B-1071
November 1967

Harvesting and Drying
Selected Forage Crops

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Summary

Research on hay harvesting and handling operations was started at Texas A&M University in 1959. This report summarizes procedures and results during 1959-66.

Studies were made to determine the relative drying rates of selected forage crops. The moisture content of Kleingrass was reduced to 20 percent in a shorter time than alfalfa, Coastal Bermuda, Bufflegrass and perennial Sweet Sorgrass when all crops were cut at the optimum stage of maturity. Alfalfa had a faster drying rate than all crops tested, but Kleingrass reached the 20 percent level first because of its lower initial moisture content. Kleingrass had a faster drying rate than Coastal Bermuda, but this increased rate was not always great enough to allow Kleingrass to reach a storable level faster than Coastal. This depended on the initial moisture contents of the forages. Perennial Sweet Sorgrass had the lowest drying rate and the highest initial moisture content of the crops tested.

Tests were conducted to determine the effect of harvesting method on field-drying time. Little advantage was gained by using hay conditioners to reduce the moisture content of alfalfa to 50 percent. However, when it was necessary to reduce the moisture to 25 percent, the crusher used in conjunction with the conventional method of making hay saved 14 hours drying time. The hay conditioners significantly reduced the field-drying time when Sudangrass was dried to 50 and 25 percent moisture content.

In laboratory studies, crushed alfalfa reached the 20 percent moisture level in 7.8 hours, compared to 10.6 and 19.3 hours, respectively, for the crimped and unconditioned alfalfa. When the material was crushed instead of crimped, a 26.4 percent time saving resulted.

There was little difference in the time required to dry flamed and unflamed alfalfa to a moisture content of 25 percent. However, a saving of 20 hours resulted in field drying flamed, conditioned (crushed) alfalfa as compared to unflamed, unconditioned alfalfa.

A major problem in using infrared radiant energy for agricultural purposes is the lack of information concerning the absorption, transmission and reflection characteristics of agricultural products. Therefore, a study was conducted on the use of infrared radiation to dry alfalfa hay. Four sources of infrared radiation were used for these tests, each having a different spectral distribution of energy. These sources were classified according to their maximum or peak wavelength and were 1.15, 2.3, 3.0 and 5.0 microns. Three of these sources were electrical, and one was gas-fired.

Alfalfa hay having an initial moisture content of approximately 63 percent, wet basis, was irradiated for periods from 0 to 240 seconds. Results of this irradiation show that the higher the radiation intensity and the longer the exposure period for each source, the greater the rate of moisture removal. For any increment of time, the decrease in the hay moisture content was always greater for the highest intensity level of each source of radiation. Scorching of the leaves was observed at several intensity levels. For each radiant energy source, the exposure time before scorching seemed to be related to the drying rate. Each decrease in exposure time due to scorching caused a decrease in the total moisture removed regardless of the intensity levels.

Although the drying rates increased as the intensity level increased for each source, the drying rates for equal intensities varied among sources. The source which had its peak energy at 3.0 microns appeared to remove more moisture than the other sources at the same intensity level.

Based on a moisture reduction of 10 percent, wet basis, the efficiencies of the sources of infrared energy ranged from 13.0 to 38.1 percent. The 1.15-micron source had the lowest efficiency, while the 5.0-micron source had the highest. Although the highest drying capacity was obtained with the 3.0-micron source, the capacity obtained was considered too low for practical use. Dryer capacity was increased by handling the forage three layers thick but was not increased sufficiently to warrant the use of infrared energy for drying forages.

A spectrophotometer was used to obtain the infrared absorption characteristics of Johnsongrass and alfalfa. Johnsongrass leaves absorbed more infrared radiation in the 3.0–4.0-micron wavelength range than at any other wavelength. The major absorption bands for ground alfalfa occurred at wavelengths of 2.9–3.0 microns and 6.1–6.3 microns.

Studies were made to determine the effects of heat and pressure treatments on altering the drying characteristics of alfalfa. Drying rate curves plotted for each of the treatments in which samples were subjected to pressures ranging from —75 cm. Hg. to 150 psig. showed no increase in the drying rate when compared to control samples. There was no evidence of rupture of cell walls or damage to the cellular organization.

Laboratory experiments were conducted to determine the effect of freeze treatments on the drying rate of unconditioned, crushed and chopped alfalfa hay. Liquid nitrogen was used to obtain a quick-freeze treatment. In these tests little or no advantage was gained by using a freeze treatment for drying alfalfa to a moisture content of 50 percent. However, there was a significant decrease in drying time due to freezing when alfalfa was dried to a moisture content of 20 percent. A quick-freeze treatment applied to the standing crop or in the swath may be a fruitful approach to the problem of moisture release from drying forage, provided no serious effect on nutritive value is found.

Harvesting and Drying
Selected Forage Crops

J. W. SORENSON, JR. AND N. K. PERSON, JR.*

PRESERVATION OF FORAGE QUALITY is an important consideration in the development of mechanized forage harvesting and handling systems. A major obstacle to a quality product is the initial moisture content of most forage crops at the stage of maturity for highest quality. The moisture content of forages at this optimum stage is usually 75 percent and above.

In high-moisture forages, 7,000 pounds of water must be removed from 80-percent-moisture forage to produce 1 ton of hay at 10 percent moisture. If the initial moisture content is 60 percent, only 2,500 pounds of water must be removed to produce a ton of 10-percent-moisture hay. A total of 4.5 pounds of 80-percent-moisture forage are required to furnish the same amount of dry matter provided by 1 pound of hay at 10 percent moisture. When the initial moisture content is reduced to 60 percent, only 2.25 pounds of forage are required to provide the amount of dry matter in 1 pound of the dry hay.

The high energy requirements to remove large amounts of moisture from fresh-cut forage make it difficult to find economical artificial drying methods. The energy required to dry forage can be reduced considerably by allowing it to partially dry in the field before the artificial drying operation. However, the drying rate of the cut forage should be as fast as possible in the field to reduce exposure time to a minimum and lessen chances for quality reduction. A fast drying rate is even more important for forage that is completely dried in the field.

Research on hay harvesting and handling operations was started at Texas A&M University in 1959. The major objective of this research was to develop rapid and economical methods of removing moisture from forages with a minimum loss in quality. This report summarizes procedures used and results obtained during 1959-66. Two approaches were followed: (1) studies to determine the relationship of certain physical properties of forage plants to the time required for drying and (2) development of methods for rapidly removing excess moisture in the field.

REVIEW OF LITERATURE

Mechanical dewatering studies made by Casselman(1)[1] and others at the Florida Everglades Experiment Station showed that the higher the initial moisture content of a crop, the greater the amount of water removed by mechanical pressing. An increase in pressure from 40 to 60 psi increased the amount of moisture extracted; however, the increased pressure also increased the dry matter expressed with the juice. The small increase in moisture extracted at the higher pressure plus the undesirable increased loss of dry matter probably would prohibit economical use of the higher pressure. It was found that mois-

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[1]Numbers in parentheses refer to appended references.

ture and nutrient changes associated with maturity in the fresh forage were reflected in the pressed forage and expressed juices. Mechanical dewatering was beneficial in the production of grass silage and proved that good grass silage can be made, without additives, from forages grown in the Everglades.

A new system involving the harvesting and drying of alfalfa leaves in an effort to reduce harvest and storage losses was studied by Whitney and Hall(2). This new concept involves the stripping of leaves from standing alfalfa plants and leaving the stems to regenerate new leaves for future harvest. The stripped leaves and minor stems are then dried to 20 percent moisture content using fluidization drying principles. The dried leaves are pelletized and then handled in bulk, much as the current practice in handling grain. This concept has not been completely defined and explored.

Dobie and others(3) found that packaging hay at low moisture content during the dry part of the day caused only a 4 percent loss in yield, compared to a 25 percent loss when the hay was raked too dry. Hay that was both raked and packaged dry yielded 35 percent less than hay that was handled properly. In each case a loss of protein was somewhat greater than the yield loss, indicating that the reduction in yield was predominantly leaves.

Singley(4) found that during the drying of alfalfa stems, water shows a directional preference. Per unit of exposed area, water leaves the stem through a transverse section at approximately 3.5 times the rate for longitudinal section. By exposing large areas of the interior of the stems, the drying rate was increased considerably beyond that of leafy material stripped from the stems.

Kjelgaard(5) found a relationship between field losses and yield when flail mower-conditioners were used in alfalfa. For yields above 1 ton dry matter per acre the average loss was 9 percent. Below a 1-ton-yield the field loss average was 17 percent.

Byers and others(6) stated that mechanical treatment of alfalfa to increase its drying rate is of limited value because little damage is done to the cellular organization. They found that killing the plant material with steam markedly increased the drying rate by modifying the permeability of the cuticle or cell membrane.

Kjelgaard(7) reported that electric tubular quartz infrared lamps and gas-fired infrared generators dried hay with about equal ability. Conditioning the hay before infrared exposure did not effect its drying rate. Chopping slightly improved the rate of drying over no treatment. Agitation was required after 1-2 minutes of exposure to prevent scorching.

Some early work on hay harvesting and handling operations conducted by the Texas Agricultural Experiment Station has been published (8, 9 and 10).

PHYSICAL PROPERTIES OF FORAGE PLANTS RELATED TO DRYING

Since the maintenance of quality is closely related to the time required for drying, initial moisture content of forage and drying rate are important in selecting a forage crop and/or improving quality within varieties. In developing a variety with reduced field drying time, either or both factors may be considered; in selecting forage crops to be planted for feeding purposes, both factors must be considered.

Alfalfa and Coastal Bermuda were selected for a study of relative drying rates because of their importance; Kleingrass, for its potential; and perennial Sweet Sorgrass, because of its difficulty to cure.

Each crop was harvested at the optimum stage of maturity and placed on metal trays in a controlled environment room. Tray and forage sample weights were taken at the beginning of the test and periodically thereafter. These weight data were used to calculate the percent of moisture in the samples throughout the test.

The initial moisture contents for the four crops were 77.5, 68.1, 66.1 and 86.8 percent for alfalfa, Coastal Bermuda, Kleingrass and Sweet Sorgrass, respectively. The moisture contents, wet basis, at various hours during the drying period are given in Figures 1-4. These graphs also show the relative humidity and dry bulb temperatures at which each crop was dried.

Table 1 gives the time required to dry each crop to 50 and 20 percent moisture contents. Alfalfa, Coastal Bermuda and Kleingrass dried to 50 percent moisture in an average of 3.7 hours. Kleingrass reached 20 percent moisture in a shorter period than the other crops: 21.6 percent faster than Coastal Bermuda and 17.5 percent faster than alfalfa. Even

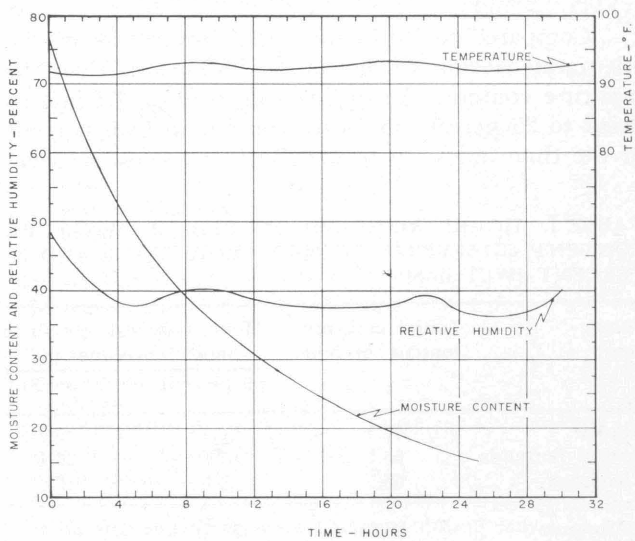

Figure 1. Moisture content of alfalfa and air conditions at various hours during the drying period.

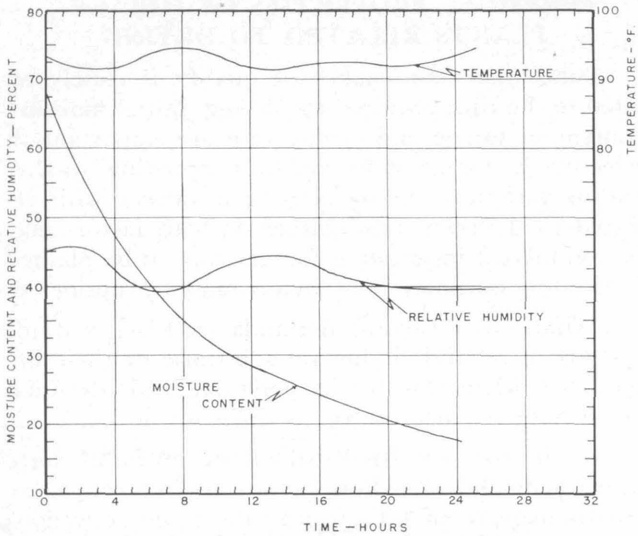

Figure 2. Moisture content of Coastal Bermuda and air conditions at various hours during the drying period.

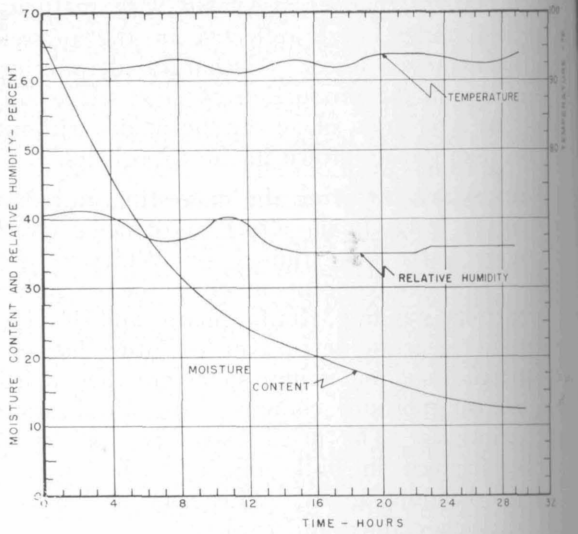

Figure 3. Moisture content of Kleingrass and air conditions at various hours during the drying period.

though these are relative values under somewhat ideal drying conditions, the decrease in time can be important in maintaining quality during the field-drying period.

Alfalfa had a faster drying rate than all crops tested, Figure 5, but Kleingrass reached the 20 percent level first because of its lower initial moisture content. There was a 11.4 percentage point difference in the initial moisture levels between alfalfa and Kleingrass, but after 16 hours this difference was only 5.0 percent because of the higher drying rate of alfalfa. Kleingrass had a faster drying rate than Coastal Bermuda, but this increased rate was not always great enough to allow Kleingrass to reach a storable level faster than Coastal. This depended upon the initial moisture content of the forages. Perennial Sweet Sorgrass had the lowest drying rate and the highest initial moisture content of the crops tested.

Compared to Bufflegrass, the drying rate of the Kleingrass seems to be more important than its moisture content. In drying rate studies, Kleingrass dried to 25 percent moisture content in 79.6 percent of the time necessary to dry Bufflegrass at the same initial moisture content. This was due to the faster drying rate of Kleingrass.

Tests conducted on the drying rate of Coastal Bermuda indicate that this forage crop has four distinct drying periods, each having a different drying rate. The faster rate occurred during the initial drying period and was maintained to approximately the 50 percent level, wet basis. The slowest rate occurred in the last of the four drying rate periods and started at a moisture content slightly below 30 percent, wet basis.

From the standpoint of energy requirements for removing moisture from forages, it is desirable to have as low an initial moisture content as possible when the forage is at the stage of maturity for the highest quality. Examples of forage crops that do have this low initial moisture content characteristic are Kleingrass and Coastal Bermuda. A forage crop

TABLE 1. HOURS REQUIRED TO REDUCE MOISTURE CONTENT OF SEVERAL FORAGE CROPS TO 50 AND 20 PERCENT (WET BASIS)

Forage crop	Initial moisture content, percent	Hours required to reduce moisture content to:	
		50 percent	20 percent
Alfalfa	77.5	4.6	19.4
Coastal Bermuda	68.1	3.4	20.4
Kleingrass	66.1	3.1	16.0
Perennial Sweet Sorgrass	86.8	55.5	[1]

[1]Test was discontinued after 85 hours at which time moisture content was 41 percent.

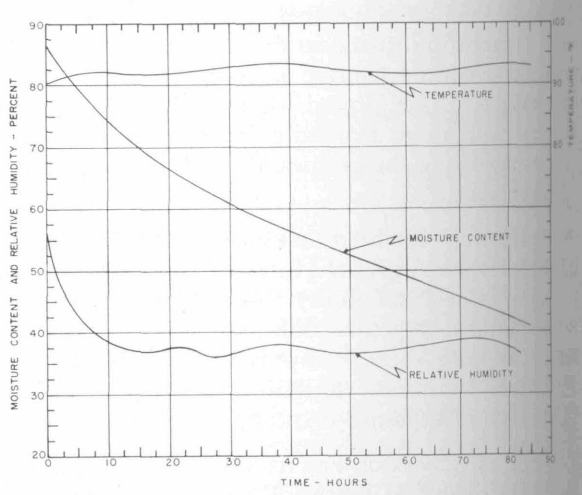

Figure 4. Moisture content of perennial Sweet Sorgrass and air conditions at various hours during the drying period.

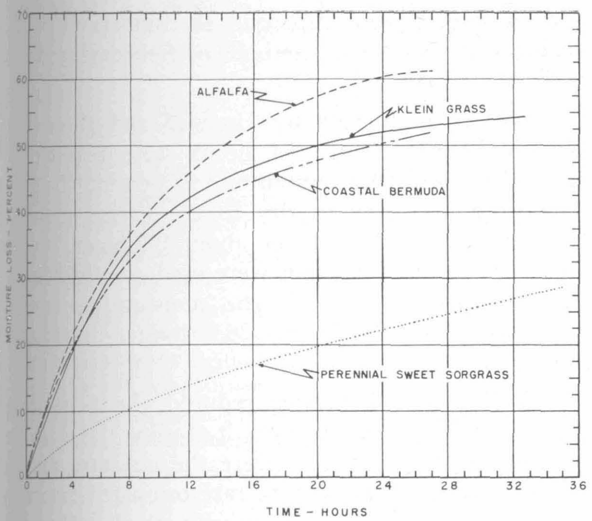

Figure 5. Moisture loss of the forage crops tested at various hours during the drying period.

with a low initial moisture content and a fast drying rate is extremely desirable from the standpoint of reducing energy requirements for removing moisture as well as providing rapid methods of field drying. Kleingrass is one example of such a crop.

FIELD DRYING FORAGE CROPS

Effect of Harvest Method on Field-drying Time

Tests were conducted near College Station in 1960 to determine the effects of different hay-making methods and equipment on the time required to field-dry alfalfa and Sudangrass.

A conventional mower, side-delivery rake, flail harvester and two types of hay conditioners were used in these tests. One of the hay conditioners crushed the material between steel and hard rubber rolls, and the other crimped the material by passing it between corrugated steel rolls. The former is referred to as a hay crusher and the latter as a hay crimper.

TABLE 2. METHODS USED TO FIELD-DRY ALFALFA AND SUDANGRASS

Alfalfa	Sudangrass
Mow—dry in swath	Mow—dry in swath
Mow—windrow immediately—dry in windrow	Mow—crimp—dry in swath
Mow—dry in swath to 50 percent moisture content—windrow—dry in windrow	Mow—crush—dry in swath
Mow—crush—dry in swath	
Mow—crush—windrow immediately—dry in windrow	Cut with flail harvester—dry in swath
Mow—crush—dry to 50 percent moisture content—windrow—dry in windrow	
Mow—windrow immediately—crush—dry in windrow	

Alfalfa and Sudangrass were cut three consecutive mornings and arranged in treatments as outlined in Table 2. The initial moisture contents ranged from 75.9 to 81.2 percent for alfalfa and from 79.5 to 84.8 percent for Sudangrass. Forages used in these treatments were dried on hardware cloth trays. After the samples were placed on the trays, they were weighed periodically to determine the drying rate of each field-drying method. When the samples were considered dry, they were collected and placed in an oven to determine their dry matter weights. These weights were used to determine the moisture contents of the samples during the field-drying period.

Field-harvesting efficiency tests were also conducted. Four harvesting methods were used: (1) mow, dry in swath and rake; (2) mow, crush, dry in swath and rake; (3) mow, crimp, dry in swath and rake; and (4) cut with a flail harvester, dry in swath and rake. After the hay had dried to a safe moisture level, it was picked up over a measured area with a forage harvester and weighed. This forage harvester had a pickup reel similar to that of a hay baler. Samples were taken from each method to determine the total dry matter content which was harvested. These values were compared to a check method which consisted of mowing and immediately picking up by hand.

Results of the different field-drying methods listed in Table 2 are given in Table 3. Alfalfa which

TABLE 3. HOURS REQUIRED TO FIELD-DRY ALFALFA AND SUDANGRASS TO MOISTURE CONTENT OF 50 AND 25 PERCENT (WET BASIS)[1]

Treatments	Hours required to reduce moisture content to:			
	50 percent (wet basis)		25 percent (wet basis)	
	Alfalfa	Sudangrass	Alfalfa	Sudangrass
Mow—dry in swath	5.5	50.0	39.5	54+[2]
Mow—windrow immediately—dry in windrow	23.3		50.7	
Mow—dry in swath to 50 percent—windrow—dry in windrow			40.8	
Mow—crush—dry in swath	3.7	5.9	25.2	28.7
Mow—crush—windrow immediately—dry in windrow	6.6		37.9	
Mow—crush—dry to 50 percent—windrow—dry in windrow			35.8	
Mow—windrow immediately—crush—dry in windrow	5.7		25.7	
Mow—crimp—dry in swath		6.6		28.3
Cut with flail harvester—dry in swath		24.4		31.0

[1]Alfalfa and Sudangrass were harvested during May and June, respectively.

[2]Test was ended after sample was in field 54 hours. Moisture content after 54 hours was 45 percent.

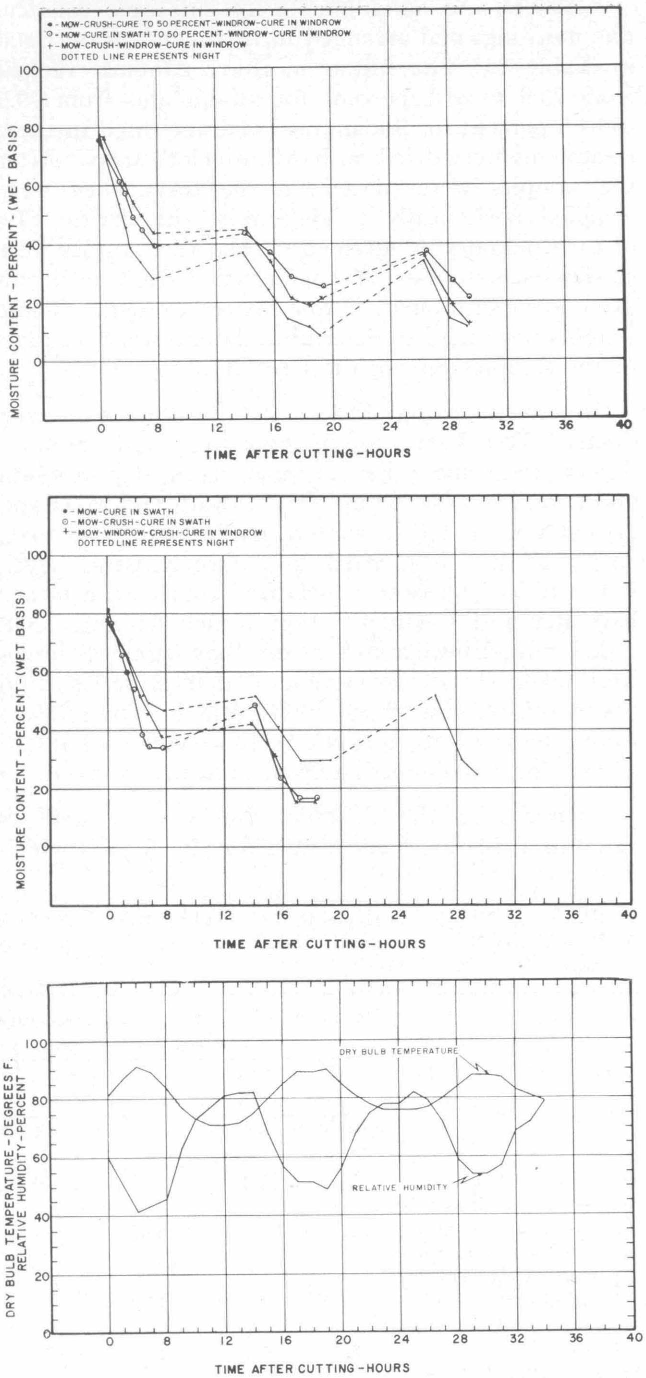

Figure 6. A comparison of the drying time of several methods of field-drying alfalfa.

was mowed and dried in the swath required 39.5 hours to reach a 25 percent moisture. When a crusher was used with this method, 14 hours were saved. The moisture content of alfalfa which was mowed, crushed and then dried in the swath was reduced to 25 percent in 25.2 hours compared to 25.7 hours when alfalfa was mowed, windrowed immediately, crushed and then dried in the windrow. The latter method shows considerable promise because there is less chance of quality loss due to leaf shattering and bleaching from the sun. A comparison of the dyring time of several methods of field-drying alfalfa is given in Figure 6.

When Sudangrass was mowed and allowed to remain in the swath, 54 hours were required to reduce the moisture content to 45 percent, Table 3. The time necessary to dry to 25 percent moisture content was estimated to be about 192 hours. When a hay crusher and crimper were used, the field-drying time required to reduce the moisture content to 25 percent was 28.7 and 28.3 hours, respectively, Figure 7.

A flail-type harvester reduced the field-curing time on Sudangrass. As a result of using this machine, it required 31 hours to reduce the moisture content to 25 percent. This drying rate compared favorably with the crushing and crimping methods. However, results from field-harvesting efficiency tests indicate that this is not feasible because of excessive dry matter losses when this machine is used.

Results of tests conducted to determine the losses encountered with the different methods of harvesting are given in Table 4. The flail harvester had a higher percentage field loss than the other harvest methods. The loss while harvesting Sudangrass with

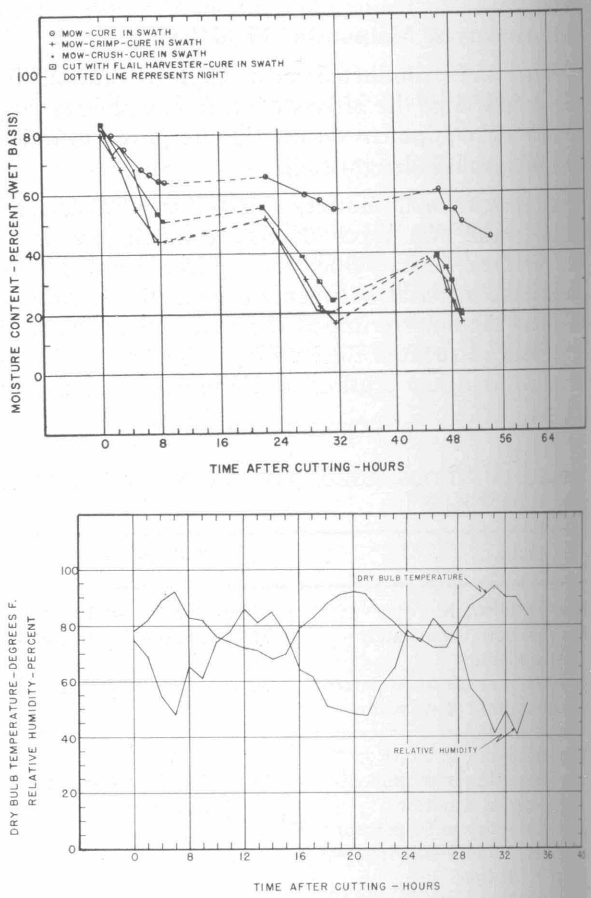

Figure 7. A comparison of the drying time of several methods of field-drying Sudangrass.

TABLE 4. FIELD HARVESTING EFFICIENCY TESTS, 1960

	Percent moisture at time hay was picked up, wet basis		Yield per acre, pounds dry weight		Percent loss compared with check	
	Alfalfa	Sudangrass	Alfalfa	Sudangrass	Alfalfa	Sudangrass
Mow–pick up immediately by hand (check treatment)	70.1	77.1	1,398.3	2,935.9		
Mow–dry in swath–rake–pick up with forage harvester	21.3	50.5	1,158.7	2,365.3	17.1	19.4
Mow–crush–dry in swath–rake–pick up with forage harvester	15.5	26.1	1,097.7	2,400.2	21.5	18.2
Mow–crimp–dry in swath–rake–pick up with forage harvester	18.0	25.1	1,267.6	2,330.5	9.3	20.6
Cut with flail harvester–dry in swath–rake–pick up with forage harvester	16.8	27.4	283.1	1,254.5	79.8	57.3

a flail harvester was 57.3 percent compared to an average of 19.4 percent for the other methods. Harvesting losses for alfalfa were 79.8 percent with the flail harvester compared to an average of 16.0 percent for the other methods.

When artificial drying is used in conjunction with field-drying, the time the forage is in the field after cutting is greatly reduced, since it is necessary to remove only a portion of the moisture in the field. Under these conditions, the value of using a hay conditioner for alfalfa is questionable. Alfalfa which was mowed and dried in the swath required 5.5 hours to reach a moisture content of 50 percent. When a crusher was used, the moisture content was reduced to 50 percent in 3.7 hours, a saving of only 1.8 hours. However, the crusher may be justified when the moisture content is reduced to 20 percent because the reduction in drying time may mean the difference between the crop remaining in the field

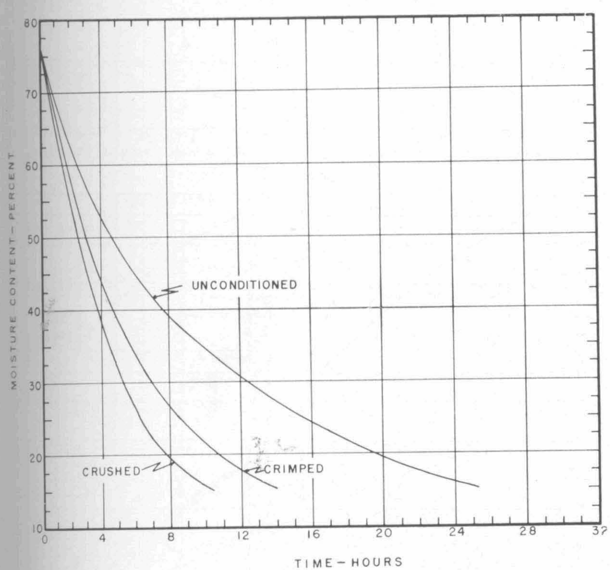

Figure 8. Comparison of moisture content at various hours during the drying period for different methods of conditioning alfalfa.

overnight or not, Figure 8. In comparative drying tests under controlled conditions, crushed alfalfa reached the 20 percent moisture level in 7.8 hours, compared with 10.6 and 19.3 hours, respectively, for the crimped and unconditioned alfalfa. When the material was crushed instead of crimped, a 26.4 percent time saving resulted. A comparison between crushing and no conditioning showed a saving of 59.6 percent in drying time.

Flaming Alfalfa

Field tests were conducted to determine the effects on drying time of flaming alfalfa with a conventional flame cultivator. There was little difference in the time required to dry flamed and unflamed alfalfa to a moisture content of 25 percent. However, a saving of 20 hours resulted in field-drying flamed, conditioned (crushed) alfalfa as compared to unflamed, unconditioned alfalfa.

DRYING WITH INFRARED RADIATION

Research was conducted to determine the effectiveness of using infrared energy to dry alfalfa hay. The objectives were to determine (1) the effects of exposure time, intensity of radiation and wavelength distribution on the rate of moisture removal, (2) the penetrating characteristics of different infrared sources and (3) the capacity and efficiency of drying with different sources of infrared radiation.

Four sources of infrared energy were used, each having a different spectral distribution of energy. Three of these sources were electrical, and one was gas-fired. All sources were assumed to emit energy which follows the laws of radiation for black bodies and were classified according to their maximum or peak wavelength. These maximum wavelengths were designated by the respective manufacturers and were 1.15, 2.3, 3.0 and 5.0 microns.

To achieve radiation of the desired intensity levels, small individual units were combined to make a single source. The construction of these sources is

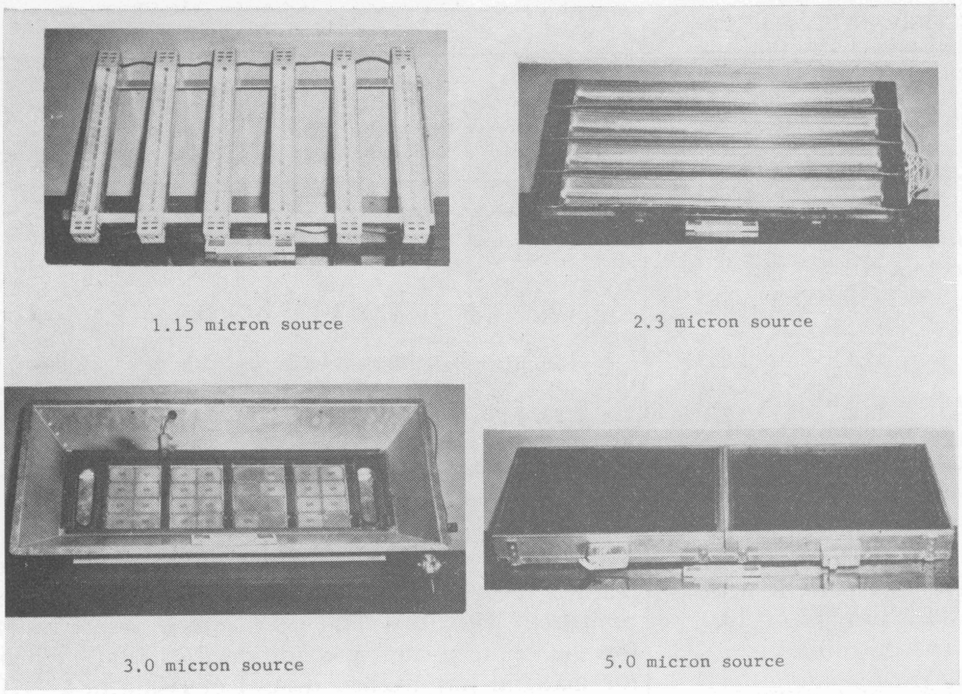

Figure 9. Sources of infrared radiation used in this research.

shown in Figure 9. All sources except the 5.0-micron source radiated from an overall surface area of approximately 640 square inches. The radiating area of this source was about 740 square inches.

To study the effects of the various factors listed in the objectives, it was necessary to irradiate hay at the same relative intensity levels of radiation for each source. Some means had to be provided to determine these intensity levels, regardless of wavelength distribution. For this purpose, a thermopile was constructed of thin copper plates with thermocouples attached underneath, Figure 10. A dull, black paint was used on top of each plate so that the absorption would be approximately the same for all wavelengths used. The relative amount of energy from each source at different heights above the hay was obtained with the thermopile, Figure 11.

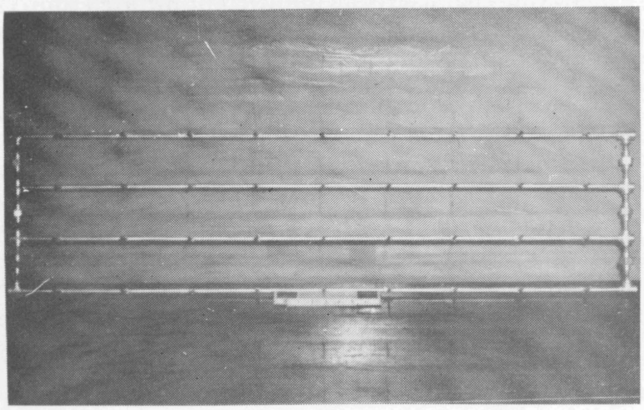

Figure 10. Thermopile used to determine relative amount of energy from each source at different heights above the hay.

Assuming that the absorption characteristics of the black paint did not vary significantly over the wavelength range used, then equal temperature rises would closely approximate equal rates of irradiated

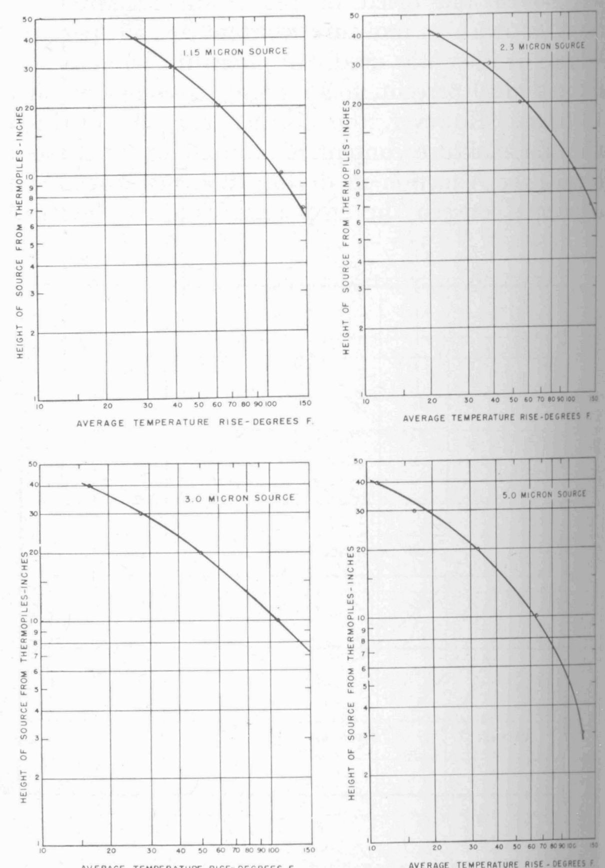

Figure 11. Calibration curves of source height versus temperature rise of the thermopile.

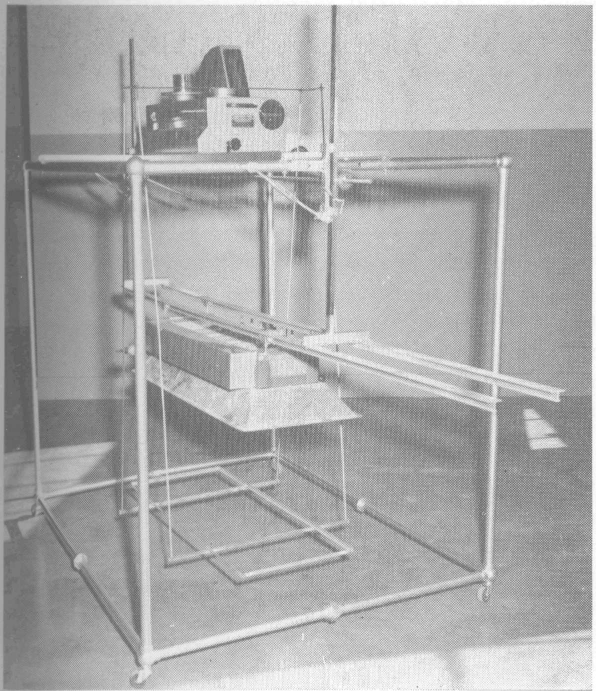

Figure 12. Apparatus used to determine the rate at which moisture was removed from irradiated hay. Sample on hardware cloth tray was placed on frame under infrared source. Frame was suspended from scale at top so that weight loss readings could be made at intervals during test period.

energy. Consequently, to irradiate hay at the same intensity level it was necessary only to select an average temperature rise on the thermopile and determine from the graphs the corresponding heights for each source.

Crimped and uncrimped hay were transported from the field to the nearby test area. Only enough material was cut at one time to test completely one source; therefore, the moisture content of the hay was approximately the same throughout each test.

After the material was brought into the test facility, it was divided into 200-gram samples and placed in single layers on hardware cloth trays. These trays were then placed under the radiation sources using an apparatus with a frame suspended from a scale so that a weight loss reading could be recorded for any interval of time, Figure 12. At the end of each test, the samples were dried in an oven to determine the dry matter content.

To determine the penetrating characteristics of the sources, three similar layers of hay were placed on top of each other and irradiated. Each layer was separated from the other by hardware cloth. After the combined sample was irradiated for a given time, the individual layers were weighed to determine their total weight loss.

Single layers of hay were placed on hardware cloth trays and exposed to energy from each source. Enough hay was used in each test so that maximum radiation from each source would be intercepted by the sample. The exposure time needed to reduce the initial moisture content by 10 percent, wet basis, was determined. This was used to determine the efficiency. The drying capacities were calculated by correcting sample weights to a 20 percent moisture basis.

Alfalfa hay having an initial moisture content of approximately 63 percent, wet basis, was irradiated in these tests. The irradiation periods ranged from 0 to 240 seconds, depending upon the time at which the leaves started to scorch.

Results show, Figure 13, that the higher the radiation intensity and the longer the exposure

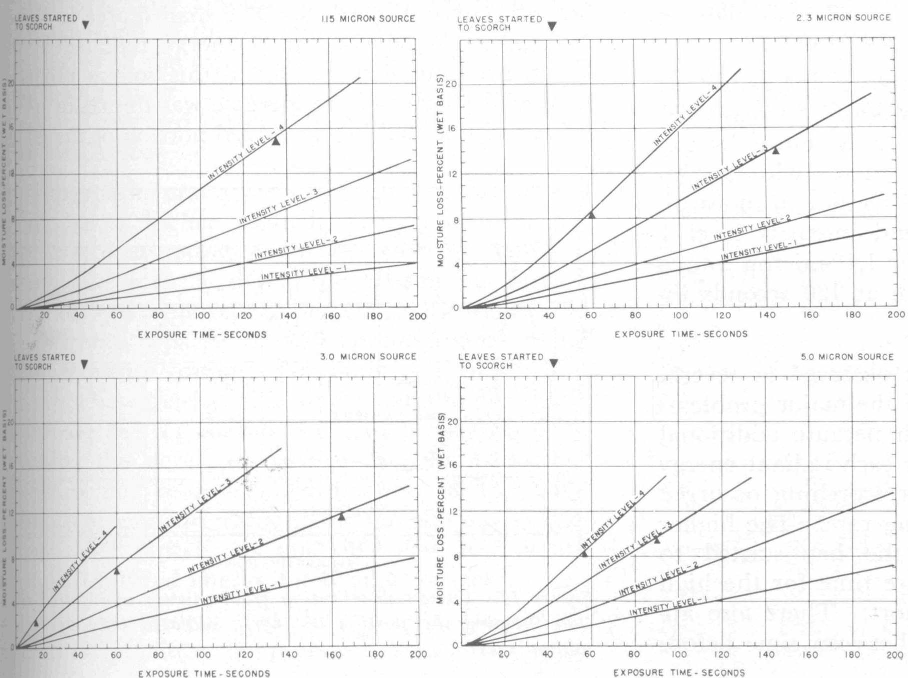

Figure 13. The rate at which moisture was removed from alfalfa hay irradiated for different exposure times under the 1.15, 2.3, 3.0 and 5.0-micron sources.

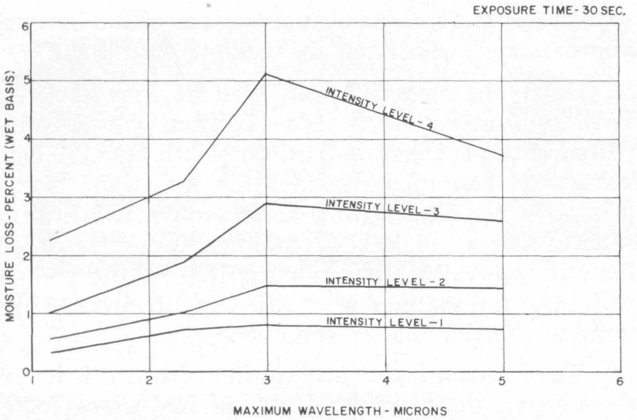

Figure 14. Moisture loss after 30 seconds exposure time plotted against the maximum wavelength of each source of radiation.

period for each source, the greater the rate of moisture removal. Intensity level 1 in the graphs represents the lowest intensity used in these tests and intensity level 4 the highest. The first portion of each curve indicates a variable rate of drying, but after 20-60 seconds of exposure, the water was removed at a constant rate. The time necessary to obtain this constant rate varied with the level of intensity and wavelength distribution.

After a constant rate was obtained, each intensity level resulted in a different rate of moisture removal, indicated by a different slope for each curve. For any increment of time, the decrease in the hay moisture content was always greater for the highest intensity level of each source of radiation. For example, hay which was irradiated for 60 seconds by the 1.15-micron source lost 0.9, 1.4, 2.8 and 5.4 percent moisture for intensity levels 1 through 4, respectively. Moisture lost from hay irradiated with the other sources increased progressively with intensity levels similar to those resulting from the 1.15-micron source.

The drying rate at the higher intensities as compared to the lower intensity levels increased as the exposure time increased. This is shown by the increasing distance between the curves with an increase in exposure time. The difference in moisture loss between intensity level 4 and intensity level 1 after 60 seconds exposure from the 1.15-micron source was 4.5 percent. This difference at 120 seconds increased to 10.8 percent.

Scorching of the leaves was observed at several intensity levels. This was one of the major problems encountered during this research because additional exposure burned the leaves. For each radiant energy source, the exposure time before scorching occurred seemed to be related to the drying rate. The higher the intensity level the faster the hay started to scorch; consequently, the exposure time for the high intensity levels was extremely short. There also appeared to be some relationship between time before scorching and initial moisture content. Hay having high initial moisture contents (70-80 percent) did not scorch as fast as hay having a lower moisture content.

The 3.0-micron source scorched the leaves after a shorter exposure time than the other sources. At intensity level 3 the leaves started to scorch after 60 seconds exposure. The same condition resulted after 15 seconds at intensity level 4. Each decrease in exposure time due to leaf scorching caused a decrease in the total moisture removed regardless of the intensity levels. For example, radiation from the 3.0-micron source at intensity level 4 removed 2.4 percent moisture before scorching, while 7.3 percent was removed at intensity level 3.

Although the drying rates increased as the intensity level increased for each source, the drying rates for equal intensities varied among sources. This was due to the spectral response characteristics of the hay. An approximation of the hay absorption rate at different wavelengths was made by plotting the moisture loss against the peak wavelength of each source, Figure 14. The source which had its peak energy at 3.0 microns appeared to remove more moisture than the other sources at the same intensity level. This was more apparent as the intensity level increased. At the highest intensity used, the 3.0-micron source removed 5.1 percent moisture in 30 seconds compared to 2.25 percent for the source which had its energy peak at 1.15 microns. This meant an increase in the moisture removal rate of about 126.6 percent for a 30-second exposure.

An infrared energy source which has its peak wavelength between 3.0 and 5.0 microns may further increase the drying rate without increasing the intensity. The energy distribution of the four sources was plotted so that the total energy was the same for each curve, Figure 15. The shaded area in Figure 15 represents the portion of energy radiated by the 3.0-micron source only. Since this source produced a faster drying rate, the increase was the result of the energy distributed in the shaded portion of the graph.

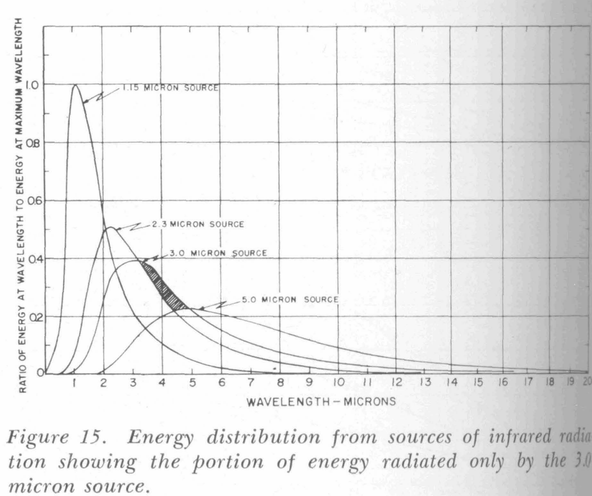

Figure 15. Energy distribution from sources of infrared radiation showing the portion of energy radiated only by the 3.0-micron source.

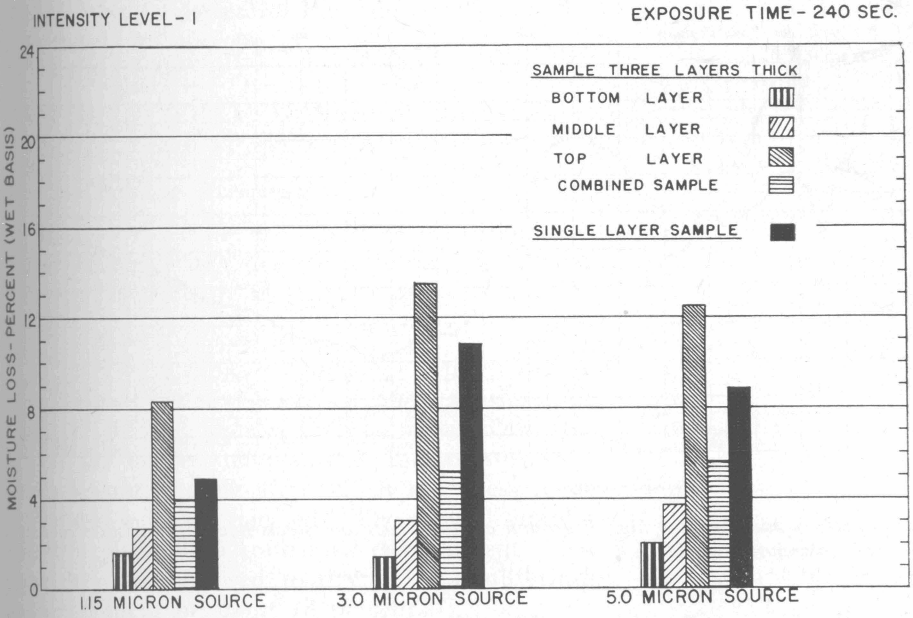

Figure 16. Moisture removed from each layer of hay which was three layers thick as compared to a single layer.

The depth which infrared radiation will penetrate a material largely determines the quantity that can be dried by a given size source. In order to increase the amount of hay under the radiation sources used, additional layers were placed on top of each other, and the moisture loss was recorded for each layer, Figure 16. At intensity level 1, the bottom layer of hay did not lose more than 2 percent moisture, while the top layer lost as much as 13.5 percent. Moisture loss from the combined samples, the three layers being considered as one, ranged from 4.9 to 5.6 percent. The layer closer to the source of radiation always lost more moisture than the other layers. Some radiant energy was transmitted through the top layer to the middle and bottom layers, depending upon the absorption characteristics of the hay. A portion of the radiant energy did not come in contact with the top layer, since this layer did not form a solid mass. Therefore, a small amount of energy was received directly from the source by the other two layers.

The capacity of a dryer which handles three layers of hay has a higher capacity than one handling single layers, assuming equal decrease in moisture content. In such a dryer the 3.0-micron source, Figure 16, will remove 5.2 percent moisture in 240 seconds with a capacity of 1.70 pounds (based on 20 percent moisture content) per hour per square foot of hay. The capacity of a dryer handling a single layer would be 1.11 pounds per hour per square foot. Increasing the depth of hay to increase the dryer capacity is not recommended because of the wide variations in moisture contents within the hay. Also, the increased capacity is not sufficient to warrant the use of infrared energy for drying forages.

It became evident that the top layer was drying faster than previous single layers under the same conditions. This proved to be the result of an additional heating effect caused by the other layers of hay when different types of trays were used to hold the hay under the radiation sources.

All the energy which was not intercepted by the hay was either transmitted, absorbed and/or reflected by the supporting tray. In the case of the hardware cloth tray, this energy was lost because there was no medium to absorb it. A solid sheet of aluminum was painted dull black and used as a tray. The results showed, Figure 17, that most of the energy lost with the hardware cloth could be used. After a 160-second exposure, the black tray increased the moisture loss 89.25 percent over the hardware cloth tray because most of the remaining energy was absorbed by the black tray. This energy was converted into heat and transferred to the hay primarily by conduction. Since there was a time lag needed to heat the tray and transfer this heat to the

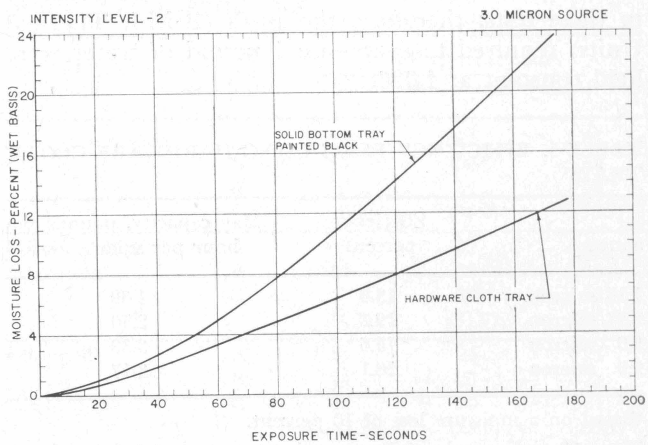

Figure 17. Effect of a solid tray painted dull black on the moisture removal rate of hay irradited by 3.0-micron source.

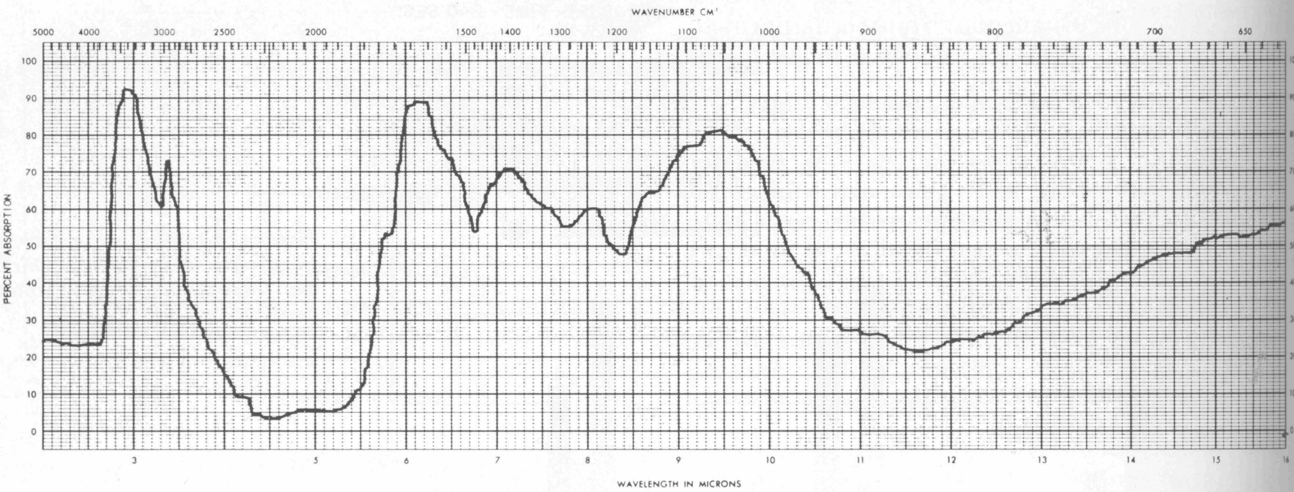

Figure 18. Absorption characteristics of pelletized mixture of 2 Mg. of ground alfalfa leaves and stems having a moisture content of 8 percent, wet basis, mixed with 400 Mg. of Potassium-Bromide.

hay, the longer the exposure time the greater the increase in moisture removal up to some equilibrium point.

Efficiency and capacity are important in a drying installation. They are probably more important when drying hay than other crops because of the lower money value of hay. To determine the efficiency and the capacity of drying with different sources of infrared radiation, single thickness samples of alfalfa were placed on hardware cloth trays and irradiated under each source. Each source was placed as close as possible to the hay, and sufficient sample areas were used so that all emitted energy was intercepted by the sample.

The efficiency and capacity of each source are presented in Table 5. These efficiencies represent the overall efficiency of the installation and were calculated by the following formula:

$$\text{Efficiency} = \frac{\text{(Lbs. water removed)}\ \text{(Btu's to evaporate 1 lb. water)}}{\text{(Units of power or fuel)}\ \text{(Btu content per unit)}} \times 100.$$

The hay temperature was assumed to be constant in these tests; therefore, the Btu's (British Thermal Units) required to evaporate 1 pound of water were held constant at 1,026.

TABLE 5. EFFICIENCY TESTS USING HARDWARE CLOTH TRAYS[1]

Source	Efficiency percent	Hay capacity, pounds per hour per square foot[2]
1.15 micron	13.0	1.69
2.3 micron	19.3	2.50
3.0 micron	15.6	3.38
5.0 micron	38.1	3.17

[1]Based on a moisture loss of 10 percent.

[2]Capacity in pounds of hay per hour per square foot of hay surface area. Weight of hay calculated on a basis of 20 percent moisture content (wet basis).

The efficiencies ranged from 13.0 to 38.1 percent, while the capacities ranged from 1.69 to 3.17 pounds per hour per square foot of hay area, Table 5. These data are based on a moisture reduction of only 10 percent. For purposes of comparison, the weights of hay used to calculate the capacity were corrected to a common basis of 20 percent moisture content (wet basis). The 1.15-micron source had the lowest efficiency while the 5.0-micron source had the highest. The 1.15-micron source also had the lowest capacity, but the 3.0-micron source, rather than the 5.0, had the highest capacity. This was attributed to the inability of the 3.0-micron source to convert input power into useable infrared energy as efficiently as the 5.0-micron source.

FORAGE CROP ABSORPTION WAVELENGTHS

A spectrophotometer was used to obtain the infrared absorption characteristics of Johnsongrass and alfalfa. Previous research showed the importance of being able to expose a forage crop to only the wavelengths which are most readily absorbed by the crop.

Studies with Johnsongrass showed that the leaves absorbed more infrared radiation in the 3.0-4.0-micron wavelength range than at any other wavelength. An insignificant amount of energy was absorbed at 5.6 microns but increased again between 6.4 and 8.0 microns to a level which may be considered another major absorption band.

Finely ground mixtures of alfalfa leaves and stems having an initial moisture content of 8 percent, wet basis, were used to determine the infrared absorption characteristics of alfalfa. With the aid of an infrared spectrophotometer the samples indicated one minor and two major absorption bands, Figure 18. The major bands occurred at wavelengths of 2.9-3.0 and 6.1-6.3 microns with an absorption of 92 and 88 percent, respectively, of the total energy. The minor band absorbed 79 percent of the total energy and was located at 9.4-9.5 microns.

EFFECT OF TREATMENTS ON DRYING CHARACTERISTICS OF FORAGE CROPS

Heat and Pressure Treatments

Studies were made to determine the effects of heat and pressure treatments on altering the drying characteristics of alfalfa in an attempt to increase its drying rate.

Samples were subjected to temperatures ranging from 100 to 1,000° F. under chamber pressures of minus (−) 75 cm. Hg. to 150 psig. Samples were held at the desired temperature and pressure for various lengths of time after which the pressure or vacuum was suddenly released. The treated samples were then placed in a controlled environment room where they were allowed to dry to an equilibrium moisture content of about 18 percent.

Portions of the alfalfa stem that had been subjected to a pressure of 125 psig. and held at that pressure for 10 minutes before releasing were examined for cellular damage. Both cross-sections and longitudinal sections showed no rupture of cell walls or evidence of damage to the cellular organization. Drying ratio curves plotted for each of the treatments in which the samples were subjected to pressures ranging from −75 cm. Hg. to 150 psig. without the addition of supplemental heat showed no increase in the drying rate when compared to the control samples. No correlation was obtained from the temperature test data since it was concluded from these experiments that the correlation depends upon internal hay temperature and not upon the measured temperature of the air surrounding the product. Even though internal temperatures are a function of the surrounding air temperature, there was not sufficient time for the hay to reach equilibrium without burning.

Freeze Treatments

Laboratory experiments were conducted to determine the effect of freeze treatments on the drying rate of unconditioned, crushed and chopped alfalfa hay. The tests included various treatment combinations using slow-freeze and quick-freeze processes. Twenty-five gram samples of alfalfa hay harvested at 10 percent bloom stage of maturity were used in these experiments.

Long hay was cut into 1-inch lengths for the chopped samples. The crushing treatment was applied by passing the sample between two hard rubber rollers. Liquid nitrogen was used to obtain a quick-freeze treatment. The samples were placed on screen trays and immersed in liquid nitrogen until frozen (less than 15 seconds). The slow-freeze treatment was obtained by suspending the sample in a deep-freeze unit for 24 hours. All the hay used for the tests was cut by hand from the same general location in the field. The samples for one replication were harvested and treated the same day. The treatments for three replications were applied on three consecutive days. Following each treatment, the samples were placed in a conditioned room held at 85° F. and 60 percent relative humidity. The drying rates were determined by periodically weighing the samples. After equilibrium was reached, the samples were oven-dried at 220° F. to determine dry matter weights.

The time required for the samples to reach 50 and 20 percent moisture, wet basis, is presented in Tables 6 and 7. The data show that crushing after slow freezing has no additional effect on the rate

TABLE 6. HOURS REQUIRED TO DRY LONG AND CHOPPED ALFALFA HAY TO MOISTURE CONTENT OF 50 PERCENT (WET BASIS) WITH SLOW-FREEZE AND QUICK-FREEZE PROCESSES

Hay condition	Replication	Treatment, hours None	Slow-freeze	Quick-freeze
Long, uncrushed	A	22	21	17
	B	26	15	12
	C	21	13	12
		(23.0) [1]	(16.3)	(13.7)
Long, crushed (before freezing)	A	14	11	10
	B	14	9	8
	C	10	8[2]	8
		(12.7)	(9.3)	(8.3)
Chopped	A	10	8	7
	B	10.5	8	6
	C	10	8	6.5
		(10.2)	(8.0)	(6.8)

[1]Figures in parentheses are averages of three replications.
[2]Estimated.

TABLE 7. HOURS REQUIRED TO DRY LONG AND CHOPPED ALFALFA HAY TO MOISTURE CONTENT OF 20 PERCENT (WET BASIS) WITH SLOW-FREEZE AND QUICK-FREEZE PROCESSES

Hay Condition	Replication	Treatment, hours None	Slow-freeze	Quick-freeze
Long, uncrushed	A	80	64	64
	B	80	56	52
	C	70	54	54
		(76.7) [1]	(58.0)	(56.7)
Long, crushed (before freezing)	A	65	32	35
	B	50	33	33
	C	37	30[2]	30
		(56.7)	(31.7)	(32.7)
Chopped	A	35	24	24
	B	34	25	23
	C	35	26	24
		(34.7)	(25.0)	(23.7)

[1]Numbers in parentheses are averages of three replications.
[2]Estimated.

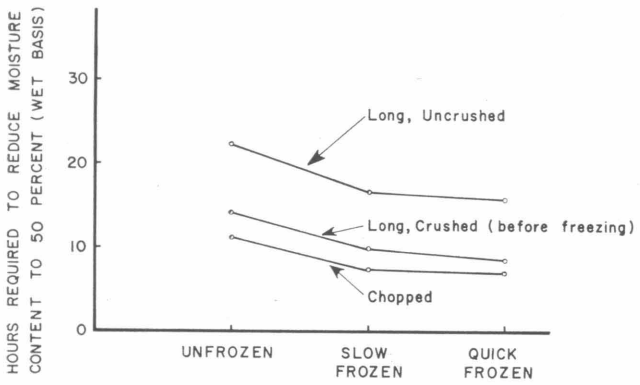

Figure 19. Effect of freeze treatments on the time required to reduce the moisture content of uncrushed, crushed and chopped alfalfa hay to 50 percent, wet basis.

of drying and that crushing after quick freezing has about the same effect as crushing before quick freezing. The times given in Tables 6 and 7 do not include the 24-hour slow-freeze period.

The average values from tables 6 and 7 are presented graphically in Figures 19 and 20. In these tests little or no advantage was gained by using a freeze treatment for drying alfalfa to a moisture content of 50 percent. However, when alfalfa was dried to a moisture content of 20 percent, there was a significant decrease in drying time due to freezing, with no significant difference between slow-freeze and quick-freeze treatments.

Also, there was a significant difference between the uncrushed, crushed and chopped treatments for drying to 20 percent moisture. Chopped hay, frozen or unfrozen, showed the fastest drying rate, followed by crushed and uncrushed hay, in that order. However, the difference between crushed and chopped hay was not significant for drying to 50 percent moisture.

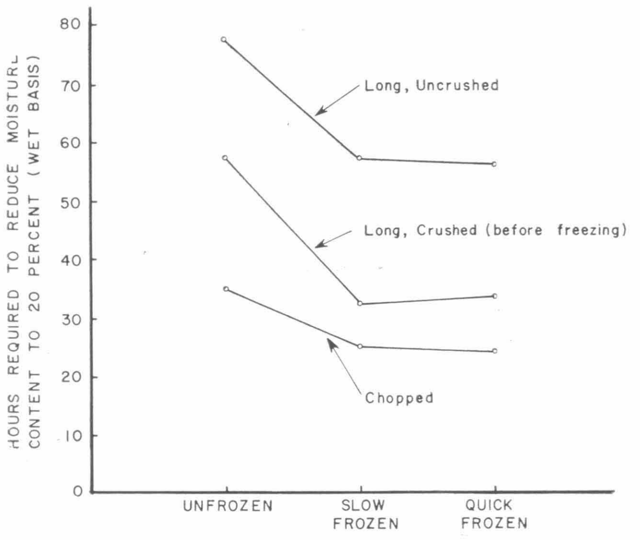

Figure 20. Effect of freeze treatments on the time required to reduce the moisture content of uncrushed, crushed and chopped alfalfa hay to 20 percent, wet basis.

A quick-freeze treatment applied to the standing crop or in the swath may be a fruitful approach to the problem of moisture release from drying forage, provided no serious effect on nutritive value is found.

ACKNOWLEDGMENTS

The authors express their appreciation to Ethan C. Holt, professor, Department of Soil and Crop Sciences, Texas A&M University, for his assistance in conducting these tests.

Appreciation is also expressed to the New Holland Machine Company, Division of Sperry Rand Corporation, New Holland, Pennsylvania for providing equipment for field studies.

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