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FURTHER STUDIES WITH CRUSHED BALED HAY
AND A PRELIMINARY INVESTIGATION OF
FACTORS INVOLVED IN PELLETING HAY

Thesis for the Degree of M. S.
MICHIGAN STATE UNIVERSITY
Leon Franklin Sanderson
1956



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FURTHER STUDIES WITH CRUSHED BALED HAY AND A
PRELIMINARY INVESTIGATION OF FACTORS

INVOLVED IN PELLETING HAY

By

LEON FRANKLIN SANDERSON

AN ABSTRACT

Submitted to the College of Agriculture of Michigan
State University of Agriculture and Applied
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Approved

H. F. McColl

Since hay making is subject to weather conditions, a large loss results due to extended drying periods and due to leaf shattering caused by the common methods of harvesting. Before this loss can be reduced a method is needed to reduce field drying time.

Crushing alfalfa increases the drying rate, but the drying time exceeds the average period between rainfall in humid regions. The increase in drying rate accelerates as drying conditions improve, but the decrease in total drying time remains at from three to four hours in most cases.

Tedding crushed alfalfa does not increase the rate of drying when the yield is 1.5 tons per acre.

The quality of baled alfalfa when placed in an open storage is affected by the density and moisture content of the bales and the weather conditions during the storage period. Must will develop in bales with 6 pounds per cubic foot densities and 12 percent moisture content. Crushing does not affect these limits.

Pelleting the hay is a possible method of solving the many problems inherent with common methods of harvesting hay. Fundamental requirements for obtaining good quality pellets are needed before a machine can be made which will produce pellets from long field cured hay.

The pellet density-moisture-pressure relationship for

green alfalfa is given by the equation

$$Y = e^{0.805 - 0.000002682(Z + 7360)(X - 42.2)},$$

where

Y - pellet density - grams per cubic inch

X - moisture content - percent

Z - pelleting pressure - pounds per square inch

The coefficients of this equation are altered by a change in time of pressure application or quality of hay.

The hay should be below 30 percent moisture content to obtain firm pellets. Pellet densities of 25 pounds per cubic foot are recommended for two inch diameter pellets. These can be obtained with 15 percent moisture content hay by applying a pressure of 5000 pounds per square inch. Increasing the weight of material in each pellet or decreasing the time of pressure application will result in a lower pellet density.

Two inch diameter pellets are faster and easier drying than either chopped or baled hay. The narrow diameter reduces the wet centers found in baled hay and also the partial pulverization of hay stems during pelleting allows better drying characteristics than obtained with chopped hay.

Firm pellets are easier to handle than baled hay and can be mechanically loaded and stored. Storage space requirements are reduced and pellets can be both mechanically

and self-fed to livestock.

Pelleting reconditioned baled hay is similar to pelleting green hay. The only noticeable difference is the period of time required for pressure application to obtain good quality pellets. The presence of available starches and sugars is more important to forming a good quality pellet than the period of time the hay has been in storage. These nutrients are reduced after a period in storage, however, and in some cases additives may be necessary to restore the binding qualities.

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INTRODUCTION

For centuries man has dried grasses and legumes in the field in order to make these materials suitable for storage. Until recent years this practice has been satisfactory and the only improvements in hay harvesting have been these which made it possible to put up hay with fewer man hours of labor per ton. This can be seen from studying available statistics.

After World War I a rural population of 31,614 000 people produced 96,687,000 tons of hay per year (8). and in 1953 the farm population of 21,890,000 people produced 105,000,000 tons of hay (9). At the same time the average yield dropped from 1.58 tons per acre (op. cit.) to 1.42 tons per acre (op. cit.).

Thus, even though this was a period of rapid farm mechanization, very little improvement in quality of hay produced or reduction of loss of nutrients has occurred. LeClerc (7) has said that 10 to 50 percent of the value of a hay crop may be lost due to hay being damaged during natural field curing with traditional harvesting methods.

Dexter (3) reported that in feeding trials with hay it was found that hay quality was preserved best by rapid drying, and that an extended drying period is detrimental.

even though no mustiness occurs. Artificial drying reduces the loss caused by natural curing, but the increased cost is prohibitive in many cases (4).

Since weather conditions are uncertain in most of the major hay producing regions, it is essential to the problem of obtaining better quality hay that a method for significantly reducing the field curing time be found. Even in the humid areas drying time is reduced by crushing the hay between large rolls, but in many cases this reduction is not great enough to warrant the added cost of crushing the hay (5).

Along with the problem of rapid drying to procure high quality hay, are the methods of harvesting hay. Bender (1) stated that the common methods used for harvesting hay were a failure because of the damage to hay quality and loss of valuable plant nutrients. LeClerc (7) has suggested a method on which experiments have been done in England as a possible solution to this loss. Grass cakes were made from green hay with a compressing machine.

Although pelleted feeds were introduced in the United States in 1929 (6), very little fundamental work has been done relative to making larger pellets or cakes. Considerable interest has been shown in harvesting hay by pelleting but much more information is needed before it will be possible to perform pelleting on the scale exhibited with other

methods of harvesting (2).

Hay pellets have also been suggested as a method of reducing storage space requirements (ibid). The increased cost of storage facilities has caused much interest in reducing the storage requirements by compressing the hay into dense pellets which can be fed to livestock.

The study included in this thesis was preceded by eight years of research on baled hay harvesting and drying. The results of the eight years of research has indicated that further study is necessary to determine a method for decreasing field drying time. The objectives of this study, therefore, were to investigate crushing and tedding as a method of field curing hay to obtain high quality roughage, and to determine the fundamental factors involved in pelletizing hay as a possible solution of the many problems inherent in common methods of harvesting hay.

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A STUDY CONCERNING THE EFFECT OF TEDDING UPON THE DRYING
RATE OF CRUSHED HAY; THE RELATION OF WEATHER CON-
DITIONS TO THE EFFECT OF CRUSHING AND THE
EFFECT OF CRUSHING ON THE SAFE STOR-
AGE LIMITS OF BALED HAY

Reasons for the Study

The quality of hay produced in humid areas such as Michigan has not improved greatly during the mechanization of hay harvesting. Much of the hay production is still lost due to damage in the field by rain or molding in storage, since an average period of two days between rainfall is less than the time required for natural field curing of hay (6).

Hodgson (5) said that as much as 15 percent of a hay crop may be consumed by field fermentation losses during an extended drying period. Bleaching from the sun is another deterrent to quality hay resulting in losses of carotene. Bender (1) has said that losses as great as 50 percent of the crop value may occur during natural field curing of hay.

Each of these losses is due to a long drying period and can be reduced by decreasing the field drying time. Harvesting at a higher percent moisture content* reduces each of

* Moisture contents in this thesis are percent wet basis.

these losses as well as decreasing leaf shattering of the dry hay during harvesting operations.

Harvesting of high moisture content hay, however, introduces other more serious problems. Damp hay will respire and a rise in temperature may occur. Molds develop rapidly in warm, damp hay (8). If the temperature rises above 158°F., microorganisms are no longer active (ibid), but spots of scorched hay will occur. If heating is allowed to proceed unchecked, spontaneous ignition may occur with the resultant loss of the hay and structure.

Even if the hay does not ignite, serious losses of organic matter will occur (ibid) with possible losses of 100 percent of pure digestible protein, 47 percent of all fats, 94 percent of the sugars and 52 percent of hemicellulose.

Hodgson (5) stated that artificial drying is successful in stopping much of this waste, but the cost of the installation and operation is prohibitive in many instances.

Kleis (7) investigated the quality of hay produced in the East Lansing area. The majority of the bales inspected were at best musty, even though many of the farm operators did not realise they had any musty hay. This indicated a need for more information related to the storage of hay.

Review of Literature

Hopkins (6) found that crushing increased the rate of

drying of the leaves by the same amount it increased the rate of drying of the alfalfa stems. He stated that the only gain by crushing in Michigan would be if crushing made it possible to store the hay in less time with fewer operations and thus preserve more of the crop. However, the average drying period for crushed hay is longer than the average time between rainfall of two days (ibid) and thus crushing alone is of little value in the majority of cases.

In research at Wisconsin (2) it was found that crushing decreased the field drying time during both good and average drying weather and that the decrease in drying time was somewhat greater in good weather.

Heavier yields (ibid) were reported to have had smaller gains in drying rate. This would seem to be due to two factors; crushing is less effective in a heavy swath due to the cushioning effect and matting of the crushed hay becomes more prevalent.

Bruhn (ibid) found that operating the rolls at higher pressures produced more effective crushing, but at the same time the tendency to clog the rolls increased. He reported that crushing at a higher roll speed with respect to the ground speed resulted in more effective crushing. This was due to thinning out the material between the rolls and thus reducing the cushioning effect.

Multiple crushing was reported by Bruhn (ibid) to have

had considerable success in Wisconsin since it increased the drying rate more than once-over crushing with no noticeable increase in loss of leaves.

Ramser (10) reported that crushing improved the palatability of hay by reducing coarse stems so that they were less harsh and brittle.

Hopkins (6) made a study to determine the relation of bale density and moisture content to the quality of alfalfa hay stored in a natural draft ventilation mow. In order to obtain must free bales the hay should be dried to 20 percent moisture content before baling, and the bale density should not be greater than 6 pounds per cubic foot. He indicated that somewhat higher moisture contents and densities are allowable if a little mustiness is acceptable.

Objectives

This study was made to obtain essential information related to improving the methods of harvesting and storing baled hay, and thus reduce the yearly financial loss which farmers sustain.

The objectives of this study as outlined briefly are to find:

1. The effect of tedding upon the drying rate of crushed hay when the tedding is done immediately after crushing.

2. The effect of crushing upon the field drying rate of hay as this effect is related to weather conditions.
3. The effect of crushing upon the relationship between the density of bales, moisture content of the hay when baled, and the quality of alfalfa hay stored in a natural draft ventilation mow.

The field experiments were concerned with finding new methods for decreasing the time required for drying hay in the field. This consisted of experiments to determine the effect of tedding immediately after crushing upon the drying rate of the hay. Also investigated was the effect of weather conditions upon the increase in drying rate by crushing the hay.

The storage experiments were concerned with delineating the relationship of mold development in crushed baled hay during storage to the density of bales and moisture content when baled.

Apparatus

The Forage Crusher The forage crusher used in these tests was a trailing type implement with two 6 inch x 80-inch smooth steel rolls (Figure 1). The rolls were spring loaded and propelled by the tractor power take-off. This crusher did not have a mower attached and could not be connected to a tractor with a rear mounted mower. This made it

necessary to make a separate operation of crushing after the hay had been mowed.

The hay was lifted and fed into the crushing rolls by a power take-off driven, rotating cylinder with retracting spring teeth. This pick-up worked well as long as it was at the correct level above the ground surface. However it was difficult to adjust the pick-up for varying ground conditions.

The crusher worked well in alfalfa and jamming of the rolls was slight. The jamming that did occur was as a result of foreign materials such as corn stubble refusing to pass between the rolls.

The Forage Rake-Tedder. The side delivery rake-tedder used in these tests was a ground driven, cylindrical-reel type (Figure 2). In order to make it possible to ted a single windrow in a test plot, three teeth on the front end of each reel bar were turned up 180 degrees so that the width of raking was narrowed to seven feet.

The hay swath was torn apart by the tedder and tossed into the air several feet. In observing the swaths of hay in dense areas of the field after tedding, the action of the tedder was effective in fluffing both crushed and uncrushed hay.

The Bale Sampler. The bale sampler used in these tests was designed and constructed by Eggleton(4). This device consists of a two-inch diameter stainless steel tube approx-

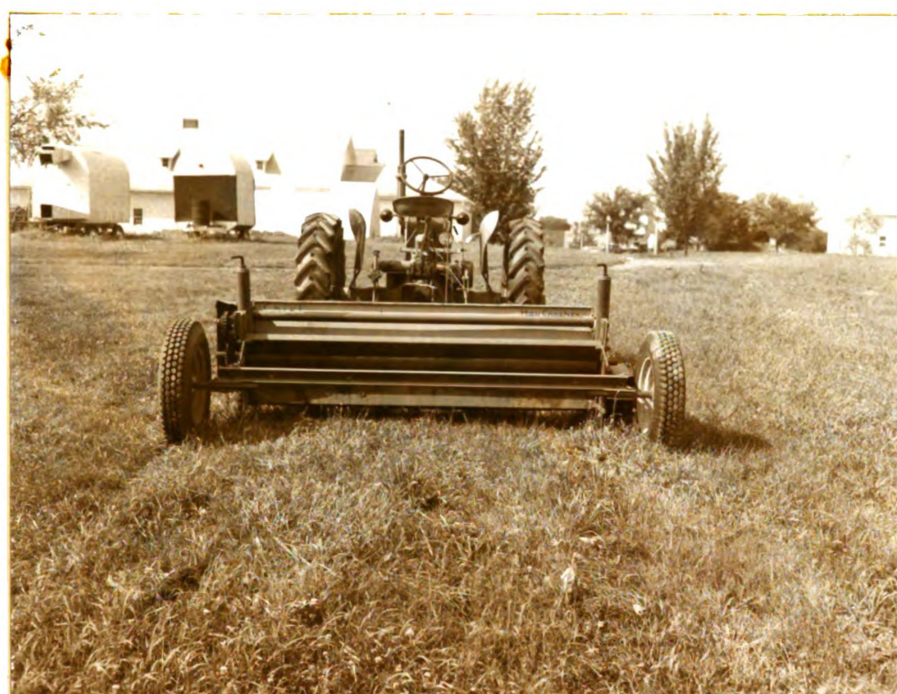


Figure 1. Forage Crusher used in the Study.

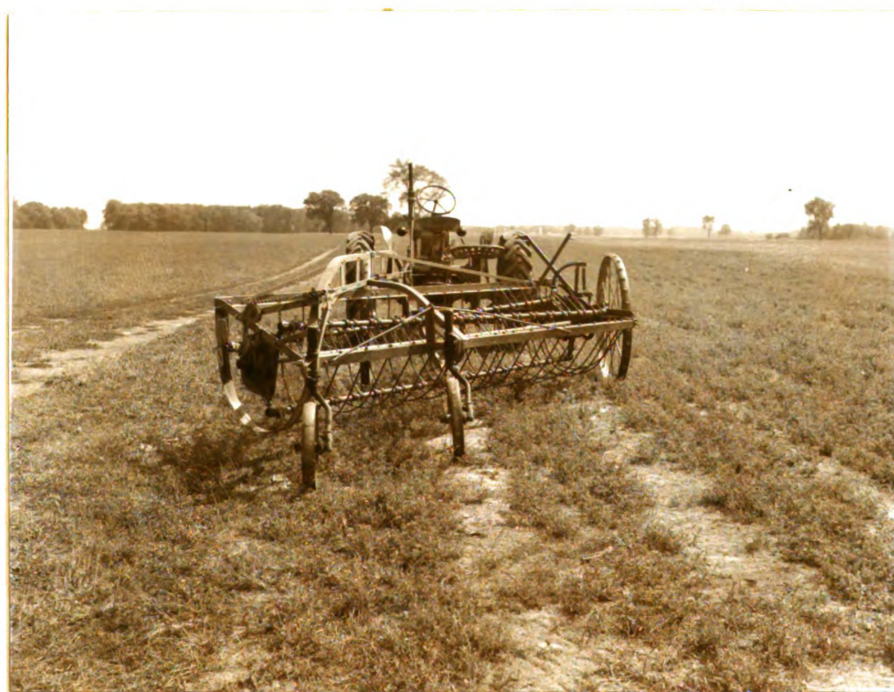


Figure 2. Forage Rake-Tedder Used in the Study.

imately two feet long. A saw toothed blade is attached to the end of the tube and the device is rotated by a 5/8 inch standard electric drill which is mounted in a cradle. The bale is held in a rack where the rotating tube is forced against the end of the bale to cut a core sample from the bale.

Field Experiments

These experiments were carried out to obtain data pertinent to reducing the required time for field drying hay. This study was set up to determine the effect of tedding immediately after crushing upon the drying rate of alfalfa. The effect of crushing upon the drying rate was also studied during different conditions of temperature and relative humidity.

A twenty acre field of first year alfalfa was used for these experiments. The alfalfa had been seeded in corn the previous fall and had been cultipacked once after removal of the corn. The lack of cultivation caused the hay to be growing in narrow bands between the old corn rows.

Design of the Experiment. This study was designed so that the effect of crushing upon the drying rate of alfalfa could be evaluated during several different weather conditions. In order to have a comparison, one half of the plot was crushed and the other half was left uncrushed as a

control.

In order to determine the effect of tedding upon the drying rate, the crushed and uncrushed plots were each divided into a tedded and an untended plot. Thus, there were four plots with different treatments.

Each plot was composed of four seven-foot wide swaths and was approximately forty rods long. To reduce the effect of variations in fertility and density of growth, the four treatments of each test were conducted on one large plot. This plot was then divided into four ten-rod long blocks.

The drying rates of each of the four treatments was determined by taking moisture samples from each of the blocks for each of the treatments at intervals during the drying period. During the first cutting tests, one sample was taken from each of the blocks for each of the treatments. This was changed during the second cutting tests to two samples to increase the precision of the experiment. The results were then analyzed as a randomized block experiment.

Outline of the Treatments.

1. Mow hay, no tedding, determine drying rate, rake at 40 percent and bale at 20 percent moisture content.
2. Mow hay, ted immediately, determine drying rate, rake at 40 percent and bale at 20 percent moisture content.
3. Mow and crush, determine drying rate, rake at 40 percent moisture content and bale at 20 percent.

4. Mow, crush, and ted, determine drying rate, rake at 40 percent, and bale at 20 percent moisture content.

The treatments were raked at 40 percent moisture content to reduce the amount of leaf shattering.

Moisture Content Determination. In order to obtain an accurate measure of the moisture content of the hay in the windrow a cross-section was removed by cutting with shears and placed in a ten-pound paper sack. The sack was then closed and labeled with an identification number. Windrow samples were weighed inside the equipment trailer within one hour after sampling (Figure 3).

The samples were later taken to the laboratory and placed in a steam drying oven operating at 150°F. for not less than 48 hours. The samples were weighed upon removal from the oven and the moisture content computed from this data.

The moisture content of the bales was found by cutting a core from the middle of one end of each bale with the bale sampler. These samples were weighed and dried in individual sacks and the moisture content computed from this data.

Climatological Data During the first cutting tests psychrometric readings were taken at regular intervals with a sling psychrometer. Wind and cloud cover were noted and the total rainfall was recorded with a Standard Weather Bureau Rain Gauge.

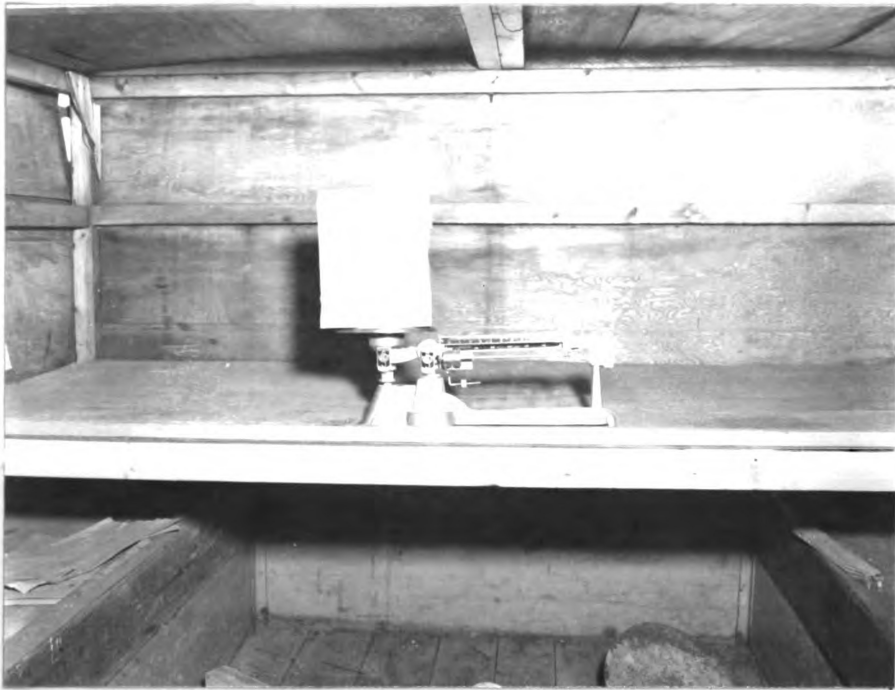


Figure 3. Weighing Moisture Samples in the Equipment Trailer



Figure 4. Equipment for Determining Weather Conditions.

A hygrothermograph and an instrument shelter were used for the second-cutting tests in order to obtain continuous readings of weather conditions. The hygrothermograph was located about a foot above the ground and calibrated with an aspirator psychrometer at least twice each day in order to get an accurate measure of the relative humidity and temperature at the ground surface. Wind velocities were recorded with an anemometer wind totalizer located three feet above the ground (Figure 4).

First Test. The first test was started on June 15, 1955. The ground was saturated with moisture after several days of heavy rainfall. The mowing was started at 10:00 a. m. Crushing and tedding were done as soon as mowing was completed at 11:30 a. m. The hay was sampled at intervals for moisture content (Table 1) and was raked into windrows at 1:00 p. m. on June 16. The treatments were all baled on June 17 at 3:00 p. m.

Second Test. This test was mowed at 9:00 a. m. and crushing was started at 9:45 a. m. , June 22. The tedded swaths were completed by 11:00 a. m. and moisture samples were taken at intervals (Table 2). The hay was raked at 3:00 p. m. June 23 and baling was started at 1:30 p. m. the following day. June 24.

Third Test. The second-cutting tests were begun on July 20. The hay was mowed, crushed, and tedded at 10:00 a. m.; 11:00 a. m.; and 11:30 a. m. respectively. Weather

and moisture content data were taken as before, but two samples were taken from each block for each treatment (Table 3) to increase the precision of the tests. The hay was raked at 3:30 p. m. the same day and baling was started at 10:00 a. m. July 22.

Fourth Test. Mowing, crushing and tedding were started at 9:30, 10:30, and 10:45 a. m., respectively, on July 24. The drying rate was determined by taking moisture samples at intervals (Table 4) and the hay was raked at 4:30 p. m. the same afternoon. Rain had been forecast and the baling was delayed in order to determine the effect of crushing upon the drying rate after a rain. No rain occurred, however, before the hay was baled at 11:00 a. m. August 1.

Analysis of the Data. A complete analysis of variance was carried out on all of the data reported in this experiment. Each set of moisture content samples was analysed as a randomized block to find significant differences between moisture contents of hay from various treatments. The average moisture contents were then plotted to show the drying rate of each treatment with moisture content versus drying time for each test (Figures 5, 6, 7, and 8).

The drying rate during the first day of each test before it was raked was computed for each treatment (Table 7). These rates in percent moisture loss per hour were then analyzed using the F test with treatments versus days to

Table 1. First Cutting Moisture Contents - Test 1
June 15, 1955

Time		Uncrushed		Crushed		
Day	Hour	Untedded I	Tedded II	Untedded III	Tedded IV	
June		Average moisture content - percent				
15	12:00 AM	70.93	69.64	67.09	68.99	
	2:30 PM	57.78	60.22	54.14	55.82	**
	4:00 PM	54.14	53.34	50.31	48.85	
16	10:00 AM	46.42	42.85	40.41	44.02	*
	1:00 PM	39.32	40.71	28.78	30.67	**
	3:15 PM	32.73	33.89	30.50	31.46	
	4:30 PM	31.52	34.51	24.01	24.91	**
17	9:00 AM	28.64	30.91	25.47	22.19	
	10:00 AM	23.41	25.74	18.60	17.04	
	2:15 AM	17.42	22.42	14.78	17.21	

All data average of four samples except 10:00 AM June 17 average of two samples. Each set of moisture data was analyzed as a randomized block. Each set of moisture content data which indicated a significant difference in moisture content as a result of crushing is starred.

* Data significant

** Data highly significant

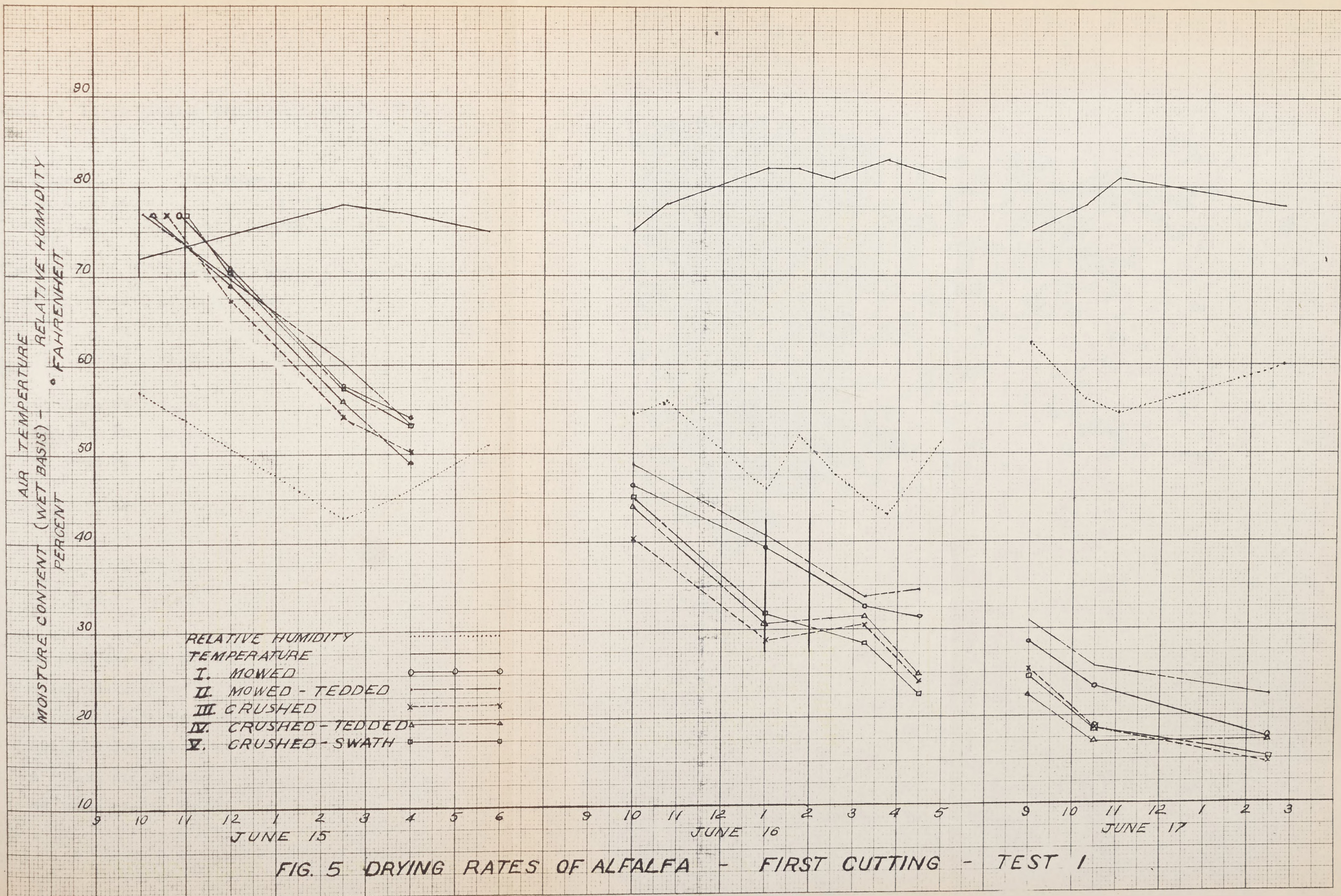


FIG. 5 DRYING RATES OF ALFALFA - FIRST CUTTING - TEST I

Table 2. First Cutting Moisture Contents - Test 2

June 22, 1955

Time		Uncrushed		Crushed	
Day	Hour	Untedded I	Tedded II	Untedded III	Tedded IV
June		Average moisture content - percent			
22	11:30 AM	68.43	68.30	66.17	67.42
	2:15 PM	61.80	59.29	57.53	52.87
	4:00 PM	57.34	61.16	53.27	53.63 **
23	11:45 AM	48.42	46.69	36.56	41.67 *
	2:15 PM	42.33	40.88	32.85	37.46 *
	3:30 PM	38.49	40.89	22.64	31.34 *
24	10:15 AM	33.63	38.60	28.28	26.64 *
	11:30 AM	32.62	32.33	25.05	23.20 **
	1:45 PM	32.20	30.88	20.13	24.58 **
	2:30 PM	26.57	28.72	20.37	17.25 **

All data average of four samples. Each set of moisture data was analyzed as a randomized block. Each set of moisture content data which indicated a significant difference in moisture content as a result of crushing is starred.

* Data significant

** Data highly significant

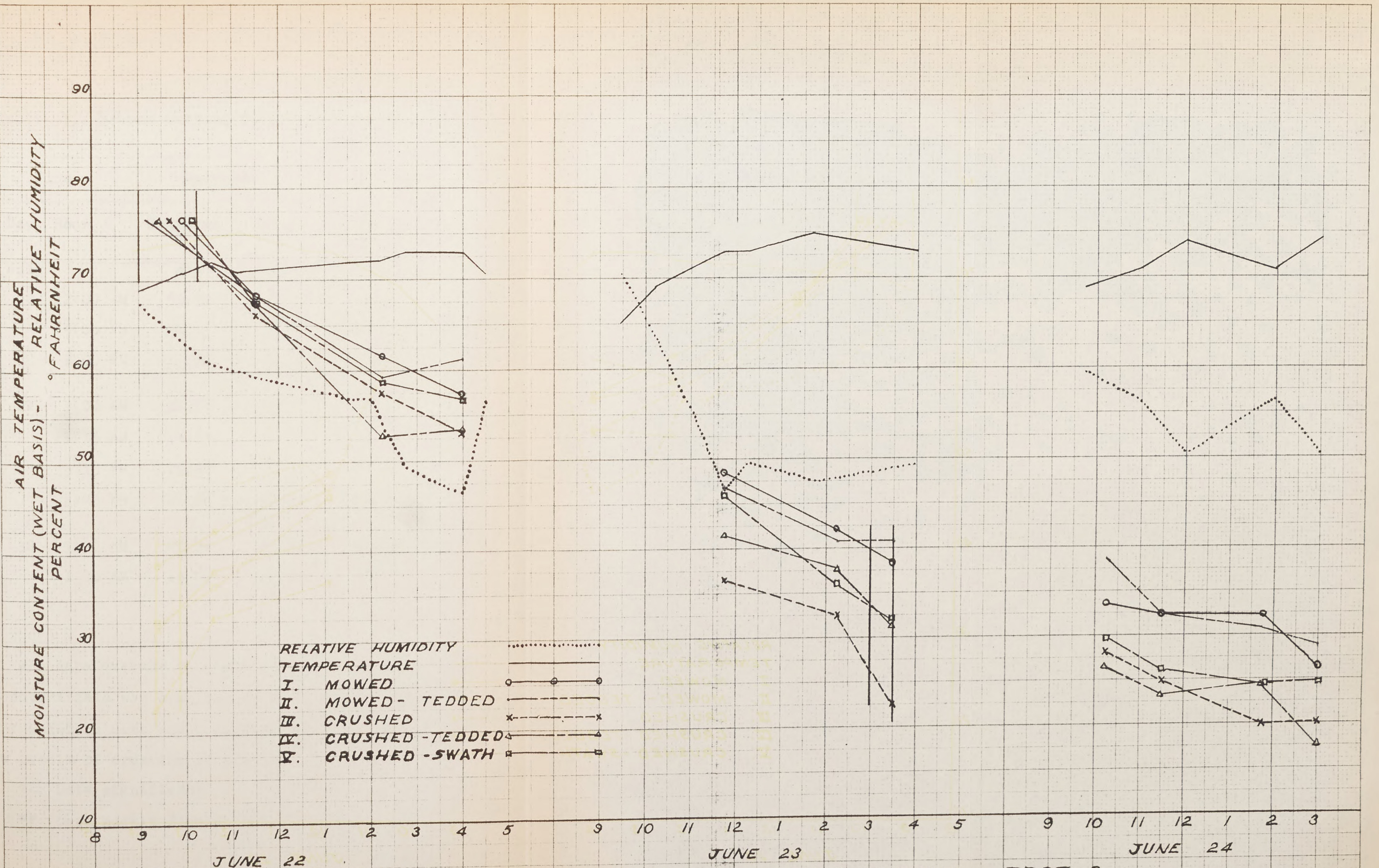


FIG. 6 DRYING RATES OF ALFALFA - FIRST CUTTING - TEST 2

Table 3. Second Cutting Moisture Contents - Test 3
July 20, 1955

Time		Uncrushed		Crushed		
Day	Hour	Untedded I	Tedded II	Untedded III	Tedded IV	
July Average moisture content - percent						
20	12:00 AM	59.89	57.16	61.83	60.40	**
	3:00 PM	45.13	49.42	37.83	38.06	**
	8:00 PM	35.48	41.00	29.38	27.97	**
21	9:00 AM	31.50	33.95	28.03	22.65	*
	11:15 AM	26.30	29.97	17.84	18.42	**
	3:15 PM	18.25	26.90	12.91	11.62	**
	7:45 PM	21.90	23.33	13.19	12.37	**
22	9:30 AM	21.91	23.31	17.82	14.91	**
	11:00 AM	19.75	21.39	19.12	9.12	*

All data average of eight samples. Each set of moisture content data was analyzed as a randomized block. Each set of moisture data which indicated a significant difference as a result of crushing is starred.

* Data significant

** Data highly significant

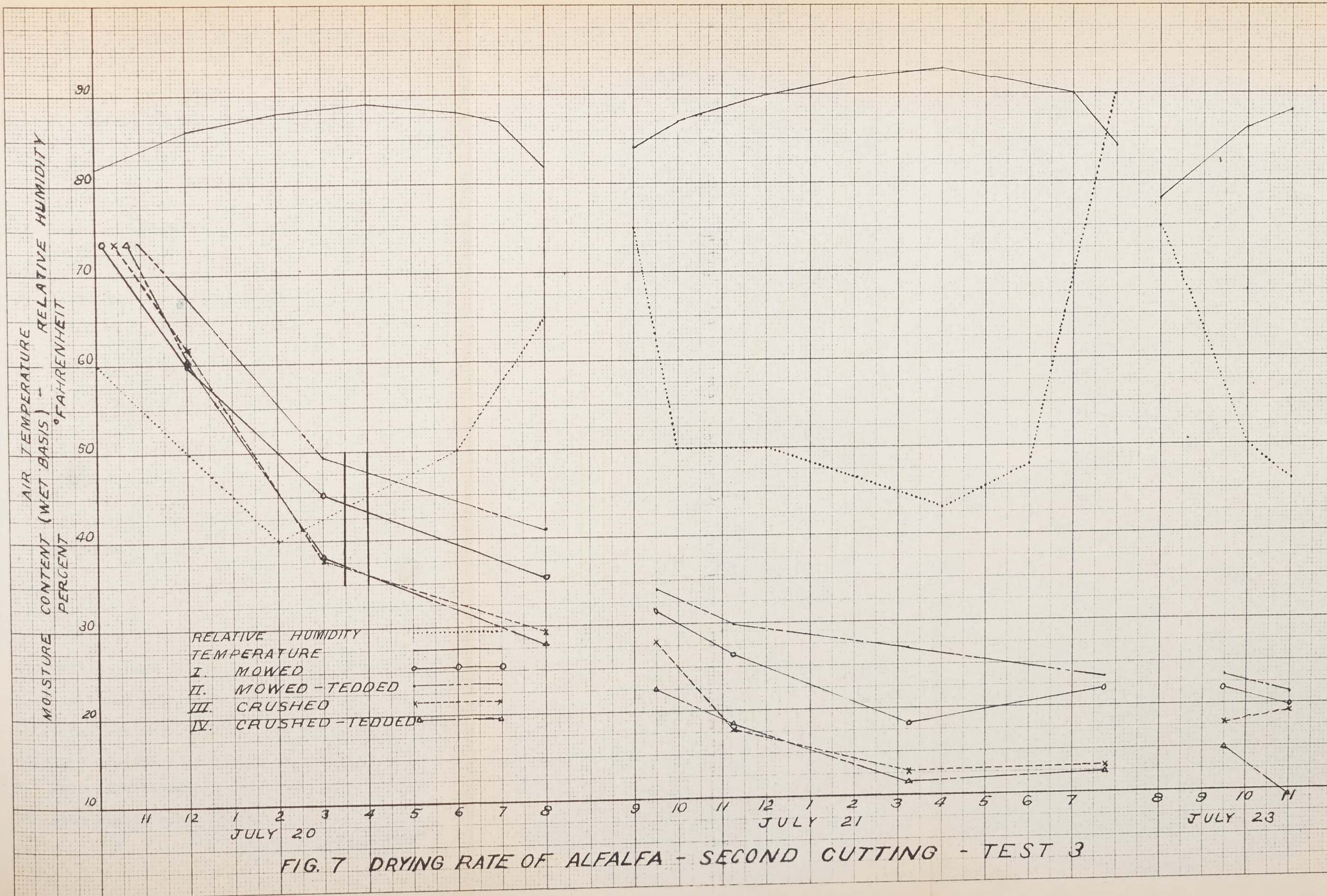


Table 4. Second Cutting Moisture Contents - Test 4
July 29, 1955

Time		Uncrushed		Crushed		
Day	Hour	Untedded I	Tedded II	Untedded III	Tedded IV	
July		Average moisture contents - percent				
29	11:30 AM	64.65	64.17	55.86	59.53	**
	4:00 PM	40.19	38.53	25.99	28.79	**
30	9:00 AM	39.41	36.43	27.30	31.17	**
	3:00 PM	21.16	18.86	13.14	13.34	**
31	7:00 PM	21.42	13.60	10.91	10.84	
August						
1	9:30 AM	16.30	16.79	15.80	15.08	
	11:00 AM	10.97	11.88	11.97	11.50	

All data average of eight samples. Each set of moisture content data was analyzed as a randomized block. Each set of moisture data which indicated a significant difference in moisture content as a result of crushing is starred.

* Data significant

** Data highly significant

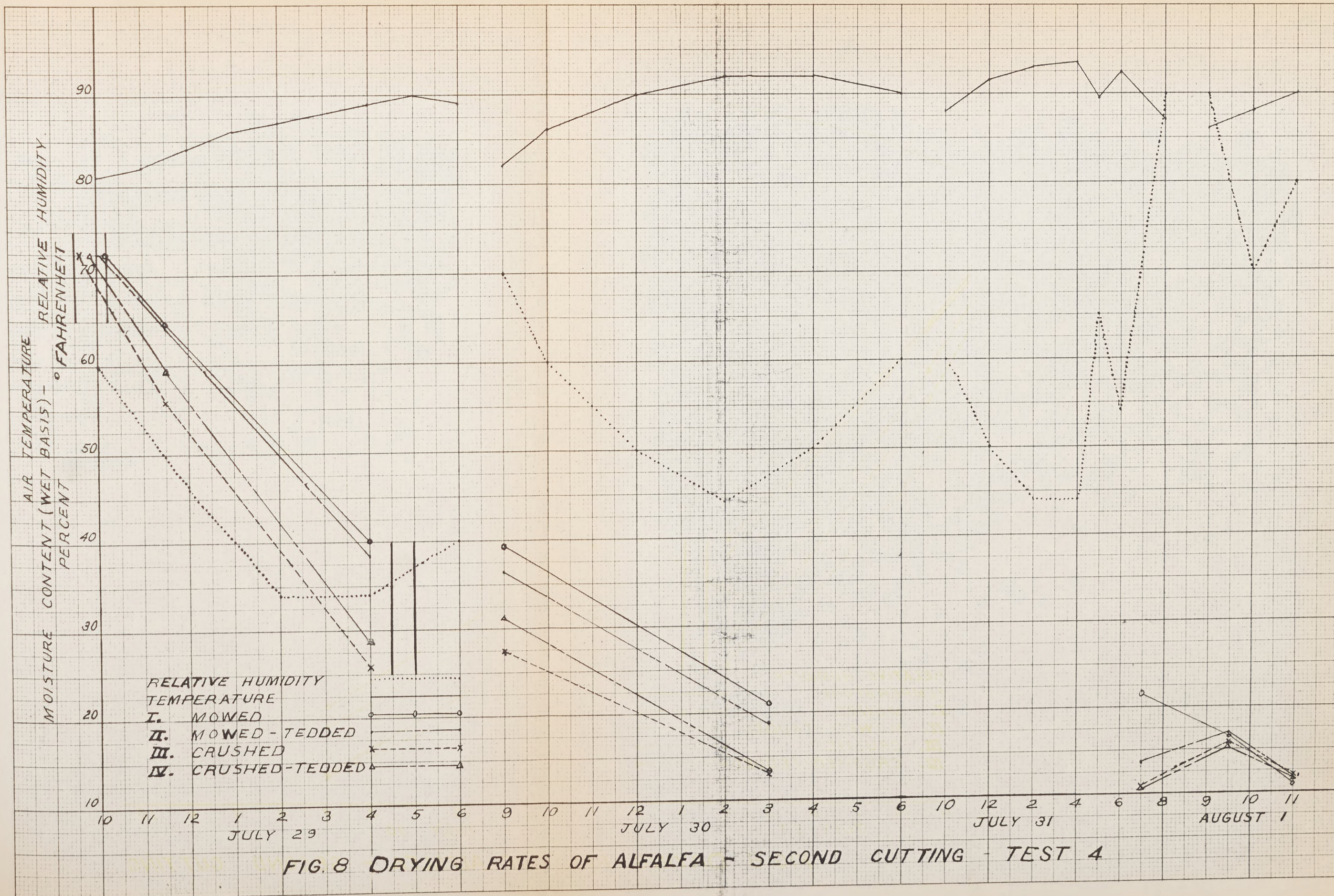


Table 5. The Effect of Crushing on Drying Rate as Related to Weather Conditions

Date	Drying Rate			Weather Conditions	
	Uncrushed I	Crushed III	Increase of III over I	Temp. High	Humidity low
	Percent moisture loss per hour*			°F	Percent
June 15	4.197	4.340	0.143	78	48
June 22	2.460	2.866	0.406	73	46.5
July 20	4.920	8.000	3.080	89	40
July 29	<u>6.115</u>	<u>7.467</u>	<u>1.352</u>	90	34
Average	4.423	5.667	1.243		

* Drying rates for the first day before the hay was windrowed.

Table 6. The Effect of Crushing Alfalfa Upon the Drying Time

Test	Total Drying Time			Weather Conditions	
	Uncrushed I	Crushed III	Decrease of III from I	Temp. High	Humidity Low
	Hours			°F	Percent
1	50.00	47.75	2.25	78	48
2	55.00	52.00	3.00	73	46.5
3	28.25	24.50	3.75	89	40
	29.25	26.25	3.00	90	34

Table 7. The Effect of Tedding on Drying Rate of Alfalfa

Date	Drying Rates of Tedded Versus Untedded Hay					
	Not Crushed			Crushed		
	Untedded I	Tedded II	Increase II over I	Untedded III	Tedded IV	Increase IV over III
	Percent moisture loss per hour*					
June 15	4.197	4.075	-0.122	4.340	5.035	0.695
June 22	2.460	1.586	-0.874	2.866	3.064	0.198
Average of First Cutting	3.329	2.831	-0.498	3.603	4.050	0.447
July 20	4.920	6.063	1.143	8.00	7.446	-0.554
July 29	6.115	6.410	0.295	7.467	7.685	0.218
Average of 2nd Cutting	5.518	6.237	0.719	7.734	7.566	-0.168
Overall Average	4.424	4.534	0.110	5.669	5.808	0.139

* Drying rates for the first day of drying before the hay was wind-rowed.

determine if any of the treatments had a significant effect upon the drying rate of alfalfa. The t test was then used to determine whether tedding or crushing was effective. The average drying rates and the differences between the drying rates of treatments for the four tests were then compared (Tables 5, 6 and 7).

The Results of Tedding. At no time during the tests was the effect of tedding upon the drying rate of crushed hay significant when the tedding was performed immediately after crushing. Although decreases in the drying rate as well as increases occurred, none of these differences were large enough to be significant (Table 7).

When the drying rates of tilled and untilled treatments were each averaged for the four tests, tedding caused an increase in drying rate for both crushed and uncrushed hay. Tedding increased the drying rate of uncrushed hay 0.110 percent moisture loss per hour. The increase in drying rate of crushed hay as a result of tedding was 0.139 percent moisture loss per hour. This difference in increase in drying rate due to tedding between crushed and uncrushed hay was negligible.

It was observed that in areas of the field where the alfalfa yield was light, very little matting of the crushed alfalfa occurred and it was difficult to determine whether a swath had been crushed without inspecting individual stems.

Where the hay was denser, matting was frequent and the crushed swaths were easily distinguished from the uncrushed swaths. In these dense areas the effect of tedding was also much easier to observe than in the light areas since the swath was in a more ruffled condition after tedding.

The hay yield per acre was below the average for Michigan of 1.5 tons per acre (9). The first cutting averaged 1.45 tons per acre, while the second cutting produced only 1.05 tons per acre. If the hay in the test plot had been denser, tedding would have had a greater effect, but this effect would not be significant unless a much larger sample of moisture content was taken.

The Results of Crushing. Crushing caused an increase in the drying rate of alfalfa in each of the four tests. The four tests had an average increase in the drying rate of 23.3 percent as a result of crushing on the first day of drying before the hay was windrowed (Table 5). The analysis of variance indicated this increase was significant.

It can be seen (Table 5) that as drying conditions improved, the increase in drying rate due to crushing became greater. During poor drying weather with drying rates of 4.197 and 2.460 percent moisture loss per hour for uncrushed hay, crushing increased the drying rate only 0.143 and 0.906 percent moisture loss per hour, respectively; whereas during more favorable drying weather with drying rates of

4.920 and 6.115 percent moisture loss per hour for uncrushed hay, crushing increased the drying rate 3.080 and 1.352 percent moisture loss per hour, respectively.

The fact that the test with the lowest drying rate did not indicate the lowest increase as a result of crushing is due to two main factors. The most important is that the effectiveness of the crusher depends on the amount of material passing through the rolls. The amount of material varies constantly, therefore the effect of the crusher varies also.

The other factor affecting the results is the difficulty of getting an accurate measure of the moisture content of the hay. More than twice as many samples would have to be taken as were taken during the second cutting to remove the large error due to variation in moisture content of the hay in the plot.

Another method of observing the effect of crushing as related to weather conditions is to compare the hours of drying time required to reach twenty percent moisture content and the decrease in drying time as a result of crushing. It can be seen (Table 6) that although the total hours of drying time increased greatly for poorer weather conditions, the decrease in drying time as a result of crushing did not vary appreciably, except in one test.

The decrease in drying time was not less than two or greater than four hours as a result of crushing except in the

third test. Crushing indicated a decrease of eight hours in drying time in the third test.

Storage Experiments

This study was made to determine the effect of crushing upon the relationship between density of bales, moisture content of hay when baled and the quality of hay when stored in a natural draft ventilation mow.

These studies were made in the Case Hay Laboratory at East Lansing. The hay for the tests was obtained from the same field used for the field experiments.

Design of the Experiment. This study was made with crushed and uncrushed hay in order to evaluate the effect of crushing on the development of mold in stored baled hay. Both crushed and uncrushed hay were baled over a range of moisture contents. The moisture limits were set by previous work (6) which indicated that hay would be moldy when baled above 35 percent and would be must free when baled less than 20 percent moisture content. In order to get a range of densities, the tension on the baler was varied from loose to tight at each of the four moisture ranges chosen between 35 and 20 percent moisture content.

Briefly, the procedure was to bale four windrows of crushed hay and four of uncrushed hay at a desired moisture range. The first windrow was baled with the tension springs

on the bale chamber completely loosened; the second windrow was baled with the springs just snug; the third had three to four additional turns applied and the fourth had the maximum pressure allowed without breaking the baling twine. Each bale was tagged to identify it. The bales were all taken to the hay laboratory where each bale was weighed, and a core sample removed for moisture content determination.

The bales were space-stacked in the hay laboratory (Figure 9). This was done by leaving spaces up to six inches wide between the stacked bales which allowed the natural circulation of air around each bale in the stack. This is called natural draft ventilation, or natural mow drying.

The bales were inspected for must after a period of 12 to 16 weeks in storage. A scale which classifies the extent of must development was set up for grading the hay. These grades were:

Must free - no must present

Slightly musty - a trace of must present

Musty - bale has decidedly musty characteristics or
is moldy.

First-Cutting Test. This experiment was started on June 27. The hay was mowed at 2:00 p. m. and crushed immediately. Both plots were raked at 9:00 a. m. on June 28. The baling was started at 2:00 p. m. June 28, and was completed at 2:00 p. m. June 29.



Figure 9. Space-stacked Bales in an open Mow.

Core sampling of bales and weighing was completed by the evening of June 30. These bales were stored in two closed bins of the hay laboratory. The dimension of one mow was 12 x 20 feet and the other was 24 x 20 feet. The walls and floors were covered by plywood and the only circulation of air was through the open doors and the roof ventilators.

The average daily temperature high during the first week of storage was 72°F. Precipitation occurred on four days of the first week with a total rainfall of 0.66 inches for the week. The United States Weather Bureau twelve-year average for East Lansing was 71°F. and 62 percent relative humidity for the month of July.

The bales in this test were opened for inspection after 16 weeks of storage.

Second-Cutting Test. Hay was mowed at 10:00 a. m. and raked at 4:00 p. m. July 25. Baling was begun the following day and was completed by 12:00 a. m. July 27.

The humidity had been very high during the latter part of the test and 0.45 inches of rain fell immediately after the hay was sheltered. The sampling and weighing was completed by the evening of July 26. These bales were stored in an open bin of the hay laboratory. Two sides of the bin were open and the floor consisted of a one inch wire mesh layed over the joists.

The average daily temperature high during the first week of storage was 82°F. and the average daily relative humidity

low was 50 percent. The United States Weather Bureau Twelve-year average for August was 69°F. and 65 percent relative humidity. The bales in this test were opened for inspection after twelve weeks in storage.

Analysis of Data. The results of the storage tests were compiled and plotted graphically with moisture content at time of baling versus bale density. The quality of the hay in each bale was indicated by a symbol. The upper and lower limits of the three grades of must development for crushed (Figure 10) and uncrushed (Figure 11) alfalfa were then drawn.

Maximum Moisture Content and Bale Density for Must Free Bales. In preliminary tests during 1952 Eggleton (4) found that must and mold free baled hay occurred at densities below 7 pounds per cubic foot. Hopkins (6) continued the tests in 1953 and reported that during storage periods of eight weeks must occurred at not lower than 19 percent moisture content. The results of the storage tests during 1955 indicate that must occurred in hay which was stored at 12 percent moisture content during a storage period of 16 weeks. Wright (11) reported that must occurred in hay at moisture contents as low as 13 percent. He stated that it may take as long as 300 days to appear.

This indicates that as the storage period is extended must will appear in bales with lower original moisture

contents. This is understandable since must may develop on hay that is dry enough to prevent mold, if the humidity of the air surrounding the hay rises above equilibrium with the hay (3). Dexter (ibid) stated that equilibrium for 14 percent hay would be 75 percent relative humidity. Over longer periods of storage more opportunity will occur for humid conditions above equilibrium.

Effect of Crushing upon Must Development. Crushing did not indicate a significant lowering of must development. Must-free bales did occur at slightly higher moisture contents and densities for crushed hay than for uncrushed hay. However, since this difference is only one percent, crushing is of less importance in reducing molding after the hay is stored than other factors such as temperature, relative humidity, density of bales and moisture content of the hay.

Differences Between Open and Closed Mows. There was no conclusive difference between the limits for must development in the bales stored in the open mow when compared with the bales stored in the closed mow. This indicates that drying conditions within the space stacked bales were not limited by the circulation within the bin as much as by the density of the bales.

Accuracy of Limits of Must Development. Although each limit indicated was decided by results from not more than two test bales, a linear relationship is shown between density and moisture content for the development of must in

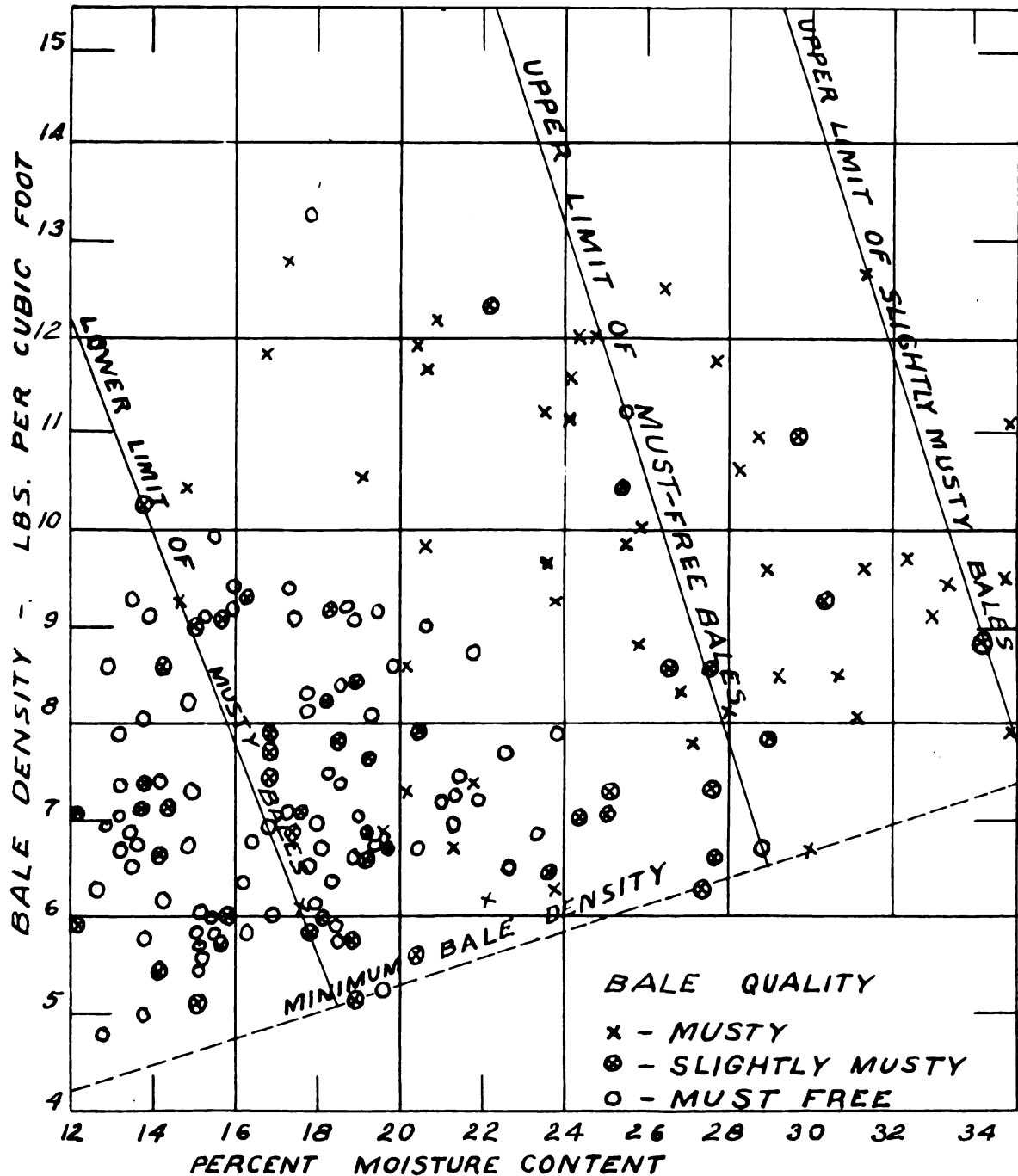


FIG. 10 THE RELATION BETWEEN BALE DENSITY, MOISTURE CONTENT AND KEEPING QUALITY OF CRUSHED ALFALFA

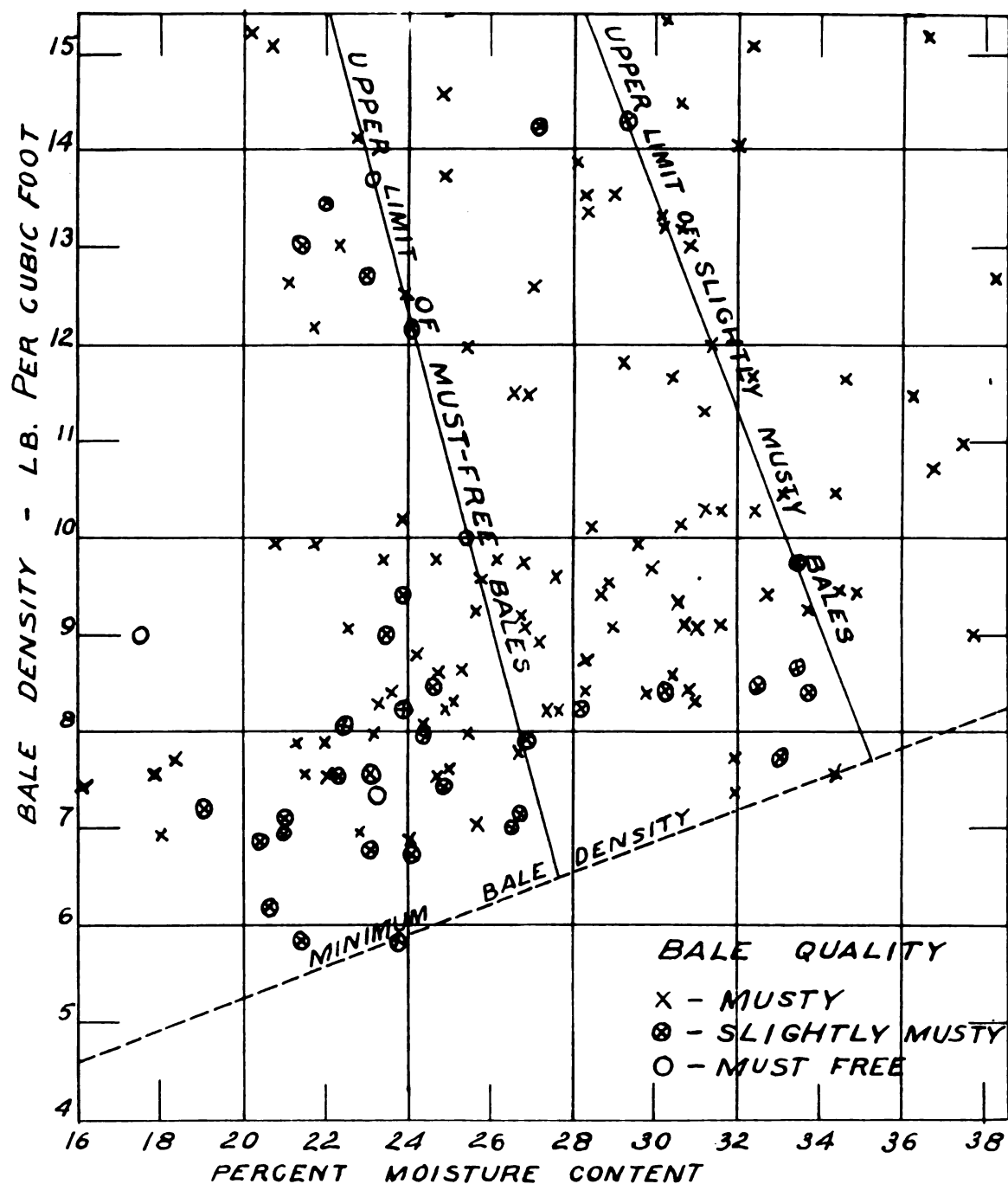


FIG. 11 THE RELATION BETWEEN BALE DENSITY, MOISTURE CONTENT AND KEEPING QUALITY OF UNCRUSHED ALFALFA

baled hay. The maximum difference in slope of the limits for must development during the 1955 tests is less than 6 degrees. This indicates that the limits are quite accurate in slope as well as being linear, but there is no method to substantiate this indication.

The upper limit of slightly musty bales in Figure 10 was drawn parallel to the upper limit of must-free bales on the same figure since the other four limits are nearly parallel.

The limits indicated (Figures 10 and 11) are only those of this sample, however, and a larger sample would not necessarily have parallel limits nor limits at the same moisture contents and densities.

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A PRELIMINARY INVESTIGATION OF FACTORS
INVOLVED IN PELLETING HAY

Reasons for the Study

Even though much research has been done to solve the problems related to the present methods of harvesting hay, many unfavorable factors still exist.

Baled hay is difficult to handle in the field and in storage. Hay that otherwise is safe for storage will mold in storage after it is baled (9). Artificial drying of baled hay is difficult and expensive. Feeding baled hay is tedious and it can neither be mechanically fed nor self-fed to livestock. A large percentage of the leaves are lost during baling and even more are lost when the bales are torn apart for feeding.

Chopped hay, however, is easily handled by machinery in the field and can be both mechanically and self-fed to livestock. A large loss of hay results from cattle refusing to eat the large amount of chaffy feed resulting from chopping and a further loss occurs from cattle trampling the hay due to the loose quality of the feed. In many cases chopping is not acceptable to the farm operators due to the extremely dusty character of the feed.

In recent years there has been a great deal of research carried out to determine the value of pelleted feeds and LeClerc (12) has suggested pelleting hay as a possible method of solving the many problems present with other methods of harvesting.

The research to date on pelleted feeds has indicated several advantages to feeding pellets. Eaton (6) found that calves consumed larger quantities of feed in the form of dehydrated pellets than in the form of long field cured hay, and that the calves grew faster as a result of this increased consumption. Blosser (2) reported that cows do not go off feed as often when eating pelleted hay as when eating chopped or ground hay. This allows heavier feeding of livestock.

Bruhn (3) stated that pellets are easier to handle than long loose or baled hay and that hay when pelleted occupies less storage space than when handled by other methods.

Most of the research on pelleted feeds has been done with pellets less than 1/2 inch in diameter. The cost of grinding hay and pelleting into these small dimensions has been questioned when feeding hay to large ruminants. There is considerable interest in a machine which can produce larger pellets from hay in the windrow with a capacity comparable with forage balers and choppers in use. No machine is available, however, which can produce pellets over one inch in diameter from unchopped hay.

Review of Literature

In processing ground feeds into pellets, Grahek (8) found that there are certain fundamental requirements of any formula to obtain good quality pellets. One of the most important of these is the binding quality of the ingredients, such as the presence of starches. These break down into sugars during the pelleting operation and form a very effective binding agent. Bruhn (3) reported that green hay can be pressed into firm pellets as large as two inches in diameter without the addition of any binding material or any prior treatment.

With ground feeds Grahek (op. cit.) found that making pellets without a binding material was less efficient because of the excess pressures and power required. He indicated that conventional pellet mills were now operating with pressures from 4000 to 10,000 pounds per square inch. From the results of Bruhn's study (op. cit.) it is indicated that additional binding material is not necessary when pelleting hay. He obtained pellet densities of 40 pounds per cubic foot with pressures of 4000 pounds per square inch. When the pressure was greater than this pellets were not easily eaten by livestock.

If pellet diameter is reduced, Grahek (op. cit.) found that a pellet mill of given die speed and horsepower will increase output while still maintaining pellet quality

or hardness. This result was with ground formulas, however, and may not be the same for long hay.

These results indicate that much more work is necessary relative to the fundamental pressure-moisture relationship and the final density of the pellet as well as the time of application of the pressure before a portable pelleting machine can be perfected.

Objectives

The study was made to determine the requirements for obtaining firm, palatable pellets suitable for feeding to livestock.

Briefly, these objectives are to determine:

1. The effect of pelleting pressure upon the expansion and final density of two inch diameter hay pellets.
2. The effect of moisture content of hay at time of pelleting upon the expansion and final density of two inch diameter hay pellets.

This study was made to obtain fundamental information related to pelleting hay as a preliminary study of an overall project for the possible development of a pelleting machine.

Apparatus

Reconditioning Chamber. The reconditioning chamber was constructed so that a high humidity could be controlled around the hay. A barrel was used with a steam inlet and outlet. A false bottom was installed to keep the hay above any condensate and the cover was connected with a rubber gasket to insure a moisture tight seal.

Pelleting Apparatus. In order to determine fundamental principles of pelleting it was decided to use a hydraulic press to apply pressure to a hay sample in a cylinder and ram device (Figure 12). This allowed accurate measurements to be made and results could be reproduced and checked with very little error.

The load exerted by the press had been calibrated with a pressure gauge certified by the United States Bureau of Standards and these results were extrapolated so that the load exerted by the press could be found by merely measuring oil pressure. The pressure gauge used for the tests was calibrated and these results were combined with the press calibration (Figure 13) to make the measurement of load on the ram. The pressure on the pellet was calculated from the area of the cylinder and the load on the ram.

The pelleting cylinder was constructed with a standard two-inch pipe. This was placed on a flat horizontal base and the ram forced down into it. With hay above 30 percent

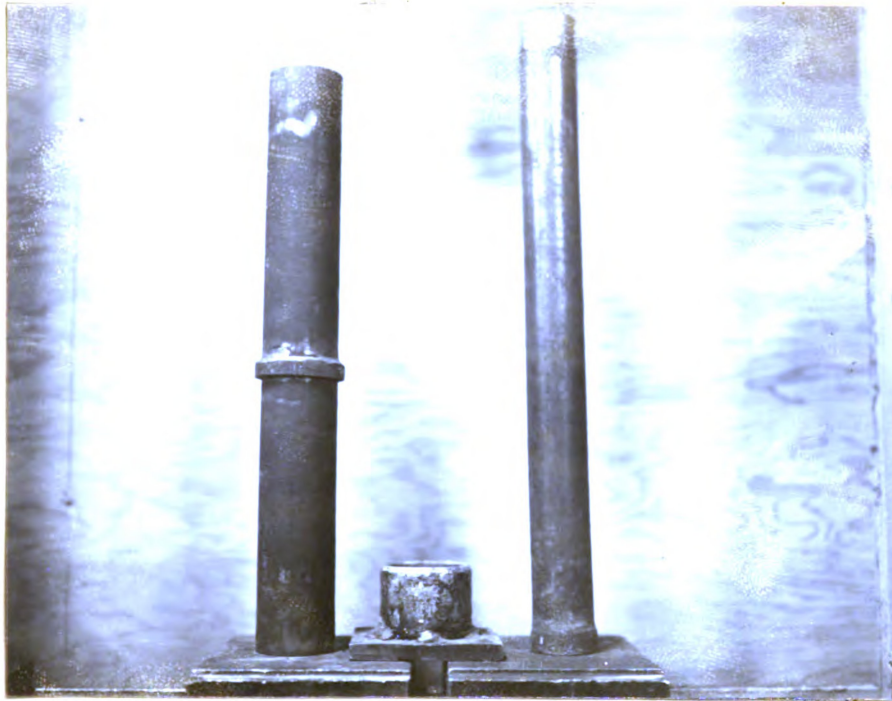
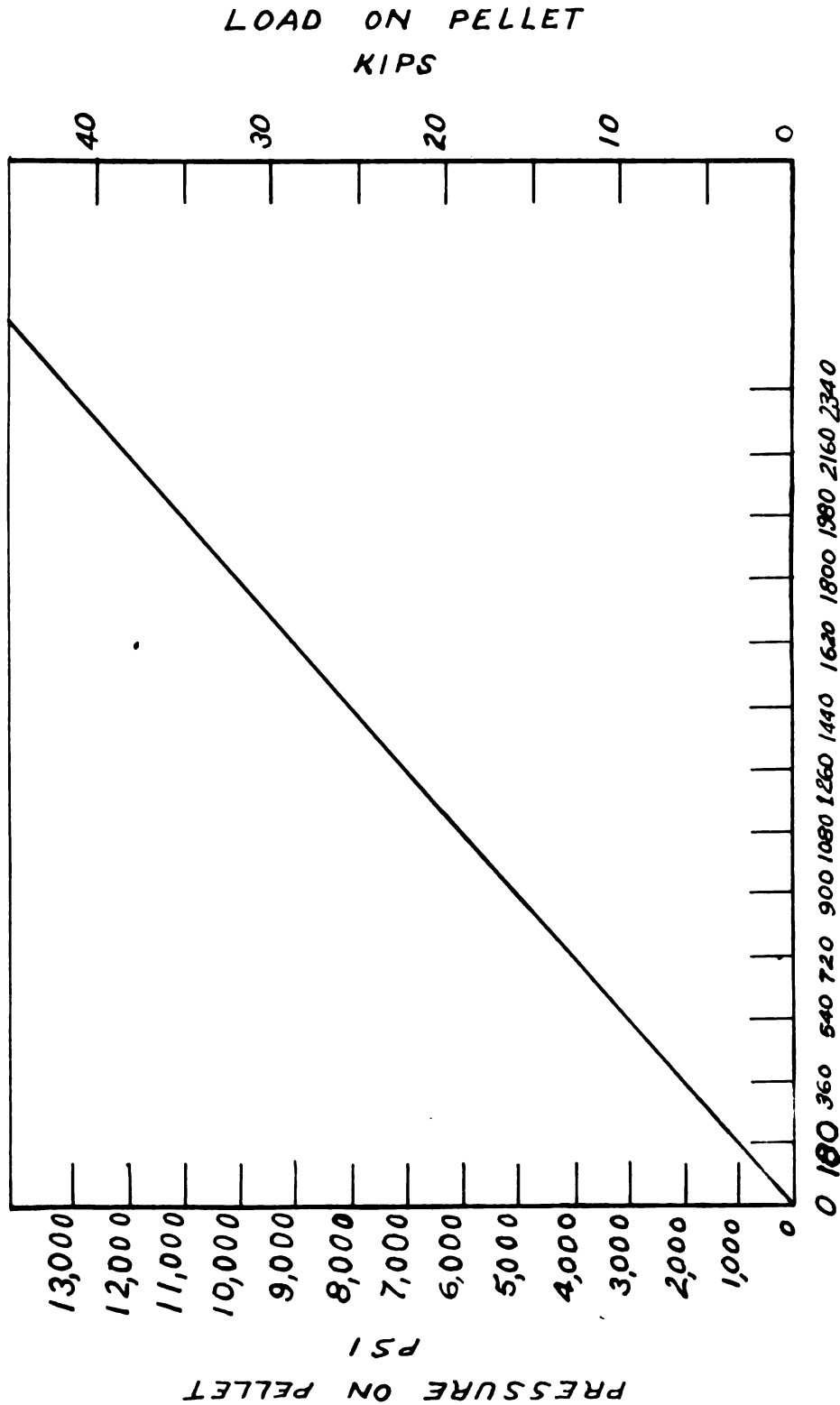


Figure 12. Pelleting Apparatus: Cylinder, Sleeve and Base,
and Ram.

HYDRAULIC PRESS CALIBRATION CURVE



P 51
PRESSURE IN HYDRAULIC CYLINDER

FIGURE 13

moisture content this device was not satisfactory. The damp hay acted as a hydraulic material when pressure was applied and oozed from the chamber between the base and the bottom of the cylinder.

To correct this a sleeve (Figure 12) was welded to the base. A loose fit was made between the sleeve and the cylinder so that when pressure was applied the cylinder would not lift from the base. This allowed much higher pressures to be obtained with moisture contents above 30 percent without loss of material from the cylinder.

Experimental Procedure

Pelleting Reconditioned Baled Hay. These tests were made with reconditioned baled hay before green hay was available from the field. This was done to determine certain fundamental characteristics of pellets early in the studies and aid in the development of the apparatus.

In order to experiment with hay over a large range of moisture contents the hay was reconditioned by holding it in a high humidity atmosphere until the hay was at the desired moisture content. This procedure was not satisfactory, however, since the hay did not absorb moisture uniformly. Part of the hay was quite dry while other areas were soaked. The hay acquired a dark brown color similar to that subjected to severe weather damage. This indicated that valuable dry

matter and nutrients were lost in the reconditioning process.

When the hay had reached the desired moisture content in the reconditioning chamber, a hay sample of desired size was inserted in the pelleting cylinder. The pelleting was done by using a hydraulic press to apply pressure to the ram on the hay sample. The maximum pressure and the period of time held on the pellet was then recorded for each pellet. The length of the pellet while under maximum pressure was found by measuring the protruding length of the pelleting ram (Figure 14). The pellet was then ejected from the cylinder (Figure 15) and weighed.

After the wet weight was recorded the pellet was placed in the electric drying oven, operating at 150°F. The pellet was reweighed at intervals until it had reached a constant weight. The first and final weights were used to determine the percent moisture content of the pellet at the time of pelleting. The percent linear expansion of the pellet was computed from the minimum and final length measurements.

Pelleting Green Hay. As soon as green hay was available the studies on pelleting freshly cut hay were begun. In order to pellet hay over a range of moisture contents, the freshly cut hay was placed in an electric drying oven until it had dried to the desired moisture content.

The sample was then inserted in the pelleting cylinder and the desired pressure applied. The time of application

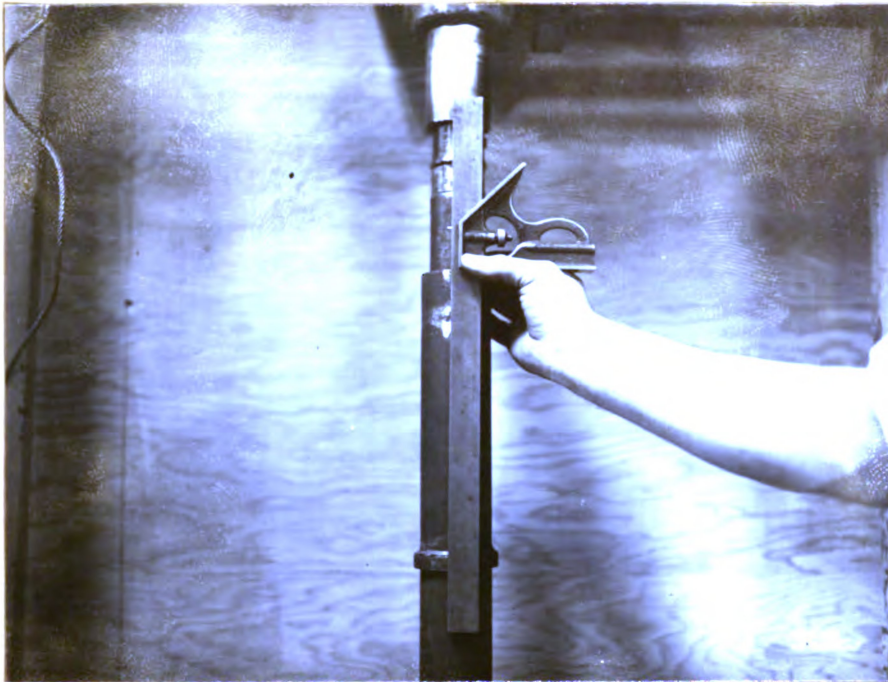


Figure 14. Measuring pellet length under maximum pressure

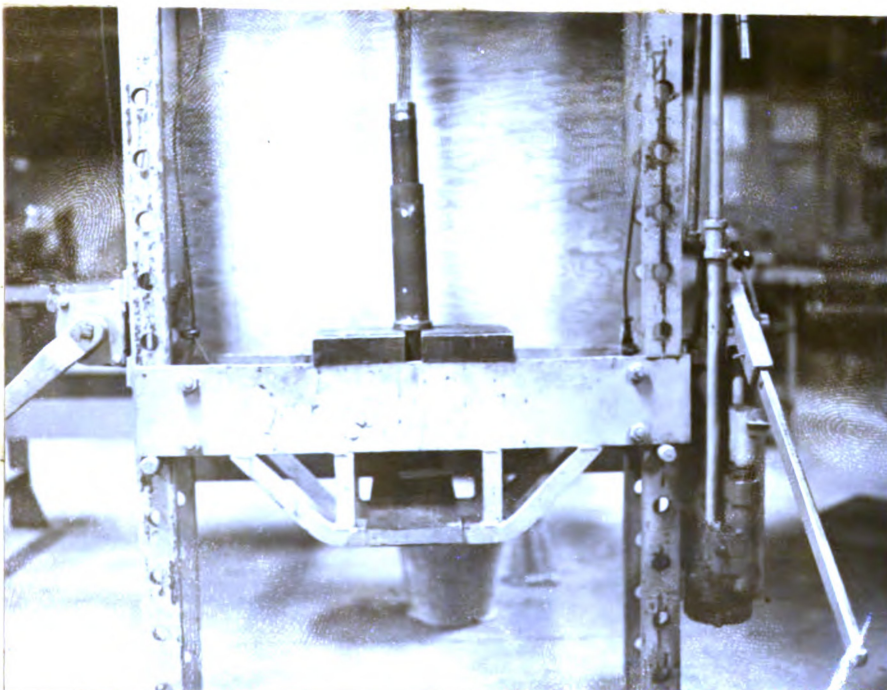


Figure 15. Ejecting the pellet from the cylinder

of the pressure and the minimum height of the pellet was recorded. The pellet was then ejected from the cylinder and weighed. The pellet was then returned to the oven until completely dry in order to determine the moisture content when pelleted. The pellets were removed from the oven when dry and the final weight recorded. The pellet was then measured for both length and diameter to be used in computing expansion, final density and final volume.

Discussion of Results

Results of Pelleting Reconditioned Hay. The linear expansion of each pellet was computed from the length of the pellet when maximum pressure was applied and the length of the pellet after it had been dried in the oven. The density of the pellet was determined from the final volume and the percent moisture content was computed from the wet and dry weights of the pellet.

This data was plotted to show the expansion-moisture relationship (Figure 16) for reconditioned baled hay and the density-moisture relationship (Figure 17). Because of the small number of samples and the large variation between pellets, no regression lines were computed for this data.

These tests indicated that the final density of the pellet is determined by the density when pressure is applied

LINEAR EXPANSION-MOISTURE RELATION

RECONDITIONED HAY

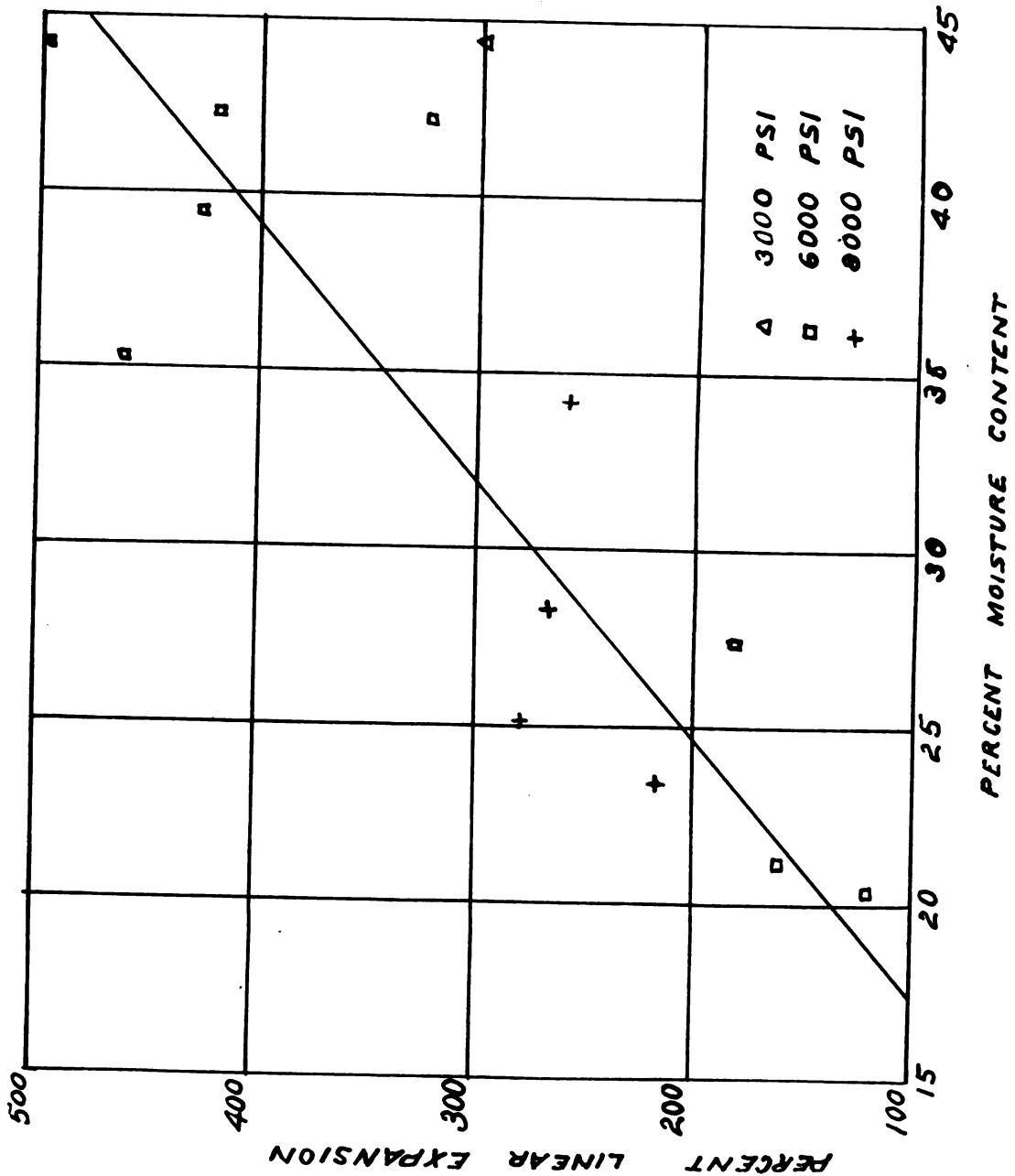


FIGURE 16.

DENSITY-MOISTURE RELATION RECONDITIONED HAY

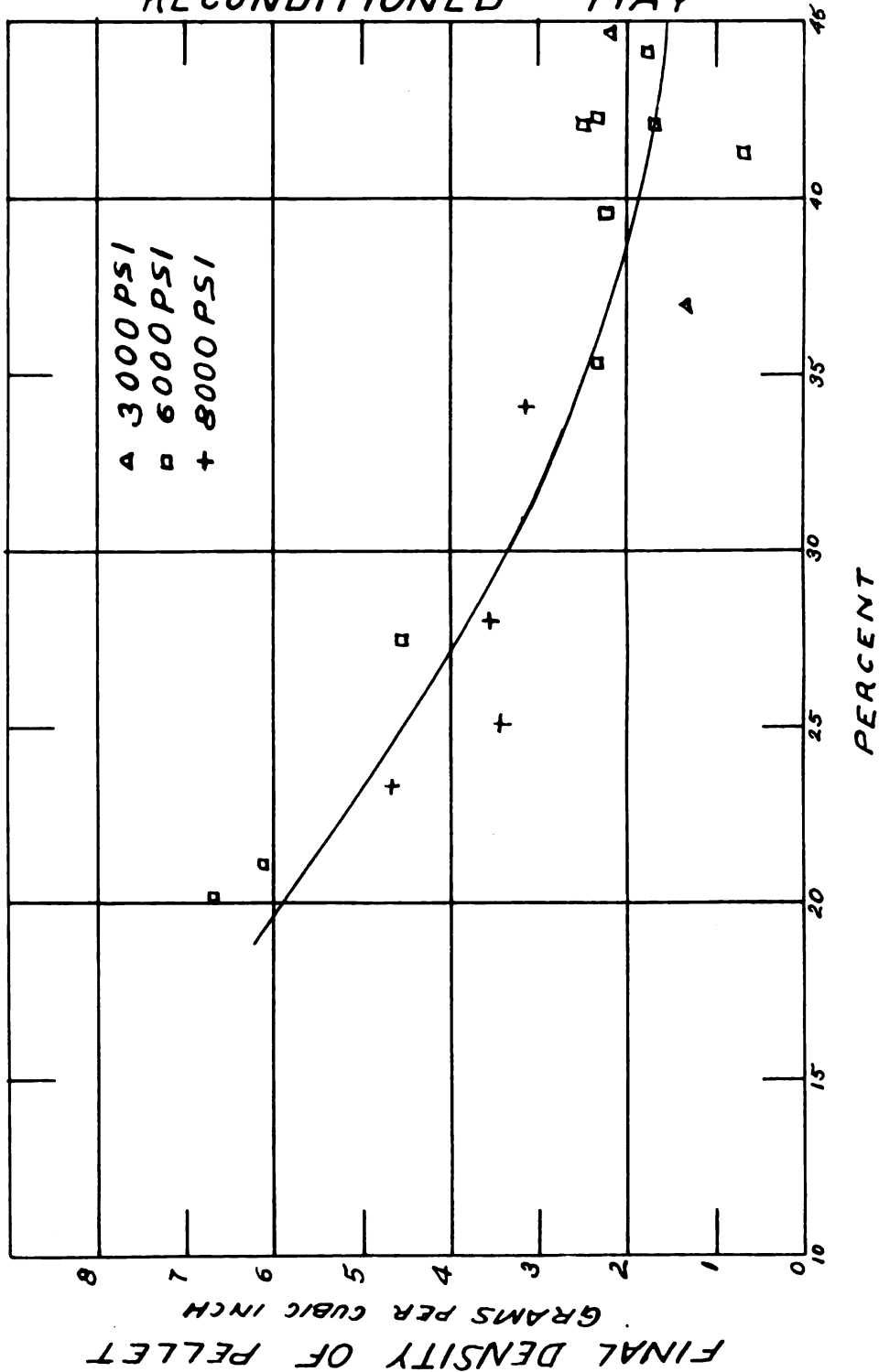


FIGURE 17. MOISTURE CONTENT - WET BASIS

and the expansion after release of the pressure.

The density when pressure is applied is limited by the moisture content of the hay. When the hay is above 35 percent moisture content, it reacts as a hydraulic material as pressure is applied and will ooze from the cylinder through the clearances allowed for air. As pressure is increased the hay will begin to spurt out and it then becomes impossible to hold the pressure.

As moisture content is increased, the maximum pressure obtainable without loss of material from the cylinder is decreased. This has made it difficult to obtain accurate results with high moisture content hay.

When material is forced from the cylinder during the pelleting process, the result is a poor quality pellet. Although one end is usually satisfactory, the other end is loose due to the lower pressure after the loss of material.

When pelleting reconditioned hay the percent linear expansion is less for lower moisture content hay (Figure 16). This is due to the increased elasticity and the reduced brittleness of the hay stems at higher moisture contents.

This results in a higher density with pellets made from hay at higher moisture contents. The density-moisture relationship for reconditioned hay (Figure 17) indicates that a decrease in moisture content from 30 to 20 percent before

pelleting would result in an increase in density from 12.6 to 22.1 pounds per cubic foot. These values were found by multiplying the values found on Figure 17 for density by a conversion factor of 3.813 to obtain density in the more common units of pounds per cubic foot.

When reconditioned hay is above 30 percent moisture content, a quantity of liquid is squeezed from each pellet as it is made. The amount of liquid increases as the pressure and moisture content are increased. Although this involves a loss of nutrients, this loss is not important since the hay is dry when taken from storage and need only be brought up to 15 to 18 percent moisture content for pelletizing.

The time required to apply pressure to the pellet to obtain a dense, firm pellet indicates a need for an additional binding material when pelletizing reconditioned hay. The expansion increased when pressure was held for less than two minutes and no firm pellets were obtained when pressure was held for less than one minute. This indicates that the efficiency of pelletizing reconditioned hay would be increased with the addition of a binding material.

The need for an additional binding material is due to the loss while in storage and during the reconditioning process of sugars and starches (12) necessary for creating a bond between the hay stems.

This would also be a method of adding to the feeding value of old hay, since Grahek (8) suggested several high energy ingredients for use as binders. Midds, millrun, shorts and other forms of wheat starch were listed as desirable binding materials.

Results of Pelletting Green Hay. The linear expansions as well as the final densities were computed from the length and diameter measurements of the pellets. The percent moisture content of the pellets at the time of pelletting was computed from the wet and dry weights.

A graph was made of the final density versus the moisture content of the pellets. In order to represent the density-moisture relationship, curvilinear regression lines were computed for the 3000, 5000 and 8000 pound per square inch pelletting pressures. A parabola was used to obtain the following equations;

at 3000,

$$Y = 9.097 - 0.3412X + 0.004544X^2,$$

at 5000,

$$Y = 10.896 - 0.4236X + 0.005813X^2,$$

and at 8000,

$$Y = 14.053 - 0.6474X + 0.01038 X^2,$$

where

Y - density-grams per cubic inch

X - moisture content-percent

These results indicated that an exponential equation might be a more accurate representation of the density-moisture relationship, especially at higher moisture contents. The parabolas can not be used to predict density at higher moisture contents because of the minimum points.

The following equations resulted when an exponential equation was used to represent the density-moisture relationship and these are shown on Figure 19.

At 3000

$$Y = e^{2.0305 - 0.0276 X},$$

at 5000

$$Y = e^{2.242 - 0.03351X},$$

and at 8000

$$Y = e^{2.568 - 0.04054X}.$$

These equations indicate a definite linear relationship between the pressure used in pelleting and the computed coefficients. The parabolas indicated a relationship, but it was not definitely linear.

The least squares method was used to get an estimate of the effect of pressure on the coefficients of the equation

$$Y = e^{a + bX}. \quad (1)$$

Allowing Z to represent pressure in pounds per square inch, $a = AZ + B$ and $b = CZ + D$. (2, 3)

Substituting these into (1) results in

$$Y = e^{(AZ + B) + (CZ + D)X}. \quad (4)$$

DENSITY-MOISTURE RELATION GREEN HAY

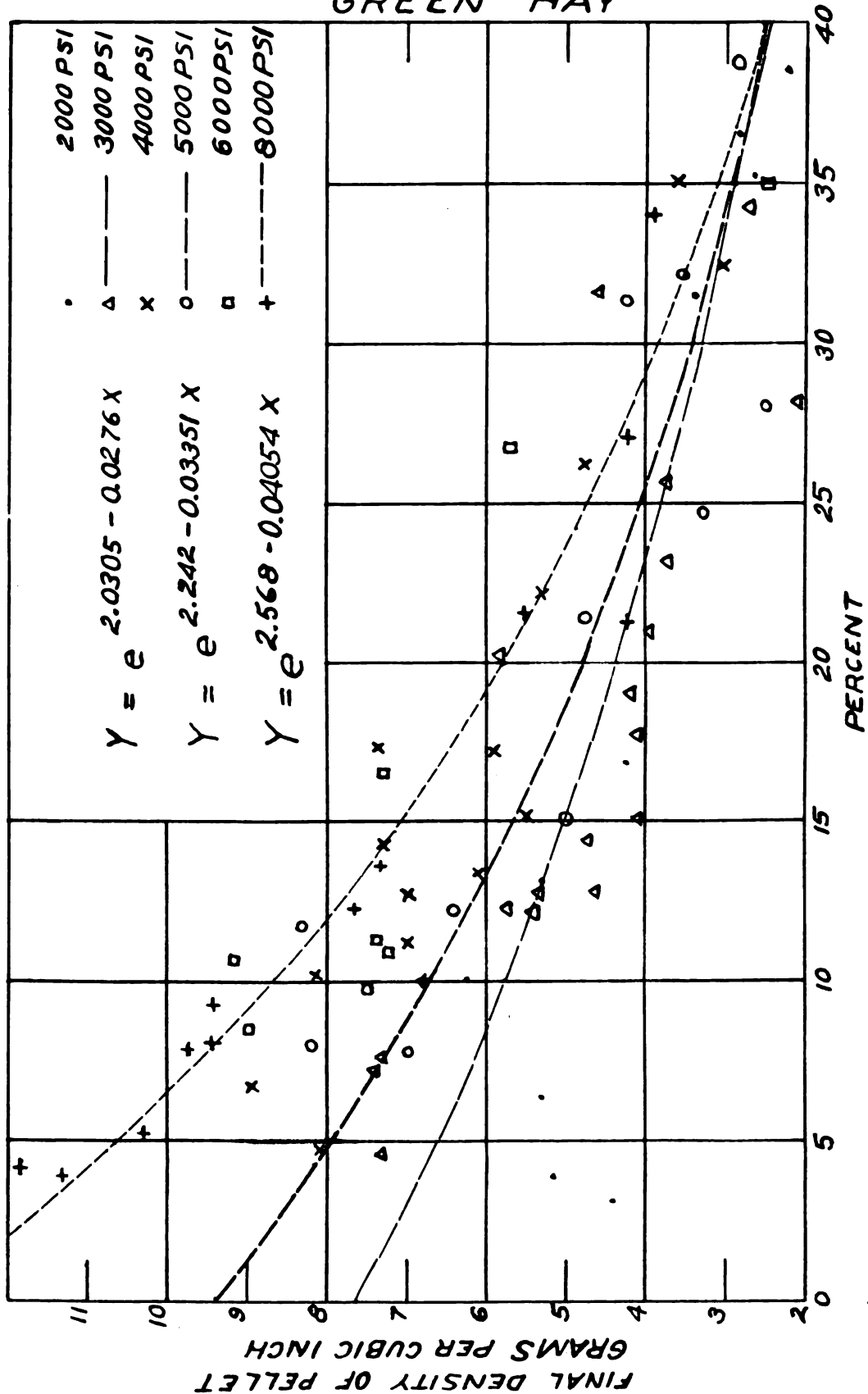


FIGURE 19. MOISTURE CONTENT - WET BASIS

Solving (4) gives

$$Y = e^{(B - \frac{AD}{C}) + C(Z + \frac{D}{C})(X + \frac{A}{C})}$$

The equation for the pellet density-moisture-pressure relationship with the computed coefficients is

$$Y = e^{0.805 - 0.00000268(Z + 7360)(X - 42.2)}$$

Although this is an estimate of the real relationship, a more rigorous representation would be given by computing a multivariate regression with a greater number of samples using the equation

$$\log Y = B + AZ + CZX + DX$$

involving four variables.

A variation of time of pressure application or maturity and quality of alfalfa would alter the coefficients in any of these equations.

A graph was made of the moisture content versus the percent linear expansion (Figure 18). Regression lines were computed for the 3000, 5000 and 8000 pound per square inch pressures with an exponential equation. These equations showing the pellet expansion-moisture relationship were;

at 3000

$$X = e^{1.20 + 0.00805Y},$$

at 5000

$$X = e^{1.151 + 0.01046Y},$$

LINEAR EXPANSION-MOISTURE RELATION GREEN HAY

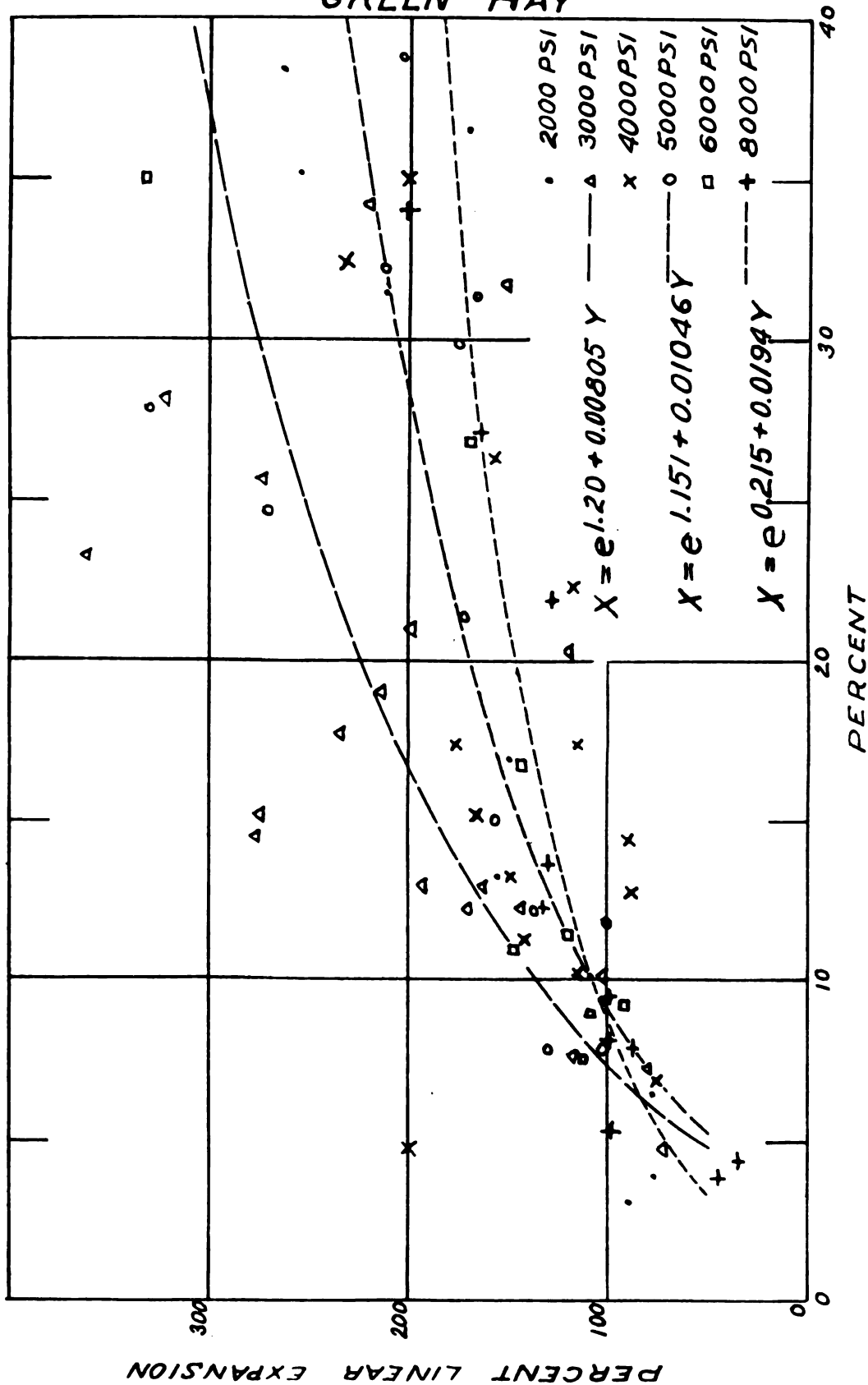


FIGURE 18. MOISTURE CONTENT - WET BASIS

and at 8000

$$X = e^{0.215 + 0.0194Y}$$

where

X - moisture content-percent

Y - linear expansion-percent.

There is no linear relationship between the coefficients of these equations and the pressures used during pelleting. At the lower moisture contents the regression lines cross (Figure 18). This is due to the large error involved in measuring and computing the percent linear expansion rather than a characteristic of pelleting alfalfa.

A more complete study was made of the pellet density-moisture relationship for green hay then was carried on with reconditioned hay. The curvilinear regression lines indicate the difference in density as a result of using different pressures at any given moisture content. At twenty percent moisture content an increase of pressure from 3000 to 8000 pounds per square inch will increase the final pellet density from 16.6 to 22.1 pounds per cubic foot.

These values were found by multiplying the values for density obtained on Figure 19 by a conversion factor of 3.813 to obtain density in the units of pounds per cubic foot. The effect of increasing pressure is illustrated in Figures 20, 21 and 22.

A decrease in moisture content from 30 to 15 percent

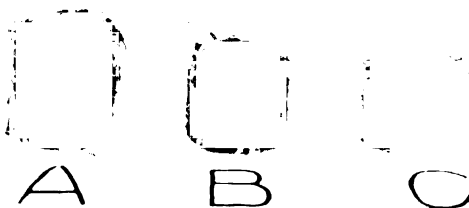


Figure 20. Density-Pressure Relationship at 12.5 % M. C.

Pellet	Pressure-psi	Density-lbs. per cu. ft.
A	3000	21.0
B	5000	24.8
C	8000	29.4



Figure 21. Density-Pressure Relationship at 21 % M. C.

Pellet	Pressure-psi	Density-lbs. per cu. ft.
A	3000	15.3
B	5000	18.3
C	8000	21.0

before pelleting with a pressure of 8000 pounds per square inch will result in an increase in final pellet density from 14.5 to 27.1 pounds per cubic foot. Figures 23, 24 and 25 were made to illustrate this effect.

It can be seen that moisture content of the hay is as important to quality of pellet as the pressure used in pelleting. It is obvious that hay should be as dry for pelleting as for baling or chopping and that pellets may be made from low moisture hay. This will reduce the complexity of problems involving the drying of hay pellets.

By studying the density-moisture relationship (Figure 19) it can be seen that an increase in pressure will result in an increase in density of pellet. Other factors become more important as the pressure is increased, however. Power requirements are increased and the strength and design problems of a pelleting machine become more complex. It would probably result in greater efficiency if a binding agent was added rather than using higher pressures than those used in this study.

Pellet densities should not be greater than 30 pounds per cubic foot due to the large pressures required to obtain densities as great as this with hay between 15 and 25 percent moisture content.

For feeding cattle a density range between 15 and 30 pounds per cubic foot would seem desirable. Below this

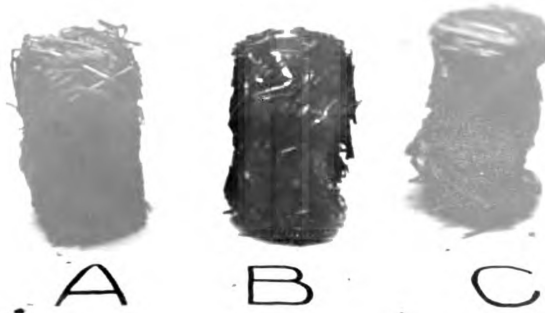


Figure 22. Density-Pressure Relationship at 33 % M. C.

Pellet	Pressure-psi	Density-lbs. per cu. ft.
A	3000	10.5
B	5000	13.3
C	8000	14.9



Figure 23. Density-Moisture Relationship with 3000 psi.

Pellet	Moisture Content-%	Density-lbs. per cu. ft.
A	5.0	28.6
B	12.5	21.0
C	21.0	15.3
D	34.0	10.5
E	41.0	9.9



Figure 24. Density-Moisture Relationship with 5000 psi.

Pellet	Moisture Content-%	Density-lbs. per cu. ft.
A	8.0	31.1
B	12.5	24.8
C	21.0	18.3
D	32.0	13.3
E	39.0	11.1



Figure 25. Density-Moisture Relationship with 8000 psi.

Pellet	Moisture Content-%	Density-lbs per cu. ft.
A	4.0	45.7
B	7.9	29.1
C	14.0	28.2
D	27.0	16.2
E	34.0	14.9

range pellets are not firm enough to withstand normal handling. With pellet densities greater than this there would be a danger of sore mouths to many livestock due to the increased hardness. Decreasing the size of pellet would probably allow an increase to be made in this range.

It was found that if the amount of material inserted in the cylinder was increased, the resultant pellet density was decreased even when the moisture content and pelleting pressure were not changed. This was due to the cushioning effect of more hay and the greater friction against the walls of the cylinder. This was also one of the reasons for a variation in the data since the weight of the pellets was not controlled during the study. The dry weight varied between 45 and 70 grams for most of the pellets made in this study.

The increase in percent linear expansion as moisture content is increased, indicates that hay should be pelleted at as low a moisture content as possible. However, when moisture content is below 5 percent, even the highest density pellets will not endure handling. This is due to the lack of adhesion between the hay stems at these low moisture contents.

Even though the period of pressure application was held at one minute during the pelleting study with green hay, 30 seconds was satisfactory to obtain a firm pellet in most

cases.

It was not necessary to add a binding material with any of the green alfalfa used in this study. This was due to fact that all the alfalfa was dried to the desired moisture content immediately after cutting in order to reduce any loss of nutrients and dry matter.

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SUMMARY AND CONCLUSIONS

Since the making of hay is subject to weather conditions a large loss in quality and nutrients results each year due to extended drying periods during poor weather. A further loss occurs each year due to leaf shattering caused by the common methods of harvesting.

Before the loss resulting from damage by rain in the field or molding of partially cured hay can be reduced, a method is needed that will reduce the required time for field drying.

Crushing alfalfa increases the drying rate, but the drying time is still longer than the average period between rainfall in the humid hay producing regions. The increase in drying rate increases as drying conditions improve, but the decrease in drying time as a result of crushing remains at three to four hours, even when the drying period is extended over several days due to poor weather.

Tedding crushed alfalfa immediately to break up the mat of hay left by the crusher does not increase the drying rate when the yield is less than 1.5 tons per acre.

The quality of baled hay when placed in an open storage is affected by the density and the moisture content of the bales as well as the weather conditions during the storage

period. Must will develop in bales which have densities of six pounds per cubic foot and moisture contents as low as 12 percent, if weather conditions are favorable for must development during the storage period. Crushing does not affect the limits of must development when the bales are stored in a natural draft ventilation mow.

Pelleting the hay is a possible method of solving the many problems inherent with common methods of harvesting hay. Fundamental requirements for obtaining good quality pellets are needed before a machine can be made which will produce pellets from long field cured hay.

The pellet density-moisture-pressure relationship for green alfalfa is given by the equation

$$Y = e^{0.805 - 0.000002682(Z + 7360)(X - 42.2)},$$

where

Y - pellet density - grams per cubic inch

Z - pelleting pressure - pounds per square inch

X - moisture content - percent.

The coefficients of this equation are altered by a change in time of pressure application or quality of hay.

The hay should be below 30 percent moisture content to obtain firm pellets. Pellet densities of 25 pounds per cubic foot are recommended for two inch diameter pellets. These can be obtained with 15 percent moisture content hay

by applying a pressure of 5000 pounds per square inch. Increasing the weight of material in each pellet or decreasing the time of pressure application will result in a lower pellet density.

Two inch diameter pellets are faster and easier drying than either chopped or baled hay. The narrow diameter reduces the wet centers found in baled hay and also the complete pulverization of hay stems during pelleting allows better drying characteristics than obtained with chopped hay.

Firm pellets are easier to handle than baled hay and can be mechanically loaded and stored. Storage space requirements are reduced and pellets can be both mechanically or self-fed to livestock.

Pelleting reconditioned baled hay is similar to pelleting green hay. The only noticeable difference is the period of time required for pressure application to obtain good quality pellets. The presence of available starches and sugars is more important to forming a good quality pellet than the period of time the hay has been in storage. These nutrients are reduced after a period in storage, however, and in some cases additives may be necessary to restore the binding qualities.

RECOMMENDATIONS FOR FUTURE RESEARCH

This study has indicated several factors related to pelleting hay which require further research. Although the basic density-moisture-pressure relationships have been determined, further study is needed to find the effect upon these relationships when various factors are changed or allowed to vary.

The determination of the effect of shorter durations of pressure application is necessary before pellets can be produced at the rate necessary for efficient field operation.

A study is needed to determine the best shape and size for producing, handling, storing and feeding pellets. This will involve a study of the efficiency of producing various forms, of the handling ability and durability of various dimensions and densities, of bin storage density and feeding trials with pellets.

The study of efficiency should consider the power and final density relationship for producing pellets. An evaluation should be made of possible methods for loading and conveying hay pellets with the least amount of break-up and loss of dry matter.

Extensive feeding trials are needed to determine the effect of pelleting hay on the feed consumption and the production of livestock. The relation of consumption to the

size, shape and density of hay pellets should be found.

Longer period studies should be carried out to determine the drying characteristics of pellets of various sizes and densities and how these compare with chopped and baled hay.

Further study is needed to establish a relationship between the final density and firmness of a pellet and the available starches in hay. This would allow pelleting to be done when the hay was at the optimum maturity for obtaining firm pellets.

Work should be carried out evaluate the possible advantages of using heat to aid in obtaining firm pellets. Heat in the form of steam is used to aid in obtaining good quality pellets with the present pelleting mills. This might be a method of increasing pelleting rate without increasing the pressure or adding a binding material.

As soon as the pelleting fundamentals are available it will be necessary to carry on an extensive development program to evaluate the possible methods and machines for producing pellets.

A list of possible methods for producing pellets is as follows: (1) converted baler or ram type, (2) hydraulic pelleting mill, (3) belt type, (4) screw type, (5) extrusion mill, and (6) roller type. The continuous type operation is more efficient, but a positive action will not jam as easily.

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