INTRODUCTION

Haymaking in the humid parts of the U.S. is the most risky operation that farmers engage in. Standing hay is extremely high in moisture and must be dried to at least 25% moisture or less before it can be stored without spoilage. Most farmers rely on natural field drying processes to cure their hay. Natural drying is often slowed by high relative humidity. Rainfall frequently occurs before the hay has dried which further slows the drying process and can result in serious nutrient and yield losses. Haymaking is also a labor-intensive farming operation and, until recently, involved a large amount of manual labor.

Most of the problems associated with haymaking could be solved if hay dried quickly in the field, or if it could be stored at high moisture without spoilage. A combination of both rapid drying and high moisture storage could revolutionize haymaking. These problem areas, as well as the labor problem, have attracted considerable research interest in recent years.

HAY DRYING

The weight of water that must be evaporated from a hay crop in order to dry it to a safe moisture percentage for storage is about four times the weight of the dry hay. While this is a large amount of water and normally requires two or three days to evaporate under field conditions, it represents only about six hundredths of an inch of water, if the hay crop yields 2 tons of dry matter per acre. This quantity of water could be evaporated from a free water surface or from a standing hay crop in 4 to 6 hours on a sunny day. Thus, the problem in hay drying is not the amount of water that must be evaporated but rather the resistance to evaporation afforded by the structure of the plant. Resistance to water loss is a highly desirable attribute for living plants because it allows the plants to withstand drought stress. However, the same phenomenon prevents hay from drying rapidly.

Enhanced Drying. Resistance to water loss results from a waxy layer (cuticle) on the surface of leaves and stems and from membranes and constituents within the plant cells. Water loss from cut forage plants has been experimentally increased by subjecting the plants to treatments that disrupt the cuticle and internal membranes. The initial rate of water loss (Figure 1) is greater seven times faster when the hay was treated with petroleum ether than when the hay was untreated. The drying rate loss ether than when the hay was untreated. This is presumably due to resistance to water loss caused by factors other than the cuticle.

Figure 1. Moisture content of untreated (○) and petroleum ether (■) treated orchardgrass during drying at 43% relative humidity in the laboratory. (Adapted from Leshem et al. 1972.)
INNOVATIONS IN HAY HARVESTING AND STORAGE

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Purdue University
West Lafayette, IN

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Enhanced Drying. Resistance to water loss results from a waxy layer (cuticle) on the surface of leaves and stems and from membranes and constituents within the plant cells. Water loss from cut forage plants has been experimentally increased by subjecting the plants to treatments that disrupt the cuticle and internal cell membranes. The initial rate of water loss (Figure 1) is much faster when the hay was treated with petroleum ether than when the hay was untreated. The drying rate has slowed considerably at about 50% moisture even though the rate of evaporation from the cuticle has returned to normal. This is presumably due to resistance to water loss caused by factors other than the cuticle.

Figure 1. Moisture content of untreated (○) and petroleum ether (■) treated orchardgrass during drying at 43% relative humidity in the laboratory. (Adapted from Lesher et al. 1972.)

Similar increases in drying rate can be achieved by macerating tissue to disrupt cell structure. Figure 2 shows results of a study by Krutz et al. (1978) in which the drying rate of
untreated and macerated alfalfa was compared. Macerated material
dried to less than 20% moisture by 5 hours after harvest. Un-
treated material was approximately 61% moisture 5 hours after
harvest.

Figures 1 and 2 clearly show that hay can be made to dry
quickly if the resistance to evaporation is overcome. Neither
field applications are practical. Hay conditioning
at increasing water loss from cut forage are being studied.

Enhanced Drying - Field Applications. Hay conditioning,
which is an attempt to break the plant enough to speed drying,

Several field trials have been conducted in which potassium
carbonate has been used to enhance drying. Potassium carbonate
treatment disrupts the cuticle and thus speeds water loss from
plants. The most promising field results have been reported by
Tullberg and Minson (1978) in Australia. Results of one of their
studies are shown in Figure 3. Carbonate treated hay dried to
less than 25% moisture by midday on the day after cutting. Appli-
cation rates of approximately 85 gallons/acre of 2% potassium
carbonate solution effectively enhanced drying. Similar results
have been reported in laboratory studies in the U.S. (Wieghart
et al., 1980). Potassium carbonate treatment should have no
detrimental effect on forage quality.

Other researchers (Wieghart et al., 1980; Seif, 1981; Harris
and May-Brown, 1976; and Harris, 1978) have used various chemi-
cals to speed hay drying. Long chain fatty acids (Wieghart et
al., 1980) and organic phosphates (Harris, 1978; and Seif, 1981)
appear to be effective drying aids. However, these materials
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Figures 1 and 2 clearly show that hay can be made to dry quickly if the resistance to evaporation is overcome. Neither of these treatment procedures have been developed for practical field applications. However, other treatment procedures aimed at increasing water loss from cut forage are being studied.

Enhanced Drying - Field Applications. Hay conditioning, which is an attempt to break the plant enough to speed drying, has been successful and is widely practiced. However, the drying rates of conditioned hay are still far below those that could potentially be achieved if plant resistance to evaporation was eliminated.

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have only been used experimentally and additional research is needed before their effectiveness under field conditions can be determined. Also, their effect on forage quality is unknown.

HIGH MOISTURE STORAGE

Hay stored above 20% moisture approaches 90 to 100% relative humidity (Greenhill et al., 1961) and favors the development of mold organisms (Gregory et al., 1963). The heat generated by the metabolic activity of these organisms causes the temperature of the hay to increase. Heat resistant fungi remain active when the temperature of the hay is 115 to 150°F. If the hay temperature rises above 150°F, chemical reactions occur which can lead to spontaneous combustion. These reactions are most likely to occur if hay is stored at 30 to 40% moisture. Some microbial growth occurs in hay even when it is stored at less than 20% moisture. As a result, dry matter loss occurs during storage. Hodgenson et al. (1946) reported that hay stored below 20% moisture lost from 4 to 10% of its dry weight during storage. The amount of dry weight lost depends upon the moisture content of the hay.

Figure 4 shows the results of a study we recently conducted at Purdue University in which the relationship between dry weight loss and moisture percentage at baling was determined with large round bales. These results indicate that almost one percentage unit of dry weight was lost during storage for each unit of moisture above approximately 10% at baling. This weight loss is presumed to reflect primarily metabolic losses from the hay. These weight losses do not include weight losses due to weathering since the bales were stored inside.

Acid Preservatives. If microbial growth in stored hay could be prevented, dry weight losses in storage would be less and hay could presumably be stored at more than 20-25% moisture without spoilage. Sheaffer and Clark (1975) have shown that organic acids and related compounds inhibit mold growth in hay stored at high moisture. Knapp et al. (1976) reported that propionic acid reduced heating and storage losses and preserved the quality of high moisture alfalfa hay when applied at 20 lbs. per ton of hay (Table 1). Lower application rates were not effective. While organic acids are effective in preserving high moisture hay, they are quite corrosive to equipment and reasonably expensive when applied at effective rates.

<table>
<thead>
<tr>
<th>Max. Storage Temp.</th>
<th>Dry Weight Loss</th>
<th>IVDMD</th>
<th>Crude Protein</th>
<th>Fiber Digest.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>124</td>
<td>15.1</td>
<td>60.5</td>
<td>16.2</td>
</tr>
<tr>
<td>Propionic acid</td>
<td>.02%</td>
<td>127</td>
<td>16.7</td>
<td>61.8</td>
</tr>
<tr>
<td></td>
<td>.04%</td>
<td>115</td>
<td>13.2</td>
<td>62.2</td>
</tr>
<tr>
<td></td>
<td>.08%</td>
<td>104</td>
<td>11.7</td>
<td>61.0</td>
</tr>
<tr>
<td></td>
<td>1.0%</td>
<td>86</td>
<td>7.6</td>
<td>65.0</td>
</tr>
</tbody>
</table>

Hay at harvest was 70.5% IVDMD (in vitro dry matter disappearance) and had a fiber digestibility of 51.1%.
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Figure 4. Relationship between moisture percentage at baling and dry weight loss during storage of large grass hay bales.

Table 1. Storage losses and composition of alfalfa hay baled at 32% moisture and treated with different rates of propionic acid at baling (from Knapp et al., 1976).

<table>
<thead>
<tr>
<th>Propionic Acid</th>
<th>Storage Temp.</th>
<th>Weight Loss</th>
<th>Max. IVDMD</th>
<th>Crude Protein</th>
<th>Fiber Digest. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>124</td>
<td>15.1</td>
<td>60.5</td>
<td>16.2</td>
<td>47.0</td>
</tr>
<tr>
<td>.02%</td>
<td>127</td>
<td>16.7</td>
<td>61.8</td>
<td>16.9</td>
<td>48.2</td>
</tr>
<tr>
<td>.04%</td>
<td>116</td>
<td>13.2</td>
<td>62.2</td>
<td>16.9</td>
<td>49.6</td>
</tr>
<tr>
<td>.08%</td>
<td>104</td>
<td>11.7</td>
<td>61.0</td>
<td>16.9</td>
<td>49.9</td>
</tr>
<tr>
<td>1.0%</td>
<td>86</td>
<td>7.6</td>
<td>65.0</td>
<td>16.9</td>
<td>50.1</td>
</tr>
</tbody>
</table>

Hay at harvest was 70.5% IVDMD (in vitro dry matter disappearance) and had a fiber digestibility of 51.1%.
Anhydrous Ammonia. The addition of anhydrous ammonia to hay has the potential to provide two important benefits: Ammonia hay has fungicidal properties and can be used to sterilize high moisture baled hay. Ammonia has been used in the manner to feed livestock feed and is effective in meeting the animal's needs. In each case. Protein supplementation of ammoniated hay fed to dairy cows increased animal gains on hay rations. As a result of these changes in the hay, ammoniation has increased animal gains on hay rations. Table 2 shows data obtained from a recent lactation study conducted at Purdue University in which ammoniation had increased 22% and had increased greatly and hay consumption by animals was fed to dairy cows. Hay consumption and milk production were as good with the high moisture ammoniated hay as with untreated hay. The treated hay had five percentage units higher in crude protein concentration than untreated hay.

Table 2. Effect of ammoniating high moisture alfalfa hay on crude protein percentage, hay consumption and milk production.

<table>
<thead>
<tr>
<th>Ammoniated</th>
<th>Untreated</th>
<th>Baling Treatment</th>
<th>32% Moisture</th>
<th>75% Moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude Protein (%)</td>
<td>23.8</td>
<td>18.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hay Consumed (% of body wt.)</td>
<td>2.02</td>
<td>1.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Ration Consumed (% of body wt.)</td>
<td>3.32</td>
<td>3.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fat Corrected Milk (lb/day)</td>
<td>47.1</td>
<td>47.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milk Fat (%)</td>
<td>3.83</td>
<td>3.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milk Protein (%)</td>
<td>3.13</td>
<td>3.14</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Rations approximately 60% hay and 40% concentrate. Total protein percentage. |

Ammoniation treatment also has potential as a means of increasing the protein content and digestibility of low quality hay stored dry, when added to mature grass hay, baled dry, crude protein percentage has been doubled. Fiber digestibility has also been increased greatly and hay consumption by animals has been increased 22%. As a result of these changes in the hay, ammoniation has increased animal gains on hay rations. Table 3 shows the results of a study in which ammoniated and control hays were fed with and without grain and soybean meal supplementation. Ammoniation of the hay increased animal gain in each case. Protein supplementation of ammoniated hay did not increase gain, indicating that the crude protein added by ammoniation was effective in meeting the animal's needs.

Table 3. Effect of ammoniation and supplementation on daily gain and hay consumption by steers.

<table>
<thead>
<tr>
<th>Treatment (lb/hd/day)</th>
<th>Daily Gain (lb/hd)</th>
<th>Hay consumed (dry matter) (lb/hd/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybean meal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>Untreated 0.35</td>
<td>Ammoniated 0.81</td>
</tr>
<tr>
<td>1</td>
<td>Untreated 1.00</td>
<td>Ammoniated 1.56</td>
</tr>
<tr>
<td>1.0</td>
<td>Untreated 1.17</td>
<td>Ammoniated 1.53</td>
</tr>
</tbody>
</table>

BIG BALE STORAGE

The development and use of large package hay machinery has greatly increased the mechanization and reduced the labor associated with haymaking operations. As a result, the risk of adverse weather affecting the field operations has been reduced somewhat. However, large hay packages are generally stored outside and, therefore, subjected to weather deterioration and spoilage from harvest until feeding. Weathering not only reduces the dry weight of outside stored hay bales, but also results in changes in the composition of the weathered hay. These compositional changes may drastically reduce the nutritive value of the weathered fraction. Part of these losses result from deterioration around the top and sides of bales. Additional deterioration occurs where the bale contacts moist ground.

In studies that we have conducted in southern Indiana, the in vitro dry matter disappearance (IVDMD) of the weathered fraction of grass hay bales averaged 16.3 percentage units lower than the unweathered fraction. Mixed grass-alfalfa hay decreased 24 percentage units due to weathering, while the IVDMD of the unweathered fraction had decreased only 2 percentage units during storage. Total nitrogen (crude protein) was greater in the weathered fraction than in the unweathered fraction (Lechtenberg, 1978).

The combination of weathering and dry weight loss represents the total loss associated with storing hay outside. The best estimate of these total losses is the proportion of the original package weight remaining unweathered after storage. This proportion, expressed as a percentage of the dry weight, has been calculated for hay bales stored outside on the ground and on crushed rock during two years in southern Indiana (Table 4). Crushed rock storage was used in an attempt to reduce the amount of deterioration at the soil surface.
Ammoniation. The addition of anhydrous ammonia to hay has the potential to provide two important benefits. Ammonia has fungicidal properties and can be used to sterilize high moisture baled at 30% moisture without spoilage. Alfalfa hay treated with anhydrous ammonia has been increased 22%. As a result of these changes in the use of anhydrous ammonia, the potential to provide two important benefits.

Table 2 shows data obtained from a recent lactation study conducted at Purdue University in which ammoniated alfalfa hay has been increased greatly and hay consumption by dairy cows. Hay consumption and milk production were as good with the high moisture ammoniated hay baled at 19% moisture, were fed to dairy cows. Hay consumption and milk production were as good with the high moisture ammoniated hay stored dry. When added to mature grass hay, baled in this manner is excellent livestock feed and is

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An average of 76.3% of the original hay dry weight remained unweathered at the end of storage when the hay was stored on the ground. Storing the large bales on crushed rock increased the percentage to 85.5%. Ninety-two percent of the hay stored inside during the second year remained at the end of storage.

Since there was no weathering of the inside stored hay, this loss represents dry weight loss during storage.

The proportion of the final package dry weight in the unweathered fraction is also shown in Table 4. These values are considerably higher than the above values because they represent only the visibly deteriorated hay and do not include the dry weight lost during storage.

The difference between the proportion of the hay remaining unweathered when stored outside and when stored inside represents the loss due to outside storage, 15.2% in this study. Crushed rock storage reduced the loss due to outside storage to 6.5%.

This suggests that more than half (57%) of the storage loss associated with outside storage of large hay bales occurs where the bale contacts the ground.

Even though weathering losses with big hay bales stored outside are rather large, it is difficult to economically justify building conventional type structures for hay storage, considering present interest rates. We have experimented with a pipe-frame, plastic-covered greenhouse as a bale storage structure. A 30 x 32 ft. structure can hold 54 bales and can be built at a cost of about $1.50/square foot. Our present structure has lasted two seasons without replacing the plastic cover. We anticipate that it will need to be replaced before a third season.

The cost of replacing the cover will be approximately $70 (70/ square foot). The structure is still being used experimentally, but we feel that a low cost structure of this nature may have considerable potential for large hay bale storage. We have also used the greenhouse to ammoniate large hay bales.

<table>
<thead>
<tr>
<th>Year</th>
<th>Ground</th>
<th>Crushed Rock</th>
<th>Inside</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unweathered Fraction (% of Original Bale Wt)</td>
<td>1</td>
<td>72.2</td>
<td>82.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>81.3</td>
<td>88.2</td>
</tr>
<tr>
<td>Mean</td>
<td>76.8</td>
<td>85.5</td>
<td>92.0</td>
</tr>
<tr>
<td>Unweathered Fraction (% of Final Bale Wt)</td>
<td>1</td>
<td>82.5</td>
<td>94.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>93.0</td>
<td>94.6</td>
</tr>
<tr>
<td>Mean</td>
<td>87.8</td>
<td>94.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Proportion of the original and final bale dry weight unweathered with large round bales stored on the ground, on crushed rock, and inside.
An average of 76.8% of the original hay dry weight remained unweathered at the end of storage when the hay was stored on the ground. Storing the large bales on crushed rock increased the percentage to 85.5%. Ninety-two percent of the hay stored inside during the second year remained at the end of storage. Since there was no weathering of the inside stored hay, this loss represents dry weight loss during storage.

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<td>Unweathered Fraction</td>
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<td>94.1</td>
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<td>93.0</td>
<td>94.6</td>
</tr>
<tr>
<td>Mean</td>
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References


