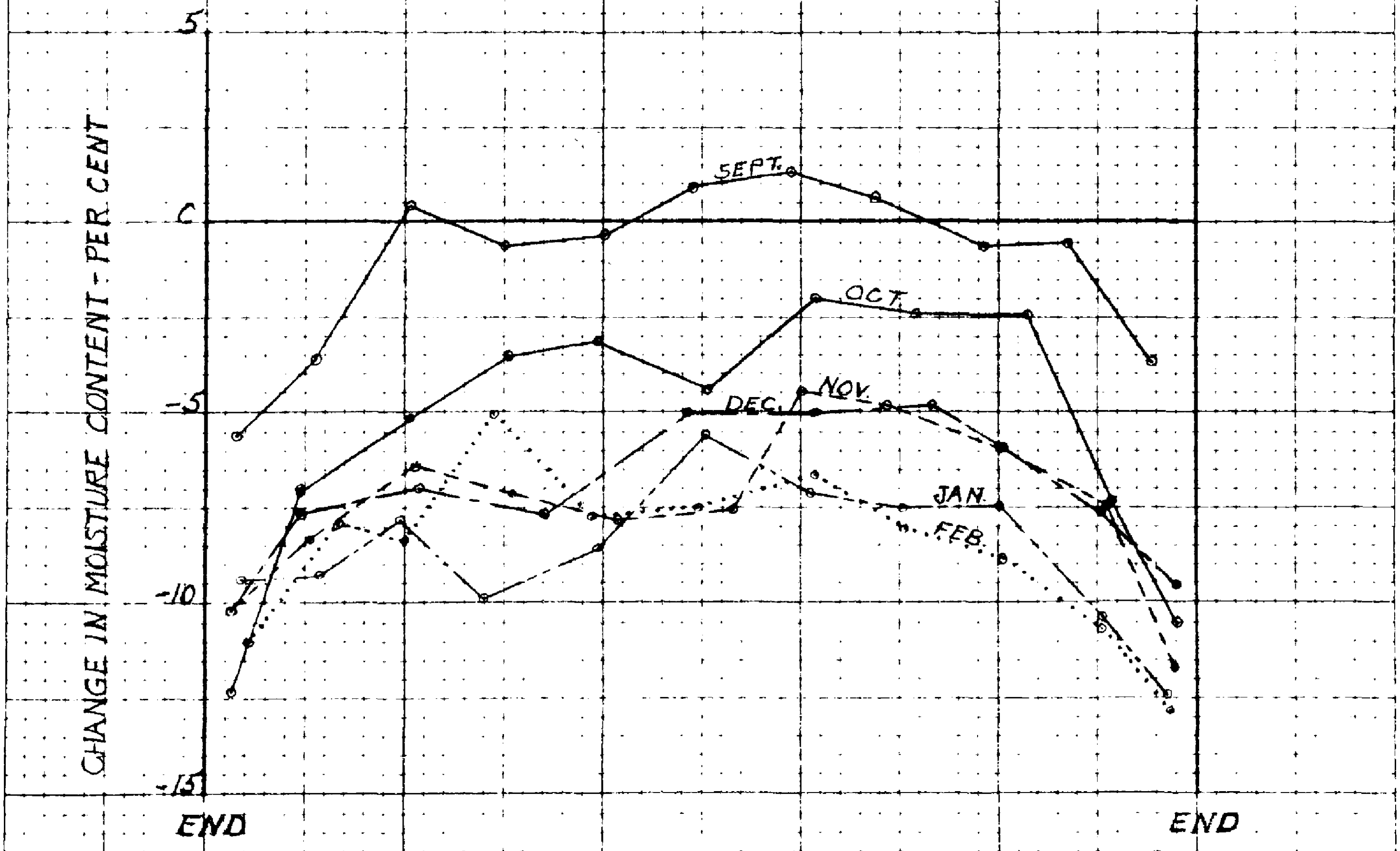

FIG. 5. CHANGE IN MOISTURE CONTENT OF HIGH MOISTURE CONTENT BALES

highest moisture content would be expected at the point farthest from a surface of the bale.

Fig. 5 and 6 indicate that very little drying took place through the centers of the bales during the first month, except on the ends. In subsequent periods some drying occurred throughout the entire bale. The most rapid drying occurred during the first three months of storage. This is to be expected because of the higher temperatures prevailing during this period and also because the rate of drying decreases as the moisture content of the hay is lowered.

The nearly straight line which was obtained in February from the low moisture content lot indicates that these bales had practically attained equilibrium with the atmosphere. On the other hand, the interiors of the bales from the high moisture content group were still several percent above equilibrium with the atmosphere. The centers of these bales had moisture contents as high as 26 percent. This moisture content is high enough to support mold development at higher temperatures. It should be borne in mind that these bales were stored individually, and if several tons of hay were stored in one lot, the hay in the center of the pile would undoubtedly dry much less rapidly than these individual bales. Evidently, if a mold inhibitor is applied to high moisture content hay it must be applied either at a rate which is fungicidal or at a rate which is sufficient to prevent mold development for a period of many months. There is no hope of applying a short lived mold inhibitor to hay that is stored indoors on the basis that the hay will dry sufficiently in a short period of time so that mold cannot develop.

A comparison of the left and right portions of the graphs indicates that the hole resulting from sampling the bales when they were placed in storage had little effect on the drying of the interior of the bales.

Kennedy and Shenk (op. cit.) reported in 1954 the results of somewhat similar tests. After 33 weeks of storage the moisture content of untreated hay was approximately uniform throughout the bale. Hay which had been treated with mold inhibitor had higher moisture contents in the center of the bale than at the ends and a higher rate of inhibitor application resulted in higher moisture content in the center of the bale. The slower drying of treated hay was attributed to reduced heat of respiration since the activity of microorganisms was reduced. Dawson and Musgrove (6) found in laboratory tests that respiration in hay after the development of microorganisms provided more than 60 percent of the heat absorbed by water evaporation when air with a high relative humidity was passed through the hay. However, respiration of hay before the development of microorganisms produced more than 25 percent of the heat absorbed by water evaporation.

The Use of Fumigants as Mold Inhibitors

The work which has been discussed up to this point has dealt with the application of inhibitors in liquid or dust form. In order to control mold it is necessary that the liquid or dust be in intimate contact with all parts of the hay. An alternate method of application is the use of a volatile inhibitor or fumigant which can be applied after the hay is in storage. The use of a fumigant in the hay storage would eliminate the difficulties of obtaining uniform application in the field but posesses the disadvantage of requiring that the hay be stored very soon after baling so that it can be treated before molds develop.

A limited number of tests were performed in which fumigants were applied to hay placed in clear plastic (tenite) tubes 1 5/8 inches in inside diameter and 36 inches long. Second cutting dry alfalfa hay which had been run through a hammermill was thoroughly moistened with cold water before it was placed in the tubes. In some cases sufficient water was used to raise the moisture content to 30 percent (wet basis) and in other cases it was raised to 40 percent moisture content. In all cases 130 grams of dry matter were used.

After the hay was placed in the tubes, the inhibitor was added, the tubes stoppered and then placed in a room maintained at 85° F.

Chloro-2-propanone (also known as chloroacetone), orthodichlorobenzene and Dowanol 93B2 (a mixture of mono- di- and tripropylene glycol methyl ethers) were tested. In the first experiment the chemicals were applied directly from a burette to the hay in the top of the tube. In a later experiment the chemicals were placed in metal cups 13/16 inch diameter by 5/16 inch deep which rested on top of the hay.

The results of the tests were evaluated by measurement of the distance from the top of the hay to the nearest mold. The results are presented in Fig. 7 which shows the distance from the top of the hay to the nearest mold expressed as a percentage of the height of the entire column. This is shown for six days after the application of the chemicals because at that time the boundary between moldy hay and non-moldy hay was usually well defined. In some cases the boundary moved upward during the first few days, and in many cases it was not clearly defined during the early period. The results indicate that all of the chemicals tested possess mold inhibiting properties but only chloro-2-propanone is sufficiently volatile for this method of application. However, the chloro-2-propanone did not prevent mold

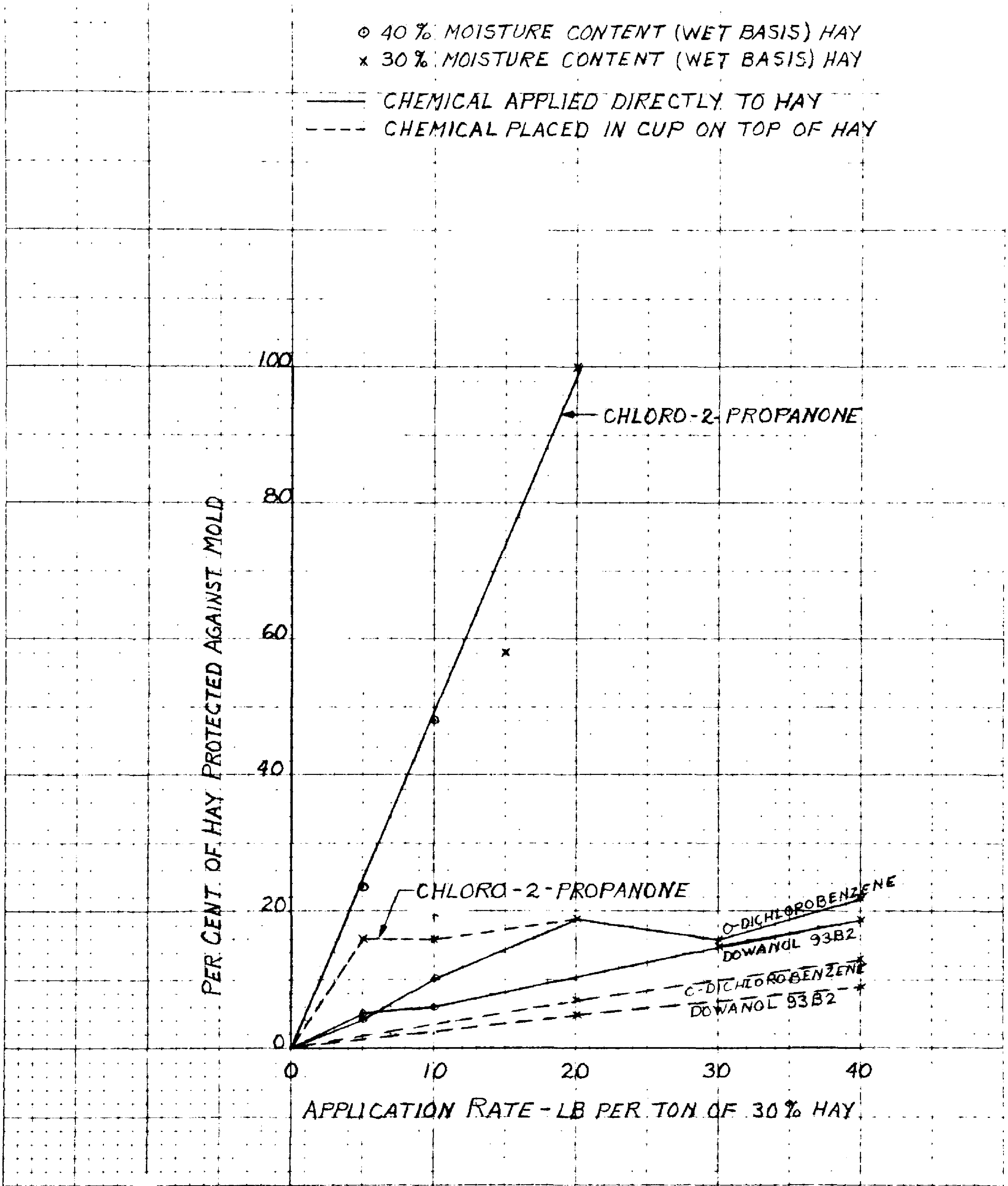

FIG. 7. RELATION OF RATE AND MANNER OF APPLICATION OF FUMIGANTS TO PREVENTION OF MOLD FOR PERIOD OF SIX DAYS.

development when it was placed in a small container on top of the hay. This was probably due to a slow rate of evaporation which resulted from the relatively small evaporative surface available. Consequently, the vapor did not penetrate the column of hay rapidly enough to prevent mold growth and, apparently, once mold had begun to develop, the fumigant could not arrest the process. Fig. 7 also indicates that 40 percent moisture content hay does not require a higher rate of application of fumigant than 30 percent moisture content hay when the rate is computed for hay at the same moisture content. In other words, the amount of fumigant required is dependent upon the amount of dry matter present and does not increase with increased moisture content.

The boiling point of chloro-2-propanone is 119° C, that of orthodichlorobenzene is 180° C and Dowanol 93B2 boils in the range of 129-299° C. Since the chloro-2-propanone penetrated the entire column of hay while the other chemicals failed to do so, the lower boiling point of the chloro-2-propanone probably accounts for the difference in penetration of the chemicals. The chloro-2-propanone has lachrymatory properties and is also toxic to humans. As a consequence, its usefulness as a fumigant for hay may be limited. At the present time no other chemicals with fungicidal properties, low boiling points, and relatively safe handling characteristics are available. A possible method of application of the higher boiling point chemicals, which has not been tried, is to vaporize the chemical in a relatively small stream of air which is blown through the hay. It would probably be necessary to vaporize the entire quantity of liquid and have it thoroughly distributed through the hay within two days after the hay enters storage. Because of lack of funds and time this method of application was not attempted.

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THE RELATION OF MOISTURE CONTENT AND BALE DENSITY TO HAY QUALITY

Because it is difficult to completely field-cure hay in humid regions without excessive loss of nutrients it is desirable that the hay be stored at as high a moisture content as possible. The moisture content is an important factor in the development of mold but if the hay dries rapidly enough mold growth will be prevented. The speed at which hay dries naturally should depend upon the temperature, humidity, and movement of the air and the bulk density of the stored hay.

Eggleton (1) reported the results of a preliminary test in 1952 in which bales were stored on end with several inches of free space between bales. It resulted generally in must- and mold-free hay at bale densities below 9 pounds per cubic foot. A 14 by 18 by 40 inch bale with a density of 9 pounds per cubic foot weighs 53 pounds.

Further tests were made in 1953 in which the bales were stacked more closely together. These tests were conducted to determine the relation of moisture content and bale density to hay quality under more conventional storage conditions.

Test Procedure

The tests were conducted on the first and second cuttings of alfalfa from farms in the vicinity of East Lansing. The first cutting, which contained a mixture of grasses, was mowed on the afternoon of July 2 and baled on the afternoon of July 4. The second cutting was mowed on the morning of August 11 and baled on the afternoons of August 13 and 14 after an intervening cloudy day with a trace of rain.

The hay was mowed with a tractor-mounted mower and raked when it had dried to a moisture content of approximately 50 percent (wet basis). Baling was started when the moisture content was approximately 30 percent. A field pickup twine-tie baler which formed bales 14 by 18 by 40 inches was used. The bales were loaded directly onto wagons and hauled to storage.

The baling was done over a period of time in which the hay dried from approximately 30 percent to 20 percent. Several times during this interval the bale density was varied to produce a range of densities from the minimum possible to a maximum of approximately 11 pounds per cubic foot. Three test bales were formed at each density.

At the storage, each bale was sampled by boring approximately one-half the length of the bale with a tube. The core collected in the tube was dried to determine the moisture content of the bale. Since all of the bales were the same size, the bale density was computed from the weight of each bale. The hay was stored in a bin of the Case Hay Laboratory which has a wire mesh floor three feet above the ground and also has two sides open to the weather.

This storage condition is referred to as natural mow drying. A gap of approximately 2 inches was left between bales when they were stacked in the bin. After a period of four weeks, the bales from the first cutting were inspected for must and mold. The hay from the second cutting was inspected after eight weeks storage.

Discussion of Results

Terry (4) reported that bin-stored hay which was dried below 20 percent moisture content within $3\frac{1}{2}$ days was of good quality and free from visible mold. Accordingly, the critical period for storage of high moisture content hay would be approximately the first 3 days of storage. In this interval the air temperature and relative humidity would influence the drying rate of the hay and the development of must and mold.

During the first three days of storage of the first cutting the average official temperature was 73° F according to the U. S. Weather Bureau in East Lansing. The normal average temperature for the month of July is 71° F.

The corresponding average temperature for the first three days of storage of the second cutting was 67° F. The normal average temperature for the month of August is 69° F.

The average relative humidities[1] for the first three days of storage of the two cuttings were 60 and 62 percent, respectively, as compared to 20 year averages of 62 and 65 percent for the months of July and August respectively. According to these data, the average temperatures and relative humidities during the first three days of storage were approximately normal and were about the same for both cuttings.

The data from both cuttings are reported in Fig. 8. This figure shows the quality of individual bales in relation to density and moisture content. The "lower limit of musty bales" indicates the minimum conditions of density and moisture content at which mustiness occurred. The "upper limit of must-free bales" passes through the points of maximum density and moisture content at which bales were found free of must. Above the upper limit all bales were musty, while below the lower limit all bales were free of must. The area between the limit lines includes a range of densities and moisture contents at which both musty and must-free bales were found. This variation in quality is

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[1] Computed from official observations at 7 a. m., 1 p. m., and 7 p. m.

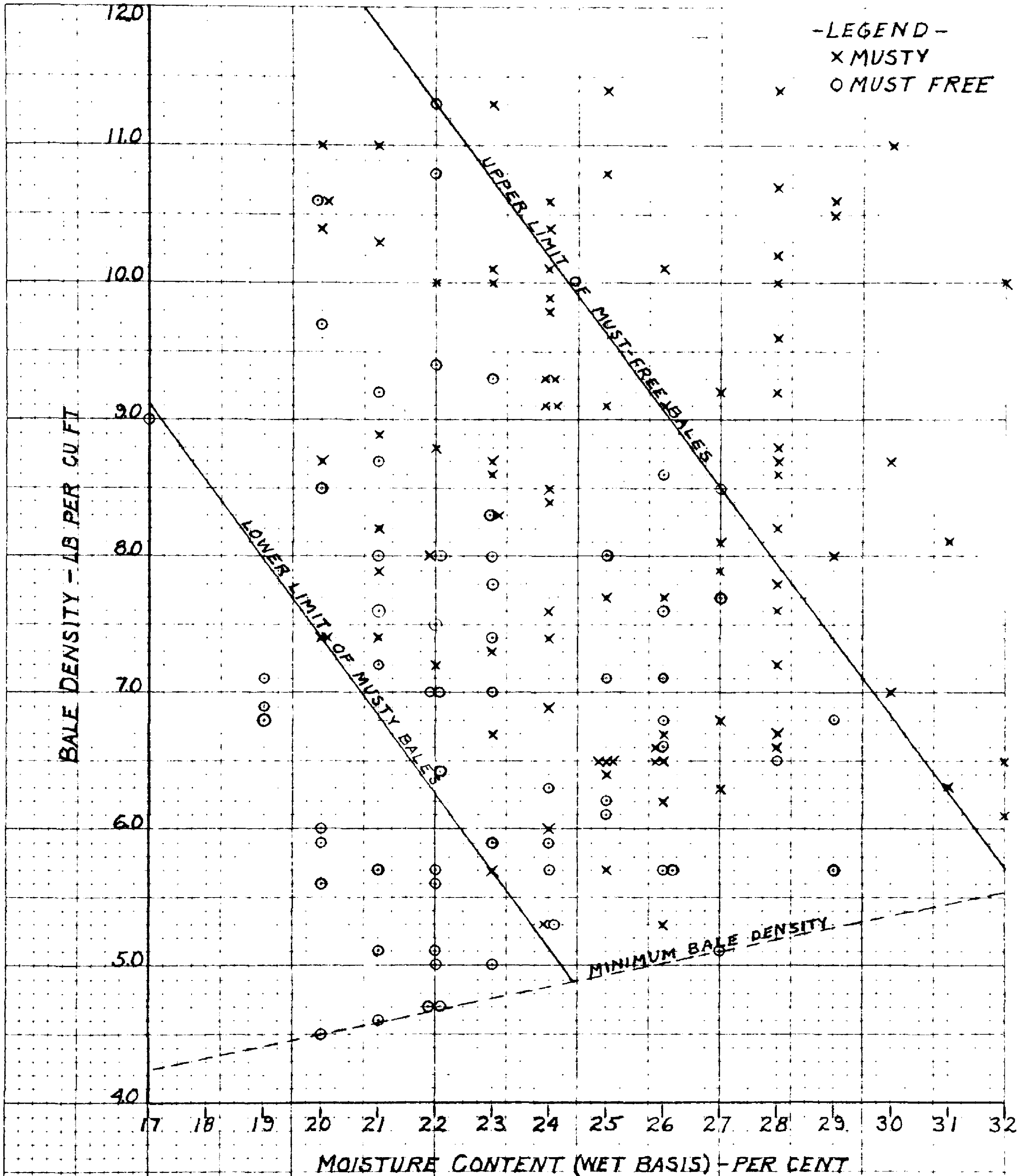

FIG. 8. RELATION OF BALE DENSITY AND MOISTURE CONTENT TO KEEPING QUALITY.

probably due in part to variations of density and moisture content within individual bales.

The observed values of density and moisture content represent an average condition within the bale, while the development of must is more likely related to the maximum conditions of density and moisture content. That is, a bale having an average moisture content low enough to prevent must and mold growth, may have small, damp, dense portions which will become musty and moldy in storage.

Varying degrees of mustiness were observed in the bales falling in the area between the limit lines. In general, as the lower limit of musty bales was approached, the degree of mustiness decreased to such an extent that only an experienced inspector would be likely to detect its presence.

The slope of the limit lines indicates that to obtain must-free hay, the bale density must be decreased as the moisture content is increased. If the area between the limit lines is divided into parallel strips of equal width, a gradual reduction of the percentage of must-free bales is found as the upper limit is approached. This, together with the slope of the limit lines, shows that a definite relation exists between bale density, moisture content, and quality.

Kleis (2) and Richards (3) made surveys of hay quality in the Lansing area. The surveys covered one first cutting and two second cuttings of alfalfa hay. Fifty-six percent of the bales from the first cutting were musty or moldy, while 39.2 percent of the bales from the second cuttings were musty or moldy. The bales ranged in density from 6.7 to 14.0 pounds per cubic foot with an average density of 10.8 pounds per cubic foot. Ninety-three percent of the bales had a density of 8 pounds or more per cubic foot.

The results presented in Fig. 8 indicate that completely must-free hay cannot be obtained under Michigan conditions at bale densities of 8 pounds or more per cubic foot with natural drying if the moisture content is above 19 percent. Thus, in order to obtain hay which is entirely free of must and mold, it is necessary to form bales of approximately 6 pounds per cubic foot density (35 pounds for a 14 by 18 by 40 inch bale) at moisture contents around 20 percent. Such bales require careful handling and it is difficult to cure hay to 20 percent moisture content in humid or rainy weather.

The complete absence of must is not a matter of primary concern in hay which is fed on the farm, because good results can be obtained with slightly musty hay. Occasional musty portions, such as may occur from the presence of a succulent weed or a wad of uncured hay, represent only an insignificant loss. If an occasional spot of must is acceptable, hay can be compressed to somewhat higher densities or loosely baled at higher moisture contents. However, dense bales of moist hay should be avoided because of the loss of food value and palatability resulting from the formation of must and mold and also because of the danger of spontaneous combustion in the hay.

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SOME EFFECTS OF CRUSHING HAY

The idea of hay crushing originated about 1930 and patent No. 1,816,998 was granted to E. B. Cushman on August 4, 1931. The first results of crushing tests were published by Bainer (2) of California in 1931. This was followed by reports from Jones and Palmer (10) of Mississippi in 1932, Zink (23) of Kansas in 1933, and further work by Jones and Palmer (11) in 1934. There apparently was a lapse of interest in hay crushing until World War II when a shortage of feed concentrates emphasized the importance of quality hay as a source of protein. Further results were reported by Jones and Dudley (13) from Mississippi and Terry (20) from New York in 1948, and by Kline (15) in 1949 from tests conducted in Michigan .

Purpose of Crushing Hay

Kleis (14) listed the following reasons for crushing hay:

1. It cracks and crushes the stems thus exposing more surface to the air with the result that the field curing time is shortened by 30 to 50 percent.
2. The weather hazard is decreased by virtue of the reduced field curing time.

3. With a decreased weather hazard the amount of field work is reduced because of less frequent tedding or turning of hay which has been wet by rain.
4. Leaves and small stems are saved when the amount of handling in the field is reduced.
5. Crushed hay has better color, and consequently higher carotene content, because of reduced exposure to the weather.
6. More nutrients are harvested because of higher carotene content and reduced loss of leaves and small stems.
7. The palatability of the stems is increased by crushing.

Mechanism of Moisture Removal from Plants

In order to understand the effect of crushing on the drying of forage plants, it is necessary to first consider the composition of the plant epidermis or skin. Perennial plants, such as alfalfa, have an epidermis composed of cork cells on all parts of the plant except the leaves and very young stems. These cork cells contain a substance, suberin, which is relatively impermeable to water. In addition, the outer surfaces of all epidermal cells are covered with cutin, another wax-like substance, which is also relatively impermeable to water. Thus, the stems are doubly protected against moisture loss by the suberin of the cork cells and the covering of cutin. Meyer and Anderson (16) stated that in most plant species of the temperate zone less than 10 percent of the foliar transpiration of water occurs through the cuticle. Thus, in living plants some 90 percent of the moisture transpired is removed through the stomata.

The stomata are microscopic openings on both top and bottom surfaces of the leaves which are opened and closed principally according to the turgor pressure in a pair of guard cells surrounding each stoma. Transpiration from the leaves occurs through evaporation of water from the cell walls within the leaves and diffusion through the stomata to the atmosphere. The rate of transpiration depends upon the difference in vapor pressure of the moisture within the leaves and the moisture in the air surrounding the leaves, the "capacity" of the stomata, mass air movements around the leaves, and temperature changes of the plant leaves. The stomata are not open continuously but rather the degree and periods of opening are influenced by the presence of light, the internal water relations in the leaf, and by leaf temperature.

The presence of open stomata in cut forages may be desired in order to speed the drying process. While there is a normal daily cycle of opening and closing of the stomata, the opening is so frequently controlled by other factors that it can hardly be relied upon for selection of the optimum time of day for mowing. Jones and Palmer (11) reported that when alfalfa was windrowed two hours after cutting, the stomata reopened and continued the normal transpiration, thus aiding in the drying process. However, when wilting occurs the stomata gradually close, and then moisture removal must occur through the epidermis of the leaves and stems.

Physical Effects of Crushing

The term crushing is not well chosen and might better be termed cracking. It is not a process of squeezing the juices from the plant but rather is a process in which the stem epidermis is cracked. This ruptures the cutinous covering and the cork cells of the epidermis thus permitting more rapid evaporation of moisture through the stem walls. In some cases, particularly plants with coarse stems, the stem may actually be broken into strips, but that is not the normal effect on alfalfa.

In the crushing process the forage is compressed between two metal rollers. In most cases four longitudinal cracks appear in the stem, two of which appear at the ends of the flattened cross-section and the other two occur approximately at the midpoints of the flattened surfaces. Figure 9 shows photographs of the cross-sections of uncrushed stems while Fig. 10 shows cross-sections of crushed stems in which cracks can be seen.

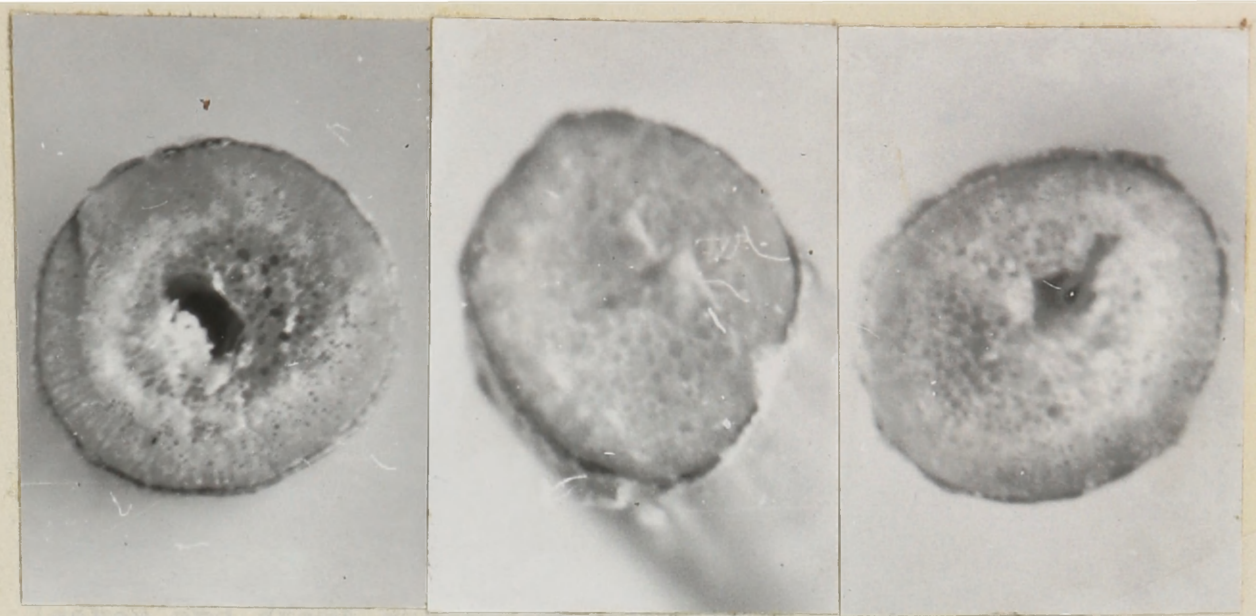

Fig. 9 Cross-sections of uncrushed alfalfa stems
(enlarged approximately 11 x)

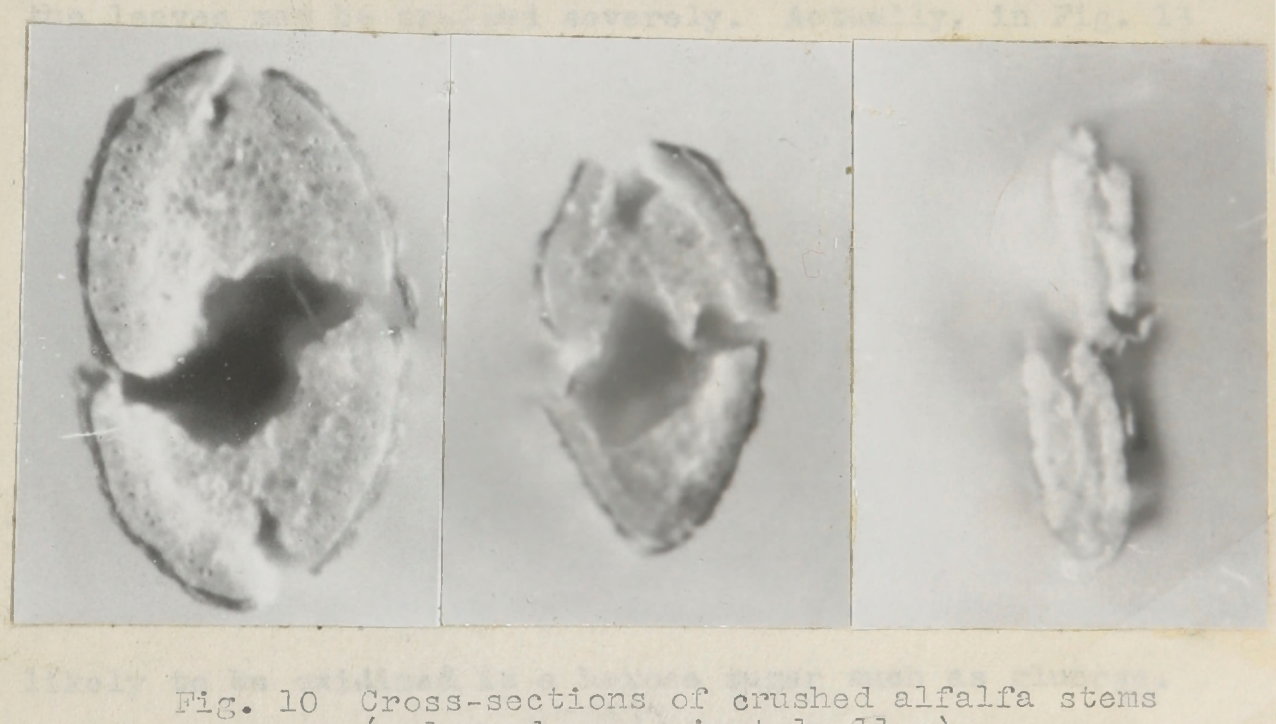

Fig. 10 Cross-sections of crushed alfalfa stems
(enlarged approximately 11 x)

Bechdel, et al (3) and White and Kalbfleisch (22) mentioned that the crushing also bruises the leaves. This may be undesirable because rupturing of the leaf epidermis will probably increase the drying rate of the leaves. The fact that the leaves of uncrushed hay dry more rapidly than the stems is shown by data presented by Zink (op. cit.). Thus bruising of the leaves by crushing may further increase the drying rate of the leaves, while it is desirable that the leaves and stems should dry at approximately the same rate. Figure 11 is a photograph of a leaf from uncrushed alfalfa, while Figs. 12 and 13 are similar photographs of leaves from crushed alfalfa. These figures indicate that some of the leaves may be bruised severely. Actually, in Fig. 13 there are two leaves which were compressed together in the crushing process. In freshly crushed alfalfa the bruised leaf areas are evidenced by a darker shade of green.

Another result of crushing is the production of heat by the plant due to increased respiration. Meyer and Anderson (op. cit.) stated that: "Wounding of plant tissues almost invariably results in a temporarily increased rate of respiration." In the resulting respiration, nutrients are oxidized and heat is produced. The substance most likely to be oxidized is a hexose sugar such as glucose. The heat of combustion of one pound of glucose is 14.8 British thermal units. However, in the respiration process, for each pound of glucose consumed 0.60 lb of liquid

Fig. 11 Leaf of uncrushed alfalfa
(enlarged approximately 16 x)

Fig. 12 Leaf of crushed alfalfa
(enlarged approximately 6 x)

Fig. 13 Leaves pressed together in crushing
(enlarged approximately 6 x)

water is produced. At 80° F this water will require 629 British thermal units for evaporation; $42\frac{1}{2}$ times the amount of heat produced. Thus, heat must be absorbed from the surroundings to evaporate the moisture produced and it is unlikely that the temperature of crushed plants will be raised as a result of the crushing treatment. If the temperature of the plants is not raised, the only result of crushing is to increase the evaporation rate under favorable drying conditions through rupture of the plant surfaces.

Factors Controlling the Drying of Hay in the Field

The rate of drying of hay in the field is affected by the continuation of the normal process of transpiration from the leaves. Jones and Palmer (op. cit.) examined the stomata of alfalfa leaves periodically after mowing. Their data showed that under Mississippi conditions most rapid drying of alfalfa occurred when it was raked into single windrows as cut, or double windrows two hours after cutting. This was attributed to transpiration of moisture from the leaves which thus reduced the moisture content of the complete plant.

When the stomata are closed moisture removal in uncrushed hay must occur through the surfaces of the leaves and stems. The mechanism of moisture movement to the plant surface is probably by liquid diffusion and the rate of drying under favorable conditions would be limited by the rate of diffusion through the plant surfaces from which it is evaporated. Henderson and Perry (9) state that the drying rate of agricultural products is proportional to the difference between the moisture content of the material and the equilibrium moisture content of the drying air. Hence, under constant conditions of air movement and heat supply, drying will be most rapid when the hay is freshly cut and the drying rate will decrease as moisture is removed.

In crushed hay the mechanism of moisture removal is more complex. Part of the moisture will be removed by diffusion to the normal plant surfaces. In addition, crushing of the plant permits more rapid movement of the moisture to the surface at the cracks in the stem, and in cases where the stem is split into strips the evaporative surface is increased considerably.

It is evident that for drying to occur, there must be both a source of heat to supply the energy required for the evaporation of the water and there must be a medium to absorb the water vapor. Either insufficient heat to evporate the moisture as rapidly as it is available at a surface, or an atmosphere which is not receptive to additional moisture can reduce the drying rate. Heat is obtained in the form of radiant energy from the sun, sky, earth, and other objects and by conduction from the atmosphere. Thus, high atmospheric temperatures and clear skies are conducive to rapid drying. In humid regions, the atmospheric humidity may frequently be the controlling factor in the drying of hay. Since the most rapid drying will occur with completely dry air, the drying rate is reduced as the humidity increases until at 100 percent relative humidity, no additional moisture can be absorbed by the air. In fact, at high relative humidities partially dry hay may reabsorb moisture from the atmosphere.

Air movement may affect the drying rate by altering the atmospheric conditions immediately surrounding the evaporative surfaces. This movement should remove air of high humidity and replace it continually with air of lower humidity. Up to some limit the rate of air movement will influence the drying rate as long as the equilibrium moisture content of the air in mass movement is below the moisture content of the hay. Carrier (6) stated:

> In materials having a slow rate of diffusion, the rate of drying follows the law of vapor-pressure difference, but the effect of velocity may be almost negligible in affecting the rate of evaporation, except in so far as it maintains a uniform condition of temperature and moisture in the air surrounding the material. This latter consideration is the chief reason for desiring good air circulation with slow-drying materials, while with rapid-drying materials the air velocity is of great importance.

Since crushed hay is capable of drying more rapidly than uncrushed hay, mass air movement may have a greater effect on the drying of crushed hay, and the minimum velocity for the maximum drying rate should be somewhat higher. When hay is in large windrows or bunches, a higher air velocity is required to produce air movement within the hay mass.

Objectives of the 1954 Hay Crushing Tests

The general objectives of the tests conducted in the haying season of 1954 were to determine the effect of crushing on the yield of nutrients and the drying rate of alfalfa hay. The specific points investigated are the effect of crushing on:

1. The drying rates of whole plants and the plant parts.
2. The absorption of rain.
3. The leaching of nutrients by rain.
4. Leaf losses from raking and baling hay.
5. The drying rate of baled hay under forced air drying.

General Test Procedure

The experiments were performed on alfalfa from a field on the college farms at East Lansing. The crushed hay was mowed and crushed with a Food Machinery Corporation mower-crusher. The uncrushed hay was either mowed with the mowing unit of the mower-crusher or a tractor-mounted mower. The hay was raked with a left-hand side delivery rake when the moisture content was approximately 50 percent unless it was desired to perform a test with hay raked at a lower moisture content. The hay was baled with a Case model NT twine-tie pickup baler and loaded directly from the baler onto a wagon. The first cutting tests were conducted with the crushing unit set to exert the maximum possible force on the hay. The second cutting tests were performed with the crushing force reduced slightly. A view of the mower-crusher used in the tests is shown in Fig. 14.

Effect of Crushing on the Drying Rates of Plants and Plant Parts

Two tests were conducted on each cutting in which the drying rates of the complete plant, the stems, and the leaves and flowers were measured. The general procedure was to mow two pairs of swaths one of which was crushed and the other left uncrushed. In order to be able to rake the swaths of crushed and uncrushed hay independently it was necessary to mow around the test swaths to provide an area which could be cleared. Before raking the test swaths, these border swaths were raked to provide an area onto which the test swaths could be raked when the moisture content was approximately 50 percent (wet basis).

Fig. 14 Rear view of mower-crusher

Immediately after mowing and crushing, samples were taken from each test swath for moisture content determinations,and sampling was continued at hourly intervals each working day until the hay was baled. Samples were taken from the swath by cutting out a transverse section from 3 to 4 inches wide with shears. Samples were taken from the windrow by cutting a similar cross-section with a carpenter's saw while the sample was compressed between two hinged boards. In the first cutting the samples were divided into two lots, one for the determination of the moisture content of the whole plant and the other for the moisture contents of the plant parts. Because the yield of the second cutting was less, separate samples were taken for the two purposes. Sampling was started at one end of the swaths and as successive samples were taken the other end of the plot was approached. As the samples were taken they were placed in closed one-gallon pails to limit further loss of moisture.

The whole-plant samples were weighed immediately and later oven-dried for 24 hours at 212 to 220° F. To determine the moisture contents of the plant parts the samples were separated by hand into stems and leaves. The flowers were included with the leaves. As soon as a sample was separated into parts the two lots were weighed and later oven-dried. In the separation of the plants into plant parts only alfalfa, clovers, and grasses were retained; weeds were discarded.

Because weather ~~factors~~ exerts a great influence on the drying rate, measurements were taken of rainfall, air temperature, relative humidity, and wind velocity. A rain gage was placed in the field in which the tests were performed along with a hygrothermograph to measure the air temperature and relative humidity. The hygrothermograph was placed on the floor of an instrument shelter. The floor of the shelter was placed about 4 inches above the ground surface. It was placed near the ground to measure the atmospheric conditions at the level of the hay. The hygrothermograph was calibrated daily with a sling psychrometer. The instrument shelter and rain gage are shown in Fig. 15. This photograph also shows the terrain on which the tests were performed.

The wind velocity was measured at hourly intervals during the working day with a velometer held at eye level. The readings obtained were an approximate average velocity over an interval of about one minute.

The first test was started on the afternoon of June 22. At this time the alfalfa was in about one-half bloom and the ground was very wet from previous rains. The mowing and crushing were performed between 1 and 1:30 p. m. There was a slight precipitation that evening. The crushed hay was raked the following day at 1:30 p. m.; the uncrushed at

Fig. 15 View of instrument shelter and rain gage

3:45 p. m. The crushed hay was baled on June 24 at 3:30 p. m. and the uncrushed hay was baled one hour later. The drying curves of the plants and plant parts are presented in Fig. 16.

The second test was started at 10 a. m. June 25. At this time the ground was still quite wet and during the following night and morning additional rain fell. The skies cleared during the afternoon and sampling was resumed the following morning. Both lots of hay were raked at 1:45 p. m. June 27. The crushed hay was baled at 3:30 p. m. June 28. The next morning a light rain fell which delayed baling of the uncrushed hay until 3:30 p. m. The results are shown in Fig. 17.

The third test was started at 10 a. m. August 3 when the second cutting of alfalfa was in about one-quarter bloom. The ground surface was still somewhat moist from the rain of July 31. The crushed hay was raked at 10:30 a. m. August 4; the uncrushed at 11:30 a. m. A light rain fell during the night which delayed baling until the following day. The crushed hay was baled at 12:45 p. m..on August 6; the uncrushed at 2 p. m. In this test the number of swaths sampled was increased to three of each treatment and the time interval between samplings was increased somewhat. Fig. 18 shows the drying curves obtained in this test.

The final test was started at 1:45 p. m. August 10 when the ground surface was quite dry. The crushed hay was raked

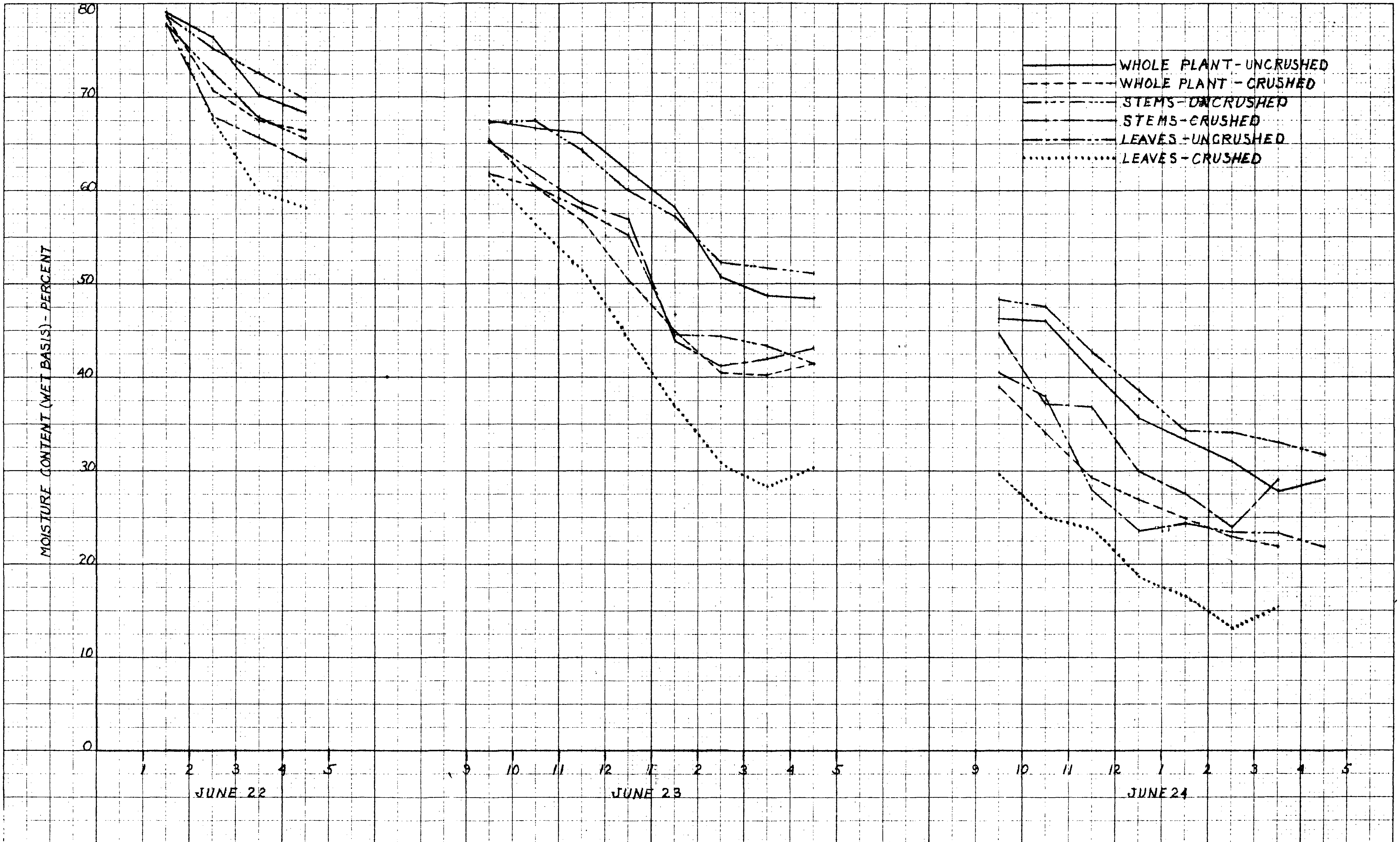

FIG. 16. DRYING RATES OF PLANTS AND PLANT PARTS - FIRST TEST

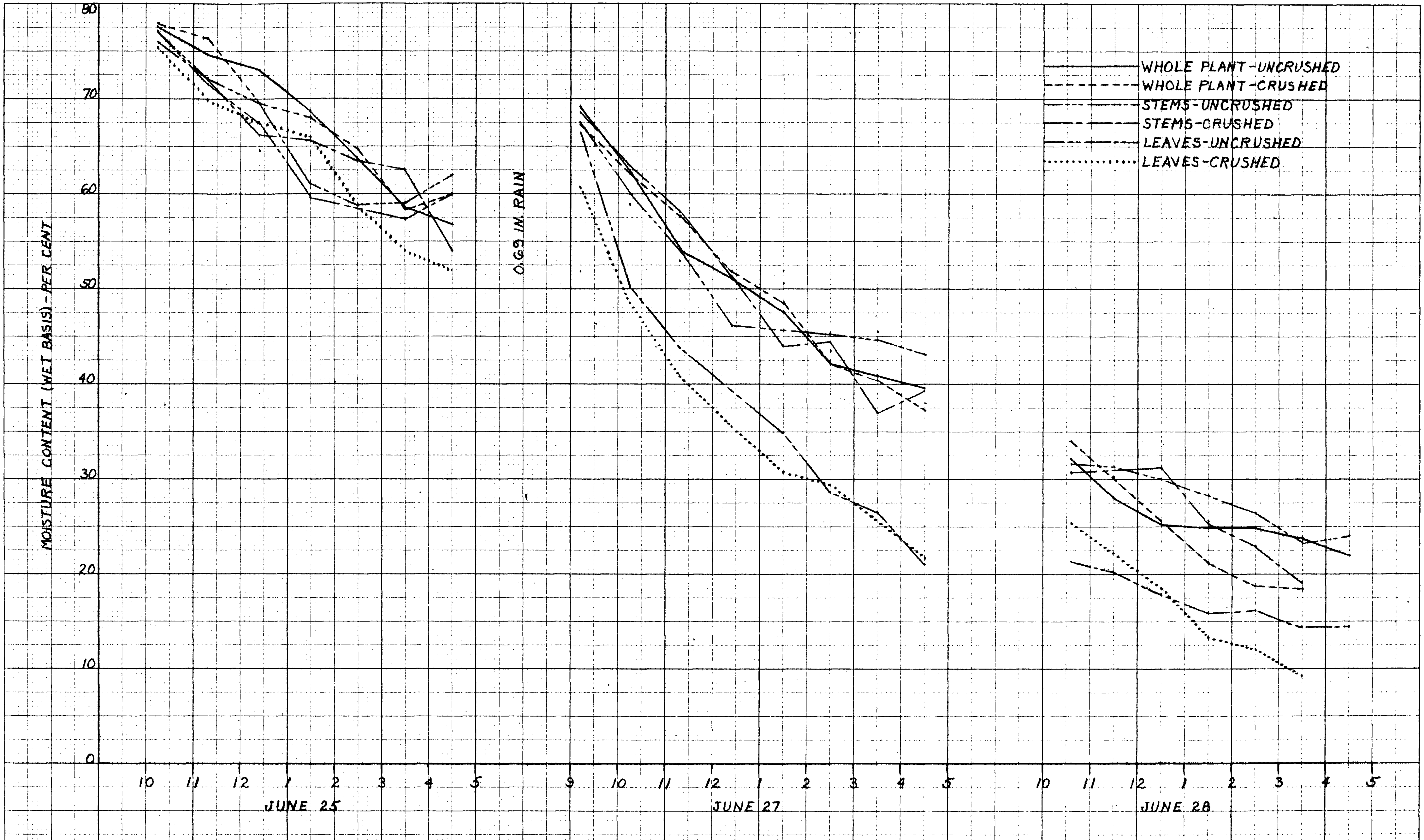

FIG. 17. DRYING RATES OF PLANTS AND PLANT PARTS-SECOND TEST

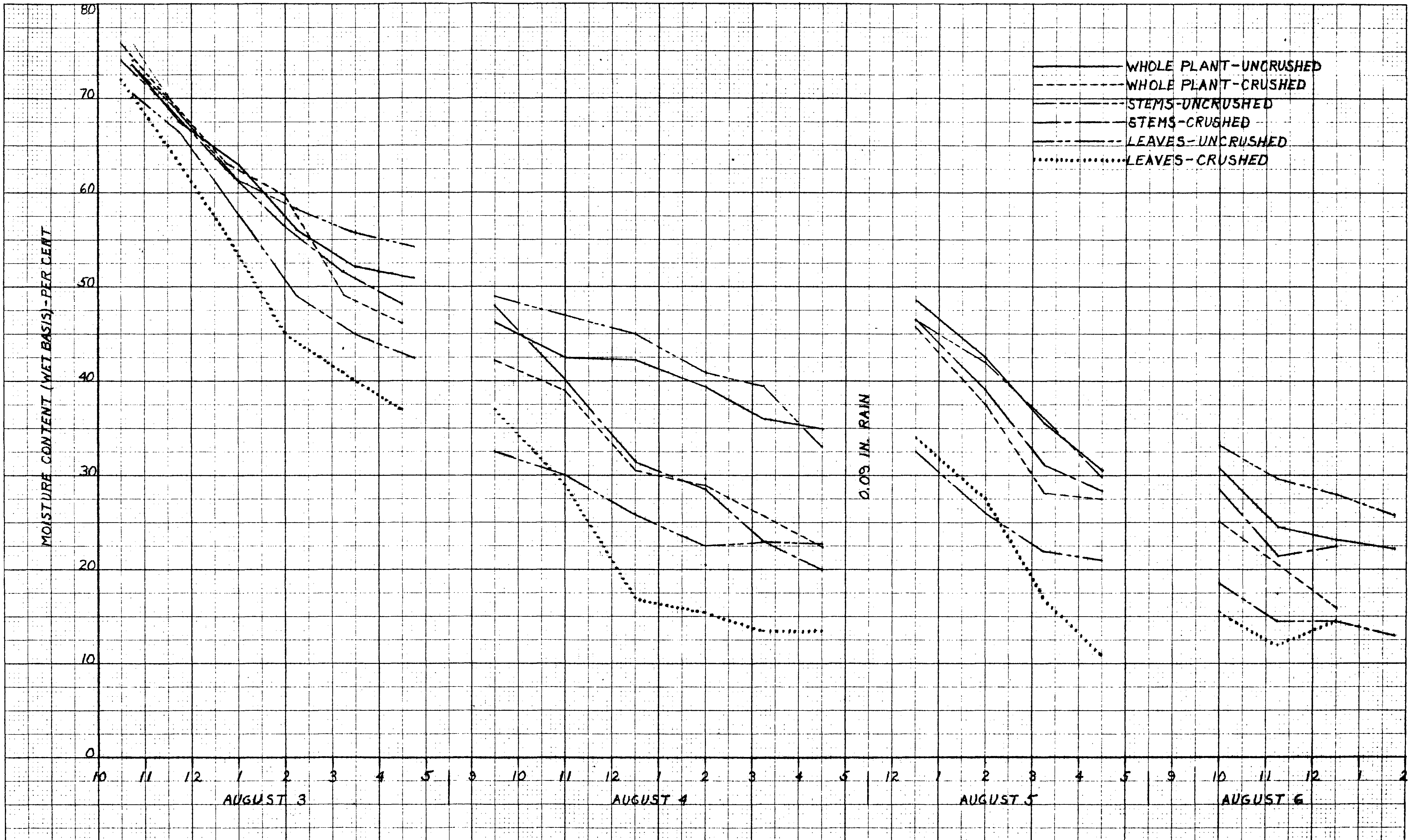

FIG. 18. DRYING RATES OF PLANTS AND PLANT PARTS – THIRD TEST

at noon the following day and the uncrushed hay was raked at 10:30 a. m. on the next day, August 12. The crushed hay was baled at 3:30 p. m. that afternoon and the uncrushed hay was baled the next day at 3:15 p. m. The drying curves of the plants and plant parts are shown in Fig. 19.

In the first and fourth tests (Figs. 16 and 19) the crushed hay dried to 20 percent moisture content (wet basis) in approximately 48 hours while the moisture content of the uncrushed hay in each case was about 35 percent at the end of the same period. In the third test (Fig. 18) the crushed hay reached 22 percent moisture content in approximately 30 hours and the uncrushed hay dried to approximately 35 percent moisture in the same interval. In these three trials, one of which was on the first cutting and two of which were on the second cutting, the crushed hay did not receive more than 0.01 inch of rain. In each case the crushed hay dried to 20 to 22 percent moisture content in the interval required for uncrushed hay to dry to approximately 35 percent. These results are in general agreement with those reported by Zink (op. cit.), Bainer (op. cit.), Kline (op. cit.) and White and Kalbfleisch (op. cit.) although Bainer's data indicated even more rapid drying of the crushed hay. Data reported by Jones and Palmer (10) from Mississippi indicated that the difference in drying rates of crushed and uncrushed alfalfa was not very great although a greater

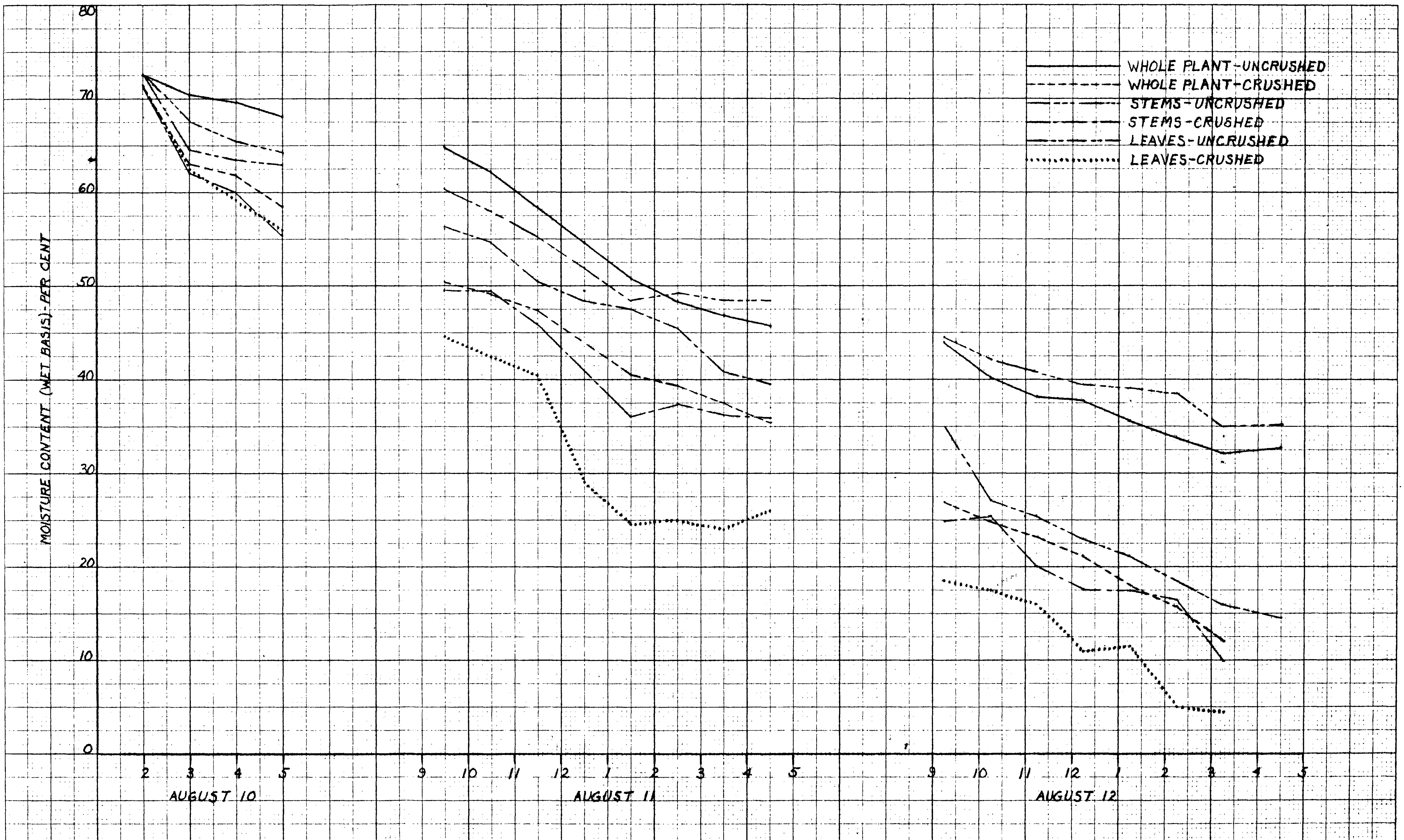

FIG. 19. DRYING RATES OF PLANTS AND PLANT PARTS – FOURTH TEST

difference in drying rates was obtained with Johnson grass. This was attributed to the coarser stems of the grass.

In all three tests in which the crushed hay did not receive appreciable rain a difference in drying rates was present from the beginning of the tests. In the second test (Fig. 17) the curves are so erratic that it is difficult to ascertain any difference in drying rates. The irregular nature of most of the curves is due to the use of too few samples. The separation of samples into leaves and stems is so time consuming that an adequate number of samples could not be handled with the help available. Likewise, in many cases where the moisture content of the whole plant is indicated as higher than that of the components it is probably due to inadequate sampling. Obviously, the complete plant cannot contain more moisture than the total in the component parts. However, if the hay contained free moisture, such as rain or dew, some of the moisture would be lost in the separation process which would indicate a higher moisture content of the whole plant than of the plant parts.

In most cases the curves do not show any absorption of moisture on nights when there was no rain. Probably if sampling had been continued later in the afternoon and started earlier in the morning an overnight rise in moisture content would have been indicated. However, in most cases sampling was started in the morning about the time when the dew had just dried from the hay. From this, the question arises as to whether the increase in moisture content at night which has been reported by Kline (op. cit.) and Jones and Palmer (10) is an increase in absorbed moisture or of free moisture in the form of dew. These data tend to indicate that the increase in moisture at night is actually free, not absorbed, moisture.

From Figs. 16 through 19 it is evident that crushing accelerated the drying of both the leaves and stems when the hay was not rained upon. The more rapid drying of the leaves is probably due, at least in part, to the crushing received by the leaves when the plants pass through the crushing rolls. The relationships between the plant moisture contents and the leaf moisture contents is not very clear in the figures. In Figs. 16 and 18 crushing appears to have done little toward making the plant parts dry more uniformly. On the other hand, in Fig. 19 it is evident that the plant parts of crushed hay dried more uniformly than those of uncrushed hay on August 12 which was not an unusually good drying day. The maximum temperature and minimum relative humidity were 76° F and 43 percent respectively. The difference may have been due to sampling since the uncrushed plant parts dried more uniformly on the following day which had a maximum temperature of 80° F and a minimum relative humidity of 39 percent.

Since crushing is known to promote more rapid drying of the stems, one might reason that the crushed plants should dry more uniformly with a consequent reduction in leaf shattering. This was investigated through the preparation of Fig. 20 which shows the relation between leaf moisture content and whole plant moisture content for both crushed and uncrushed alfalfa. The points shown on these curves are the average values obtained from Figs. 16, 18, and 19 by smoothing the irregularities and reading the corresponding moisture contents for hay which had not received more than 0.01 inch of rain. The values reported by Zink (op. cit.) for uncrushed alfalfa of 12 and 16 percent leaf moisture at plant moisture contents of 20 and 30 percent respectively fall close to the curve presented here. The relation of leaf moisture content to plant moisture content may vary a few percent depending upon the ratio of leaves to stems and the rapidity of drying. However, according to Fig. 20 crushing makes only a small contribution, if any, toward uniform drying of the plants and it cannot be expected to reduce leaf losses in haymaking purely because it promotes the drying of the stems. It may aid in saving leaves, however, through reduction of turning and tedding operations which are necessitated by rain.

The drying rates of crushed and uncrushed plants and their leaves and stems were also compared in laboratory tests using a modification of the equipment used for drying bales. The sample of about 100 grams green weight was spread out in a 9 by 20 inch basket made of metal screen

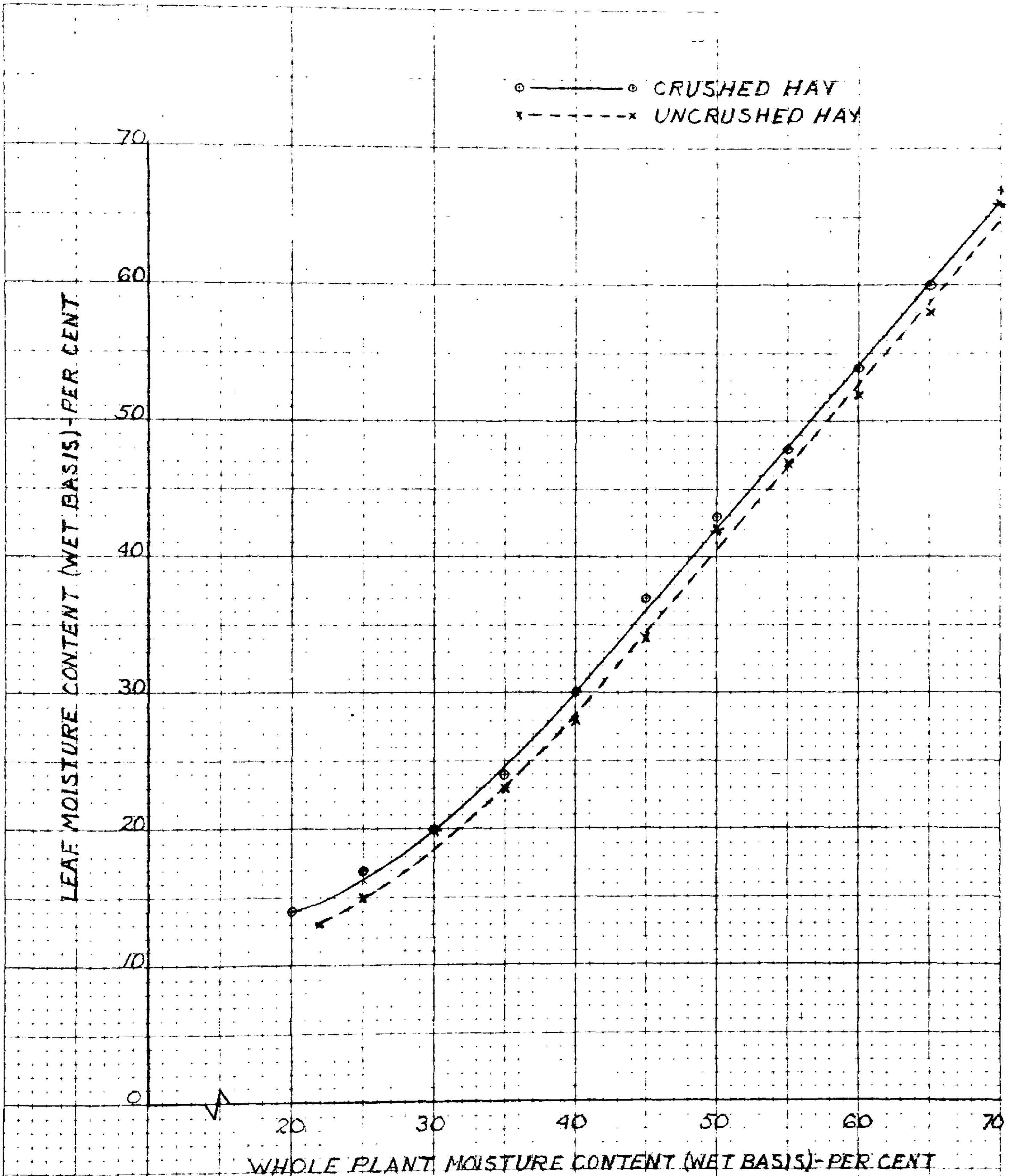

FIG. 20 COMPARISON OF LEAF MOISTURE CONTENT WITH AVERAGE PLANT MOISTURE CONTENT

and suspended from a balance into the plenum chamber of the bale drier. In this thin layer, the drying rate is limited by the diffusion of moisture to the plant surfaces and is independent of the amount of material used. The tests were run at 123° F and 28 percent relative humidity. Weight readings were taken at intervals of two to four minutes.

The results of the tests are presented graphically in Fig. 21 which shows that the leaves and stems of crushed hay dried faster than the corresponding parts of uncrushed hay, the same result as obtained in field tests. However, Fig. 21 also indicates that the leaves and stems dry more uniformly in crushed hay than in uncrushed hay which is contrary to the results indicated by the field tests. There is a basic difference in the method of conducting the two sets of tests. In the field, the leaves remained on the plant as it dried and were then removed to determine the moisture contents of the plant parts. In the laboratory the leaves were removed and then dried separately from the stems. The removal of the leaves probably alters the drying characteristics of the stems since the plants are so constructed that moisture can move from the stems to the leaves. This probably accounts for the more uniform drying of the parts of crushed hay in the laboratory and therefore, the conclusion that crushing will make little contribution toward uniform drying of the plant parts in the field still stands.

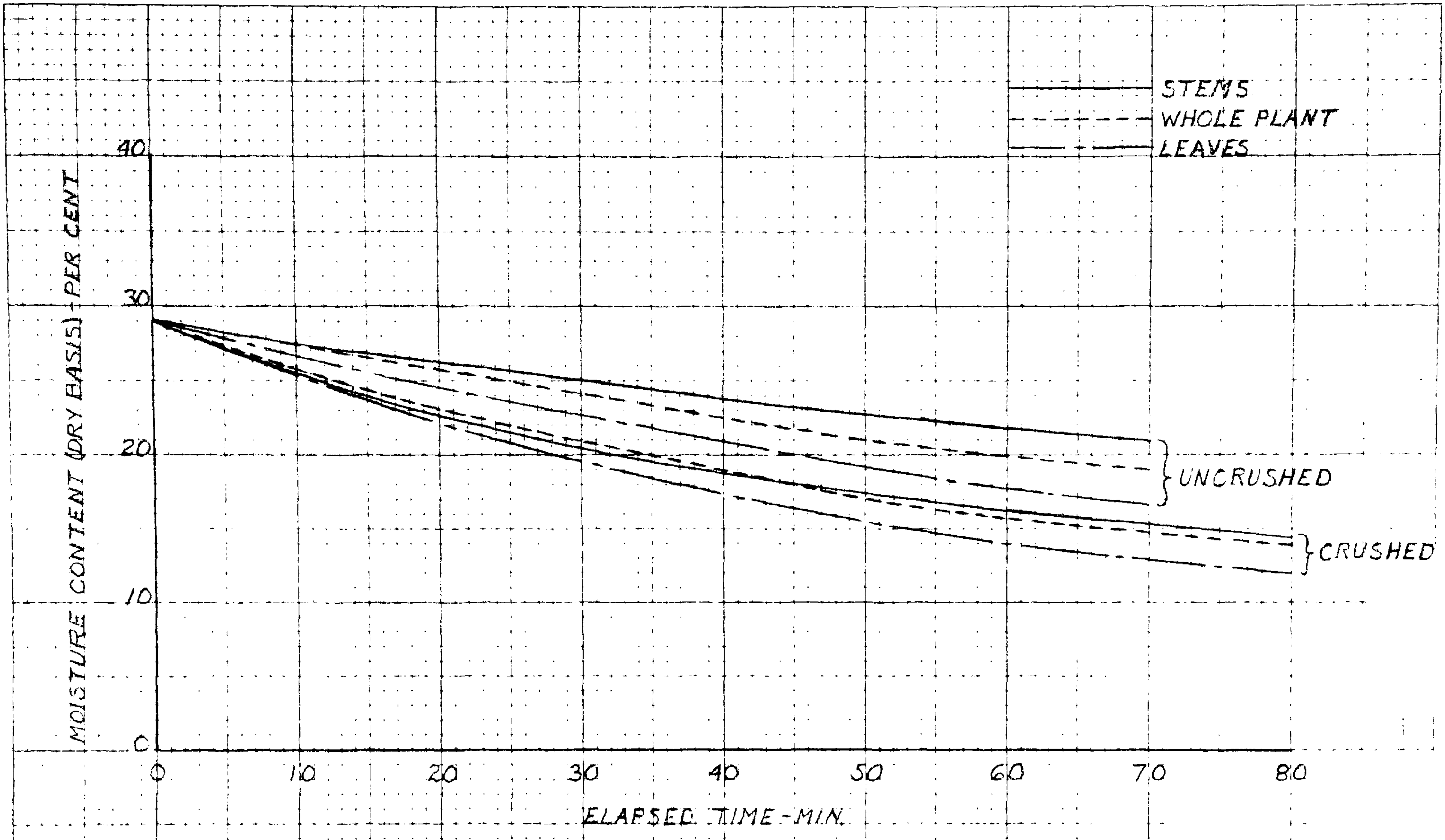

FIG. 21. DRYING RATES OF PLANTS AND PLANTS IN THE LABORATORY

Effect of Crushing on Absorption of Rain and Drying of Hay After a Rain

In the second and third tests (Figs. 17 and 18) rain fell on both the crushed and uncrushed hay. In the second test it amounted to 0.69 inch while in the third test only 0.09 inch of rain fell.

Sampling was not resumed in the second test until the day after the rain. In the afternoon immediately following the rain the skies cleared and most of the free moisture dried from the hay. In the morning when sampling was resumed there appeared to be little free moisture on the hay. Since the curves for crushed and uncrushed hay nearly coincide for the day following the rain, the two lots must have been at very nearly the same moisture content immediately after the rain. The resulting moisture content is probably dependent upon the moisture content preceding the rain and the duration of exposure to free moisture.

In Figs. 17 and 18 it is evident that there was little difference between drying rates of the crushed and uncrushed hay after a rain. This is probably due to less favorable drying conditions. Graphs of precipitation, average daily temperature, average daily relative humidity, and total daily insolation (solar and sky radiation) for the periods under consideration are shown in Fig. 22. The precipitation, temperature, and humidity values were measured in the

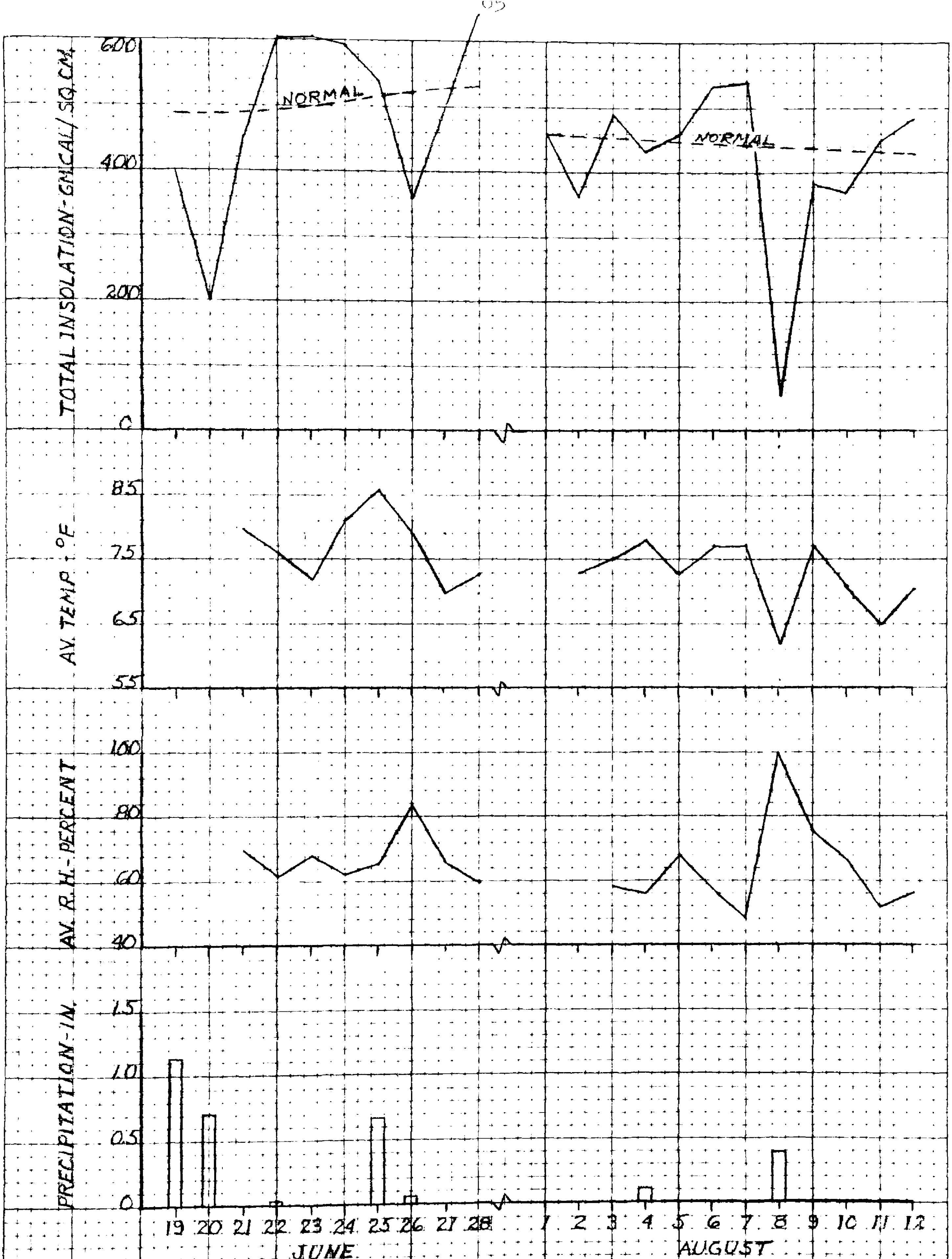

FIG. 22 PRECIPITATION, RELATIVE HUMIDITY, AIR TEMPERATURE AND INSOLATION DURING THE HAYING SEASON

hay field. The average temperatures and humidities are for the period of 9 a. m. to 5 p. m. each day, since that is the period in which most of the drying takes place. The daily insolation values are those reported by the U. S. Weather Bureau (1) for East Lansing. The normal values of insolation were obtained from a chart published by Crabb (7).

The weather pattern was generally the same following each rain. After the rain of June 25 and 26 the air temperature near the ground fell, the relative humidity rose, and the insolation rose to approximately normal. Likewise, after the rain of August 4 the temperature fell, the relative humidity rose, and the insolation was approximately normal. The same pattern of events is shown following the rain of August 8. From the foregoing there appears to be strong evidence that the climate in the vicinity of the hay was altered by the rains. The evaporation of moisture from the ground surface would lower the air temperature and raise the relative humidity. Thus, conditions would be produced in which the capacity of the air to absorb moisture is reduced and even though there is adequate heat available to evaporate moisture from the hay, the rate of drying would be limited by the atmospheric conditions. In this case, the ability of crushed hay to evaporate water more rapidly is of little use until atmospheric conditions improve.

Zink (op. cit.) published drying curves of crushed and uncrushed alfalfa. In a case where the hay was mowed and crushed within a few hours after a 0.25 inch rainfall the difference in drying rates was less than in another case in the same cutting when no rainfall had occurred immediately prior to mowing.

Since the advantages of crushing are partially lost if rain falls on the hay, the possibility of making hay without it being rained upon is an important consideration. Vary (21) published a table, which is reproduced in TABLE II, which shows the average number of consecutive days without rainfall in central Michigan during June and early July.

TABLE II

AVERAGE CONSECUTIVE DAYS WITHOUT RAINFALL, CENTRAL MICHIGAN, 1918-49.

Week	Consecutive Days of no Rainfall
First week in June	2-3
Second week in June	2-3
Third week in June	1-2
Fourth week in June	1-2
First week in July	3 plus

Since a minimum of two days is required for crushed hay to dry to approximately 20 percent moisture content, the possibility of making first cutting hay in central Michigan without it being rained upon is rather slight.

This is especially true during the third and fourth weeks in June when much of the hay is made. In the first week of July the weather is better, but hay which is left until that time is overmature and is lower in feeding value. As a consequence, there appears to be little advantage in the use of a crusher on the first cutting of hay in Central Michigan. At East Lansing the normal rainfall during the month of August, when the second cutting of alfalfa is made, is 0.69 inches less than the normal rainfall for June. With less rainfall during the second cutting the possibilities of obtaining benefits from the use of a hay crusher are greater.

The Effect of Crushing on Nutrient Content

In the previously described tests on the effect of crushing on drying rates, samples of crushed and uncrushed hay were taken for chemical analysis at moisture contents of approximately 30 to 35 percent and 20 to 25 percent (wet basis). In most cases one sample was taken from each windrow. It would have been desirable to take more samples but the analysis is laborious because of the number of determinations to be made from each sample.

Before comparing the results of the tests the meaning of the descriptive terms should be considered. Feed analysis is usually described in terms of ash, crude fiber, ether extract, protein, and nitrogen-free extract. Sometimes fermentable carbohydrates and carotene are also determined. The significance of these terms will now be considered.

Ash denotes the mineral content which remains when the organic materials have been oxidized. It is then a measure of the amount of minerals present.

The carbohydrates are usually divided into groups. Fiber contains the relatively insoluble carbohydrates such as cellulose which are not easily dissolved. Fiber is not easily digested by cattle, consequently, much of the energy is wasted and a low fiber content is desirable. The nitrogen-free extract contains the more soluble, hence more digestible, carbohydrates. It includes starches, sugars, and more soluble portions of the complex carbohydrates. Unfortunately, it also includes a portion of the lignin which has a lower feeding value than cellulose. A sub-division of the nitrogen-free extract is the fermentable carbohydrates which consists primarily of sugars. The fermentable carbohydrate content is of interest primarily in connection with ensiling of hay. Protein is an important constituent since animal tissues are built from the amino acids of which proteins consist. It contains all the nitrogenous compounds.

Ether extract contains the fats and oils from the plants including the waxes from the plant surfaces. In hay, about one-half of the ether extract consists of true fats. Fats contain about $2\frac{1}{4}$ times as much energy per pound as carbohydrates. Carotene is of some interest because it accounts for the green color in hay and is converted into vitamin A by animals.

Additional samples were taken from the first cutting hay after it had been stored in a closed bin of the Case Hay Laboratory for a period of three months.

The results from the first cutting are presented in TABLE III in which the percentages are expressed on the basis of moisture-free hay. The data from the hay which received no rain indicate that any differences between crushed and uncrushed hay were very small at the various sampling times. The exception to this is the content of fermentable carbohydrates in the uncrushed hay after storage. The low value is probably due to mold growth in the hay as a result of being stored at too high a moisture content.

The analyses of samples from the hay which received rain indicate a tendency toward higher crude fiber content and slightly lower contents of ash, fermentable carbohydrates, and protein in the crushed hay. The higher crude fiber content would result from the loss of the other constituents. However, the additional loss of nutrients from crushed hay by 0.69 inch of rainfall was not very great.

The carotene contents were generally lower than would be expected from freshly cured hay. The reason for this is not clear although it may have been due to delay in placing the samples in the drying oven. However, the results after three months of storage should be comparable. They indicate practically the same carotene content for crushed and uncrushed hay which did not receive any rain. The carotene content of

TABLE III. CHEMICAL ANALYSES OF FIRST CUTTING HAY

Date of Sampling	No. of Samples	Moisture Content (Wet Basis) percent	Field Treat-ment	Ash percent	Crude Fiber percent	N-Free Extract percent	Ferment-able Carbo-hydrates percent	Protein percent	Ether Extract percent	Carotene ppm*
6-24	1	30	Crushed	7.83	28.85	42.53	2.98	18.68	2.11	7.3
6-24	1	21		8.50	31.24	40.95	2.57	17.24	2.57	6.9
9-28	2	-		7.50	32.41	39.30	2.55	18.32	2.45	14.8
6-24	1	35	Uncrushed	7.49	31.58	41.21	3.20	17.62	2.10	8.7
6-24	1	25		8.03	32.17	40.19	2.33	17.51	2.10	9.4
9-28	2	-		7.86	33.48	37.37	0.90	19.02	2.26	14.5
6-27	2	39	Crushed 0.69 in. Rain	6.48	36.52	39.37	1.61	15.60	2.03	14.4
6-28	2	18		6.14	38.91	38.74	1.97	14.14	2.07	12.1
9-28	2	-		6.68	34.99	40.12	1.60	16.30	1.92	10.8
6-28	2	25	Uncrushed 0.69 in. Rain	6.85	34.20	40.40	2.42	16.74	1.81	18.2
6-29	2	29	Uncrushed 0.72 in. Rain	7.06	33.28	40.17	2.46	17.68	1.82	11.5
9-28	2	-		7.42	33.62	39.88	2.16	17.04	2.06	13.5

* parts per million

the uncrushed hay was reduced about seven percent by the rain while the carotene content of the crushed hay was reduced about 27 percent from the content of crushed hay which did not receive rain.

The results from the second cutting are shown in TABLE IV. There was very little difference in composition of the crushed and uncrushed hay either where the hay was not rained upon or where it received 0.09 inch of rain. The data obtained indicate that crushing has very little or no effect on the nutrient content of hay which receives little or no rain, while with heavier rainfall there is slightly more loss of nutrients from crushed hay than from uncrushed hay. Bechdel, et al (3) reported that feeding trial results indicated that crushing made no appreciable difference in the feeding value of clover hay which received no rain.

Effect of Crushing on Leaf Losses from Raking and Baling

The importance of conserving leaves in hay making has been repeatedly emphasized. Jones (12) stated: "In high-grade legume hay two-thirds or more of the digestible protein and most of the vitamin A and minerals are in the leaves." Similar statements have been made by other writers. The leaves also constitute a large portion of the hay crop. Piper (18) cited data from the Utah Agricultural Experiment Station which indicates that in first cutting alfalfa up to

TABLE IV. CHEMICAL ANALYSES OF SECOND CUTTING HAY

Date of Sampling	No. of Samples	Moisture Content (Wet Basis) percent	Field Treatment	Ash percent	Crude Fiber percent	N-Free Extract percent	Fermentable Carbohydrates percent	Protein percent	Ether Extract percent
8-4	3	28	Crushed	7.11	30.62	41.96	3.79	18.60	1.70
8-4	3	22		6.85	32.25	41.78	3.81	17.74	1.37
8-6	3	18	Crushed 0.09 in. Rain	6.71	30.84	43.01	3.14	18.04	1.40
8-6	3	28	Uncrushed 0.09 in. Rain	6.82	31.05	42.33	2.77	18.27	1.44
8-6	3	21		6.76	31.12	42.28	3.31	18.43	1.40
8-12	2	26	Crushed	6.31	31.90	42.06	5.10	17.52	2.06
8-12	2	17		6.10	33.12	42.12	4.90	16.90	1.76
8-12	2	33	Uncrushed	6.36	32.00	41.62	5.48	18.18	1.82
8-13	2	22		6.34	32.34	43.08	5.40	16.86	1.38

full-bloom stage the leaves and flowers constitute 40 to 42 percent of the plant dry matter. In the second cutting the leaves and flowers account for nearly 50 percent of the plant dry matter.

One experiment was conducted on each cutting to determine the effect of crushing on leaf losses from raking the hay at moisture contents of approximately 50 and 35 percent (wet basis), and from baling hay over a range of moisture contents of approximately 30 to 20 percent. In each trial, four plots consisting of 6 mower swaths each were used. Two plots were left uncrushed and two were crushed with the mower-crusher.. One plot of the crushed hay and one of the uncrushed hay were raked at moisture contents of approximately 50 percent. The other plots were raked at approximately 35 percent moisture content. An attempt was made to bale two windrows from each plot at moisture contents of approximately 30, 25, and 20 percent respectively.

Samples for the measurement of the percentage of leaves and flowers present were taken after mowing and crushing, after raking, and after baling. In both tests the samples after mowing and crushing consisted of a cross-section of each swath. In the first test these were taken at the same distance from the end of all swaths. In the second test a better sampling procedure was used in which the plots were divided into six lengths,and a random sampling arrangement was used in which one sample was taken from each swath in each plot. This provided a distribution of samples along the length of each plot.

In the first test the samples were taken after raking by carefully removing two handfuls of hay from each windrow, one for a moisture content determination and the other for separation into plant parts. In the second trial a randomized sampling arrangement, similar to that used following mowing, was used and the samples were taken by cutting out cross-sections of the windrows with a carpenter's saw. While perhaps a few leaves were lost by this sampling method, it was felt that it resulted in a better procedure since it sampled the whole windrow cross-section.

Samples were removed from the bales by drilling approximately one-half the length of each bale with a tube to remove a core sample along the longitudinal axis of the bale. The core samples were weighed and dried to determine the moisture content and later separated into the plant parts. In the hand separation of samples into parts, weeds were discarded and only forage plants - alfalfa, clovers, grasses - were retained. The flowers were included with the leaves. All comparisons were made on the basis of the percentage of leaves and flowers by weight contained in the total amount of dry matter.

The first test was started on July 1 when the alfalfa was in full bloom and was concluded the following afternoon because of the threat of rain, even though some of the hay was not as dry as desired. The results with regard to leaf content after raking are presented in TABLE V. The data obtained on leaf content after baling are not presented because they indicate leaf percentages considerably above the content of the original plant. No explanation for this situation has been found. The percentages of leaves and flowers shown in TABLE V are close to the values previously given as cited by Piper (op. cit.).

TABLE V

LEAF CONTENTS RESULTING FROM FIRST TEST

Treatment	Average Moisture Content When Raked Percent	Average Percentage of Leaves	
		Before Raking	After Raking
Crushed	62	38.5	38.1
Uncrushed	48	37.1	38.8
Uncrushed	41	38.1	36.2
Crushed	34	42.2	41.1

The first statistical analysis of the data indicated significant differences due to crushing and raking moisture contents. However, the significance was probably due to the higher percentage of leaves before raking in the last plot. This difference may have been due to differences between the state of maturity or composition of the hay in that plot and the other plots. To eliminate this difference each value for the last plot was decreased by the difference between the mean value for the plot before raking and the mean value before raking for the other three plots. A re-analysis of the data showed that crushing did not have any significant effect on leaf losses from raking but that there was a tendency toward a significant effect of moisture content at raking on leaf losses. When the data for both crushed and uncrushed hay were combined a significant regression of leaf content on raking moisture content resulted. This regression line is shown later in Fig. 23 in conjunction with the results of the second test.

The second test was started on the morning of August 17. Since there had been a dry period in July, the alfalfa was quite variable in size and maturity depending upon the location in the field. It varied from approximately one-quarter to three-quarter bloom. One plot of crushed hay was raked in the afternoon. Nothing was done on the test the following day because of 0.18 inch of rainfall and cloudy, humid conditions. The raked windrows were turned with the rake before they were completely dry and then re-sampled. The test was completed late in the afternoon of August 20.

Since the samples taken after turning the windrows indicated that no losses occurred from the turning operation these data are omitted from TABLE VI which shows the percentages of leaves before and after raking and after baling. Separate statistical analyses were made of the data on leaf losses from raking and from baling. The analyses showed that the effect of crushing on leaf losses from either raking or baling was not significant. However, there was a highly significant difference in leaf content after raking and after baling due to the moisture content at raking. There was also a significant effect of the moisture content at the time of baling on the leaf content after baling.

The relation of leaf content after raking to moisture content when raked is shown in Fig. 23 for both tests. The gentler slope of the regression line for the first cutting may be due to the fact that the first cutting hay was raked at generally higher moisture contents than the second cutting. The regression line of leaf content on moisture content for the second cutting is at a higher level of leaf content because the percentage of leaves was higher in the second cutting.

In Fig. 24 the regression lines of leaf content after baling to moisture content at the time of baling are shown for two levels of moisture content at the time of raking. These lines indicate that the leaf content remaining after

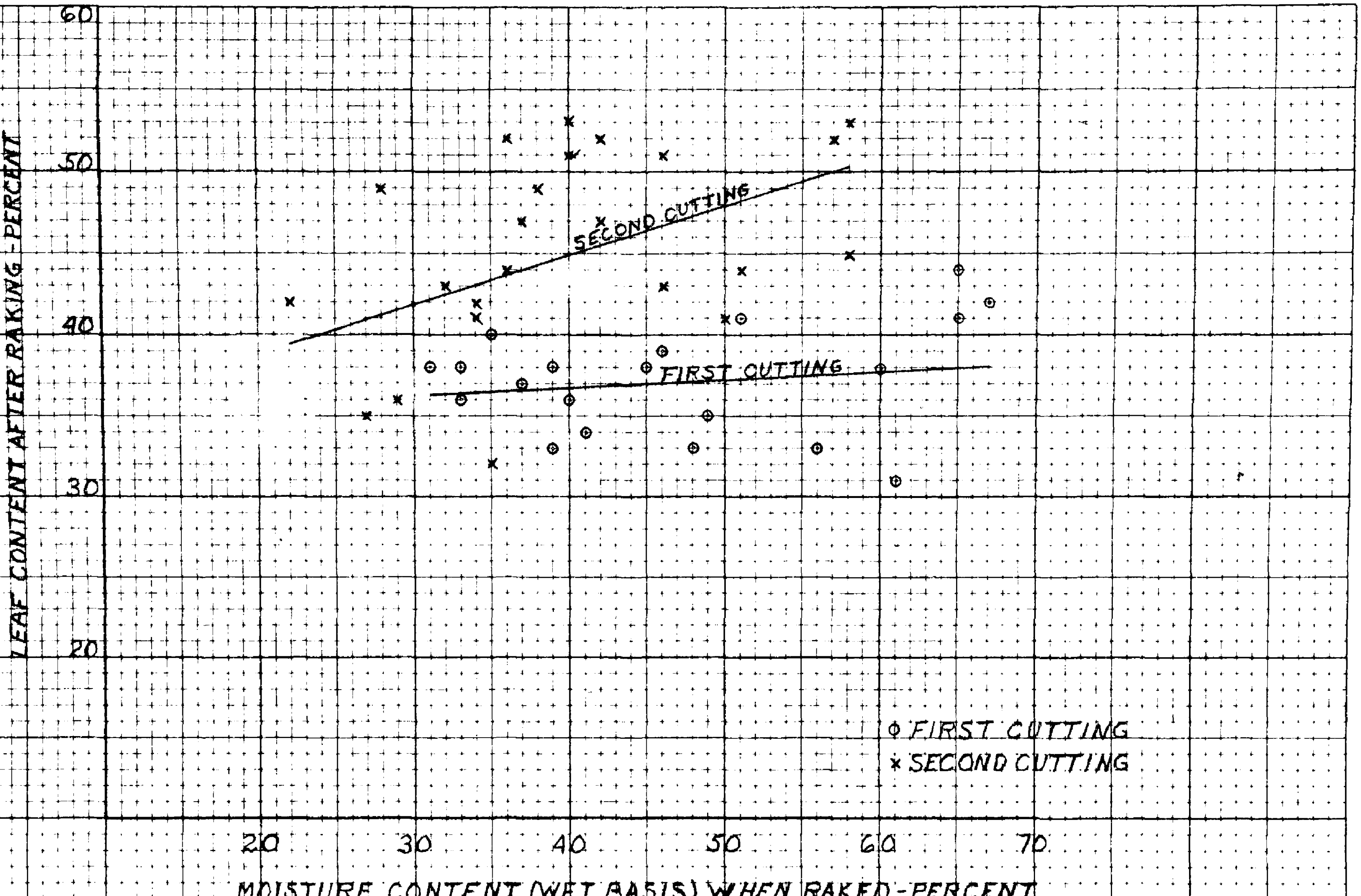

FIG. 23 RELATION OF LEAF CONTENT AFTER RAKING TO MOISTURE CONTENT WHEN RAKED

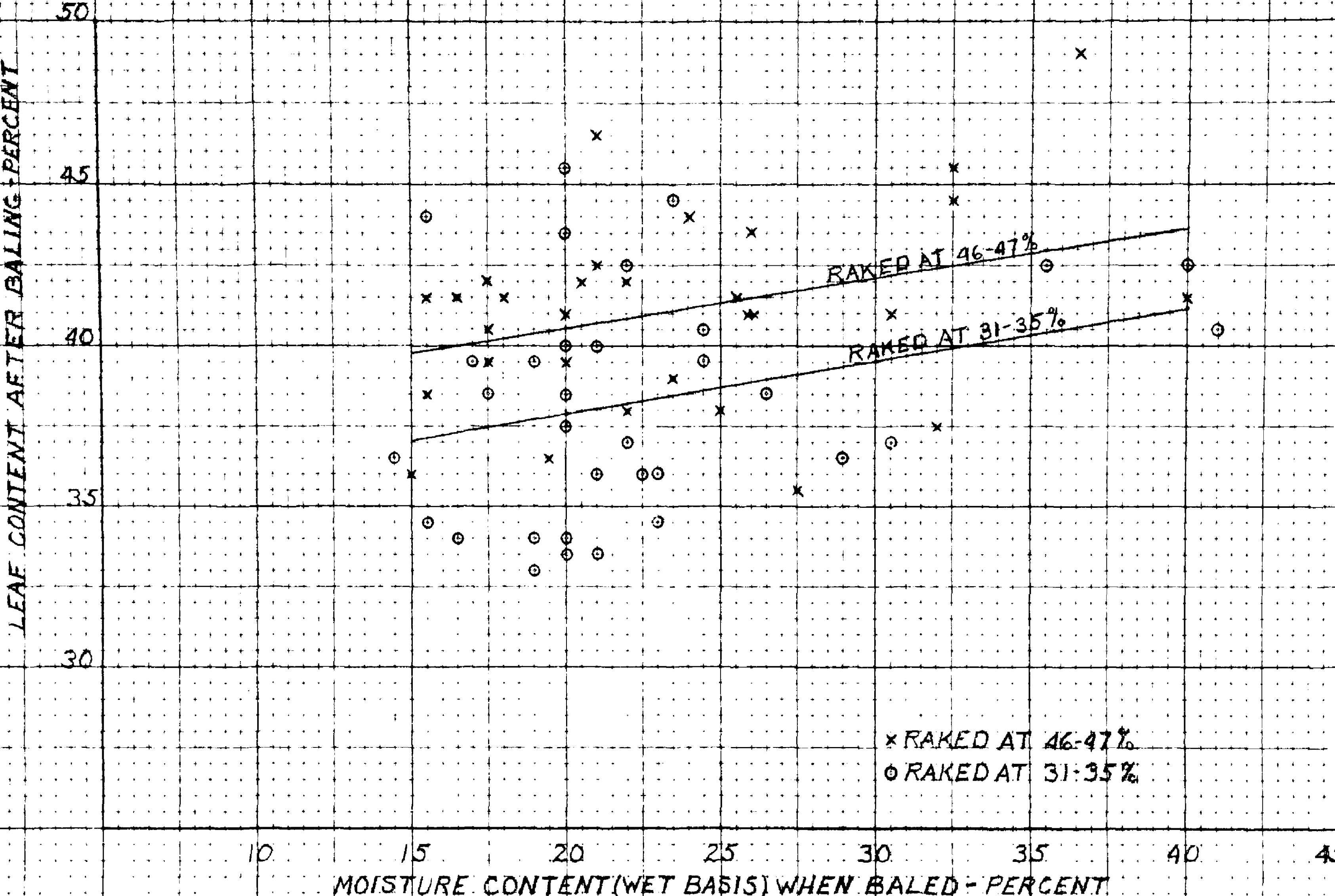

FIG. 24. RELATION OF RAKING AND BALING MOISTURE CONTENTS TO LEAF CONTENT AFTER BALING

after baling depends upon the moisture contents at which the hay is raked and baled. From this standpoint raking and baling at high moisture contents is desirable.

TABLE VI

LEAF CONTENTS RESULTING FROM SECOND TEST

Treatment	Average Leaf Content-percent			Average Moisture Content When Baled Percent
	Before Raking	After Raking	After Baling	
Uncrushed, raked at 47%	47.4	48.9	42.9 43.2 41.7	31 25 21
Crushed, raked at 47%	47.5	48.8	40.3 40.5 39.3	30 20 17
Crushed, raked at 31%	47.2	41.2	40.9 42.6 38.1	23 20 16
Uncrushed, raked at 35%	45.3	43.4	39.8 36.0 34.8	35 22 20

The conclusion that there is no saving of leaves in either raking or baling hay from the use of a crusher is consistent with the conclusions previously drawn from Fig. 20 which indicates that the leaf moisture content is virtually the same for crushed and uncrushed hay when at the same average moisture content.

Effect of Crushing on Forced Air Drying of Hay

Since crushing hay causes it to dry more rapidly in the field under favorable conditions, it might be expected to cause more rapid drying with forced air. To verify this, the drying rates of individual bales of hay with forced air were measured.

At the conclusion of the field tests on each cutting a few bales of partially-cured hay were stored in a refrigerator at 40° F. The bales from the first cutting were high in moisture content and were so moldy after a delay of 2½ weeks during which the drying apparatus was set up that they could not be used for the test. Consequently, the tests were all run on bales from the second cutting which were low enough in moisture content that mold did not develop.

The drying apparatus is shown schematically in Fig. 25. It was the same equipment as built and used by Gallaher (8). Air under pressure was supplied by a centrifugal fan with a damper over the inlet to control the rate of air flow. The air was discharged by the fan into an aluminum-lined 12 x 12 inch duct 12 feet long. The vapor pressure of the air was controlled by introducing live steam into the duct. The temperature was controlled with electric heaters. From the duct the air passed through a flexible coupling into a plenum chamber mounted on a platform scale. The air passed

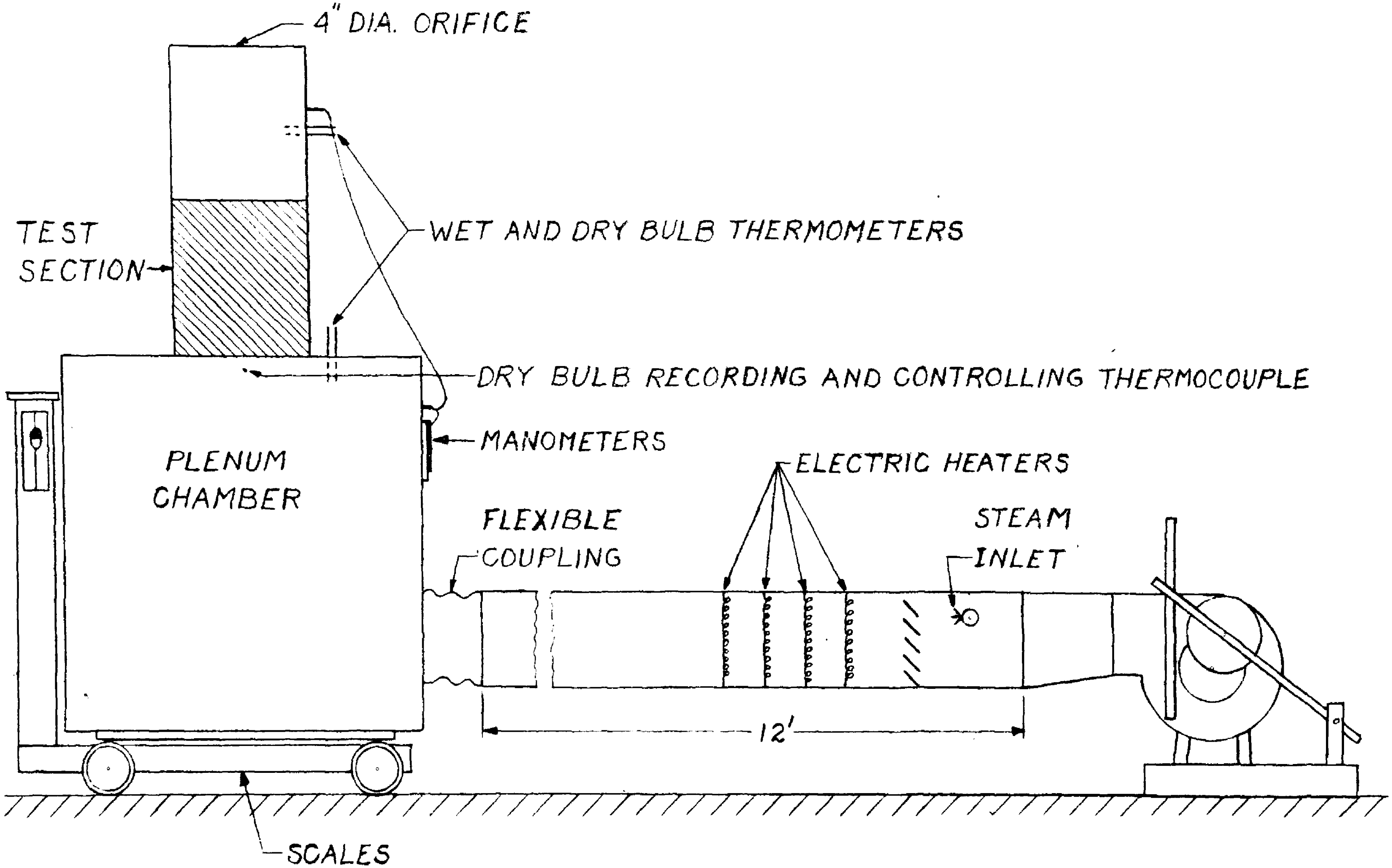

FIG. 25. SKETCH OF LABORATORY DRYING APPARATUS

from the plenum chamber through the test bale, was collected and discharged through a 4 inch diameter orifice.

The steam flow for humidity control was regulated manually. Part of the steam was bypassed to a drain to insure the introduction of live steam. The temperature control was in part manual and in part automatic. Three 2000-watt heaters were connected to manual switches. One of these heaters was connected with an external resistance so that its heating capacity in the duct could be reduced to 1000 watts. A 1000-watt heater was controlled automatically by a Brown controller through an air motor and an autotransformer. The controller was actuated by a thermocouple located in the plenum chamber about two inches below the center of the bale. The vapor pressure of the entering air was measured with wet and dry bulb mercury thermometers inserted through the top of the plenum chamber.

The rate of air flow was determined by measuring the pressure drop across the sharp-edged orifice with a micromanometer. To maintain a constant rate of air flow the damper at the fan inlet was adjusted manually when necessary. The pressure drop through the bale and the wet and dry bulb temperatures of the exhaust air were also measured.

To insure that all the air should pass through the bale, it was squeezed into an adjustable test chamber lined with one inch thick foam rubber. All bales were squeezed to a size to fit the opening in the top of the plenum chamber.

The plenum chamber was mounted on a platform scale so that the loss of weight could be measured at any time. The procedure was to weigh the bale and test section before placing it on the plenum chamber, take the scale reading, adjust the air flow, temperature, and humidity to the desired values, and then take readings at intervals of time. Readings were taken only after the system had been adjusted to the desired values. The intervals between readings varied from 15 minutes at the start of the test to one hour at the close of the test. When the bale weight was constant for several hours, the bale was removed, weighed, and sampled for moisture content. From this information the amount of dry matter present and the moisture content at each reading could be computed.

The intention was to run all tests at 120 ± 2° F and 1.0 inch of mercury vapor pressure (30 percent relative humidity) of the entering air. A later calibration of the controller showed that the tests were actually run at 123 ± 2° F. At the same vapor pressure the relative humidity was then 28 percent. Three bales each of crushed and uncrushed hay were dried.

The drying curves for the bales are shown in Fig. 26 with the time axis shifted for some bales to provide a common starting point. The dry basis is used to express the moisture content since it is more appropriate than the wet basis. On the dry basis each percentage change in

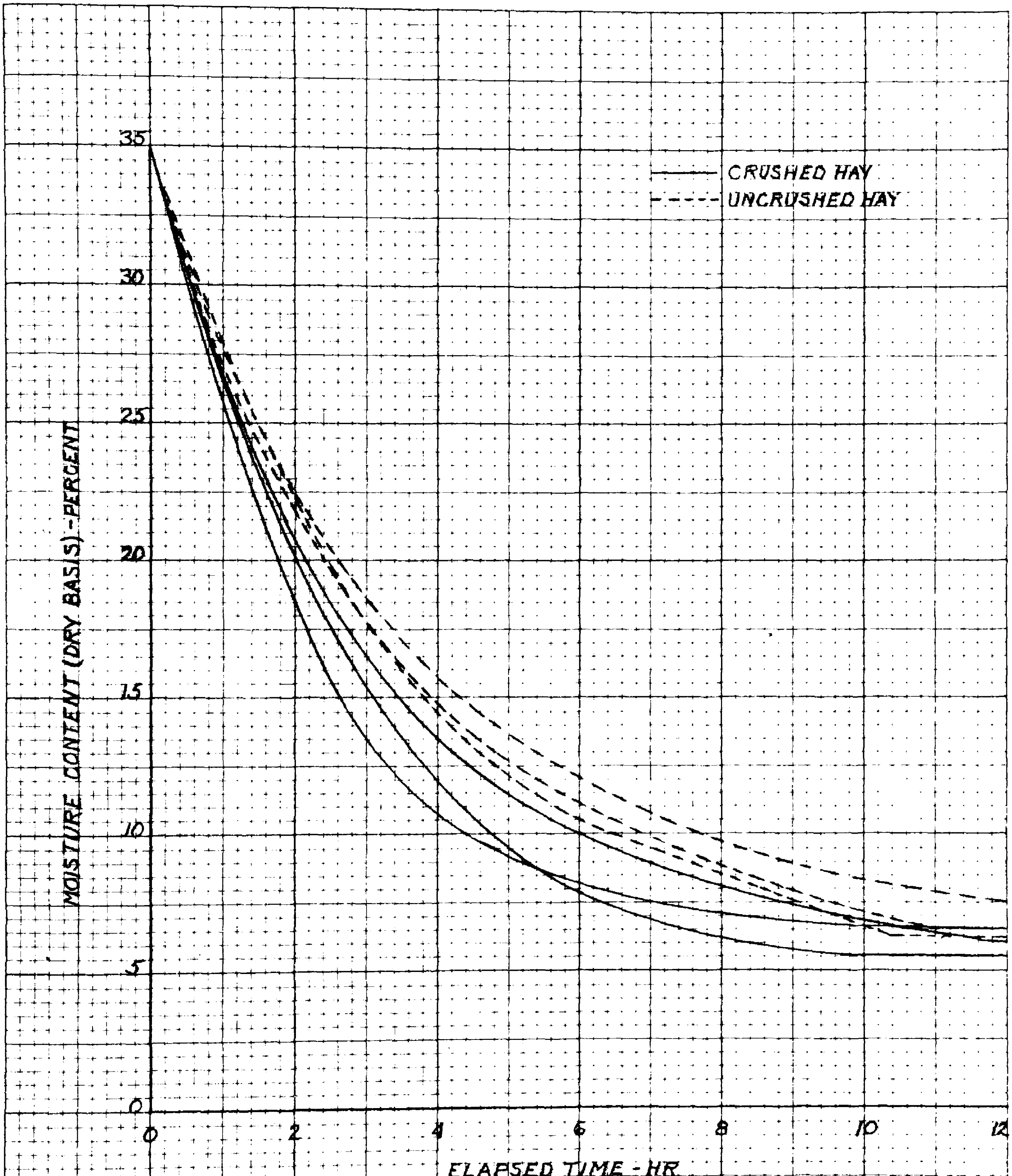

FIG. 26 DRYING CURVES OF BALES WITH FORCED AIR

moisture content represents the removal of the same amount of water. On the wet basis the amount of water removed with a change in one percent of moisture content increases as the moisture content increases. The curves show that all of the bales of crushed hay dried more rapidly than the bales of uncrushed hay. However, these curves are not the best measure of the differences in drying rates. For the same rate of air flow a bale that is low in dry weight will dry more rapidly than a heavier bale. Therefore the number of hours required per pound of dry matter to dry over a given moisture content range better expresses the difference in drying rates. These data are tabulated in TABLE VII for the range of 35 to 7.5 percent. The average drying time for the crushed hay was only (0.25/0.40)100= 62 percent of the drying time of the uncrushed hay. This should not be construed to mean that a large quantity of crushed hay placed on a hay finishing system would dry in 62 percent of the time required for an equal amount of uncrushed hay at the same moisture content. On a hay finishing system air is introduced at the bottom and it absorbs moisture from the nearest hay which is above the equilibrium moisture content of the air. Thus as time passes, the zone of drying moves upward to the surface. The advantage of crushing would then lie in the more rapid drying of the topmost hay. This should result in a small reduction in the power consumed in operating the fan.

TABLE VII

COMPARISON OF DRYING RATES WITH FORCED AIR

Bale No.	Treatment	Time to Dry from 35 to 7.5%	Weight of Dry Matter	Hours per Lb. of Dry Matter
		Hr.	Lb.	
1	Crushed	8.75	28.7	0.30
3	Crushed	6.25	28.2	0.22
5	Crushed	6.50	29.9	0.22
			Average	0.25
2	Uncrushed	9.25	26.8	0.34
4	Uncrushed	9.50	25.0	0.38
6	Uncrushed	12.50	26.0	0.48
			Average	0.40

The shorter time required for the drying of crushed hay indicates that, as one might expect, crushing alters the drying mechanism. The nature of the drying mechanism has been found to be similar in such diverse materials as soils, ceramics, and organic materials. The drying process frequently consists of two periods: a constant-rate period and a falling-rate period.

In the constant rate period a material contains so much water that liquid surfaces exist and the material dries at a rate which is established by the prevailing conditions of air temperature, relative humidity, and velocity.

For some materials the falling rate period consists of two stages. According to Newman (17) and Sherwood (19), the decrease in the drying rate during the first stage is due to a change in the nature of the evaporative surface while in the second stage evaporation is controlled by the rate of moisture movement from the interior to the surface. In both stages of the falling rate period, moisture movement is by liquid diffusion.

If a drying curve of moisture content versus time is obtained under conditions of constant temperature and humidity, the presence of the drying periods and stages can be determined through graphical differentiation of the curve. One method of doing this is to measure the slope of tangents to the curve. The slope of the tangent is then dM/dt. When dM/dt is plotted against moisture content the different stages can be readily seen.

Ideally, the drying mechanism should be studied with the material in a thin layer since the temperature and vapor pressure of the air change with the absorption of moisture from the hay. The drying curves presented previously in Fig. 21 were obtained with relatively small quantities of hay in an excess of air. Consequently, the drying rates should have been the maximum possible under the operating conditions of $123 \pm 2^{\circ}$ F and 28 percent relative humidity. The results obtained by differentiation of the drying curves for the uncrushed whole hay and the crushed whole hay are shown in Fig. 27. The values obtained for approximately the first 10 minutes of each test were excluded since the drying characteristics are necessarily different while the hay is being warmed to the operating temperature.

There are no constant rate periods in Fig. 27 since the hay was partially dried in the field, and there was no free moisture on the plant surfaces. However, the two stages of the falling rate period are indicated for both hays. The crushed hay dried more rapidly than the uncrushed in both stages and, in addition, the transition between the two stages occurred at a slightly lower moisture content in the crushed hay. These facts show that crushing significantly alters the drying mechanism in alfalfa hay.

Henderson and Perry (op. cit.) stated that for agricultural products the drying rate is proportional to the difference between the moisture content of the material being dried and the equilibrium moisture content of the drying air. This is expressed mathematically by an equation which is analogous to Newton's law of cooling:

$$dM/dt = -K\ (M - M_E) \qquad (1)$$

in which dM/dt is the drying rate, K is a constant dependent upon the nature of the material, M is the moisture content of the material at any time t, and M_E is the equilibrium

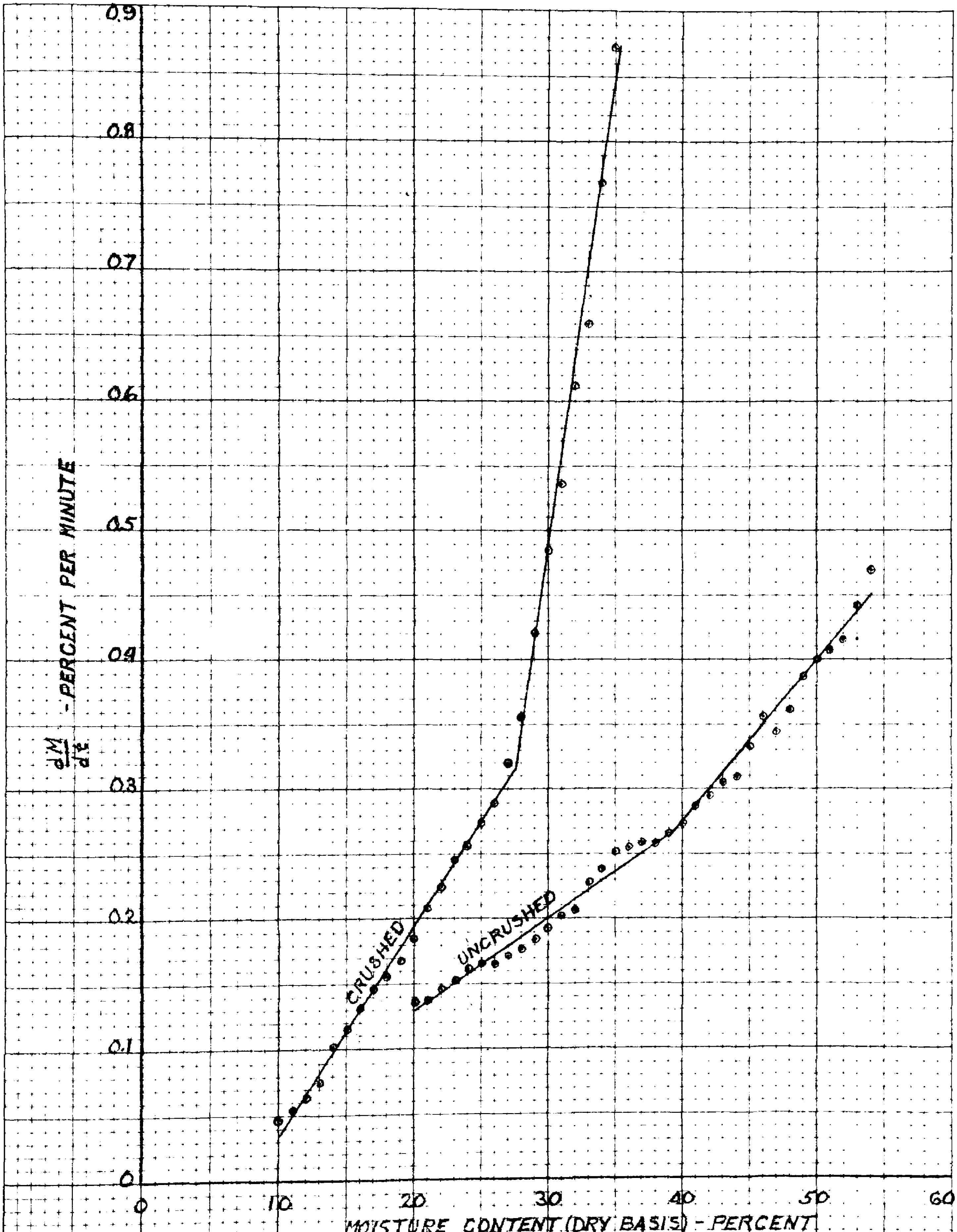

FIG. 27. RELATION OF DRYING RATE OF ALFALFA TO MOISTURE CONTENT

moisture content of the drying air. When this equation is integrated between the limits of $M = M_o$ at $t = o$ and and $M = M_t$ at $t = t$ the expression becomes:

$$\frac{M_t - M_E}{M_o - M_E} = e^{-Kt} \qquad (2)$$

The quantity $(M_t - M_E) / (M_o - M_E)$ is frequently called the moisture content ratio since it expresses the ratio of the original amount of moisture to the amount of moisture remaining. If hay which is dried under conditions of constant temperature and relative humidity obeys equation (1), a semilogarithmic graph of moisture content ratio versus time should be a straight line with slope of $-K$. This linear relationship was obtained by Brown (4) in drying 50 gram samples of alfalfa.

Gallaher (op. cit.) obtained reasonably good correlation between observed and calculated drying curves with the equation:

$$\frac{dM}{dt} = -K (P - P_a) \qquad (3)$$

in which P is the vapor pressure of the moisture in the hay and P_a is the vapor pressure of the entering air. This equation cannot be integrated unless the moisture content is expressed in terms of vapor pressure or vice versa. Henderson and Perry (op. cit.) stated that the general form of the equation expressing the relationship between moisture content and equilibrium vapor pressure is

$$1 - rh = e^{-cT} M_E^n \qquad (4)$$

in which rh indicates relative humidity and T is absolute temperature. However, replacing the rh term by a term in vapor pressures and substituting in equation (3) leads to an equation which is exceedingly difficult to integrate. Consequently, it is simpler to deal in moisture contents rather than vapor pressures.

Gallaher (op. cit.) reasoned that the drying rate should be directly proportional to the weight of dry air passing through the hay per unit of time and inversely proportional to the weight of dry matter present. Assuming this to be true, equations (1) and (2) would be modified to become

$$\frac{dM}{dt} = -(a + bG)(M - M_E) \qquad (5)$$

and

$$\frac{M_t - M_E}{M_o - M_E} = e^{-(a + bG)t} \qquad (6)$$

in which b is a constant depending upon the characteristics of the material, a is a constant which probably depends upon the temperature and vapor pressure of the drying air, and G is a mass velocity term which may be expressed in units of pounds of dry air per hour per pound of dry matter. This is equivalent to stating $K = a + bG$ and, if the reasoning is correct, there should be a linear relationship between K and G.

The applicability of equations (1) and (2) to thin layer drying of alfalfa is indicated by Fig. 28 in which the graphs of moisture content ratio versus time are linear. These curves were calculated from the data for crushed whole hay and uncrushed whole hay used for Fig. 21 with the exception the original data were used in which the uncrushed hay dried over the range of 61.9 to 26.0 percent (dry basis) while the crushed hay dried over the range of 35.8 to 11.8 percent in the time interval shown. The non-linear portion during the first 10 minutes of drying is undoubtedly due to a "warming up" period in which the hay temperature was raised. In calculating the moisture content ratios an equilibrium moisture content of 7.6 percent was used. This is equivalent to the 6.7 percent (wet basis) equilibrium moisture content at 123° F and 28 percent relative humidity obtained from a chart presented by Brown (op. cit.).

Similar calculations of moisture content ratio were made from the bale test data used for Fig. 26 in which the bales of crushed hay dried from 38.7, 38.4, and 37.4 percent (dry basis) respectively to equilibrium and the bales of uncrushed hay dried from 47.6, 45.3, and 41.4 percent

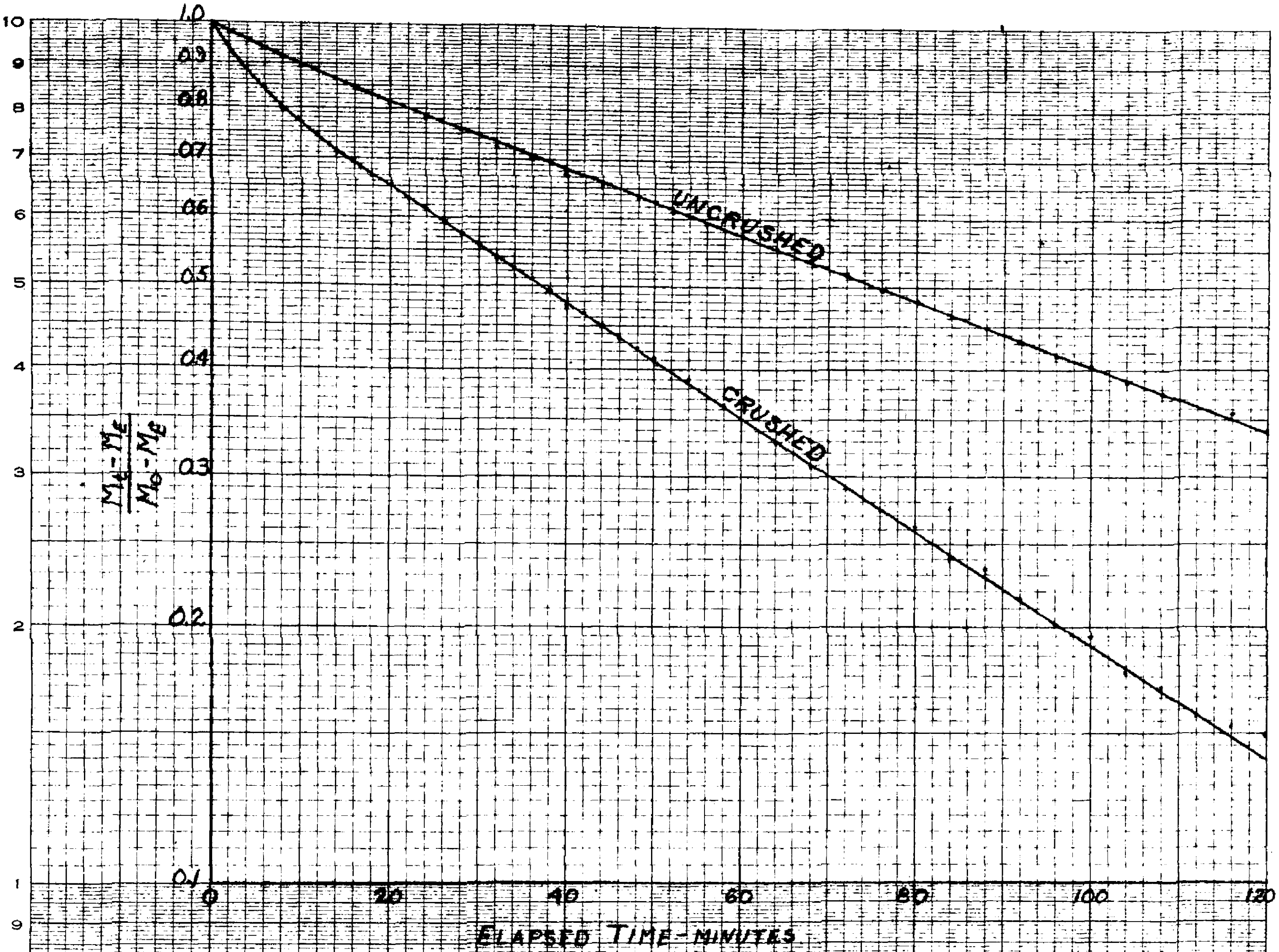

FIG. 28. RELATION OF MOISTURE CONTENT RATIO TO TIME IN THIN-LAYER DRYING

respectively. The results are shown in Fig. 29 in which a single curve is used to describe the results from the three bales of uncrushed hay. It would seem that there should have been some slight differences among the three bales since the weight of dry matter varied from 25.0 to 26.8 pounds per bale.

It may be that the diversity of results from the bales of crushed hay was due to differences in the degree of crushing among the three bales. Since crushing alters the drying mechanism, variations in degree of crushing could very well alter the constant in the drying equation. Bruhn (5) reported that the rate of field drying of crushed hay varied according to the force exerted on the crushing rolls. The hay used in these tests came from a portion of the field in which the yield was quite variable. It is quite possible that for the same crushing force a light crop will be more thoroughly crushed than a heavier crop.

The curves in Fig. 29 show a change in slope toward the end of the tests. For the uncrushed hay the change occurred between 9 and 10 percent moisture content and for the crushed hay the change occurred between 7 and 8 percent moisture content. Since these bales attained equilibrium with the drying air at moisture contents of 5.5 to 7.3 percent, the changed drying constant applies only to the removal of the very last moisture and is not a matter of great consequence. In each case the equilibrium moisture

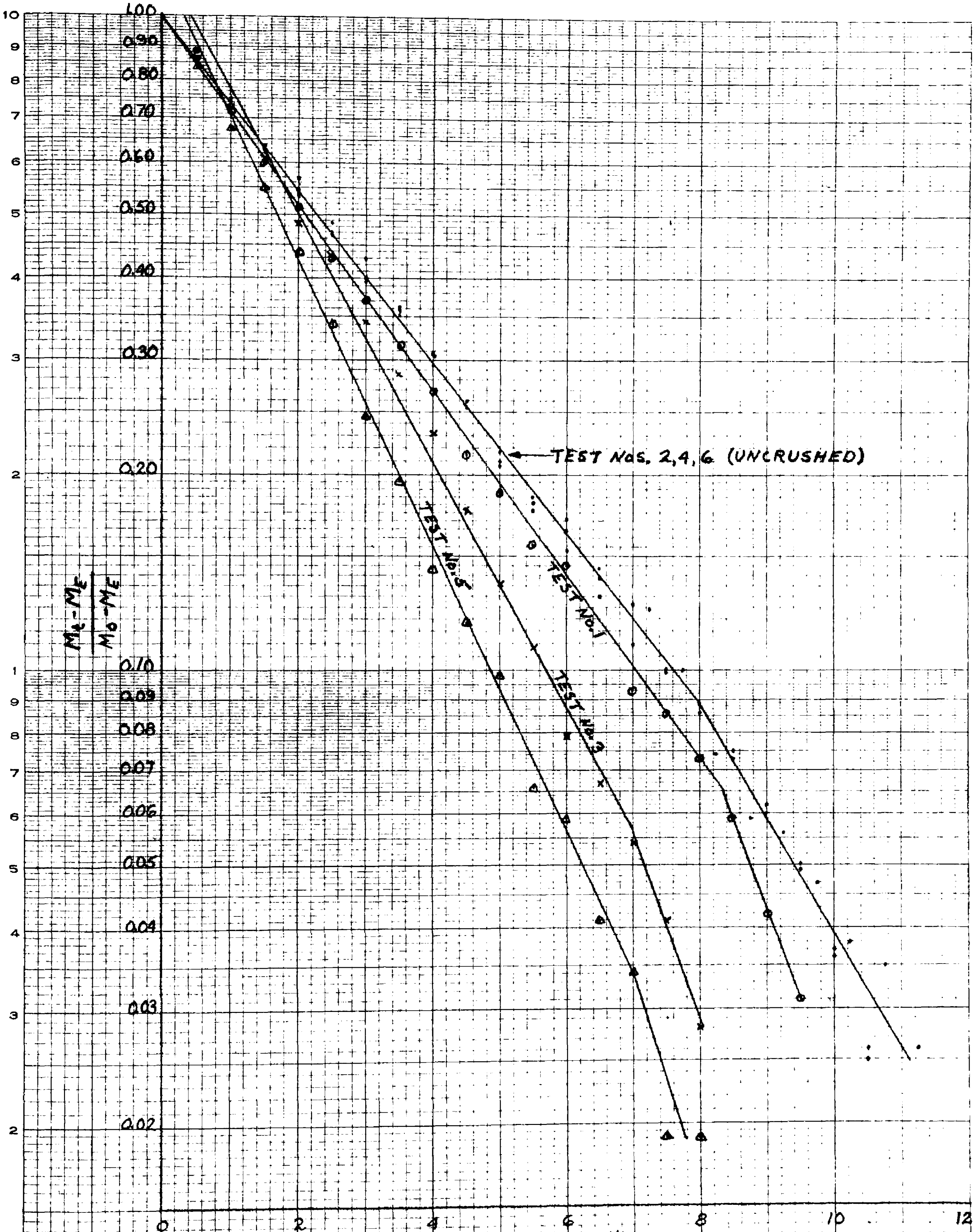

FIG. [illegible] RELATION OF MOISTURE CONTENT RATIO TO TIME IN BALE DRYING TESTS - 1954 content was assumed to be the moisture content remaining at the end of the test. Since the tests were continued for several hours after measurable weight loss ceased, the final moisture content may well be a good measure of the equilibrium moisture content for the mixture of plants present in each bale.

Because the tests were all performed at the same rate of air flow, and there was little variation in dry weight of the bales, the range of test conditions is not adequate to investigate the modified form of the drying equation expressed in equations (5) and (6). For this reason the tests performed by Gallaher (op. cit.) at 100° F and 52 percent relative humidity were used. In these tests the weight of dry matter varied from 36.6 to 66.0 pounds and the air flow varied over a range of 451 to 633 pounds per hour.

The graphs of moisture content ratio versus time for the six tests are shown in Fig. 30. The slopes of these lines were calculated to obtain the constant K of equations (1) and (2). In Fig. 31 the values of K/2.303 are plotted versus the mass velocity, G. Since a linear relationship results, the limited evidence available indicates that the form of the drying equation expressed in equation (6) is valid for alfalfa hay.

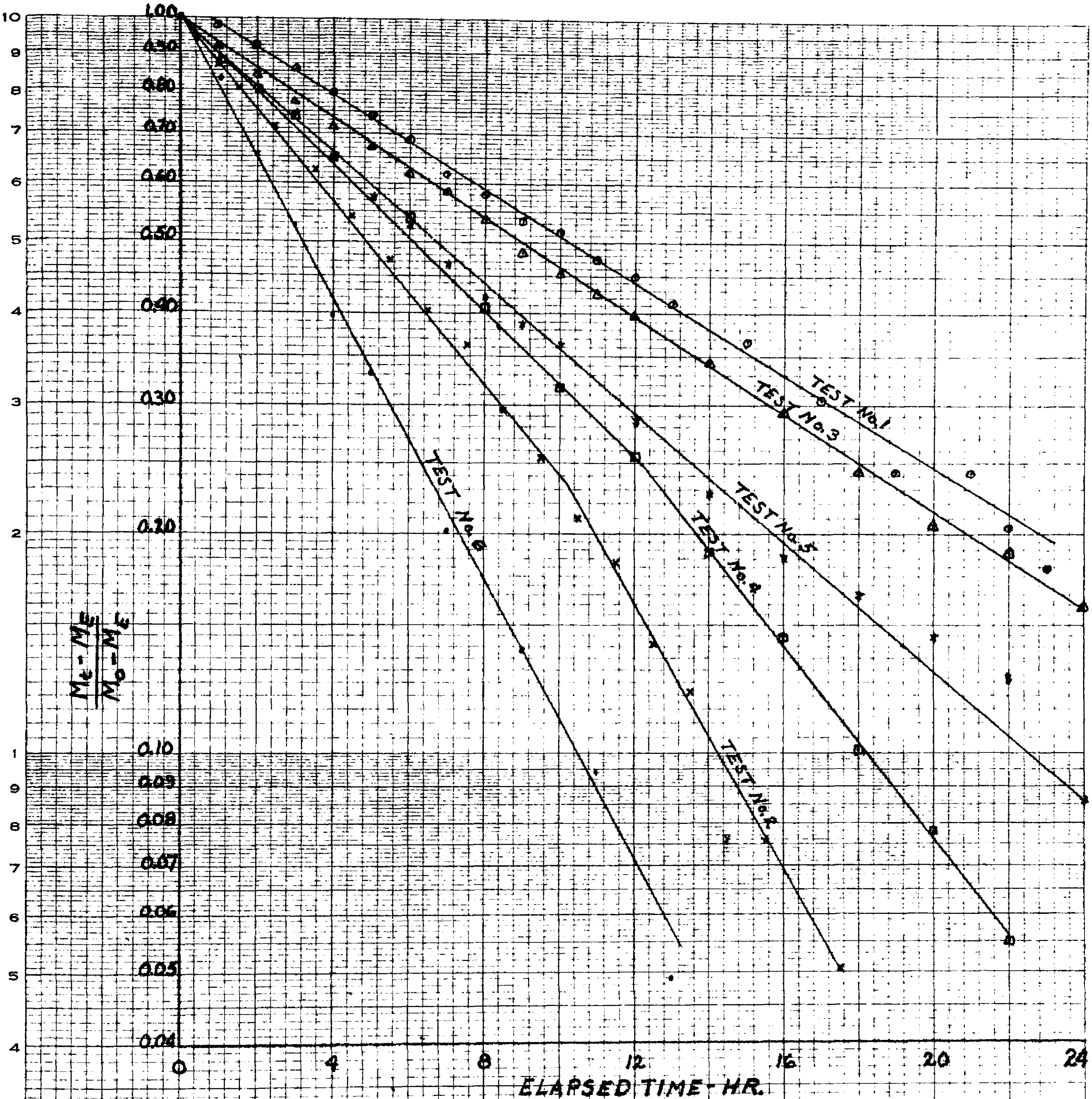

FIG. 30. RELATION OF MOISTURE CONTENT RATIO TO TIME IN BALE DRYING TESTS - 1949

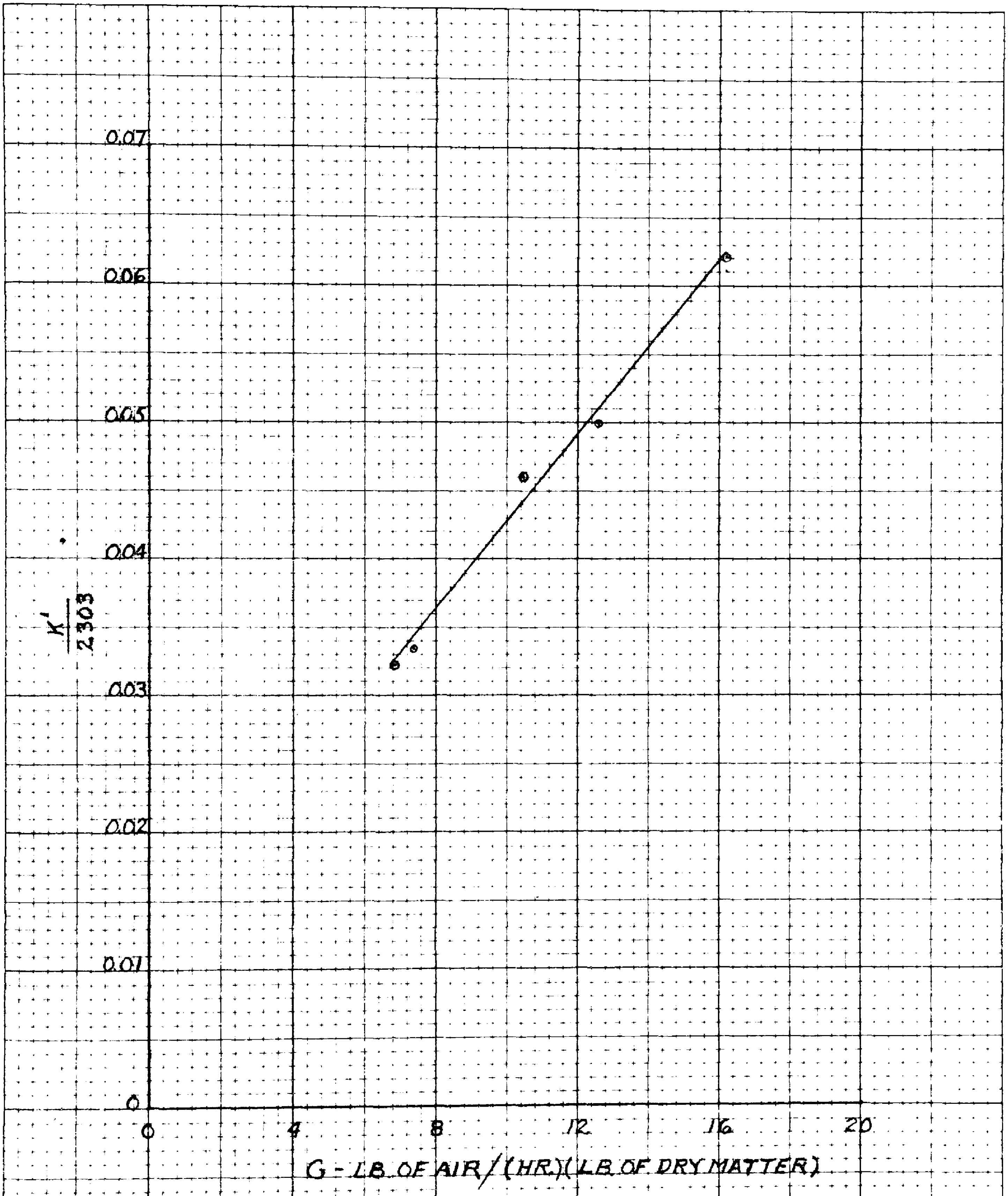

FIG. 31, RELATION OF DRYING CONSTANT TO MASS AIR VELOCITY

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SUMMARY AND CONCLUSIONS

Hay is one of our most important crops in terms of acreage grown and tonnage produced. Because the making of field-cured hay is subject to weather hazards, there is a considerable loss of nutrients from exposure to the elements. In addition, much of the nutrients is lost due to shattering of the leaves from handling the dry hay. In the search for methods of making better hay, studies were made of the use of chemical and mechanical treatments to reduce the time required for field-curing.

The major problem in the storage of partially-cured hay is the control of molds and other microorganisms which cause heating, loss of nutrients, reduction of palatability and, in some cases, spontaneous ignition of the hay.

The use of salt on hay of 30 percent moisture content at rates up to 5 percent of the weight of the hay does not prevent mold development, according to reported tests. Higher rates of salt application might control mold, but would cause salt poisoning in cattle when insufficient water was consumed. With free access to water, cattle would not suffer from the excess salt but might limit their hay consumption because of the high salt content.

Carbon dioxide reduces or prevents mold development when present in sufficient concentration. Carbon dioxide is not suitable for use as a hay preservative because it is too difficult to maintain a high concentration of the gas in a hay mow. Commercial preservatives which release carbon dioxide when in contact with moist hay have been proved worthless.

The use of a mold inhibitor to permit storage of partially-cured hay is an attractive possibility although at the present time a suitable compound is not available. The most satisfactory method of application is with a two- or three-nozzle spray boom mounted above the baler apron. A hood over the spray boom reduces wind drift considerably and provides more comfortable working conditions for the baler operator. Complete coverage of the hay is necessary since molds normally develop more rapidly than the inhibitor can evaporate or sublimate to protect untreated hay with inhibitor vapor.

The required rate of application of a mold inhibitor is dependent upon the inhibiting characteristics of the compound and the period of time for which protection is required which, in turn, is dependent upon the initial moisture content and drying rate of the hay. It is necessary that an inhibitor be applied at a rate which either: is fungicidal, will prevent mold development until the hay is fed to livestock, or will control molds until the hay has dried to a level at which mold growth cannot occur. Measurement of the drying rates of individually stored bales of hay with initial moisture contents of 25 to 35 percent indicated that it is necessary for a mold inhibitor to provide protection for a prolonged period of time.

On a laboratory scale mold growth was prevented by the use of a volatile fumigant applied to the top of a column of hay. It is necessary that a fumigant have a low boiling point in order to vaporize rapidly enough to prevent mold development.

When baled hay is placed in open storage, the final quality is affected by both bale density and moisture content. In order to obtain completely must- and mold-free alfalfa hay it should be field-cured to about 20 percent moisture content and the bale density should be about 6 pounds per cubic foot.

Crushing frequently increases the drying rate of hay by permitting more rapid evaporation of moisture from the stems. In the 1954 tests when alfalfa hay was not rained upon, crushed hay dried to 20 percent moisture content in nearly the same period of time in which uncrushed hay dried to 35 percent moisture. The plant parts of crushed alfalfa dried more rapidly than the corresponding parts of uncrushed plants with the result that crushing had little or no effect on the relation of leaf moisture content to the average moisture content of the plant. Consequently, leaf shattering will not be reduced by crushing hay unless the number of handling operations is reduced as a consequence of crushing.

Crushing was found to have no effect on leaf losses due to either raking or baling hay. Leaf losses were reduced, whether the hay was crushed or uncrushed, when the operations were performed at higher moisture contents of the hay.

When partially cured hay was exposed to the same rainfall, the crushed and uncrushed hay had very nearly the same moisture contents after the rain. After a rain the drying rate of hay was not increased by crushing. This was probably due to the rapid evaporation of moisture from the ground surface thus producing a high relative humidity in the vicinity of the hay. There appears to be little advantage in using a crusher in making field-cured, first cutting hay in central Michigan because the average period of time between rainfalls is less than the time required to field-cure hay.

Crushing had little effect on the nutrient content when the hay received no rain or 0.09 inch of rain. There was a slightly greater loss of ash, fermentable carbohydrates, protein, and carotene from crushed hay due to 0.69 inch of rain.

Under forced air drying, individual bales of crushed hay dried more rapidly than bales of uncrushed hay. Consequently, the operating time of a hay finishing system would be reduced somewhat by crushing the hay.

From an examination of the drying mechanism in crushed and uncrushed alfalfa, it was found that crushing increases the rate of drying in both stages of the falling rate period.

Evidence was obtained that in forced air drying of alfalfa hay the drying proceeds according to the equation

$$dM/dt = -K(M - M_E) \qquad (1)$$

in which the value of the factor K is altered by crushing.

RECOMMENDATIONS FOR FUTURE RESEARCH

In spite of the large amount of research which has been done, there is little basic information available on the drying of hay and other agricultural products. Consequently, fundamental research is badly needed to permit solution of the existing problems. Many of these problems could be solved analytically with available mathematical tools if the basic data were obtained for their solution.

A great need exists for the determination of the physical properties of agricultural products. It seems odd that no one has troubled to even measure the specific gravities of the common forage plants over the range of moisture contents encountered. Other constants such as specific heat, thermal conductivity, heat of respiration, shearing force, and many others are needed. Agricultural engineering can rise to a level of true engineering only when these data are made available and applied in engineering fashion.

Another field which needs to be studied is the drying mechanism in agricultural products. An understanding of the manner in which drying proceeds would permit rational design and operation of drying and conditioning equipment.