Introduction

In some areas of the country, producers store a substantial portion of their forage for winter feeding as silage or haylage. However, hay remains the most popular storage method for forage. Hay stores well for long periods and is better suited to cash sale and transportation than silage. Mechanical conditioning, which gained acceptance during the 1950’s is probably still the greatest single change in hay harvesting and storage technology during this century. However, a number of other noteworthy changes and innovations have occurred in recent years which have helped to reduce the extent of losses during hay harvesting and storage.

Developments in hay harvesting technology in recent years include chemical desiccants such as potassium carbonate, chemical and biological additives at the time of baling, and swath and windrow management equipment such as tedders and windrow inverters.

The general relationship between forage moisture concentration at harvest and losses during the field and storage phases is shown in Figure 1. Harvest losses are greatest for very dry forage and are low for very wet material like direct cut silage. However, the latter is subject to excessive storage losses due to seepage and to quality deterioration. Storage losses are generally minimized by harvesting at low moisture levels.

High moisture hay, baled between 20 and about 30% moisture has lower harvesting losses than dry hay but can suffer high storage losses and quality loss if not

Fig. 1. Relationship between forage moisture concentration and field and storage losses.
adequately preserved or dried. Many options are available in haying equipment and in new products marketed for use in hay curing and preservation is such that making informed choices can be very difficult. Research information is not available on all of these new products, however, representatives of most of the categories have been studied.

The Drying Process

When plants are growing, it is to their advantage to limit moisture losses. They do this in several ways. The outer surface of plants is covered with a waxy layer called the cuticle. The cuticle is very effective at limiting the loss of water. The great majority of water that plants use when they are intact and growing moves out through pores called stomates in the outer layer. Stomates can be opened or closed as necessary to control the movement of water and gasses from the plant. Stomates are found mostly on the leaves and although they are very numerous, cover only 1-2% of the total surface area. These well developed systems for restricting the loss of water in growing plants cause problems in obtaining fast hay curing. Due to all of these factors, moisture loss during hay curing has to distinct phases. The first and the most rapid phase covers the first 20% or so of the total drying time but accounts for up to 75% of the total water loss. During this phase, water is lost from leaf surfaces and through open stomates. British research indicates that after moisture concentration reaches about 60%, the stomates close and drying rate slows drastically. Of course, moisture is also lost through the cut ends of the stems but this is not very effective. Mechanical conditioning is effective because it physically breaks this cuticle layer which allows additional water loss through this otherwise nearly waterproof layer.

Environment strongly affects hay drying. Figure 2 illustrates the effect of humidity and temperature on hay drying. High levels of solar irradiance, low humidity levels and wind

![Figure 2. Alfalfa drying curves under excellent and poor drying conditions (From Hill et al., 1977).](image_url)
speeds of 10-15 mph are desirable. The data shown below illustrate the impact that differences in relative humidity can have on the time required for hay curing. The curing times shown are hours of daylight and do not include the dark period when no drying occurs. We can take advantage of all the sun that is available by making the swath as wide as possible, covering 75% or more of the surface area.

<table>
<thead>
<tr>
<th>Humidity</th>
<th>Curing Time</th>
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<tbody>
<tr>
<td>40%</td>
<td>20 hr</td>
</tr>
<tr>
<td>50%</td>
<td>25 hr</td>
</tr>
<tr>
<td>60%</td>
<td>30 hr</td>
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**RELATIONSHIP BETWEEN HUMIDITY AND HAY CURING TIME**

If the soil is wet, it may be best to make a slightly narrower swath to let the bare area dry and then turn the hay after it dries on top. Tedders, used just after cutting, can help to increase the interception of sun energy by spreading the hay over the entire area. It has been shown that tedding is effective in hastening the rapid, early phase of drying, but not the slower, last phase of drying. Tedding after the hay has wilted to 60% moisture will redistribute clumps and improve the uniformity of moisture concentration in the final product. Don’t ted hay that has dried to 50% moisture because that can increase DM losses and is not effective in increasing drying rate. Tedders are useful in breaking up windrows of rained-on hay to allow for redrying. Because of the shatter losses that can occur in dry hay, raking should be done at moisture levels of 40% or more (Figure 3).

**Solar Radiation**

About 20% of the incident solar radiation is reflected back into the atmosphere; the remainder is absorbed and aids in the evaporation of water. The sunshine intercepted by plants is dissipated mainly either by heating the forage material or evaporating water. However, the sun’s radiation does not really penetrate very far into the hay windrow or swath. It has been estimated that less than one-half of the radiation penetrates beyond 1 inch depth. This is a major...
reason for the emphasis placed on maintaining the maximum swath surface area during drying. This increases the proportion of the forage mass that is affected by the sun’s rays. Temperatures on the surface of a mowed swath may be as much as 40°F higher than that of the surrounding air on a sunny day.

A good way to visualize the impact of weather on hay drying is that weather sets the upper limit for how quickly a crop can dry. Other factors, such as forage species, mechanical or chemical conditioning etc. determine how close we come to achieving that potential.

**Mechanical Conditioning**

Mechanical conditioning hastens drying by breaking the cuticle layer, defeating the plant’s tendency to retain moisture. Mechanical conditioning is considered to be an effective way to improve the drying rate of all types of hay. In some cases, a good job of conditioning halved the time required for hay curing.

Just after mowing, drying occurs primarily at surfaces exposed to the atmosphere and, thus, exposed to solar radiation. The humidity level within the swath is probably near 100% just after cutting, but as drying proceeds the humidity within the swath declines and eventually approaches levels in the outside atmosphere. Increasing surface area by making a wide swath helps to intercept more sunlight and hastens drying. Swath structure, and thus drying rate, may be adversely affected by severe crushing treatments due to increased difficulty in achieving and maintaining a low density swath. Tedding may aid in maintaining a loose structure and maximum surface area. Tedding should be done shortly after mowing or early enough in the day that some moisture remains in the leaf to prevent excessive losses.

Under high humidity, relatively cool conditions, hay does not dry as rapidly as under low humidity high temperature conditions. A good corollary is found in the way in which tobacco leaves become moist and pliable under high humidity conditions. Likewise, under high humidity conditions hay may not by able to reach the 20% moisture level recommended for baling dry hay regardless of the time spent in the field. Figure 4 shows equilibrium moisture concentrations measured

![Equilibrium moisture concentrations of alfalfa hay at different temperatures and humidities (Adapted from Hill et al., 1977).](image-url)
for alfalfa hay over a range of humidity conditions at a temperature of 77°F. At a relative humidity of 80%, this graph indicates that alfalfa would not dry below 25 to 27% moisture. It is because of this problem and in order to reduce the likelihood of rain damage that alfalfa hay is sometimes baled at moisture levels above 20%. Our data comparing alfalfa hay storage in round and rectangular bales indicates that for storage without heat damage, alfalfa in round bales should be slightly drier (18% moisture) than similar alfalfa in rectangular bales.

Preserving Moist Hay

Baling hay at elevated moisture levels can reduce losses by reducing leaf loss and by helping to avoid rain damage. However, when hay is baled above 20% moisture steps should be taken to prevent the microbial growth that is responsible for heat damage and dustiness.

Respiration and Microbial Growth

Respiration and microbial growth, and some elevation in temperature during hay storage are normal and do not necessarily harm feeding value. Hay with more than 20% moisture may undergo excessive mold growth and heating that reduces both yield and digestibility compared with dry hay. Populations of fungi in stored hay peak after about 1 week of storage and this corresponds to the peak temperatures reached in the stack.

Health Effects

Mold spores contribute to colic in horses and are responsible for significant losses for this economically important industry. Breathing spores of the fungus Aspergillus fumigatus during the handling of moldy hay can cause farmer’s lung, a sometimes debilitating disease in which the fungus grows in lung tissue. Hay with a significant amount of mold and mold spores can be utilized in cattle rations because these livestock are less sensitive.

Heat Damage

Heat damage may occur in moist hay as a result of plant and microbial respiration and chemical reactions. The moisture range in which the maximum amount of heating occurs is in the 20-40% moisture range for hay. This is close to the range in moisture for dry haylage at which excessive heating is observed. Dry hay does not heat excessively because it lacks the necessary moisture to support microbial growth. Plant enzymatic activity and microbial growth can elevate temperatures to 160°F within a few days. When the temperature goes above this level, it becomes too hot for continued microbial growth and further heating results from chemical reactions. These reactions are responsible for raising the temperature to levels at which spontaneous combustion may occur.
Heating during hay storage reduces forage quality. The extent of the heat damage is related to the color change during storage is related to the amount of heat damage in composition during heating of hay or silage are detrimental to forage quality. When hay heats sufficiently to cause a very dark brown to black color, its protein may be nearly indigestible.

**Moisture Loss During Storage**

The evaporation of water dissipates the heat generated in moist hay. The thermal conductivity of dry hay is actually less than that of moist hay. Thus, as hay moisture declines due to heating, the transfer of heat to the outside air becomes less effective. Hay temperature may not rise sharply until most of the moisture has been evaporated. This heat generation in a mass of hay is caused by the growth of microbes that require oxygen. Because of the distance, the centers of large hay stacks tend to be low in oxygen supply and spontaneous combustion occurs outside this zone.

![Graph](image)

**Fig. 5.** Relationship between moisture level at baling of alfalfa hay and hay digestibility after storage (From Collins et al, 1987).

Microorganisms are responsible for this heating and the resulting increase in heat-damaged protein and molding can be very detrimental to quality. Thermophilic bacteria, the actinomycetes, grow well at high temperatures and contribute to the attainment of very high temperatures that result in hay fires in some instances. The hay temperature information shows temperatures at which fire danger becomes important. Temperatures well below that level can still reduce quality significantly. This moist hay can be preserved by the addition of organic acids at the time of baling. Propionic acid has been widely tested as a hay preservative and has proven to be very effective when it is well distributed and applied at the proper rates. The most common rate recommendations for applying organic...
preservatives to hay are shown in the following hay temperature chart. These rates are calculated on an active ingredient basis. In products containing some water, this must be considered in determining the product application rate. The rate applied must be increased for wetter hay because of the importance of maintaining the level of preservative in the water contained in the hay.

<table>
<thead>
<tr>
<th>HAY TEMPERATURE (°F)</th>
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<tbody>
<tr>
<td>70 110 150 190 230 270 310</td>
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<table>
<thead>
<tr>
<th>FIRE DANGER</th>
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<tbody>
<tr>
<td>PLANT RESPIRATION</td>
</tr>
<tr>
<td>FUNGI AND BACTERIA</td>
</tr>
<tr>
<td>HEAT RESISTANT BACTERIA</td>
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Hay Additives

Additives are sometimes used to aid in the preservation of hay above 20% by preventing microbial growth during storage. Materials shown to be effective in the preservation of moist hay include sodium diacetate, propionic acid, ammonium propionate, urea, anhydrous ammonia and others. In addition to control of microbial growth, some materials, such as ammonia and urea, may also enhance forage quality by increasing crude protein concentration and increasing fiber digestibility.

The amount of propionic acid that needs to be applied to ensure acceptable control of microbial growth is greater for hay that is higher in moisture. Apparently, the critical factor is to maintain the necessary concentration of propionic acid in the water contained in the hay. Thus, hay with more moisture requires more organic acid for preservation. Hay heating and molding can be controlled by the application of rates as low as 6 lb/ton for 25% moisture hay under controlled conditions but under field conditions about twice that rate is needed to ensure preservation.

Ammonium propionate is a buffered propionic acid material that is less volatile than propionic acid and is also less corrosive. The low pH of acid preservatives is involved in their effectiveness but it is not the only factor since ammonium propionate is effective even though it is less acidic. Formic acid, sodium diacetate, propionic acid and ammonium propionate were tested and all were found to be effective in the inhibition of fungi and actinomycetes when each organism was grown separately in culture.

APPLICATION OF BUFFERED ORGANIC ACIDS TO HAY

<table>
<thead>
<tr>
<th>Hay Moisture</th>
<th>Application Rate</th>
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<tbody>
<tr>
<td>20-25%</td>
<td>10 lb/ton</td>
</tr>
<tr>
<td>25-30%</td>
<td>20 lb/ton</td>
</tr>
<tr>
<td>30-35%</td>
<td>30 lb/ton</td>
</tr>
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</table>
Moisture Variation Within The Field

Research has shown that it is important to achieve good distribution of the material in the bale. Buffered products have the benefits of being less volatile than acid products, however with that advantage comes the problem that these materials do not move around to equalize within the bale. Some very volatile products like ammonia move so well that the anhydrous ammonia can simply be released within a stack of hay and will diffuse throughout the mass with a short time. Even the acid forms of organic acids do not move that readily but the buffered forms remain where they are placed during the application process.

Wet spots that have more moisture than the application rate is adequate for can still result in moldy areas within an otherwise well preserved bale. In a field study using alfalfa from a small field (5 acres), moisture at the time of baling varied widely depending upon the density of the swath at a particular location. Variation above and below that average will mean that some hay will receive more material than needed and other hay will receive less. Moisture levels ranged from 58 to 80% and averaged 69%. A propionic acid application rate of 19 lb/ton would be sufficient to obtain a rate of 3% of the average water content. However many of the bales were above 69% moisture and would require more material. It would be necessary to apply 28 lb/ton to insure adequate preservation of 99% of the bales from this field. These results point up the importance of wide swaths and tedding to help improve the uniformity of the moisture concentration.

Measuring Moisture In Hay

It is critical that we have dependable information on the moisture concentration in the hay in order to be sure of adequate storage if it is dry hay or that the preservative rate is adequate if preservatives are being used. A typical home microwave oven is an excellent method for determining hay moisture. A 50-100 gram sample should be weighed and dried for 6 minutes. After that time, check the sample to see whether additional drying is necessary. If so, heat for 2 minutes and recheck. This last step is repeated until no further weight is lost, indicating that the sample is dry. When the sample is dry, it can be reweighed and the moisture concentration calculated by the following formula:

\[
\text{Moisture Content} = \frac{\text{Sample Weight Wet} - \text{Sample Weight Dry}}{\text{Sample Weight Wet}} \times 100
\]

A system using regression charts with a microwave oven allows accurate determination of actual moisture with only one weighing and in a shorter drying time of 4 minutes. The shorter time is possible because the sample is not dried completely in this method. The weight after 4 minutes of drying is closely related to the actual moisture. The sample moisture is read from a chart showing columns for the microwave weight and the actual moisture.
Electronic probe testers are also available for field use in moisture determination. Of the units tested, the "Delmhorst" moisture unit did the best job of predicting actual oven moisture determinations. Based on the variation we found between measurements on the same bale, it would be necessary to take 12 readings to estimate moisture concentration within +2%. Also, although the correlation with actual oven moistures was very good, the probe reading was not identical to the actual moisture concentration. At about 17% moisture, the two would give identical readings but above that moisture level, probe readings underestimated the actual moisture concentration. A rule-of-thumb system for estimation of hay moisture when a tester is unavailable is shown below.

The same unit discussed above has been modified to automatically probe the bale inside the bale chamber between plunger strokes. These readings can be averaged and accessed continuously to allow moisture monitoring. We have the possibility of using moisture measurements of the bale either inside the bale chamber or just after tying to adjust preservative application rate continuously. If this could be accomplished it would insure adequate rates of preservative for every bale whether they needed more or less than the average.

In the absence of testing equipment, hay moisture can be estimated using changes in texture visual characteristics during drying. The table below illustrates how this system works.

**ASSESSMENT OF MOISTURE CONTENT OF HAY**

<table>
<thead>
<tr>
<th>Moisture Concentration*</th>
<th>Condition</th>
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<tbody>
<tr>
<td>30-40%</td>
<td>Leaves begin to rustle and do not give up moisture unless rubbed hard. Juice easily extruded from stems using thumbnail or knife or with difficulty by twisting in hands.</td>
</tr>
<tr>
<td>25-30%</td>
<td>Hay rustles-a bundle twisted in the hands will snap with difficulty, but should extrude no surface moisture. Thick stems extrude moisture if scraped with thumbnail</td>
</tr>
<tr>
<td>20-25%</td>
<td>Hay rustles readily-a bundle will snap easily if twisted -leaves may shatter-a few juicy stems may remain</td>
</tr>
<tr>
<td>15-20%</td>
<td>Swath-made hay fractures easily-snaps easily when twisted-juice difficult to extrude</td>
</tr>
</tbody>
</table>

*Reproduced from Hoard's Dairyman 132. 1987.*