THE EFFECT OF CONDITIONING AND PHYSICAL ENVIRONMENT ON THE FIELD DRYING OF ALFALFA

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THE EFFECT OF CONDITIONING AND PHYSICAL ENVIRONMENT ON THE FIELD DRYING OF ALFALFA

by

THOMAS TOUGAARD PEDERSEN

AN ABSTRACT

Submitted to the Michigan State University of Agriculture and Applied Science in partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE

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ABSTRACT

For hundreds of years, alfalfa has been an important animal feed. Today alfalfa is one of the most important forage crops in the United States. There are, however, large losses during the production of hay both in quantity and quality. Approximately 21 percent of the feeding value of the hay crop is lost due to weather damage during field curing. It is therefore important to find the best possible method of curing the hay -- drying to 20 percent moisture content in the shortest possible time.

The object of this research was to develop a quick method for field curing of hay. The problem was approached by studying the anatomy and physiology of the green alfalfa plant and considering the field environments while the hay is drying.

The experiments were conducted during the summer of 1957 and 1958. It is a well known fact that the leaves dry faster than the stems; therefore, part of the hay swath was turned upside down. This made the stems shade the leaves. There was, however, no difference in drying rates between this turned swath and the conventional drying method of crushing the hay in the swath.

Different mechanical treatments were applied to the alfalfa plants to hasten the evaporation, especially from the

stems. Hard crushing and penetrating the cuticle of the stems several places per inch length gave the highest drying rates. Smashing the stem every two inches for a length of half an inch, and twisting the stems resulted in slightly higher drying rates than uncrushed alfalfa plants.

While crushing of the plant increased the drying rate for the stem as well as leaves, the gain in rates was much greater for the stems. When crushing was severe, the stems dried faster than the leaves.

For some time after a rain the relative humidity of the air near the ground is nearly 100 percent. Such conditions have often existed during the first cutting of alfalfa. After mowing, the hay lies on the ground for drying for a considerable time. Water vapor lost from the wet soil by evaporation to the atmosphere moves continuously through the swath and reduces the drying process.

This influence of evaporation from the soil was eliminated by placing a vapor barrier in the form of a polyethylene sheet between the soil and the hay. This considerably increased the drying rate. It was found that black polyethylene was the best suitable, because it, besides being a vapor barrier, also absorbed radiation energy, and thereby was able to raise the temperature of the hay sample as much as 67 degrees F. This increased the drying rate of the hay. The plastic served as a sheet for collecting leaves lost during drying.

If the alfalfa was cut before 10 a.m. and crushed (clearance of less than 0.015 inches between the crushing rollers) it was possible with the black polyethylene-vapor-barrier method to dry the hay to a 20 percent moisture content during the same day it was cut. This was possible when the calculated yield did not exceed four to five tons of 20 percent moisture content hay per acre.

This research study has shown the possibilities of harvesting field cured hay the day it was cut. Because one day weather forecasts are more reliable than two to four day forecasts, weather damage, and furthermore, dew damage to hay, are reduced to a minimum.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PICTURES

APPENDIX

INTRODUCTION

For hundreds of years alfalfa has been an important crop in providing food year round for livestock. Since ancient times hay has been made largely from legumes and grasses.

The observations of the Greeks and Romans are as true today as they were when Columella wrote in A.D. 60: "...But of all legumes, alfalfa is the best, because, when once it's sown it lasts ten years; because it can be mowed four times, and even six times a year; because it is a remedy for sick beasts; because a jugerum (= two-thirds of an acre) will feed three horses plentifully for a year."

Today alfalfa is the leading forage crop in the United States. It accounts for about one-third of the annual hay crop of 100 million tons and is grown on approximately 15 million acres. The alfalfa growing areas are located principally in the Midwest and the Farm West. Michigan and California have more than one million acres each. Nebraska, Minnesota, Kansas, Wisconsin, Idaho, Montana and Iowa each grows about 700,000 acres (USDA 1948).

The value of the alfalfa hay produced by these 15 million acres represents approximately two billion dollars. There are, however, larger losses during the production of alfalfa hay, both in quantity and quality, than in any other farm crop (fruit and vegetables excepted). About 21 percent of the alfalfa crop is lost during harvesting and curing, and another 7 percent loss occurs during storage, making an annual total loss of 28 percent or more than one-half billion dollars (15).

The object of research on hay-harvesting methods is to find ways of reducing these nutrient losses and harvest hay of good quality. With today's method of field curing of good alfalfa hay the farmer must depend upon good weather for several days after cutting. It is difficult to predict the weather two or more days in advance. The result is that the farmer cannot always complete harvesting before the hay is damaged by rain while curing in the field.

If a method of fast drying of the hay in the field could be developed, i.e., hay could be harvested in operations not covering more than one day, a great step would have been taken toward better quality hay and smaller losses of nutrients.

The object of this study and series of experiments was to develop such a method by studying the anatomy and physiology of the plant and the atmosphere under which hay is cured in the field.

REVIEW OF LITERATURE

The farming operations required to produce a good seeding and to grow an alfalfa crop are well established. The difficult part of alfalfa production occurs in harvesting the forage so as to save the maximum feeding value. These difficulties in hay harvesting are found throughout the humid regions of the world. They are due in part to the fact that the period of time between rains is less than the time required to cure the hay and transport it to the barn.

The average number of consecutive days without rainfall in Central Michigan during June and early July are shown in Table I.

TABLE I

AVERAGE CONSECUTIVE DAYS WITHOUT RAINFALL, CENTRAL MICHIGAN, 1918-1949 (Vary, 1954)

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

Using the best equipment available for the conventional method of hay harvesting -- cutting the forage followed by a crushing or crimping of the stems -- a minimum of two days under good drying conditions is required to dry the conditioned hay to 20 percent moisture content.

The above table shows that the possibility for harvesting high quality first cutting hay in Central Michigan is low. This is especially true during the third and fourth weeks of June, when most of the first cutting of hay is harvested. In July the possibility for two or more consecutive days with no rainfall are considerably better, but overmatured hay has a low feeding value.

During the month of August, when the second cutting of hay is made, the average rainfall is 0.69 inches less than the normal rainfall for June. With the less rainfall during the second cutting, the possibilities of obtaining benefits from the use of hay crushers are greater. The reason for this was showed by Hopkins (1954), who found that there was little difference between drying rates of the crushed and the uncrushed hay after a rain. He found strong evidence that the climate in the vicinity of the hay was altered by rains. The evaporation of moisture from the ground would lower the air temperature and raise the relative humidity, and conditions would arise in which the capacity of the air to absorb moisture was reduced and even though there was adequate heat available to evaporate moisture from the hay, the rate of drying would be limited by atmospheric conditions. In this case Hopkins found that the ability of crushed hay to evaporate water more rapidly was of little use until the atmospheric conditions had improved.

From the above it appears that the conditions are seldom ideal for drying when the farmer has forage ready to be harvested; this accounts for great losses in dry matter and feeding value while drying the forage.

Rain damage causes leaching of nutrients, bleaching, and makes it necessary to give the hay several mechanical treatments. Windrowing and raking of the hay several times causes loss of leaves, especially when these operations are carried out at moisture contents below 45 percent. Hopkins (1955) published a table, which is reproduced in Table II. This table shows the influence of mechanical treatments on the leaf content in the hay, when the operations are carried out at different moisture contents.

From Table II it is evident that the hay contains the greatest percentage of leaves when the mechanical treatments, in this case raking and baling, are carried out at as high moisture content as possible.

The leaves are the most valuable part of the hay crop. Approximately 70 percent of the total protein and 90 percent of the carotene are located in the leaves (USDA 1948). The leaves of green alfalfa contain from 40 to 50 percent of the dry matter when the hay is harvested in the one-tenth bloom stage. The second cutting normally has a higher leaf content than the first; the 50 percent refers to the second cutting and the lower figure to the first cutting. With today's methods of curing hay in the field at least 20 percent of the leaves are lost, and this figure is often much larger when the hay receives one or more showers while remaining in the field. This means that even under optimum conditions 14 percent of the protein and 18 percent of the carotene are left in the field in the form of lost leaves.

TABLE II

LEAF CONTENTS AFTER DIFFERENT MECHANICAL TREATMENTS AT DIFFERENT MOISTURE CONTENTS (Hopkins, 1955)

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 25
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

Some of the losses in quality generally are obvious enough; among these are the loss of leaves, color, aroma, changes in physical condition, and the palatability of the feed. The latter characteristic, which constitutes what is called quality in hay, reflects other losses such as losses of dry matter, total digestible nutrients, and carotene.

The losses in nutrients are not as easily recognized as the losses in leaves, color, and aroma; from the feeding standpoint of view, however, they are of great significance.

During the interval from cutting until the forage is dry enough to store, a progression of events promotes losses and deterioration of the quality and feeding value of the forage. Freshly cut forage is a living material. The plant cells continue to respire, and the plant enzymes continue active for some time after the crop is cut. In addition microorganism naturally contained in the forage remain active as long as air is present and there is sufficient moisture. These fermentation processes affect principally the soluble carbohydrate fractions and the carotene. If the drying is prolonged, however, important losses in dry matter may also occur. Losses amounting to 5 to 15 percent of the total crop have been found to occur from so-called field-fermentation losses (USDA, 1948). This means that the method of handling the hay in the field should be designed to promote the most rapid evaporation of moisture so that the fermentation losses can be kept to a minimum.

Field cured hay will generally sweat after it is stored, and if it is undercured, it will heat in the barn (USDA, 1948). This heating process causes losses in both dry matter and feeding value. Frequently such hay will lose from 5 to 15 percent of the dry matter and nutrients while in storage. If the heating is excessive, brown and black areas of charred and burned hay may develop.

Brown or black hay appear to be palatable for livestock. This type of hay, however, has a decidedly lower feeding value. An analysis of the loss in feeding value caused by heating to different degrees is shown in Table III (USDA, 1948).

TABLE III

THE RELATIVE FEEDING VALUES OF NORMAL HAY AND OF HAY THAT HAS BEEN HEATED IN STACK (USDA, 1948)

Item	Normal hay	Brown hay	Black hay
Digestibility percentages:			
Dry matter	60	41	27
Protein	67	16	3
Fiber	41	36	14
Ether extract	45	33	42
Nitrogen-free extract	72	59	53
Calculated digestible nutrients:			
Protein	14.4	3.4	.6
Total digestible nutrients	55.8	37.7	23.4
Palatability:			
Lbs eaten for 1,000 lbs weight	20	15	10

This analysis shows that hay damaged by heating has lost almost all its content of protein, and in the case where the heating has progressed so far that black hay has developed, more than half of the total digestible nutrients are lost.

The leaf loss can be reduced and the quality of the hay improved by removing the alfalfa crop from the field before it is fully dried. The leaves of alfalfa hay generally do not shatter when the forage contains 35 to 45 percent or more moisture. When partly cured the hay is placed on a barn hay finisher for removing as much moisture as necessary for safe storage. The amount of moisture that has to be removed depends upon the initial moisture content when the crop is placed on the finisher. Table IV shows the amount of water to be removed by the drier (McCurdy).

TABLE IV

GROSS WEIGHT AND AMOUNT OF WATER TO BE REMOVED FOR DIFFERENT INITIAL MOISTURE AT STORAGE (McCurdy)

Initial moisture at storage (wet basis) percent	Gross weight to make 1 ton at 20% M.C. lbs	Water to be removed to make 1 ton at 20% M.C. lbs
20	2,000	---
30	2,286	286
35	2,460	460
40	2,667	667
45	2,910	910
50	3,200	1,200
60	4,000	2,000
80	8,000	6,000

When the crop is put on the drier at moisture contents between 35 and 40 percent, most of the water has been evaporated during the curing time in the field, but even then the hay is still wet enough to allow rapid fermentation and mold development to take place. To avoid this and thereby losses in nutrients it is important that the material be dried as quickly as possible. Table V (USDA, 1948) shows the losses of dry matter and protein by field curing and barn finishing.

TABLE V

LOSSES OF DRY MATTER AND PROTEIN BY FIELD CURING AND BARN FINISHING (USDA, 1948)

Item	Field curing			Barn finishing		
	Field losses %	Storage losses %	Total losses %	Field losses %	Storage losses %	Total losses %
Dry matter:						
1st-cutting alfalfa 1945	21	5	26	16	1*)	17
2nd-cutting alfalfa 1945	17	4	21	13	8	21
Protein:						
1st-cutting alfalfa 1945	31	2	33	26	1*)	27
2nd-cutting alfalfa 1945	29	1	30	16	10	26

*) Heated air was used in this installation to complete drying.

This table shows that the total losses are considerably lower when the method of barn finishing has been used; especially this is the case for first cutting alfalfa and is, in part, due to less favorable drying conditions in the field.

Another important advantage of the finishing method is that the crop is removed from the field more quickly in the case of threatening weather and in that way large amounts of feeding value are saved that would be lost by normal field curing.

By using ordinary sun curing methods the carotene in the hay is destroyed to an extent of 50 to 80 percent. This loss can be reduced considerably by using the barn finishing method. This is indicated in the following table (USDA, 1948).

TABLE VI

CHANGES IN CAROTENE CONTENT OF ALFALFA HARVESTED BY FIELD CURING AND BARN FINISHING (USDA, 1948)

When sample was taken	Carotene content (dry basis)	
	Field curing mcg. per gram	Barn finishing mcg. per gram
When cut	297	308
When put on drier	---	122
When dry (13 days later)	---	29
When stored	49	---
When stored 30 days	26	---
When fed	12	22

The only way this carotene loss is prevented today is by dehydrating at air temperatures running as high as 1,700 degrees F. When dehydrating alfalfa for alfalfa leaf meal, the green material is chopped and brought to the dehydrator at a moisture content of about 75 percent and is dried down to a moisture content of 8 percent. The high drying costs, $25 to $35 per ton, however, have limited the use of this method to about 2 percent of the total production. It is only economical to feed the artificially dried product to animals, who for fast growth, require food with a high content of provitamin A.

Furthermore, carotene, even though preserved during the drying process, is continually being destroyed during storage and as much as 50 percent may be lost in six months. To prevent this storage loss, the material may be sealed in oxygen-free gas, or with anti-oxidants such as 2,5-di-tertiary-butyl-hydroquinon, 6-ethoxy-2,2,4-trimetyl-1, 2-dihydroqyinolini and diphenyl-p-phenylene-diamine must be applied at levels of 0.3 and 2.0 lbs per ton of dried alfalfa. This last method has been shown to reduce the carotene destruction to one-half to one-fourth of the usual amount.

The Anatomy And Physiology Of Alfalfa

While this is not the place for a detailed description of the anatomy and physiology of the leaf of alfalfa, the mechanics of transpiration from leaves of living plants must be studied to determine how plants lose moisture.

The leaves of alfalfa are composed of a thin-walled parenchyma tissue through which numerous finely divided vascular bundles permeate and end free so that there are thousands of these veins in a square inch of the leaf. The entire leaf is covered by a single layer of cells. This layer is generally called the epidermis and is somewhat cutinized and for that reason more or less impervious to water vapor.

The epidermis of the leaf, however, is not completely intact, but perforated by numerous microscopic pores, which are called stomata. They are intercellular openings between two special formed epidermal cells -- guard cells. The parenchyma tissue of the leaf is very loosely constructed so that there are many air spaces between the cells. These intercellular spaces join with one another and finally unite with one of the large air spaces directly beneath each stoma.

In the guard cells the wall of the cell is much thinner where it borders on the epidermal cell than on the opposite side next to the stoma. When the turgor pressure of the cell is increased this thinner wall is stretched out further than the other and pulls the thicker wall bordering the stoma. This increases the size of the pore.

The Number Of Stomata

The number of stomata developed per unit area depends on different weather factors such as the relative humidity, the intensity of light and probably some other factors.

Mariana (1942) studied the effect of the humidity in the air upon the development of stomata. He came to the conclusion that the humidity favors the development of the superficial areas of the leaves, but it does not increase the absolute number of stomata. Reed and Hirano (1931) found that the density of stomata was decreased when the intensity of light was reduced.

Miller (1928) has studied the number of stomata per square inch of various agricultural plants and found the average number for the upper leaf surface of alfalfa leaf to be 680,000 and for the lower surface 555,000 per square inch. Thus, the total number of stomata per square inch is some 1,235,000. The ratio of stomata on the lower surface to upper surface is 0.816. In spite of the high number per unit area, the area of the stomata is only one to three percent of the leaf surface.

Opening And Closing Of Stomata

The stomata on the upper surface may behave differently from those on the lower. That is, those on the lower surface open more slowly and close earlier than those on the upper.

On all leaves there are a certain number of stomata that are functionless, while others are more or less inactive.

Different factors such as light, temperature, humidity and moisture cause the opening and closing of the stomata. The drying rate in hay may be increased by keeping the stomata open. For alfalfa, there is a daily cycle of opening and closing of these stomata.

Loftfield (1921) found that the stomata of alfalfa under favorable conditions are open all day and closed all night. They open two to six hours after daybreak and remain open three to six hours and then gradually close over a period about twice as long as that required for opening. When the conditions become less favorable for moisture, the stomata close partially for a time during the middle of the day; this period of midday closure increases to complete closure as the conditions become more unfavorable. With the appearance of midday closing, night opening develops and increases with the increase of day closure, until finally there is partial opening of the stomata all night and a complete closure all day.

This means that the opening and closure of the stomata is controlled by so many factors that it hardly can be relied upon for selection of the optimum time of day for mowing.

The Transpiration From Living Plants

It is generally known that all living plants require water for their existence and development, and that the plants use it in considerable amounts. Most of the water absorbed from the soil, however, takes no permanent part in the development of the plant or the metabolic process. Far the greatest part of the water escapes from the plant in form of water vapor. This form of water loss is called transpiration.

The greatest part of the transpiration takes place through the stomata, and is called stomatal transpiration. A far smaller amount, less than 10 percent of the water vapor, is lost from the leaves and stems by direct evaporation from the cuticle.

All of the living cells within the leaves are filled with liquid water, and evaporation takes place from the wet cell into the intercellular spaces which constitute a connected system, ramifying throughout the leaf and finally joining the air space just beneath each stoma.

If the stomata are closed, the evaporation from the cell wall will stop when the entire volume of air of the intercellular spaces reaches 100 percent relative humidity. When the stomata are open, diffusion of water vapor may occur through them into the atmosphere outside the stoma, unless the atmosphere has a vapor pressure equal to, or greater than, that in the intercellular spaces.

Factors That Affect The Rate Of Transpiration

Such weather factors as temperature, relative humidity and wind affect the transpiration rate.

As the temperature rises, in general, the rate of transpiration increases. Briggs and Shantz (1916) concluded in the case of alfalfa that the transpiration graph rose in advance of the temperature in the forenoon; however, in the afternoon the transpiration always fell off more rapidly than the temperature. When the transpiration had reached its night level, the temperature was still above the minimum by about one-third the daily range.

Thomas and Hill (1937) found that the rate of transpiration from a six foot square plot of alfalfa in grams per hour ranged from 200 grams to 300 grams during the night to maximum 3,000 grams about 2 p.m.; the rate of transpiration starts to rise from night time low at 6 a.m., and it reaches nearly the same level between seven and eight in the evening.

In general it is known that a decrease in the relative humidity causes a higher transpiration rate. Darwin (1914) found that the relation between relative humidity and the transpiration rate is linear. In some cases, however, the graph was actually a curve instead of a straight line. This happened when the change in the rate of transpiration lagged behind the change in relative humidity. He also discovered that the transpiration rate is not zero in saturated air, which means that the vapor tension in the leaf is higher than that of saturated air.

The effect of wind depends upon the wind velocity. In the first place, the wind tends to remove the blanket of more or less saturated air surrounding the leaves. This tends to decrease the distance the water vapor must travel to find free air conditions. On the other hand, if the wind velocity is too high, some of the stomata may close, and the rate of transpiration stops increasing and may begin decreasing.

The conclusion of all the experiments conducted concerning the influence of wind on the transpiration can be stated as follows: the water loss from most living plants does not increase as the wind velocity increases above a gentle breeze.

The effect of relative humidity and temperature upon stomatal behavior is reflected in the results obtained from methods of drying hay. (Table VII)

TABLE VII

RATE OF NATURAL DRYING ALFALFA HAY CUT FROM 8 TO 9 a.m.

(Jones and Palmer, 1932)

Method of handling	As cut	2 hrs after cut	4 hrs after cut	8 hrs after cut	20 hrs after cut	25 hrs after cut
	Moisture content in percent					
Swath	70	60	46	26	46	25
Single windrow as cut	70	62	38	21	38	22
Double windrow as cut	70	64	34	26	38	27
Single windrow 2 hr after cut	70	60	40	22	37	22
Double windrow 2 hr after cut	70	60	32	18.5	30	17
Single windrow 4 hr after cut	70	58	43	21	25	21
Double windrow 4 hr after cut	70	58	44	20	30	20.5

Jones and Palmer (1932) found that a double windrow of alfalfa two hours after cutting produced hay with a more desirable color and a lower moisture content than the hay that was cured in the swath. At the end of two hours in the swath, the stomata were nearly all closed, and plasmolysis of the cells had occurred. At the end of the same period, the stomata of the windrowed hay were partially closed and some had begun to reopen. This reopening was followed by an increased rate of water loss. The temperature inside the windrow three hours after cutting was 5 to 8 degrees Centigrade lower than in the swath while the relative humidity of the windrow was 10 percent higher than in the swath. In the subdued light of the windrow, the chlorophyl was better preserved and thus made brighter hay. The rate of natural drying alfalfa hay is shown in Table VII. This experiment was carried out by Jones at Mississippi Agricultural Experiment Station (1939). From this table it may be concluded that in Mississippi double windrowing from two to three hours after cutting gives hay with the lowest moisture content at the end of the day.

Translocation Of Water In The Plant

Besides the loss of water through transpiration from the leaves, much smaller amounts are utilized in photosynthesis and growth. A still smaller amount is lost in cuticular transpiration from the stems.

The water enters the plant mainly through the epidermal of the root hairs at or near the tips of the roots. After crossing the cortex, endodermis and a part of the pericycle, the water finally enters the lumina of the vessels of the root system. When in the vessels the water moves upward through the stem and out in the leaves. In the mesophyl it moves from cell to cell. From this point, however, most of the water is lost from the cells by evaporation into intercellular spaces. As much as 98 to 99 percent of the water obtained from the soil is lost from the plants by transpiration, and has no other function than just keeping the plant wet.

INVESTIGATIONS OF THE SUMMER OF 1957

The Distribution Of Water In Green Alfalfa

From research in plant physiology, it is well known that actively growing sections of the plant, such as growing stems, root-ends, flowers, and leaves, utilize a considerable amount of water. It has not been possible, however, to find any exact figures concerning the distribution of water throughout the entire plant of alfalfa.

The first experiment was conducted, concerning the basic factors involved in field drying hay, to determine how water is lost and percent of total loss from various parts of the plant.

The distribution of water in the plant was determined for alfalfa plants of different ages. The alfalfa plants were divided into three groups:

1) Young alfalfa plants in pre-bloom stage
2) Alfalfa in 1/10 bloom stage (normal maturity for hay)
3) Old alfalfa plants past full bloom (1/4 seed pods)

Immediately after cutting, the heads and leaves were separated from the stems. The water content of heads (flowers plus flowerbuds) and leaves was determined separately. Starting at the top end of the stem, these were cut in two inch lengths. The stem pieces from the different sections of the plant were collected and the moisture content was determined separately for each stem section.

Discussion of Results

The moisture content was determined on wet basis. The results for the stems are shown in Figure 1, those of the heads and leaves in Table VIII.

Figure 1 indicates that the highest moisture content was found in the growing parts of the stem. In the stem just below the heads the moisture content in young and middle age alfalfa was found to range from 83.5 to 85.5 percent. In old alfalfa plants the moisture content at the same place was something lower -- about 76 percent.

The further away the sample was taken from the growing point, the lower the moisture content. From the curves, it appears that the decrease per unit length was considerably larger near the top end than in the lower stem part. The lowest moisture content of all plants was near the root. It was 60 percent in old plants, while in middle-age and young alfalfa at the same place, it was 12 - 13 percent higher, namely in both cases 72 percent. The average moisture content for old, middle-age and young alfalfa was 65.3, 73.7, and 77.3 percent, respectively.

Table VIII indicates that the moisture contents in heads as well as leaves decreased with the age of the alfalfa plant. This seems reasonable -- the younger the plant, the more un-

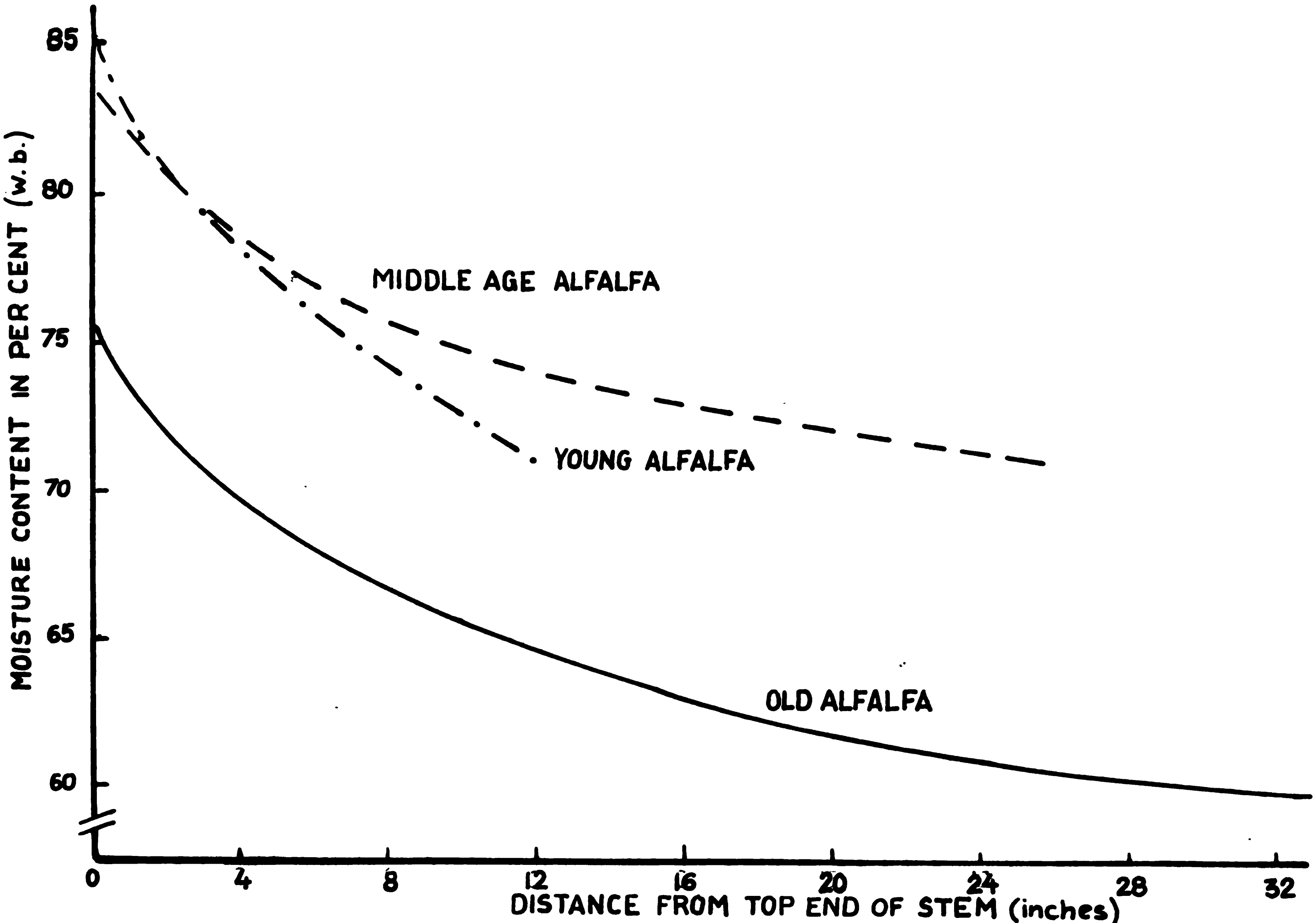

Fig. 1 Moisture content of alfalfa stems of various ages.

developed leaves and heads; the results in Table VIII thus corresponded with those found in the analysis of the stems, where it also was found that the growing parts have the highest moisture content.

TABLE VIII

THE MOISTURE CONTENT IN LEAVES AND HEADS OF ALFALFA

Age	Moisture Content Leaves	Moisture Content Heads
	percent (w.b.)	
Old alfalfa	64.4	68.2
Middle-age alfalfa	70.8	80.2
Young alfalfa	77.1	----

Turning Of The Swath Of Alfalfa Hay In Order To Increase The Drying Rates Of The Stems

It is a well observed fact that the alfalfa leaves dry faster than the stems. In order to decrease this difference in drying rate, an experiment was initiated in which part of the hay swath was turned upside down. Such an inversion of the swath caused most of the stems to be placed on the upper side of the swath, where they were exposed to sun and wind, and the leaves were shaded by the stems.

This experiment was conducted on crushed and uncrushed alfalfa hay. The four treatments were as follows:

Picture 1. The hay cut and swath turned upside down.

Picture 2. The hay cut and left to dry in swath.

1) The hay cut and left to dry in the swath.

2) The hay cut and the swath turned upside down immediately after cutting.

3) The hay cut, crushed and left to dry in the swath.

4) The hay cut, crushed, and the crushed swath turned upside down immediately after crushing.

The research was first carried out July 5 and 6, 1957. It was repeated July 16 and 17, 1957. All the treatments from the first experiment were repeated and two additional treatments were added. Those were as follows:

5) The hay cut and left to dry in the swath for four hours; after four hours of drying the swath turned upside down.

6) The hay cut, crushed and left to dry in the swath for four hours; after four hours of drying the swath turned upside down.

In each of the experiments, there were three replications.

Discussion of Results

The results of the first experiment are shown in Figure 2. The data indicated that crushing of hay increased the drying rate, whereas turning of the swath did not influence the drying rate. The irregularity of the curves between 8:30 and noon on July 6 was due to the fact that some of the samples were collected before the rain started (indicated on the diagram), and some collected during the first ten minutes of the rain. All the samples from the plots containing crushed hay were taken before the rain started. This was the reason for

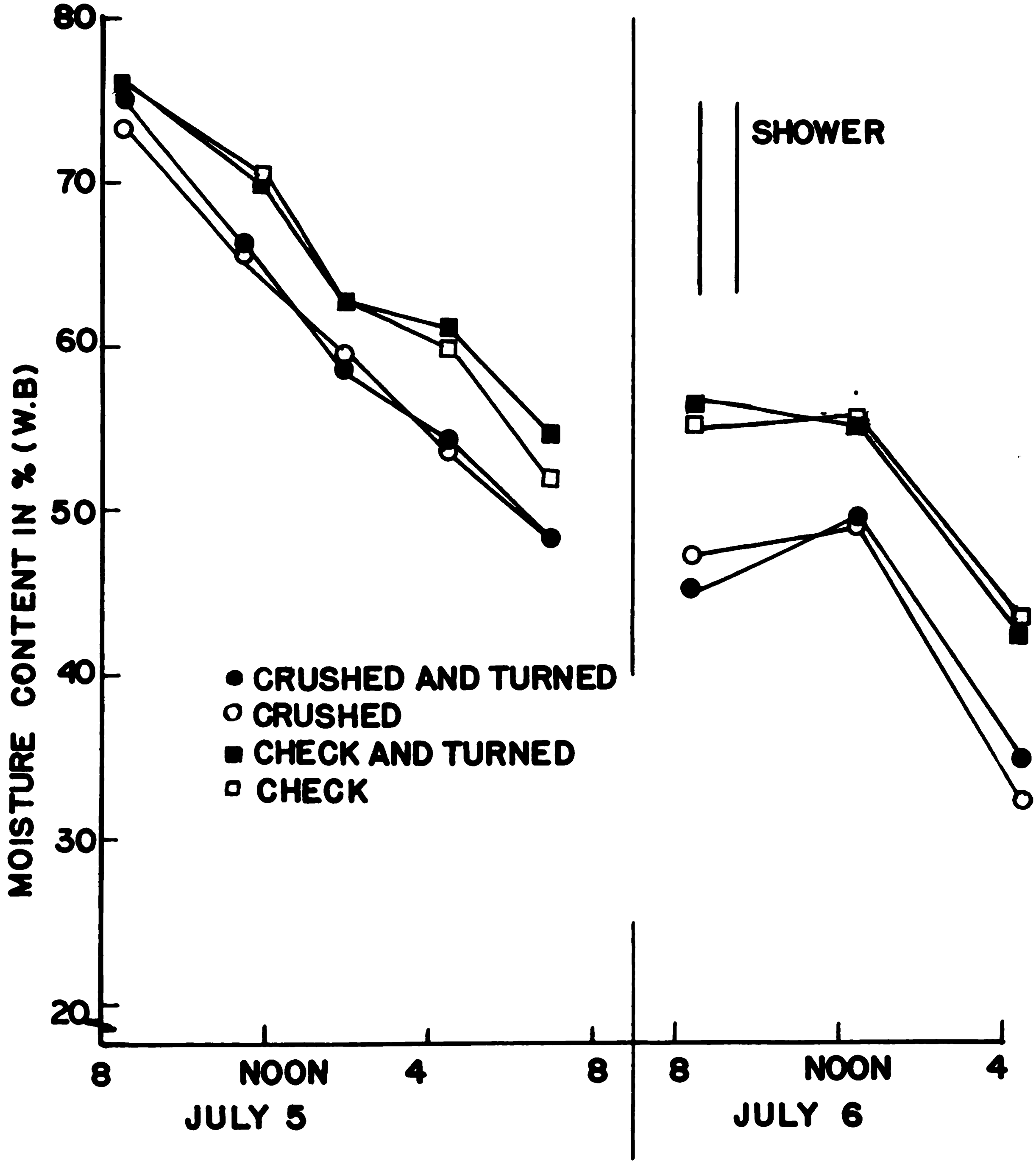

Figure 2. Drying curves for alfalfa hay, where part of the hay swath was turned upside down.

the increase in moisture content of the crushed samples between 8:30 and noon. The uncrushed samples were already partly wetted by the rain when they were bagged, hence, there was little or no increase in moisture content in these samples.

TABLE IX

MOISTURE CONTENT OF DIFFERENT TREATED ALFALFA HAY DURING DRYING IN THE FIELD

Date	July 16				July 17		
Hour	9:30 a.m.	1:00 p.m.	4:00 p.m.	7:00 p.m.	9:00 a.m.	noon	4:00 p.m.
Treatment	Percent moisture (w.b.)						
Crushed	76.7	55.2	41.3	37.3	31.6	27.8	16.3
Crushed plus turned at 9:30	77.8	57.8	43.4	35.7	33.0	27.9	19.3
Crushed plus turned at 1:30	77.2	56.1	42.8	35.2	32.7	19.5	14.3
Cut plus turned at 9:30	75.7	60.2	43.7	40.7	39.8	29.1	29.5
Cut at 9:30 plus turned at 1:30	74.9	58.4	43.6	42.8	43.7	33.2	24.9
Check	74.9	54.1	44.5	41.6	42.9	30.9	23.8
Temperature(°F)	75	80	77	77	75	78	82
Relative humidity (%)	51	46	52	72	68	52	44

Table IX shows the results of the second experiment. An analysis of the above two experiments showed that no increase in drying rate could be secured by inverting the swath. This was the case when the hay was turned immediately after the conventional treatments as well as when the hay was left to dry four hours before turning.

Different Treatments Of Alfalfa Hay In Order To Get Quicker Evaporation.

After turning of the swath had failed to give any increase in evaporation, and taking into consideration the anatomy and physiology of alfalfa, it was evident that the only way to increase the rate of evaporation from alfalfa lay in breaking the cuticle. As previously mentioned this layer covers stems as well as leaves, and consists of cutinized cells impervious to water vapor. It is more important, however, to break that on the stems than that on the leaves which has the stomata as natural openings for transpiration.

An attempt was made to find the most efficient way of breaking the stem. The following treatments were applied to alfalfa plants:

1) Alfalfa plants cut in pieces of 2 inches length.
2) Alfalfa plants cut in pieces of 6 inches length.
3) Alfalfa plants cut in pieces of 10 inches length.
4) Crushing of the plant (This crushing was more severe than that normally carried out by commercial hay-crushers.)

Picture 3. Plant cut in pieces of 2 inches.

Picture 4. Plant cut in pieces of 6 inches.

Picture 5. "Twisted" stems of alfalfa.

Picture 6. "Penetrated" stems of alfalfa.

Picture 7. Uncrushed alfalfa.

Picture 8. "Smashed" alfalfa.

5) The stems smashed every two inches in a length of one-quarter to one-half inch.

6) The surface broken by twisting the stems.

7) The surface broken by penetrating several places every inch by means of a thin nail.

8) Normal alfalfa plants with no treatments.

The plants used in the experiment were all of the same state of maturity (approximately one-tenth of the heads were flowering). They all had a uniform length of 22 inches and were all cut at 8:30 in the morning. All the mechanical treatments were completed before the first weighing took place. This was done within 30 minutes after cutting.

In order to get completely uniform drying conditions for all the treatments the experiment was conducted in the research laboratory in a constant temperature room, where the temperature and the relative humidity was kept at respectively 84 degrees F and 68 percent during the entire drying time. Weighing of the samples took place after 1.5, 3, 5, 8, 14, 24, 36 and 48 hours of drying. After finishing the experiment, the moisture content in the dried samples was determined by drying to constant weight in electric oven at 212 degrees F. Finally, the percentage of the total water evaporated at each weighing was calculated.

Discussion of Results

The results from the experiment are shown in the curves in Figure 3 and Figure 4. The curves of chopped hay indicate that chopping of alfalfa in short lengths (2 inches) immediately after cutting increased the drying rate. The long cuts required a longer drying time than the check. According to the anatomy of alfalfa and the above experiment, it would seem reasonable that the fastest evaporation possible could be obtained when the plant was cut in lengths which were less than the diameter of the stem. This treatment was not, however, included in this research work.

The highest rate of drying occurred when the hay was crushed, but nearly the same rate was obtained when the surface was "penetrated". Smashing the stems every two inches and twisting them were nearly equal in regard to increasing the drying rate but not as effective as hard crushing or "penetrating" of the stems.

TABLE X

TIME REQUIRED TO REDUCE THE MOISTURE CONTENT OF HAY TO 20%

Treatments	Check	Penetrated	Smashed	Twisted	Crushed	2 in.	6 in.	10 in.
				Hours				
Time required to reach 20% M.C.	45	22	28	29	20	36	More than 48	

In Table X is shown the time required for the different treatments to reach a moisture content of 20 percent.

When studying this table it should be remembered that this research was conducted in constant temperature room at

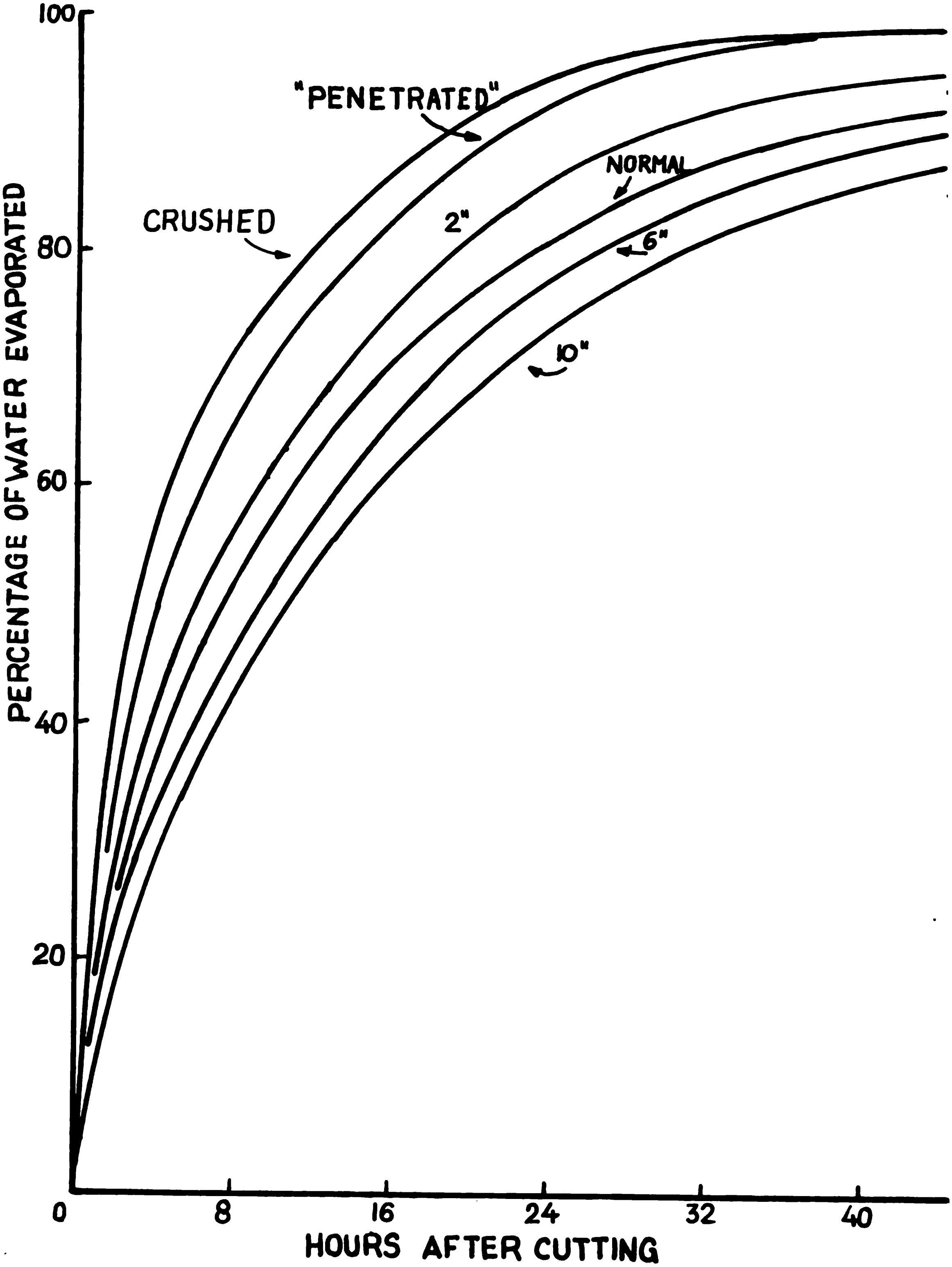

Figure 3. Drying curves for alfalfa plants treated in different ways.

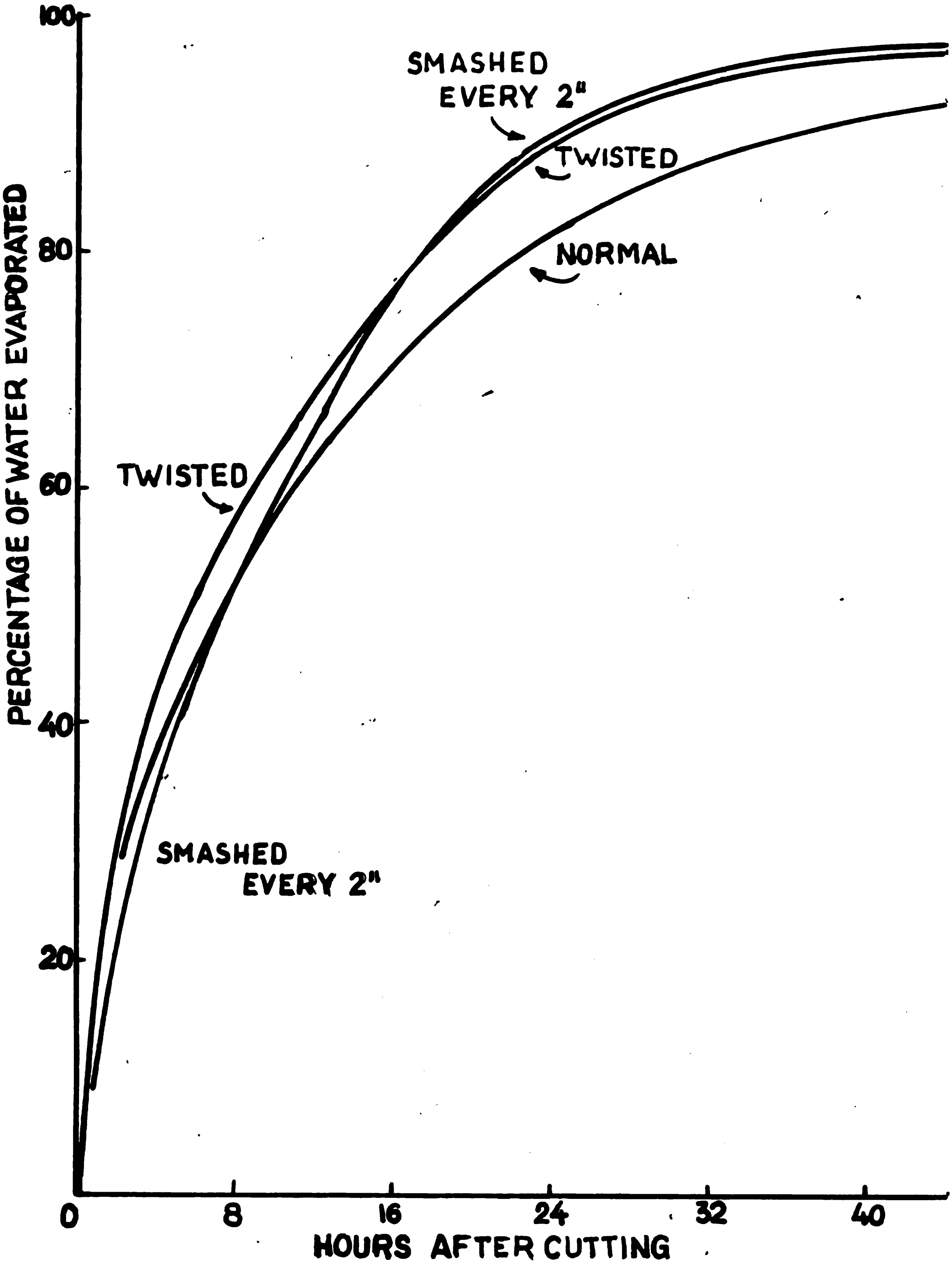

Figure 4. Drying curves for alfalfa plants treated in different ways.

84 degrees F and a relative humidity of 68 percent. On a good haying day the drying conditions are better and should result in a shorter drying time.

Differences In The Evaporation Rate From Leaves And Stems.

As mentioned before, under normal curing conditions leaves always dry much faster than the stems (USDA, 1948). Research has shown that when the crop has dried to an average moisture content of 25 percent, the leaves will be at approximately 15 percent and the stems at approximately 35 percent moisture. This differential in drying rate is one of the factors that causes a considerable loss of leaves and even a greater decrease in feeding value of the hay.

In order to determine the influence of the different treatments on the rate of evaporation from leaves and stems separately, an experiment similar to the previous one was conducted. In this case, the leaves were separated from the stems immediately after the treatments were finished. The treatments were the same as in the previous research.

Discussion of Results

The curves of evaporation obtained from this research are shown in Figure 5 through 11. They indicate that only when the stem surface was nearly disintegrated (hard crushed or "penetrated"), the rate of evaporation from the stems approached that of the leaves.

The drying rate curves for leaves showed high evaporation during the first and second hour after cutting. In the third hour of drying the evaporation was lower but still of considerable amount. An average 43.6 percent of the total moisture was evaporated during the first three hours after cutting. Between three hours after cutting and equilibrium moisture the evaporation rate (slope of curve) was nearly constant and considerably less than during the first hours of drying.

The constant decrease in drying rate in leaves from one and one-half hours to three hours after cutting may be the result of the loss of surface openings caused by the progressive closing of stomata. On account of a decreasing turgor pressure in the guard cells most of the stomata may be closed after three hours of drying. After that the evaporation takes place only through the cuticle and possible wounds caused by mechanical treatments. On account of this and the fact that alfalfa leaves are very thin, it seems reasonable that the rate of evaporation is nearly constant until the moisture content reaches the point of equilibrium.

Table XI shows the number of hours required to dry the leaves and stems to 20 percent moisture. The leaves, the hard crushed and the "penetrated" stems dried to 20 percent in 18 to 21 hours. The alfalfa stems chopped in 2 inches length dried in 37 hours. All other treatments required more than 48 hours to reach this moisture content.

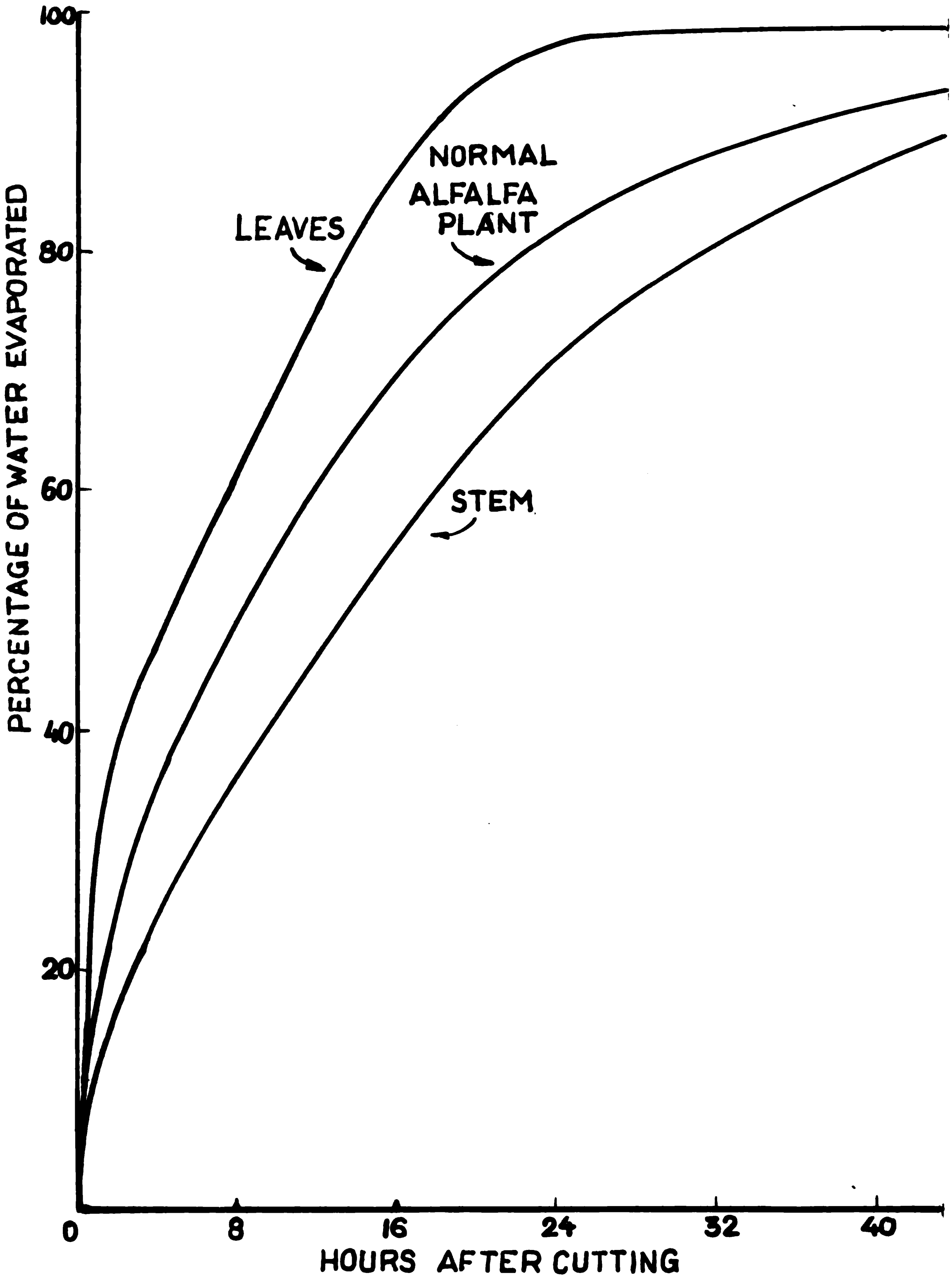

Figure 5. Drying curves for normal alfalfa plants, when leaves and stems are dried separately.

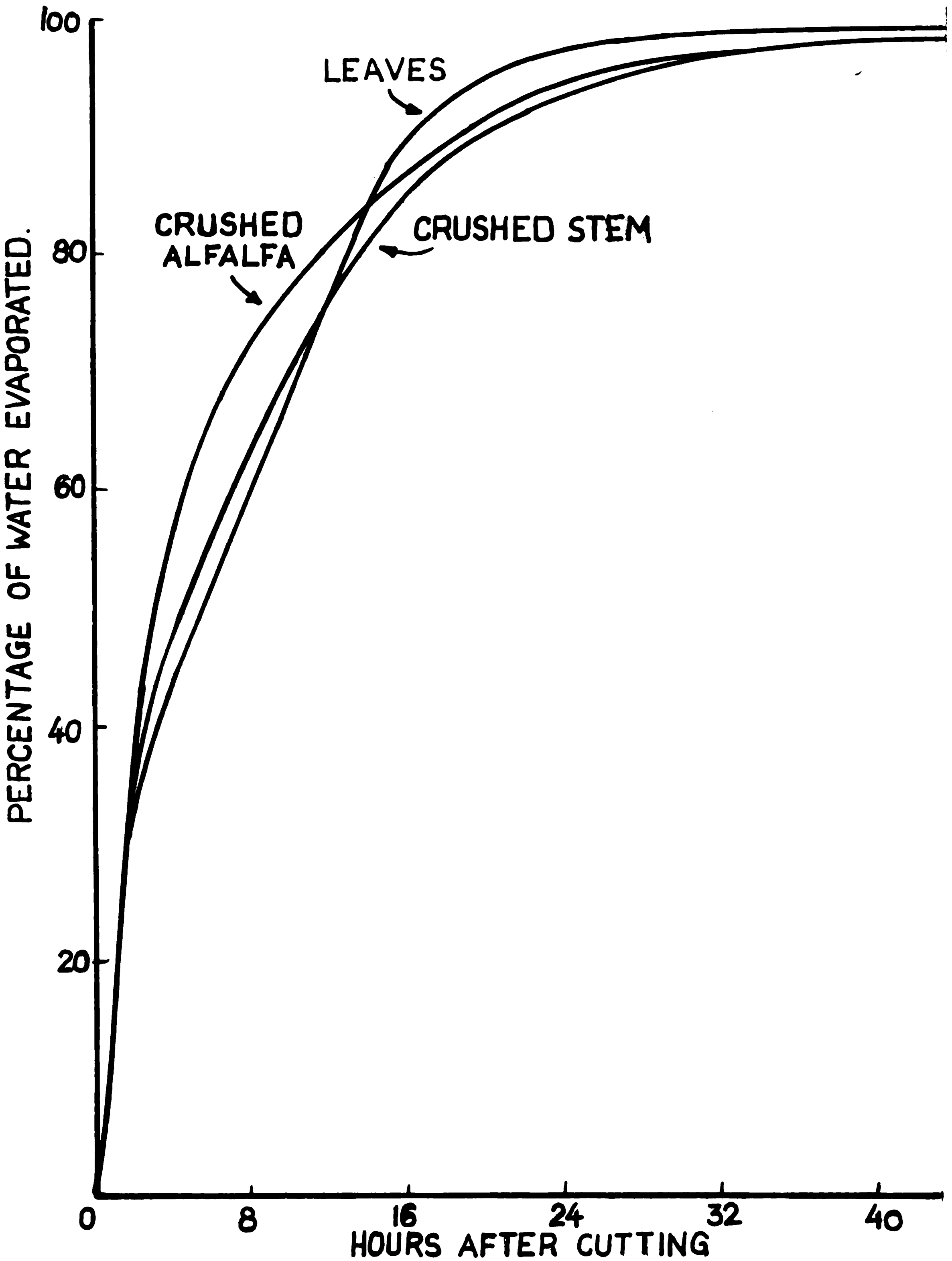

Figure 6. Drying curves for crushed alfalfa when leaves and stems are dried separately.

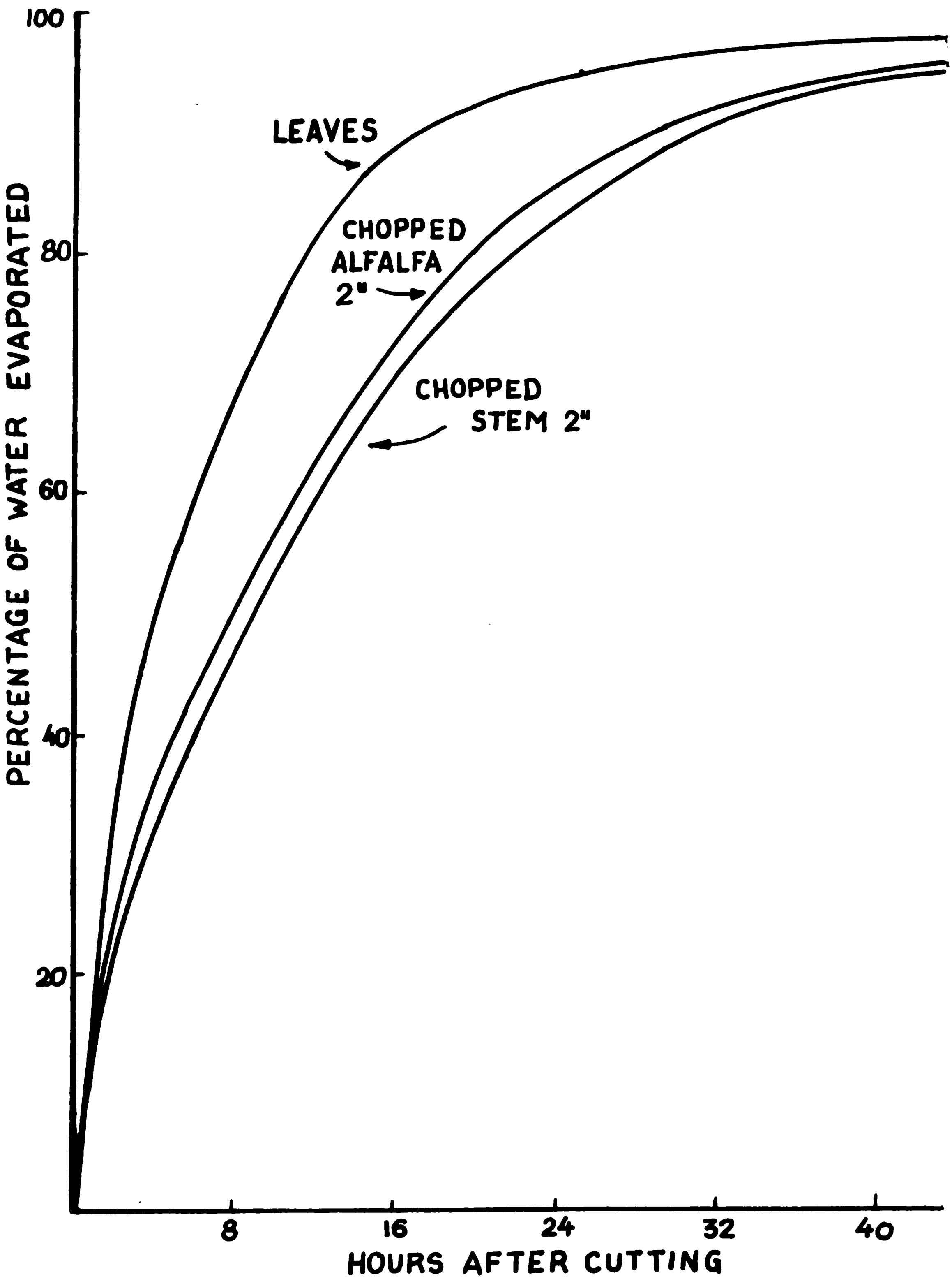

Figure 7. Drying curves for chopped alfalfa (2 inches) when leaves and stems are dried separately.

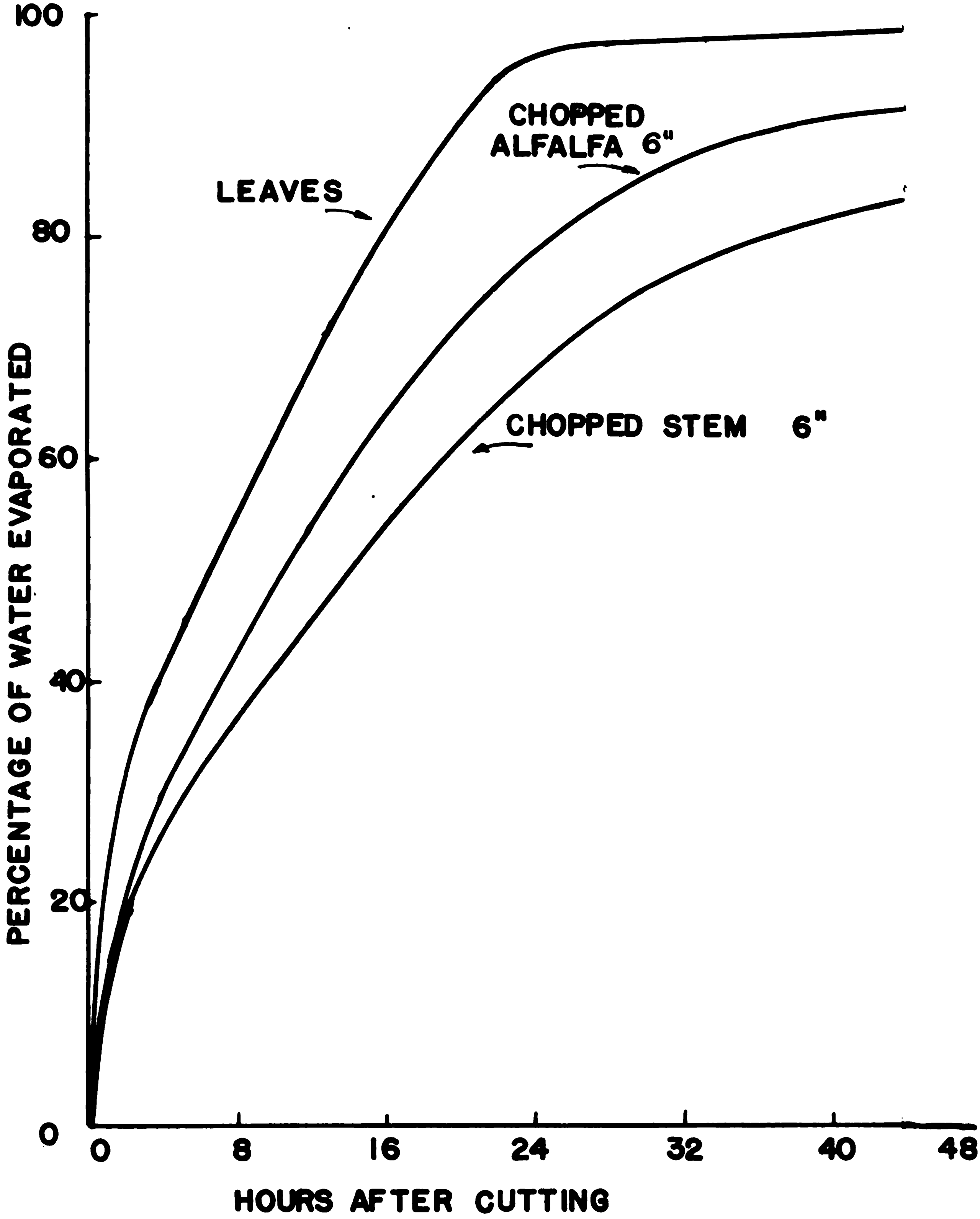

Figure 8. Drying curves for chopped alfalfa (6 inches) when leaves and stems are dried separately.

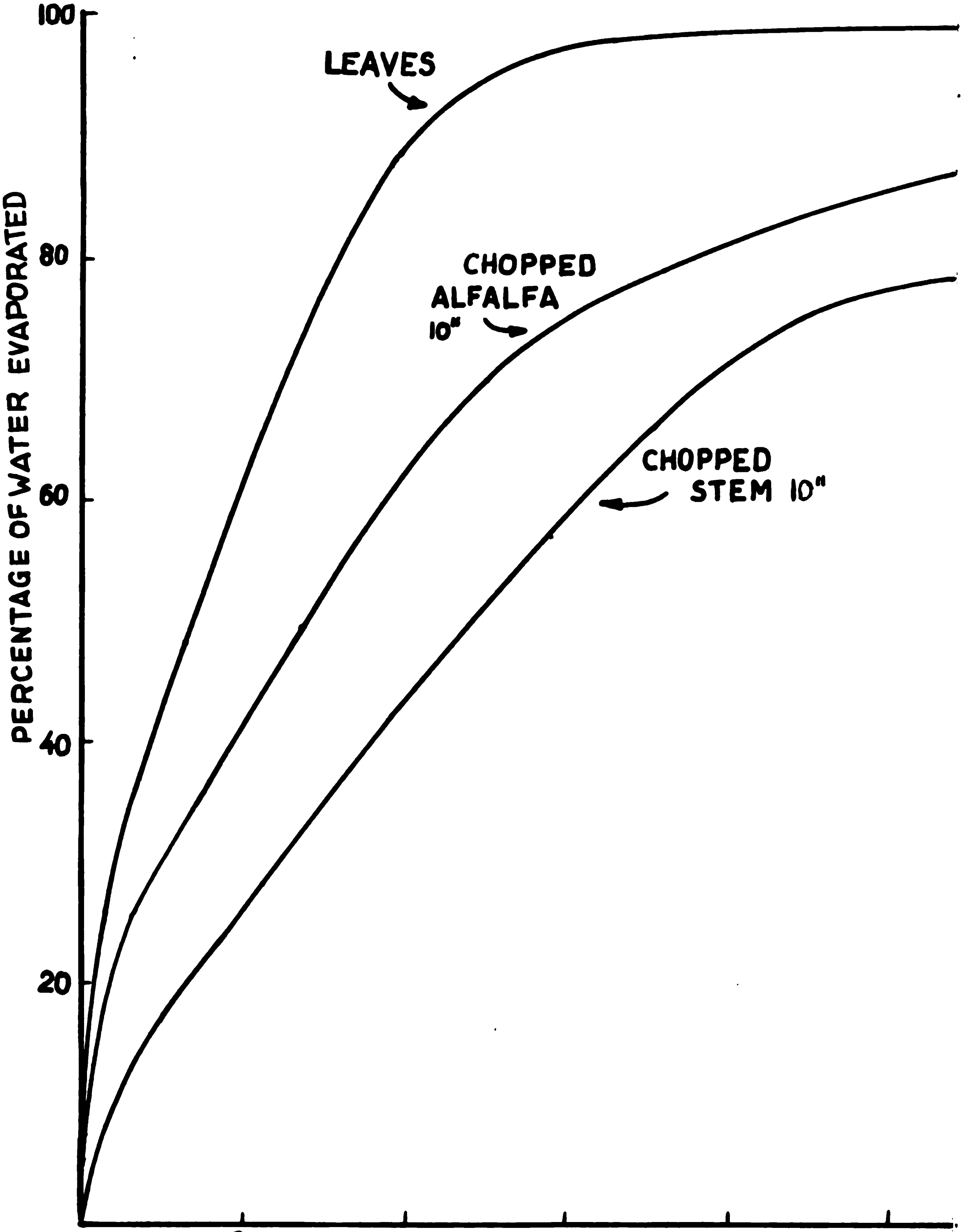

Figure 9. Drying curves for chopped alfalfa (10 inches) when leaves and stems are dried separately.

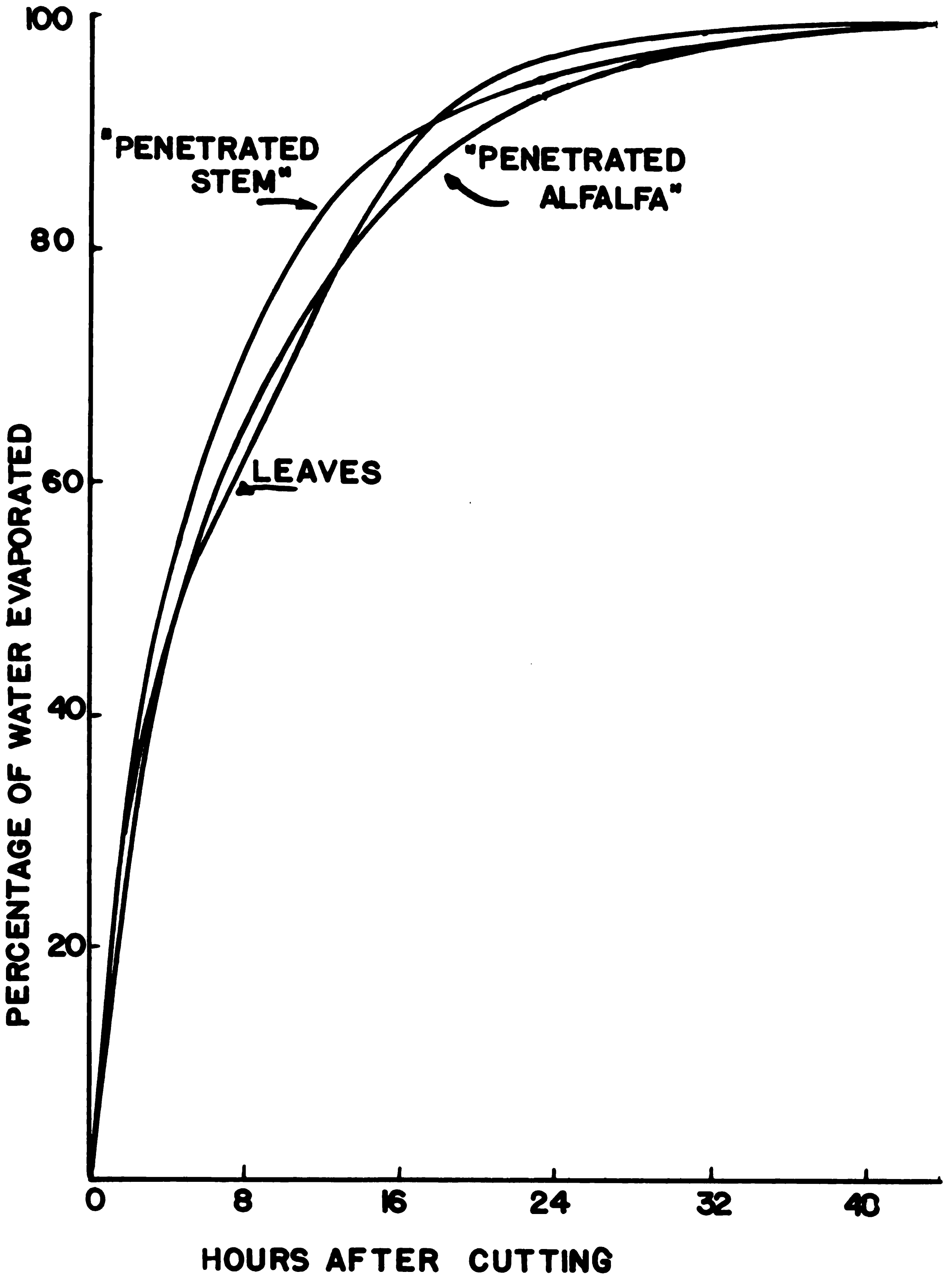

Figure 10. Drying curves for "penetrated" alfalfa when stems and leaves are dried separately.

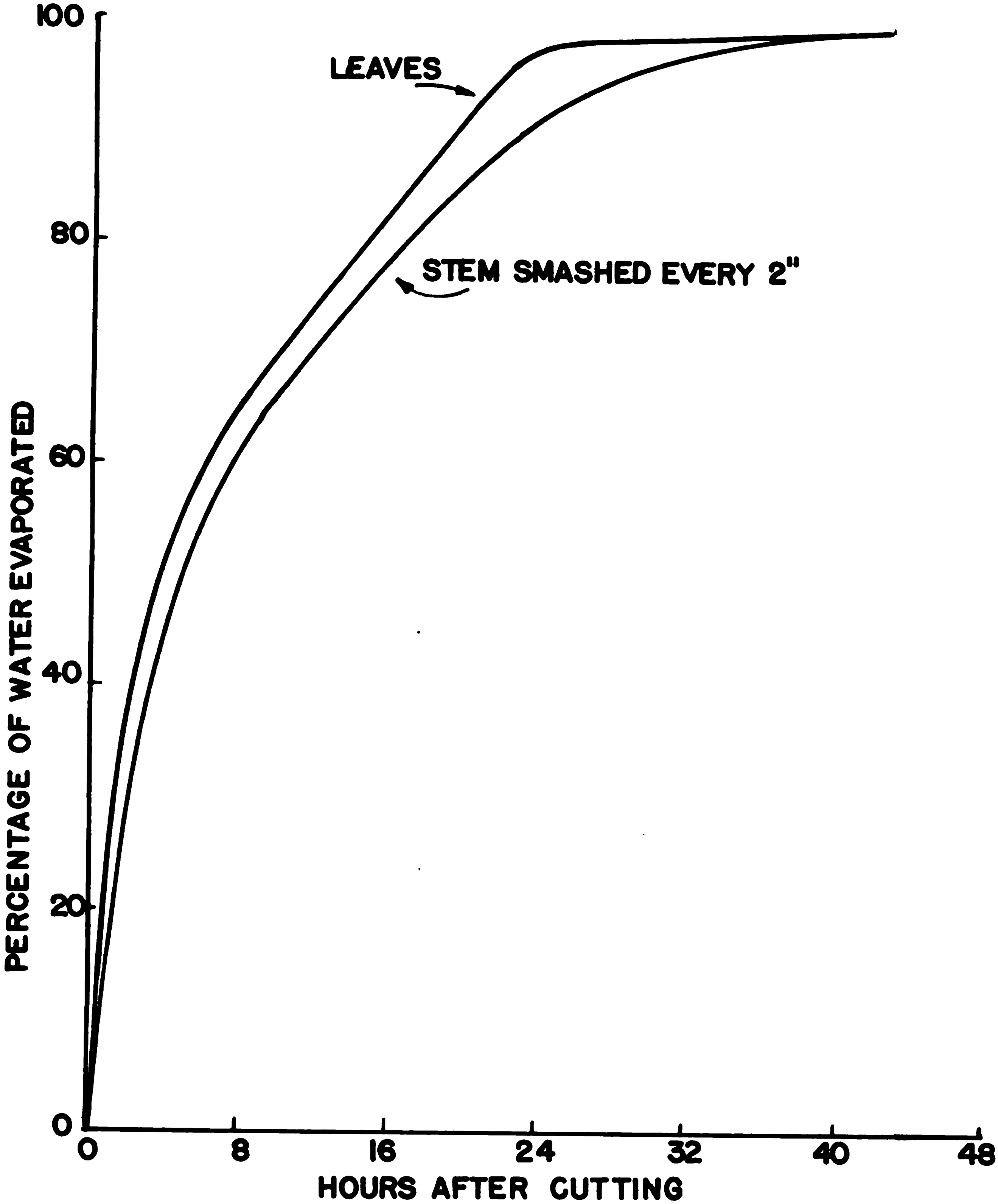

Figure 11. Drying curves for alfalfa with stems smashed every 2 inches when leaves and stems dried separately.

TABLE XI

TIME REQUIRED FOR SEPARATED LEAVES AND STEMS TO REACH 20 PERCENT MOISTURE CONTENT

Item	Check	Pene-trated	Smashed	Crushed	2 in.	6 in.	10 in.
				Hours			
Leaves	19	18	21	18	21	21	18
Stems	over 48	18	26	19	37	more than 48	

Drying Time For Alfalfa When The Leaves Are Separated From The Stem Versus Drying Time When The Stems And Leaves Are Dried As A Unit.

From the results of the previous experiments, the evaporation of leaves plus stems was computed. These were compared with those obtained from alfalfa plants dried as a whole plant.

The results are shown in Figure 12 through 17. In these figures the dashed curve represents the treatment -- leaves and stems dried separately. The full curve shows the results of leaves and stems drying as a normal plant.

These curves indicate that the drying time was the same for alfalfa hay, whether the leaves were dried together with the stems or they were dried separately. The assumptions or theories stated by different scientists (Palmer and Jones, 1932 and 1939) that the main portion of the water in the hay leaves the plant through the stomata of the leaves, are invalid. An analysis of the above data indicates that water was not translocated in the severed plant. Water located in the stem when the plant was mowed did not move to the leaf for evaporation but remained in the stem wall and was lost by evaporation through the stem. It should be remembered that by separating the leaves from the stems, open wounds were created at each place where a leaf was cut from the stem. This would naturally favor the evaporation rate of the stems as well as that of the leaves.

Sectional Drying Rates Of Alfalfa When Different Degrees Of Crushing Are Applied.

An experiment was conducted to determine the path of water movement in the alfalfa stem during the drying process. The research conducted by Jones and Palmer (1932) on windrowing of alfalfa hay two hours after cutting does not answer the question, "Does the water move radial to the surface of the stem during the drying, or does the main part of the water move longitudinal in the stem, following the natural ways for transporting water in the green alfalfa plant?".

Following degrees of crushing were applied to the alfalfa plant:

1) Uncrushed alfalfa.

2) Crushed alfalfa (similar to that done by a commercial hay crusher).

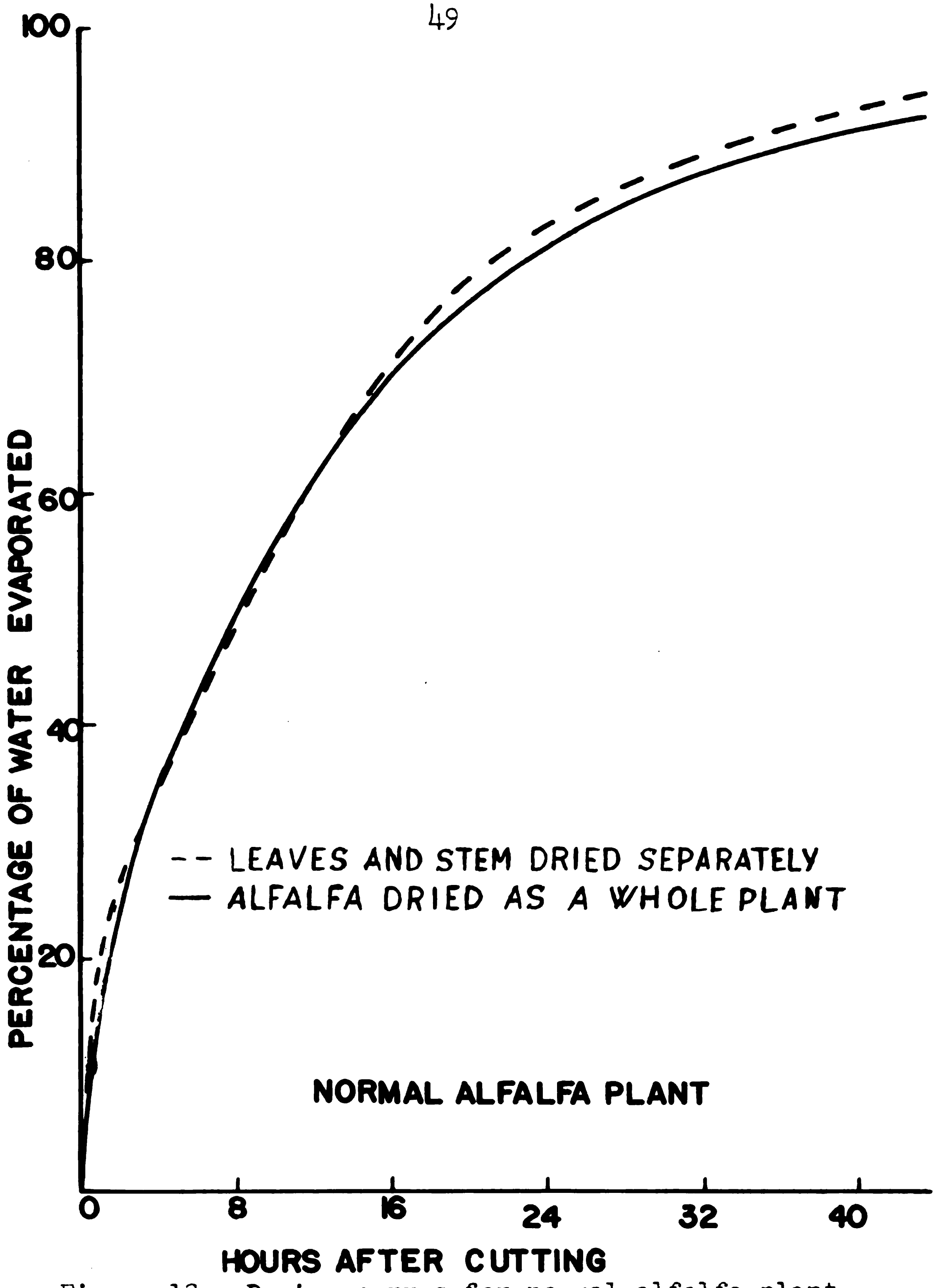

Figure 12. Drying curves for normal alfalfa plant.

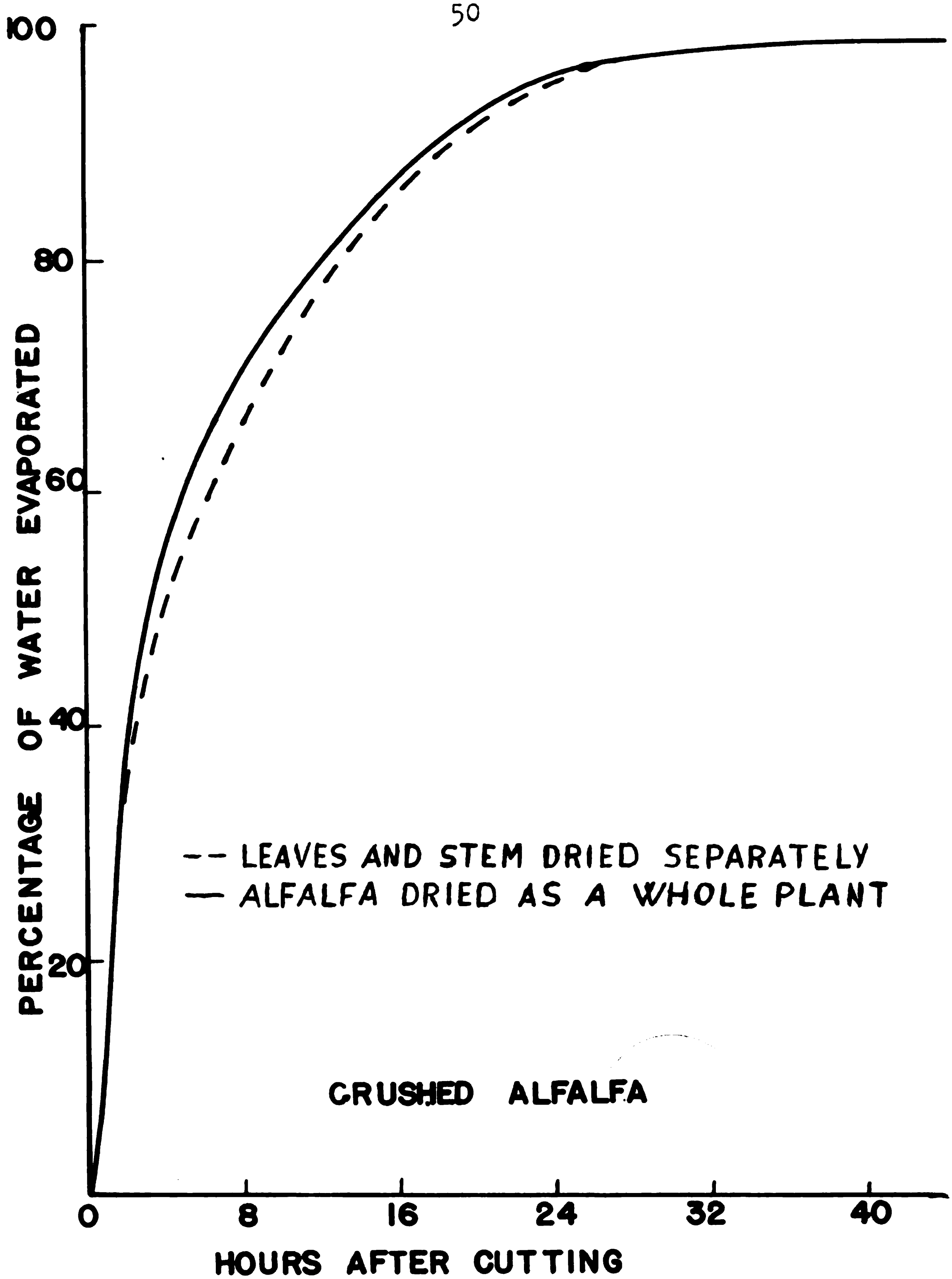

Figure 13. Drying curves for crushed alfalfa.

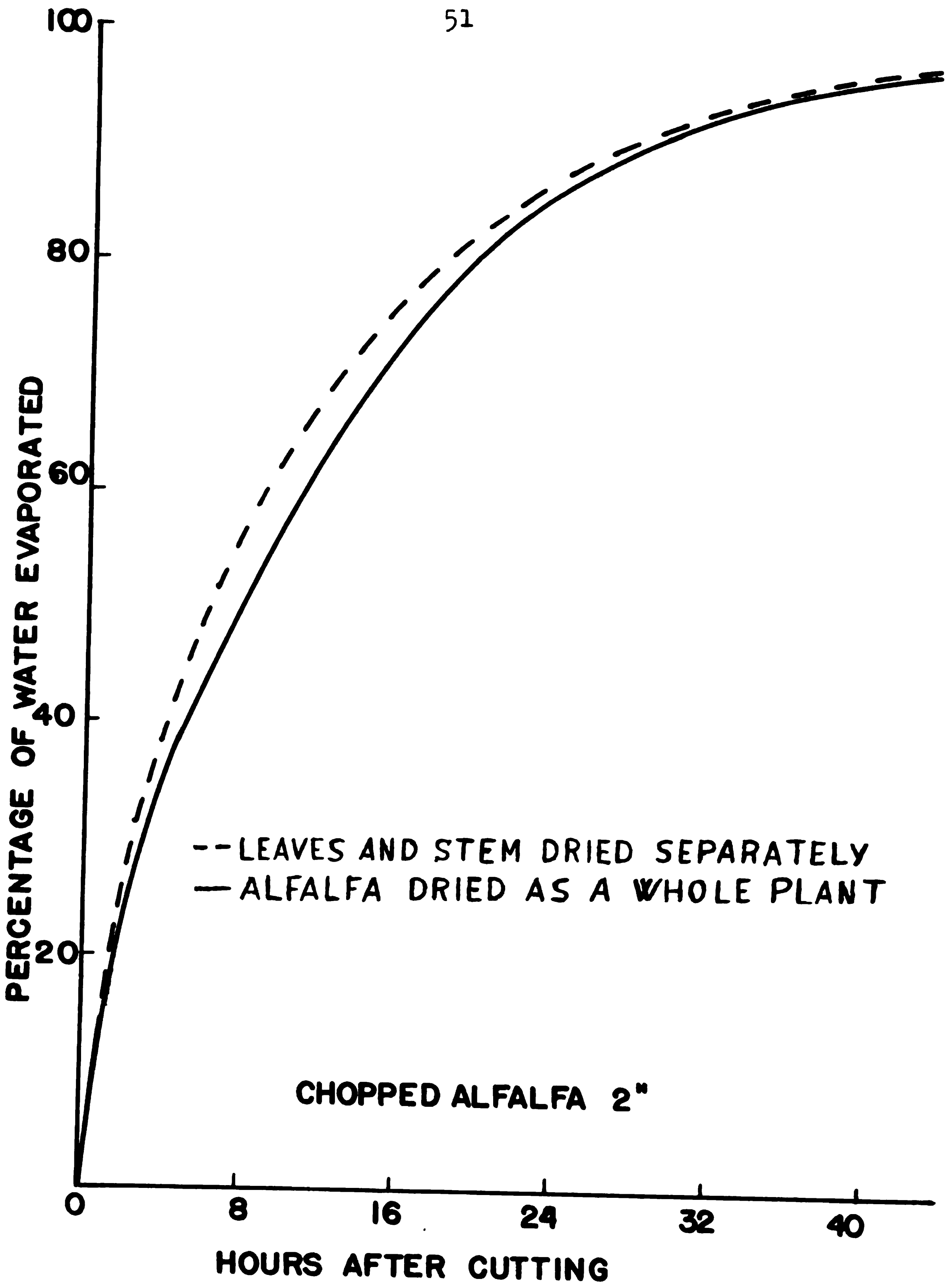

Figure 14. Drying curves for alfalfa chopped in lengths of 2 inches.

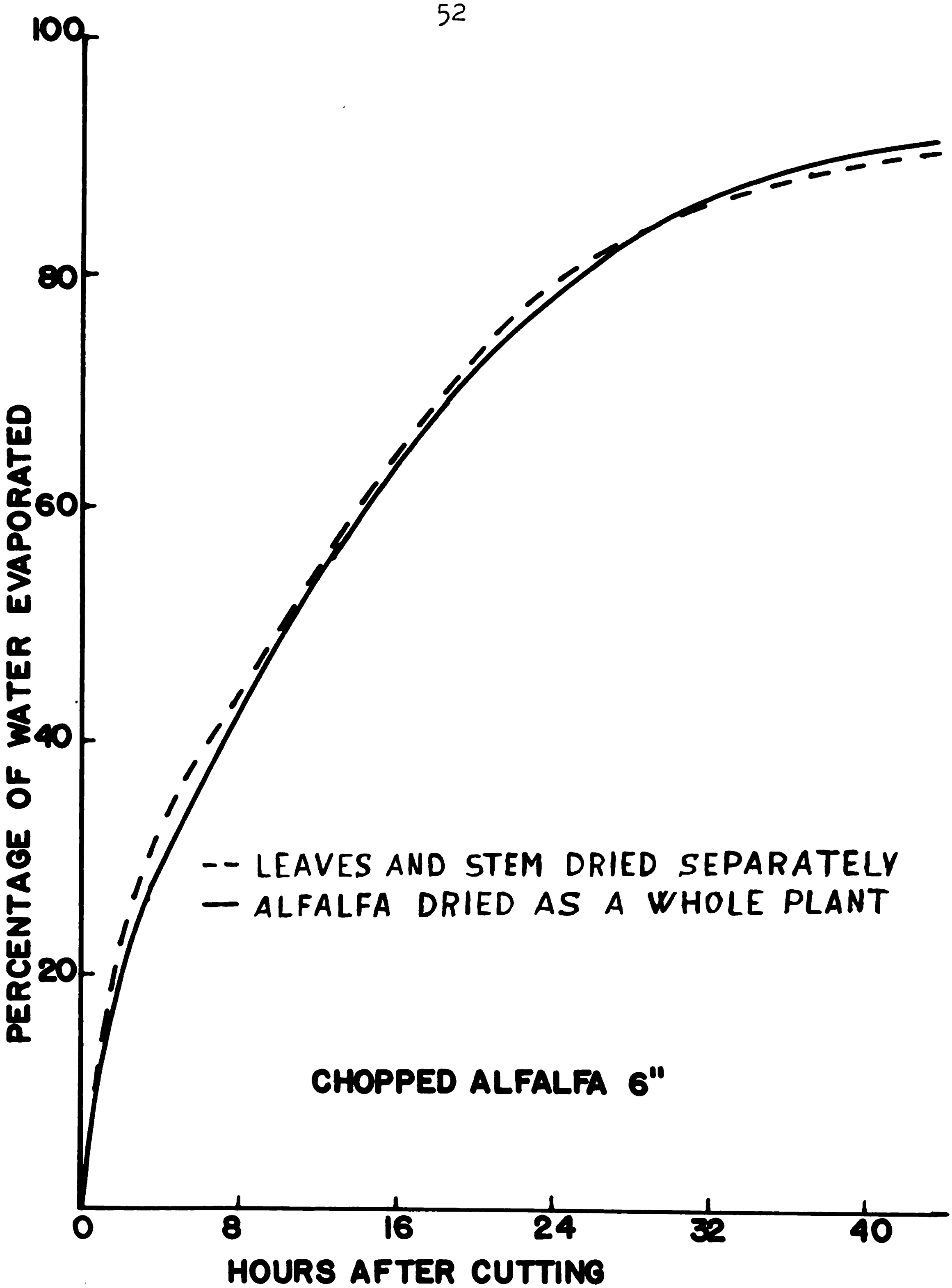

Figure 15. Drying curves for alfalfa chopped in lengths of 6 inches.

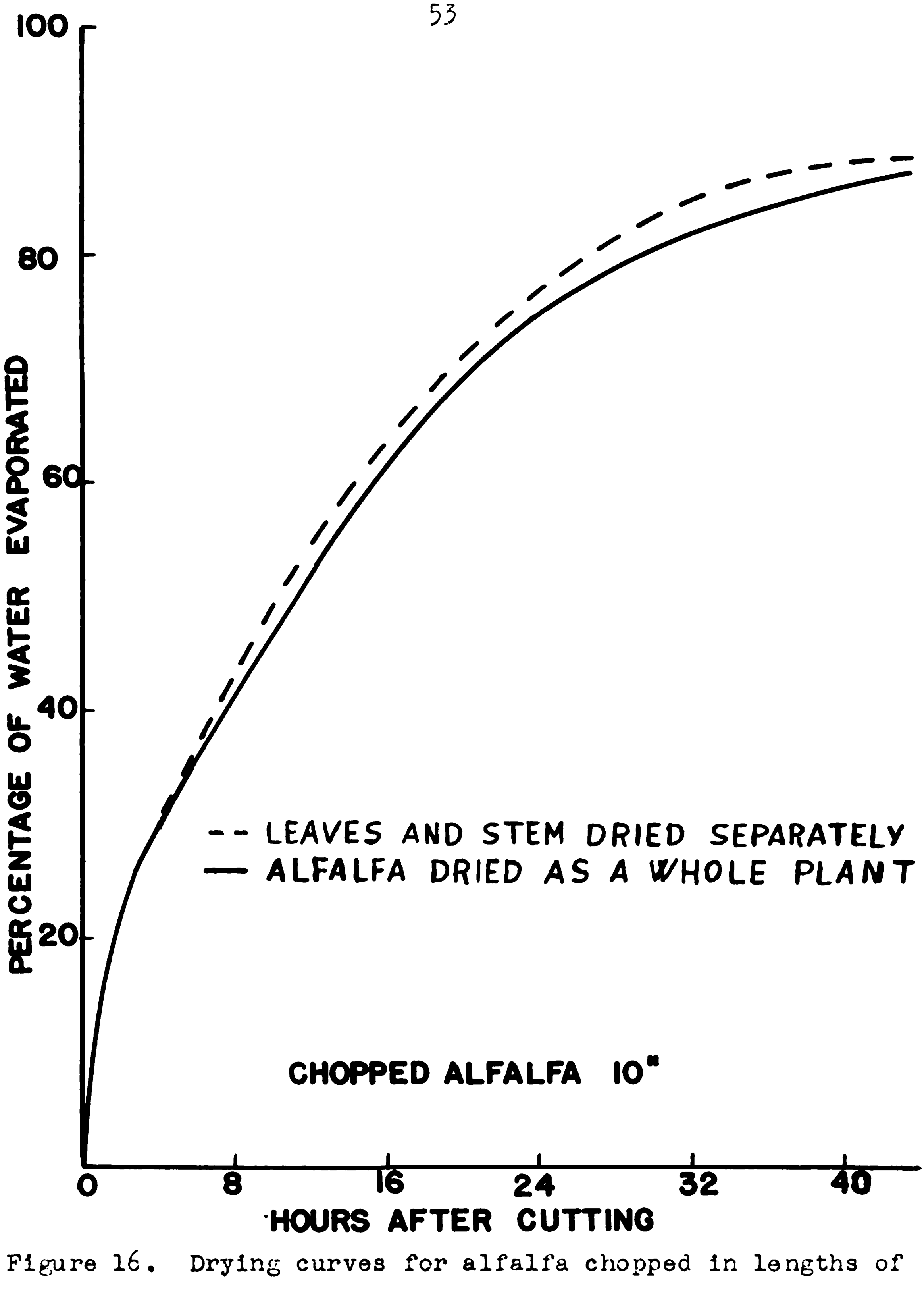

Figure 16. Drying curves for alfalfa chopped in lengths of 10 inches.

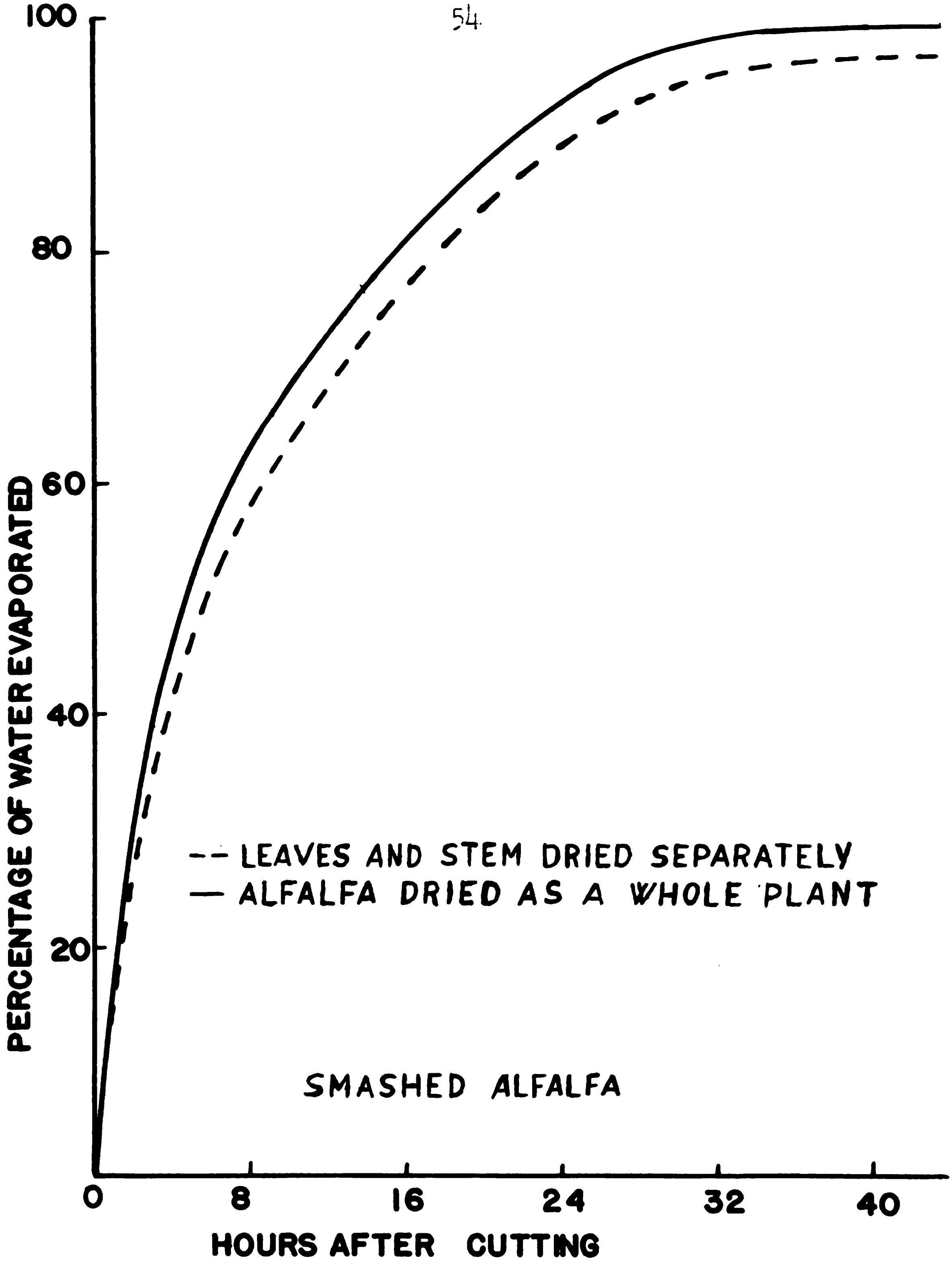

Figure 17. Drying curves for alfalfa "smashed" every 2 inches.

3) Hard crushed alfalfa (considerable amounts of juice appearing on the stem surface).

To get uniform drying conditions throughout the whole research period the experiment was conducted in the research laboratory at a constant temperature of 84 degrees F and a relative humidity of 59 percent. The moisture content was determined after 0, 2, 7, 12, 23, 28, 48 and 144 hours of drying. Immediately before each moisture determination the leaves were separated from the stem, and the remaining stems were divided into four groups according to the distance from the top end of the stem. The stem pieces from the different groups were collected and the moisture content was determined separately for each stem section. The alfalfa plants used in the experiment were all of the same maturity and had a uniform length of 22 inches.

Discussion of Results

Table XII shows the results of the experiment. The data indicate that both degrees of crushing applied in the experiment increased the drying rates of stems as well as leaves. The drying rates of the stems was, however, increased considerably more than that of the leaves. This was especially true for the hard crushed alfalfa; here the stems dried out quicker than the leaves.

The experiment shows that the moisture movement in the stem was mainly radial; only in the case of the uncrushed alfalfa did a small longitudinal movement take place. For

TABLE XII

THE MOISTURE CONTENT IN DIFFERENT SECTIONS OF THE ALFALFA PLANT THROUGHOUT THE DRYING TIME.

Hours of drying	Treatment	Section of plant (inches from top)				
		Leaves	0-6	6-12	12-18	18-22
		Percent moisture (w.b.)				
0	Uncrushed	70.2	72.2	70.7	69.3	66.8
2	Uncrushed	67.1	67.7	67.3	66.1	57.6
	Crushed	67.6	67.2	65.1	60.3	60.1
	Hard crushed	66.1	57.8	57.4	52.7	53.4
7	Uncrushed	63.7	64.5	63.8	62.0	55.1
	Crushed	59.1	61.6	60.1	59.6	56.4
	Hard crushed	47.4	37.4	34.9	22.0	25.9
12	Uncrushed	61.7	63.3	62.0	61.3	54.0
	Crushed	49.0	50.4	43.2	39.6	37.2
	Hard crushed	32.9	25.1	17.0	10.9	9.7
23	Uncrushed	37.8	49.8	49.6	46.9	46.6
	Crushed	31.7	30.4	25.6	14.9	15.4
	Hard crushed	18.3	16.3	11.7	10.4	9.9
28	Uncrushed	25.5	46.0	45.9	39.2	32.1
	Crushed	26.3	30.6	23.1	11.2	11.6
	Hard crushed	11.4	11.0	10.2	10.1	9.7
48	Uncrushed	12.9	37.5	39.7	35.1	22.6
	Crushed	9.2	14.4	14.0	10.9	8.7
	Hard crushed	8.4	8.7	8.4	7.3	7.2
144	Uncrushed	7.7	7.8	7.6	7.6	7.7

this treatment the difference in moisture content between the upper and lower part of the stem was 9.5 percent at the time of cutting, while the same difference was 14.9 percent after 48 hours of drying; and, furthermore, at the latter time the highest moisture content occurs in the middle section of the plant. A comparison of the moisture content of uncrushed alfalfa at 0 and 48 hours of drying also indicated that the greatest longitudinal water movement took place in the lower stem portions.

INVESTIGATIONS OF THE SUMMER OF 1958

Evaporation From The Soil And Its Influence On The Drying Rate Of Alfalfa.

An analysis of the results of the experiments previously described indicated that the most effective method of decreasing the drying time mechanically was obtained by crushing the plant to such a degree that the outer cell layer was nearly completely destroyed. This method in itself, however, did not increase the drying rate to the extent that hay can be cut, conditioned and field dried in one day under Michigan conditions. Even when "complete" crushing was applied, the hay would still have to be left in the field overnight and thereby exposed to the damage of dew, or it would have to be artificially dried. It therefore seemed natural next to analyze the surroundings in which alfalfa is dried in the field.

After cutting, the hay lies on the ground for drying. The soil contains moisture which is continually being lost to the atmosphere by evaporation. This moisture raises the relative humidity of the soil surface air, and tends to slow down the drying rate. During parts of the day and night the hay may gain moisture from the high humidity air. When the hay is placed in the swath for curing, the water vapor generated from the soil can escape only through the layer of hay, and thereby cause a decrease in vapor pressure differential between the hay and the air surrounding it. In Michigan, the soil is often near field capacity when the first cutting of alfalfa is harvested.

An experiment was conducted in which hay was placed on soils with two different moisture contents; air dry soil containing 4.3 percent moisture, and soil with a moisture content of 15.0 percent. Half the area of both these soils was covered with transparent polyethylene, impermeable to water vapor. Uncrushed and hard crushed alfalfa were dried on these soils. The research was carried out in the research laboratory in order to get uniform drying conditions throughout the whole drying period.

The results from the experiment are given in the curves of Figure 18 and Table XIII. The curves in Figure 18 represent the percentages of total water in the green plant evaporated at a given time. They indicate that there was little or no difference in the drying rates of hay when it was dried on air dry soil, air dry soil and wet soil covered with polyethylene. The air dry soil under the hay seemed to have increased the drying rate a small amount. The difference between the three treatments, however, was so small that it would not have any practical influence on the drying time. For this reason the curve drawn, is the average line for the three; the maximum deviation from this did not exceed two percent.

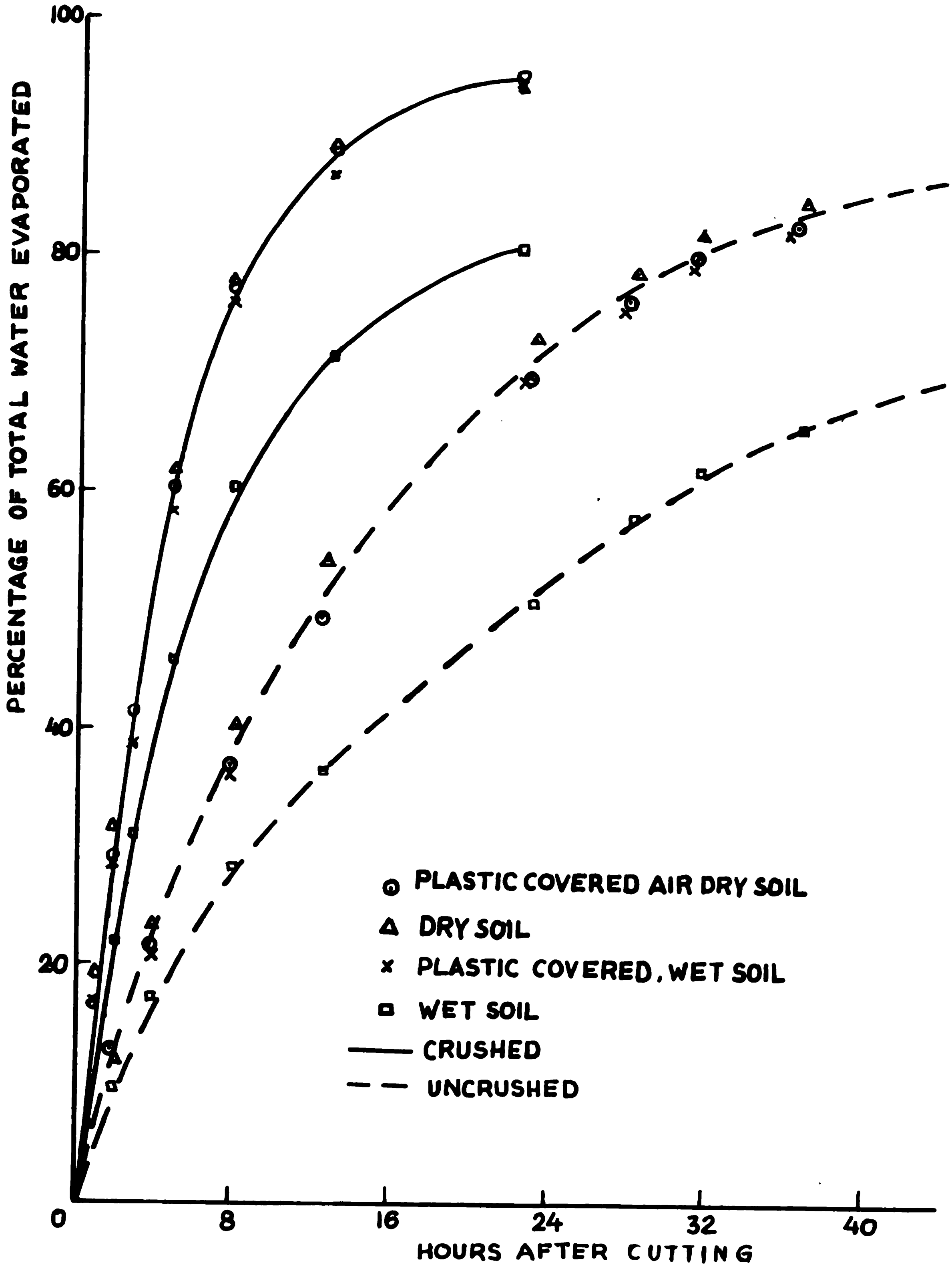

Figure 18. The influence of evaporation from the soil on the drying rate of alfalfa.

The difference between these treatments and that of drying the hay directly on the soil containing 15 percent moisture was considerable. After 22 hours of drying, 80 percent of the water was evaporated from the hard crushed alfalfa on wet soil, while the corresponding number was 94 percent for hay placed on dry soil or polyethylene covered soil. For the uncrushed samples the difference was even greater, although not nearly as much water had been evaporated.

TABLE XIII

THE MOISTURE CONTENT (W.B.) IN THE DIFFERENT SAMPLES AFTER 8 AND 22½ HOURS OF DRYING.

Treatment	Hours of drying 8	22½
	Moisture content in percent (w.b.)	
Crushed + dry soil - polyethylene	43.4	16.7
Crushed + dry soil	43.4	14.1
Crushed + wet soil - polyethylene	45.2	15.2
Crushed + wet soil	58.1	40.3
Uncrushed + dry soil - polyethylene	68.6	52.5
Uncrushed + dry soil	67.4	50.6
Uncrushed + wet soil - polyethylene	67.0	52.4
Uncrushed + wet soil	71.3	63.7

Comparison of the figures in Table XIII (22½ hours of drying) shows that covering wet soil with a sheet, impermeable to water vapor, caused the hay to dry to approximately 15 percent in $22\frac{1}{2}$ hours, when it was hard crushed, while the uncrushed hay had reached a moisture content of only 52 percent. The corresponding figures for hay on wet soil were 40.3 and 63.7, respectively.

The experiment clearly indicates that it was possible to reduce the drying time in the field by eliminating the influence of a moist drying bed. When studying these data it should be remembered that it was a laboratory experiment. The drying time in the field can be expected to be considerably shorter on account of the influence of solar radiation and greater air movement through the sample.

Effect Of Vapor Barriers Upon Field Drying Rates.

The experiments presented above have shown that hard crushed hay dried quickest when the influence of evaporation from wet soil was eliminated.

In order to take advantage of the solar energy, this experiment was conducted in the field. The alfalfa was cut at 8:30 a.m. The crushing of the alfalfa in this and the remaining experiments was conducted on a model hay crusher constructed by Dr. James L. Butler (1958). The crushing unit consists of two cylindrical rollers with a smooth surface. Contrary to the conventional hay crushers, where the rollers are spring loaded, this model crusher was constructed in such a way that the clearance between the rollers is variable and can be fixed at any chosen clearance.

The following treatments were applied to the alfalfa:

1) Hard crushed (a severe crushing where the distance between the rollers was fixed with a clearance of less than 0.010 inch), and placed on black polyethylene.

2) Hard crushed and placed on transparent polyethylene.

3) Crushed (this crushing approximately equal to that of a commercial hay crusher) and placed on black polyethylene.

4) Crushed and placed on transparent polyethylene.

5) Crushed and placed on the ground.

6) Uncrushed and placed on black polyethylene.

7) Uncrushed and placed on transparent polyethylene.

8) Uncrushed and placed on the ground.

All the treatments were applied less than half an hour after cutting. The alfalfa was placed on the different drying beds in such a way that 200 grams of green material covered one square foot. Moisture content determinations were carried out after 1, 2, 3.5, 5, 6.5, 8, 9.5, 23, 24, 27, 30, 32, 47, 49, 51 and 55 hours of drying. At the same time that the moisture contents were determined, measurements were taken of the sample temperature, the surface temperature of the polyethylene, the temperature of the air, and the relative humidity of the air. The temperature of the air and the relative humidity was measured 6 inches above the ground.

Discussion of Results

The results of this experiment are shown in Figure 19, Table XIV, and Table XV. In Figure 19, moisture content in percent (dry basis) is plotted versus drying time on semi-log paper. An analysis of the graph for hard crushed alfalfa shows that the drying rate is nearly constant to 25 percent moisture (= 20 percent wet basis). When artificial drying is applied to material, this is usually not the case. It should, however, be remembered that when drying is conducted in the field, the relative humidity in the air decreases from sunrise to mid-afternoon. If the drying of the product can be completed during the time of decreasing relative humidity, the vapor pressure differential between the hay and the surrounding air will continually increase. This is the reason for obtaining a more constant drying rate, than if the relative humidity of the drying air was held constant throughout the entire drying time.

Only in the case of hard crushed alfalfa on black and transparent polyethylene was it possible to obtain a moisture content of 20 percent (w.b.) within the period of decreasing vapor pressure of the air. In Table XIV is shown the number of hours required to reach a moisture content of 20 percent (w.b.).

None of the checks on the ground reached a moisture content of 20 percent (w.b.) within three days of drying. At 4:30 p.m. of the third day the crushed sample showed a mois-

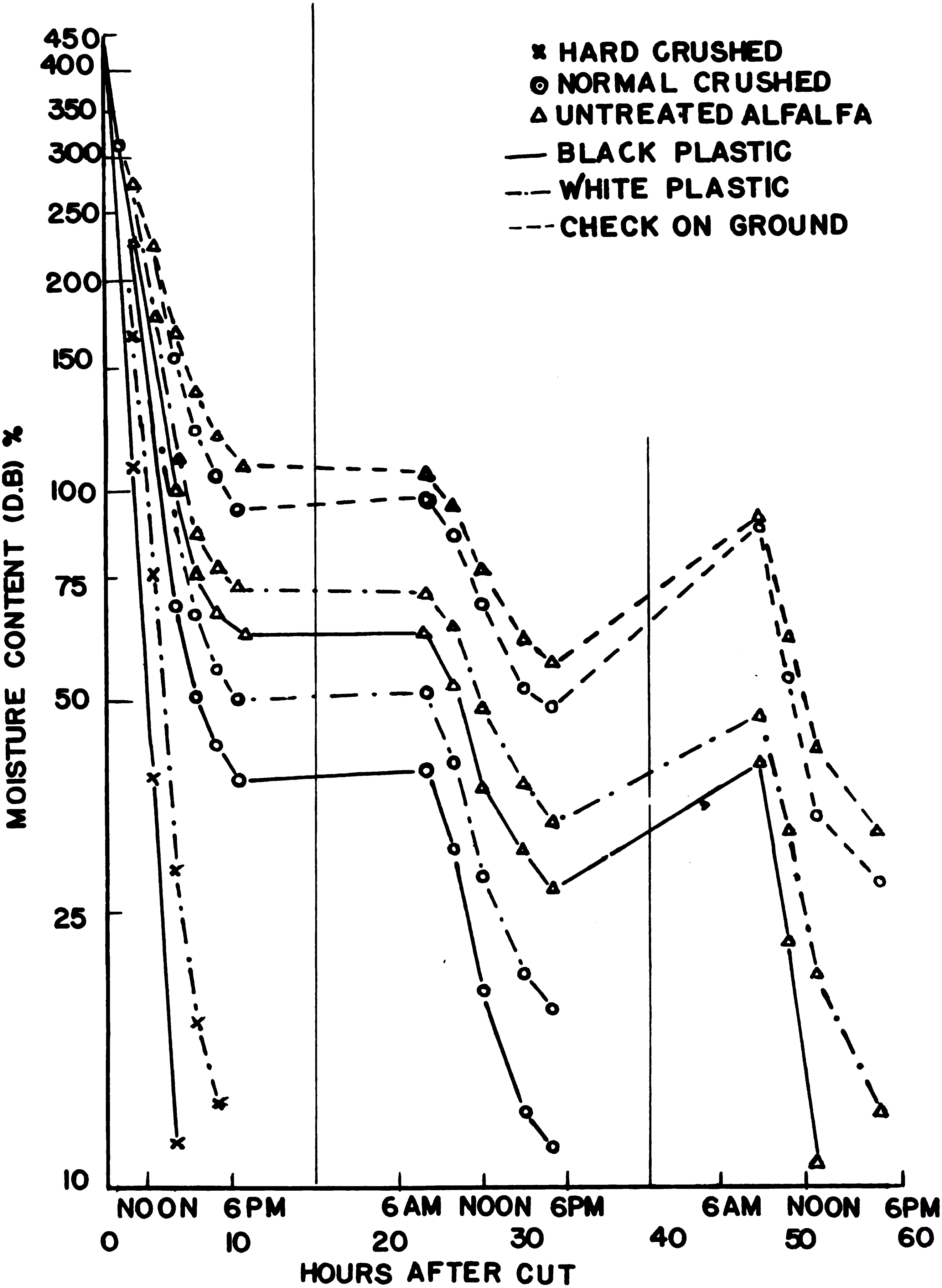

Figure 19. The effect of vapor barriers upon field drying rates.

ture content of 21.6 percent (w.b.), that of the uncrushed 24.5 percent (w.b.).

TABLE XIV

REQUIRED TIME FOR THE DIFFERENT TREATMENTS TO REACH A MOISTURE CONTENT OF 20 PERCENT (W.B.)

Treatment	Time
	Hours
Hard crushed alfalfa on black polyethylene	4.0
Hard crushed alfalfa on transparent polyethylene	6.5
Crushed alfalfa on black polyethylene	25.5
Crushed alfalfa on transparent polyethylene	28.5
Uncrushed alfalfa on black polyethylene	49.5
Uncrushed alfalfa on transparent polyethylene	51.5
Crushed alfalfa on ground	more than 56.0
Uncrushed alfalfa on ground	

Table XV sets forth the variation in temperature of the different hay samples, the surface temperature of the polyethylene, the temperature of the air, and the relative humidity of the air.

During the first day of the experiment, when the sun was shining, the energy received by the polyethylene by radiation was able to raise the surface temperature of the black and transparent plastic an average of 40.3 and 21.2 degrees F, respectively. The maximum temperature of the polyethylene

TABLE XV

THE TEMPERATURE OF HAY SAMPLES, SURFACE OF POLYETHYLENE, AIR, AND RELATIVE HUMIDITY OF THE AIR.

Time	Temperature in Degrees Fahrenheit											R.H. 6 in. above soil	Remarks
	Hay Sample								Plastic		Air		
	BHC*	BC*	BN*	THC*	TC*	TN*	CC*	CN*	B*	T*			
												%	
10am	85	86	93	81	89	90	79	75	111	94	77	51	
11am	83	106	106	83	98	105	83	80	122	99	77	45	
0:30pm	96	104	103	86	94	100	86	83	122	102	77	40	
2pm	98	114	114	97	105	108	93	89	122	99	77	39	
3:30pm	114	115	110	96	106	110	90	88	123	104	79	44	
5pm		100	101	88	98	96	88	85	108	95	79	54	
6:30pm		82	82		80	79	75	73	74	75	76	56	P.C.
8am		79	80		78	78	72	72	83	78	74	63	O.C.
10am		84	86		82	83	79	78	93	87	76	59	O.C.
12am		99	100		94	94	88	86	117	99	78	52	O.C.
3pm		101	101		95	96	88	88	114	104	80	57	H.
5pm		94	94		90	90	84	83	102	90	76	59	H.
8am			87			84	73	73	84	82	73	61	
10am			106			102	90	84	130	111	78	52	
12am			130			125	99	100	150	130	83	47	
4:30pm						94	89	88		96	81	47	

* B = Black polyethylene
T = Transparent polyethylene
HC = Hard crushed alfalfa sample
C = Crushed alfalfa sample
N = Uncrushed alfalfa sample
P.C. = Partly cloudy
O.C. = Overcast
H. = Haze

was obtained on the third day. The maximum temperature of the black polyethylene reached 150 degrees F and that of the transparent, 130 degrees F, which corresponded to an increase above the air temperature of 67 degrees F and 47 degrees F, respectively.

Even on the second day of the experiment, when it was partly cloudy or overcast the main part of the day, the increase in temperature was considerable. As an average it amounted to 24.2 degrees F and 16.4 degrees F for black and transparent polyethylene, respectively.

The radiation energy caused the temperature in the hay to rise above the temperature of the surrounding air. As it appears from Table XV this increase was largest for the hay placed on black polyethylene. It was somewhat lower for the sample on the transparent polyethylene, and lowest for the sample placed on the ground. No averages can be taken here because the rise in temperature depends on the amount of evaporation from the sample. When the evaporation from the hay was high, as it was in the case of the hard crushed sample on black and transparent polyethylene during the first two hours of drying, the increase in the sample temperature was relatively small. In this case most of the absorbed energy was apparently used for evaporation of water from the sample. As soon as the amount of water evaporated per unit time decreased, the sample temperature increased.

The Influence Of Swath Thickness On Drying Rate Of Hay Placed On Polyethylene.

The quantity of alfalfa, or the thickness of the layer of alfalfa, placed on the polyethylene sheet will obviously affect the drying rate. To determine the maximum amount of hay that could be placed per square foot of polyethylene and still be able to reach 20 percent moisture content within the same day as the hay was cut, the following initial weights of alfalfa were placed on black polyethylene:

1) 100 gram per sq. ft. (equal to 1.2 tons of 20 percent hay per acre)

2) 200 gram per sq. ft. (equal to 2.4 tons of 20 percent hay per acre)

3) 400 gram per sq. ft. (equal to 4.8 tons of 20 percent hay per acre)

4) 600 gram per sq. ft. (equal to 7.2 tons of 20 percent hay per acre)

5) 800 gram per sq. ft. (equal to 9.6 tons of 20 percent hay per acre)

These samples were all crushed with a clearance less than 0.010 inches between the rollers on the model crusher.

Discussion of Results

The result of this experiment is shown in Figure 20. The graphs indicate that all the samples reached a storable moisture content the same day as the hay was cut. This moisture level of 20 percent (w.b.) was obtained after field drying the following number of hours:

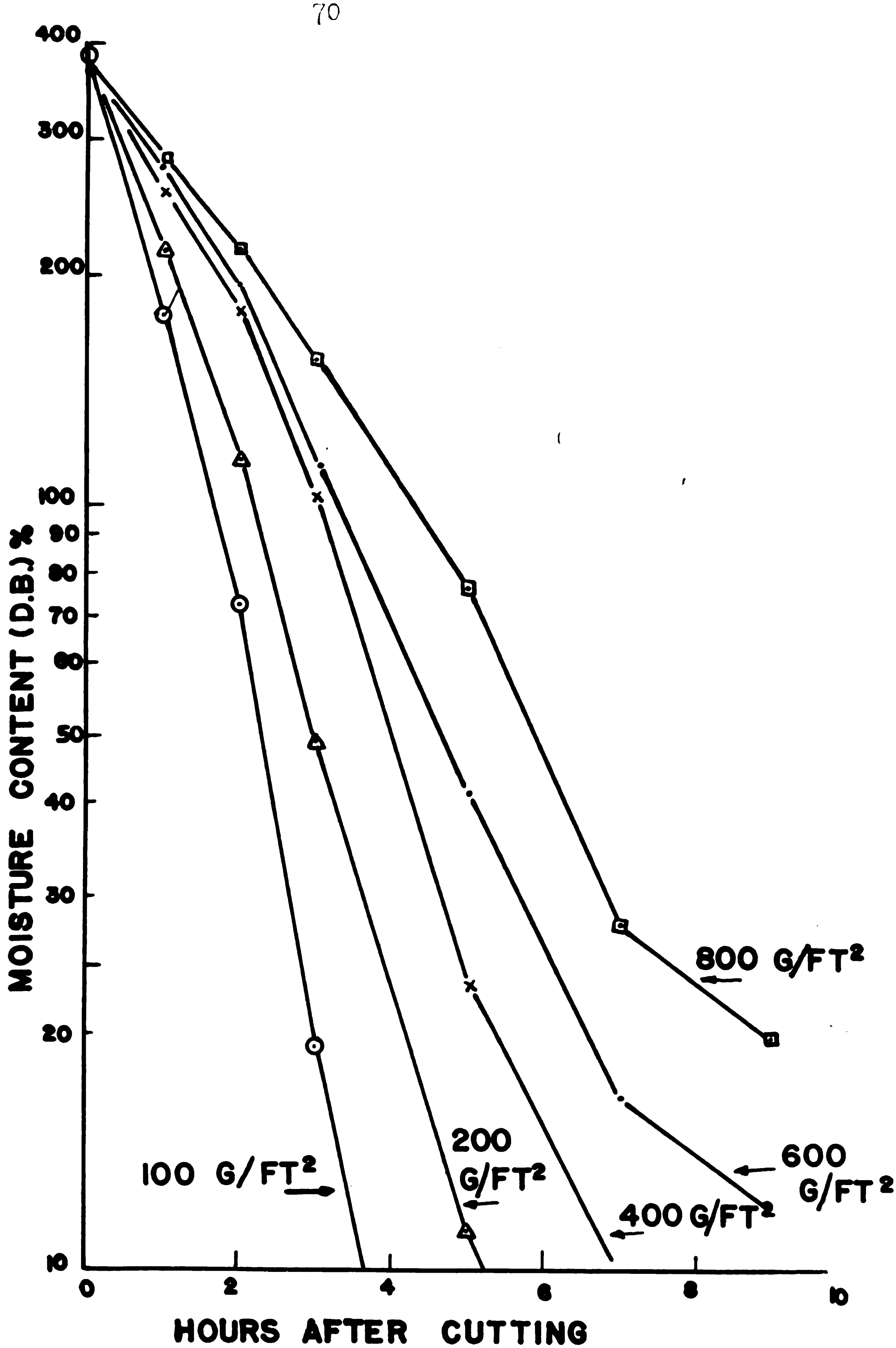

Figure 20. Drying curves for alfalfa when different initial amounts per sq. ft. are placed on black polyethylene.

100 gram sample after 2.8 hours

200 gram sample after 3.9 hours

400 gram sample after 5.0 hours

600 gram sample after 6.1 hours

800 gram sample after 7.7 hours

It is important to notice that even with an amount of hay equal to 7.2 tons of 20 percent hay per acre it was possible on a good drying day to store hay 6 hours after cutting. The results indicate that it would not be necessary to cover the whole field with polyethylene to dry the hay. A swath can be placed on a strip of polyethylene 1/3 to 1/2 the width of the mower cutterbar -- depending upon the yield of alfalfa.

In Table XVI is shown the climatical data which corresponds to the above discussed experiment.

TABLE XVI

THE TEMPERATURES OF HAY SAMPLES, SURFACE OF POLYETHYLENE, AIR, AND RELATIVE HUMIDITY OF THE AIR.

Time	Temperature in Degrees Fahrenheit							R.H. of Air
	Hay sample					Plastic	Air	
	100gr	200gr	400gr	600gr	800gr			
								%
10am	90	91	82	80	73	122	75	63
11am	100	87	82	80	76	136	77	47
12am	103	104	90	84	78	136	79	44
2pm	118	120	110	96	86	130	82	38
4pm		99	100	90	88	122	81	40
6pm			86	84	82	96	80	42

The Influence Of Degree Of Crushing On The Drying Rate Of Alfalfa.

This experiment was conducted to determine the degree of crushing needed to field dry alfalfa to storable moisture content the same day as it is cut. The hay was cut at 8:30 a.m. All the samples were dried on black polyethylene. The following clearances between the crushing rollers were used:

1) Less than 0.005 inch
2) 0.0125 inch
3) 0.0250 inch
4) 0.0500 inch
5) 0.1000 inch
6) Check (uncrushed sample)

Moisture determinations were made after 1, 2, 3.5, 5.5, and 6.5 hours of drying. The amount of initial green material placed on the polyethylene for drying was 300 grams per square foot, which corresponds to 3.6 tons per acre of hay with a moisture content of 20 percent (w.b.).

Discussion of results

Figure 21 indicates the results of this experiment. Only with clearances of less than approximately 0.015 inch between the rollers was it possible to dry the hay to a moisture content of 20 percent (w.b.) within the same day as it was cut. This moisture level was reached after 6.5 hours of drying for the hardest crushed sample, and after 8 hours for the sample

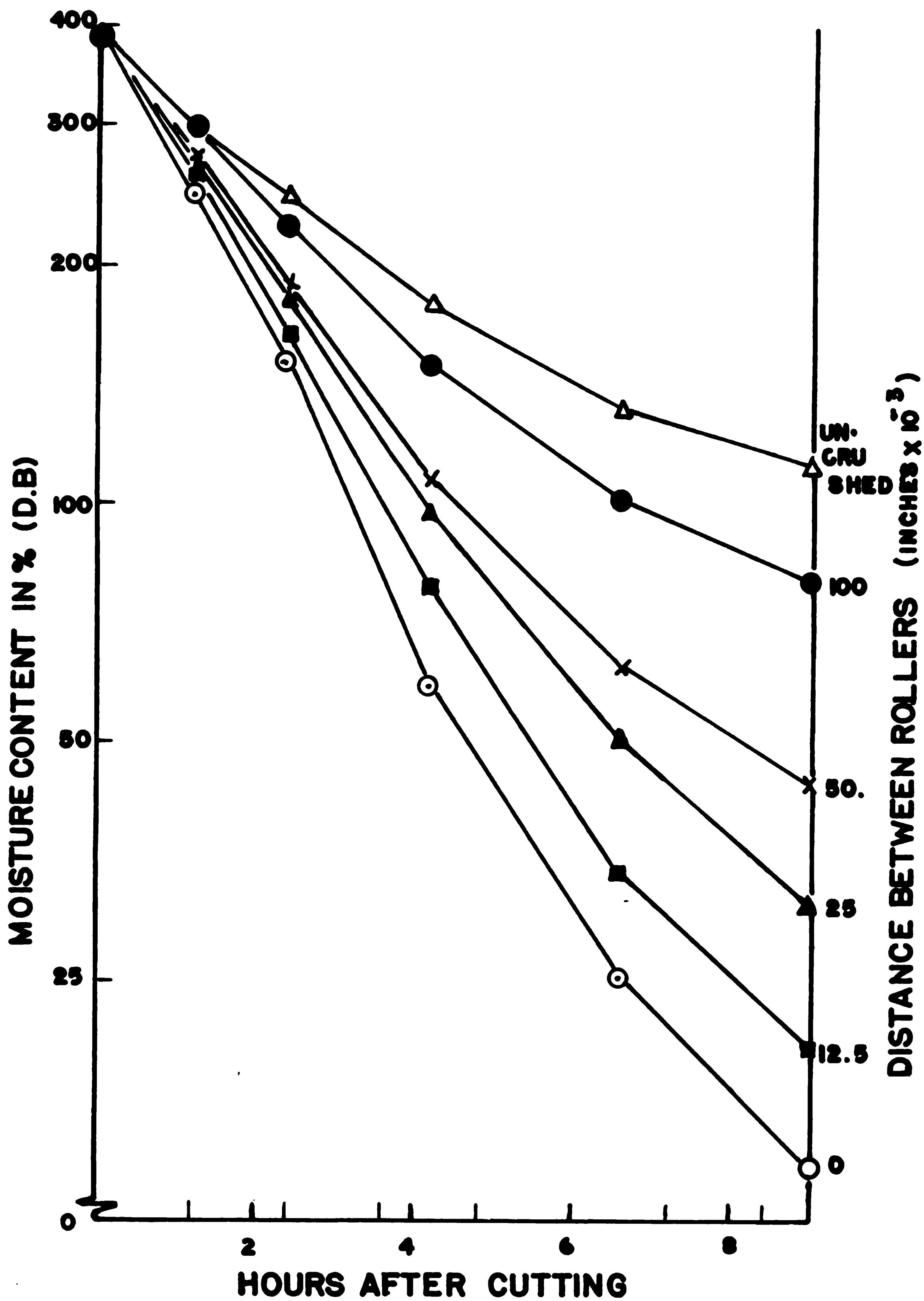

Figure 21. Drying curves for alfalfa crushed at different degrees.

Alfalfa crushed at clearance less than 0.005 inches.

Alfalfa crushed at clearance 0.0125 inches.

Alfalfa crushed at clearance 0.025 inches.

Alfalfa crushed at clearance 0.050 inches.

crushed with 0.0125 inch clearance between the rollers. During most of the day on which this experiment was conducted the weather was partly cloudy to cloudy. This explains the relatively low drying rates.

Drying Curves Of Alfalfa Cut At Various Times Of The Day.

The purpose of this experiment was to determine how late in the day hay could be cut and still be field dried to storable moisture content during the day of cutting. Samples with an initial weight of 300 grams were placed on black polyethylene. A hard crushing (clearance less than 0.010 inch) was applied. The samples were cut and placed on drying trays at 9 a.m., 11 a.m., 1 p.m., 3 p.m., and 5 p.m.

This experiment was conducted for two days. During the first day, the weather was partly cloudy, the temperature of the air varied from 66 degrees F to 75 degrees F. The drying conditions improved somewhat during the second day in that the sun shone all day but the temperature range was the same as on the first day.

Discussion of Results

The results of the experiment are indicated in Figure 22. The climatical data from the experiment is shown in Table XVII. Only the sample cut at 9 a.m. reached a moisture content of 20 percent (w.b.) during the cutting day. By interpolating between the cutting at 9 a.m. and the cutting at 11 a.m., it is apparent that a 10 a.m. cutting would have dried to a moisture content of 20 percent in approximately 8 hours of drying, or by 5 p.m.

TABLE XVII

THE TEMPERATURE OF HAY SAMPLES, SURFACE OF BLACK POLY-ETHYLENE, AIR, AND RELATIVE HUMIDITY OF THE AIR.

Time	Temperature in Degrees Fahrenheit							R.H. of Air	Remarks
	Sample cut at					Plastic	Air		
	9am	11am	1pm	3pm	5pm			%	
11am	80					96	70	52	
1pm	82	78				120	75	50	P.C.*
3pm	82	81	76			86	73	49	P.C.
5pm	82	80	76	72		81	72	50	C.
7pm	68	67	66	67	66	67	66	72	C.
8am	67	67	66	67	66	78	65	74	
10am	104	95	90	88	81	115	72	67	
12am		101	100	96	93	130	75	50	
2pm		99	99	96	97	113	73	57	P.C.

* P.C. = Partly cloudy
C. = Cloudy

All the samples, except the 5 p.m. cutting picked up moisture during the night. The dryer the sample, the greater the quantity of moisture absorbed during the night. This could be expected because the vapor pressure differential between the air and the hay sample is largest in the case of a dry sample.

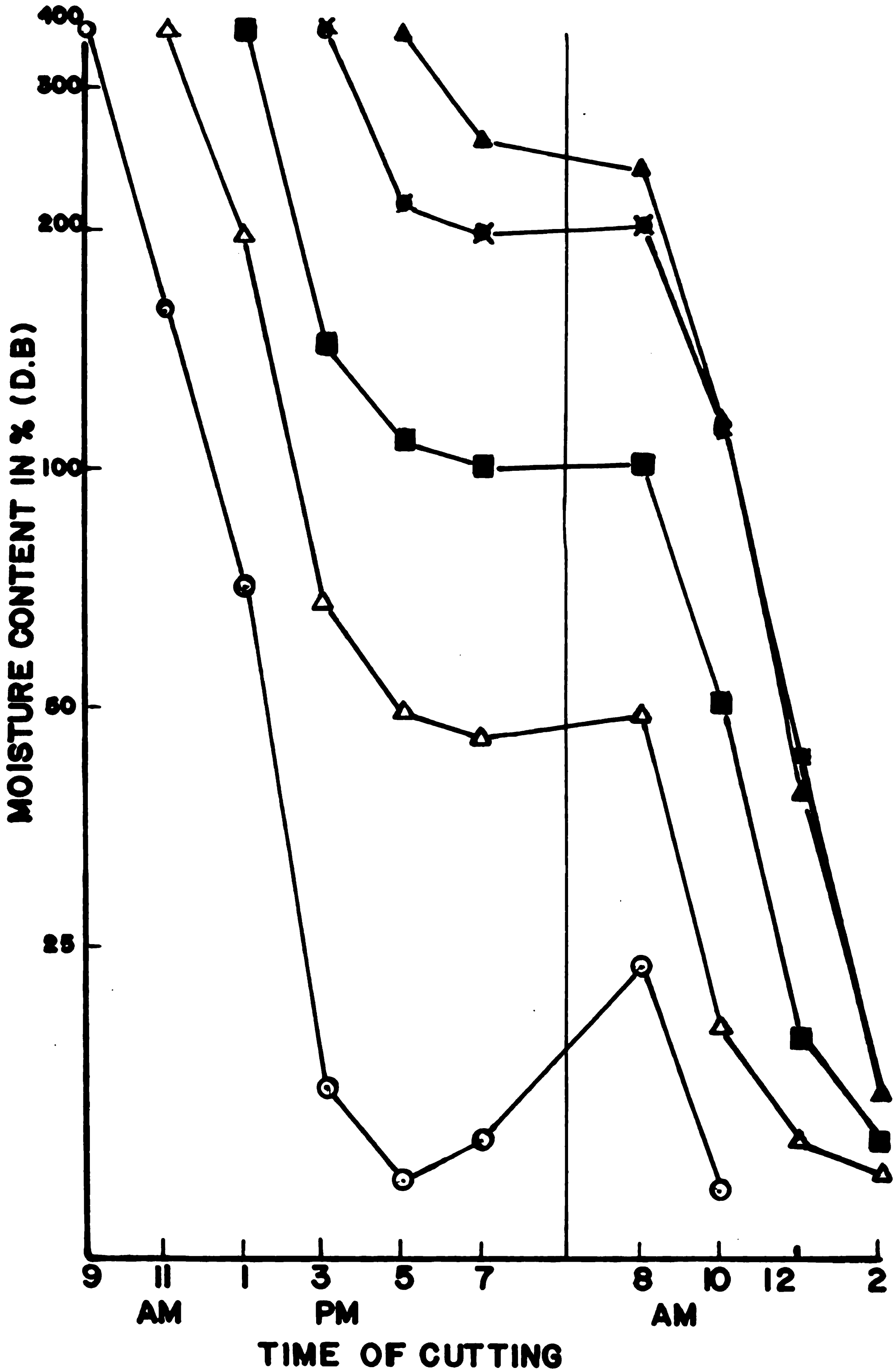

Figure 22. Drying curves for alfalfa cut at various times of the day.

The sample cut at 5 p.m. lost some water during the night. There can be two different explanations to this phenomenon. The vapor pressure of the hay may possibly have been higher than that of the air during the night, or the sample may have lost the moisture early in the morning before the first moisture determination was taken at 8 a.m. Because no measurements were taken between 7 p.m. and 8 a.m., these are the only explanations that can be given to the loss of water during the night. It should, however, be noted that the moisture picked up during the night disappeared from the sample before 10 a.m. the following day.

SUMMARY OF RESULTS

Hay is the most important forage crop in the United States. Because field-curing subjects hay to weather damage and as a result causes considerable loss of nutrients, it is important to find the best possible method of curing the hay.

In order to increase the drying rate of the stems, different treatments were applied to alfalfa plants. This experiment showed that the fastest evaporation was obtained when the stems were hard crushed, or when the stem cuticle was penetrated several places per inch of length. Lower rates were recorded when the stems were twisted, smashed or cut in pieces of 2 inches length.

When the hay was crushed, the drying rate of the leaves as well as that of the stems was increased. This increase, however, was considerably higher for the stems than for the leaves. If "hard crushing" was applied, the stems dried faster than the leaves.

By inserting a vapor barrier between the soil and the drying hay, the effect of evaporation from a wet soil was eliminated, and the time necessary to dry the hay to storable condition was considerably decreased. When black polyethylene was used as vapor barrier, it absorbed radiation energy and heated the hay as much as 67 degrees F above the temperature of the surrounding air.

The results of this study indicated that hay mowed before 10 a.m., crushed (clearance between rollers less than 0.015 inches) and placed on black polyethylene sheets, will have dried to a storable moisture content of 20 percent before 4 p.m. and may be harvested the same day it was cut.

CONCLUSIONS

The conclusions that can be drawn from the study of the anatomy and physiology of alfalfa and the research conducted on hay drying can be stated in the following points:

1. The complete break up of the cuticle causes the stems to dry ahead of the leaves.
2. Nearly all the stomata are closed after three hours of drying. After this period the drying rate decreased considerably and stayed nearly constant until equilibrium with the surrounding air was obtained.
3. The younger the alfalfa hay when cut, the higher the moisture content.
4. Eliminating the influence of water vapor transfer from soil to hay during the drying time in the field increased the drying rates.
5. The drying time was decreased by placing the hay on a shield of black polyethylene. The black plastic absorbed the radiation energy from the sun; thereby the hay was heated and the drying rate increased.
6. By severely crushing and placing it on black polyethylene, the moisture content of the hay was reduced to 20 percent within six to seven hours.

7. It is possible to cut the hay in the morning and take it to the barn in storable condition the same day.

RECOMMENDATIONS FOR FUTURE RESEARCH

In spite of the large amount of research which has been carried out in the field of hay harvesting, there are amazingly few basic data available. In order to develop any theoretical theory for drying of alfalfa hay, basic data concerning the equilibrium moisture contents are needed. Little data are available, and these are inconsistent. Other constants such as specific heat, thermal conductivity, shearing force, heat of respiration are required.

A prototype machine for hard crushing of the hay and placing it on the polyethylene strip should be built. In connection with this experiment an economical analysis of the method should be conducted.

A chemical analysis of the hay harvested by this quick method should be performed in order to determine possible higher content of nutrients, especially protein and carotene.

Because of the hard crushing, it is doubtful that it will be possible to bale the hay without considerable loss. Pelleting of the alfalfa hay seems to be the ideal solution.

The physical properties of pellets made from hard crushed hay should be determined.

APPENDIX

Dimensional Analysis Applied To Drying Of Alfalfa Hay

All the experiments in the above discussed research were designed to develop a faster method of field drying of alfalfa hay. Only a few of the experiments were conducted in a partly controlled atmosphere -- temperature and relative humidity being held constant. Measurements of wind velocity were not obtained. Because of this, the data obtained were not sufficient for the testing of a mathematical expression for drying of alfalfa hay. An analytical solution for field drying of hay, furthermore, would be extremely difficult due to the transient conditions.

After the research in the summer of 1958 was completed, it appeared that a solution to the hay drying problem might be obtained by means of dimensional analysis. The author will, therefore, on the basis of the experience gained during the two years of research work in the field of hay drying, propose the following approach to the dimensional analysis without having sufficient data to prove it.

It is reasonable to assume that the ratio of the initial amount of water in alfalfa to the amount of water present in the hay at any time of the drying process is a function of the following:

1. The vapor pressure differential between the air and the hay.

2. The wind velocity.

3. The time of drying.

4. The ratio of the initial thickness of the stem to the thickness of the crushed alfalfa stem.

5. The density of the alfalfa hay -- to keep this constant during the drying time, it is taken on dry matter basis.

6. The thickness of the swath.

These relations are combined in the following equation:

$$\frac{W_o}{W} = \phi\ (\Delta p,\ V,\ T,\ \frac{L}{l},\ \rho\ ,\ h)$$

where W_o = Initial amount of water in alfalfa, (lb)

W = Amount of water at any time, T, (lb)

Δp = Vapor pressure differential between air and hay (psi)

V = Velocity of air (ft/hr)

T = Hours of drying

L = Initial thickness of stem (in)

l = Thickness of stem after crushing (in)

ρ = Density of hay on basis of dry matter (lb/ft^3)

h Thickness of swath (in)

Solving the problem with Δp, V, and h as incompatible variables gives:

$$II_1 = \phi\ (\frac{W_o}{W}, \Delta p,\ V,\ h) = \frac{W_o}{W} \qquad (1)$$

$$II_2 = \phi\ (T, \Delta p,\ V,\ h) = \frac{T \times V}{h} \qquad (2)$$

$$II_3 = \phi\ (\rho, \Delta p, V, h) = \frac{x\ V^2}{p\ x\ h} \qquad (3)$$

$$II_4 = \phi\ (\frac{L}{I}, \Delta p, V, h) = \frac{L}{I} \qquad (4)$$

$$II_1 = \phi\ (II_2)\ (II_3)\ (II_4) \qquad (5)$$

or

$$\frac{W_o}{W} = \phi\ (\frac{T\ x\ V}{h})\ (\frac{\rho x V^2}{\Delta p\ x\ h})\ (\frac{L}{I}) \qquad (6)$$

Experiments should be carried out varying II_3 and holding II_2 and II_4 constant.

From a plot of II_1 against II_3, the relationship

$$(II_1)_{\overline{2},\overline{4}} = \phi_1\ (II_3.\ \overline{II}_2,\ \overline{II}_4) \qquad (7)$$

where the bars denote constant values, could be determined.

From a second set of experiments with II_2 and II_3 held constant and II_4 varied, the relationship of

$$(II_1)_{\overline{2},\overline{3}} = \phi_2(II_4,\ \overline{II}_2,\ \overline{II}_3) \qquad (8)$$

could be determined from a plot of II_1 versus II_4.

In a similar way, the relationship

$$(II_1)_{\overline{3},\overline{4}} = \phi_3\ (II_2,\ \overline{II}_3,\ \overline{II}_4) \qquad (9)$$

can be determined from a plot of II_1 versus II_2.

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