HOP DRYING DETAILS AND IN-BALE QUALITY
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To simplify information, trade names of products have been used. No endorsement of named products is intended, nor is criticism implied of similar products which are not mentioned.

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HOP DRYING DETAILS
AND
IN-BALE QUALITY

A three-year research project was initiated in 1970 to consider quality improvement through better hop drying techniques. The specific objectives were to find the reliable criteria that characterize quality, establish acceptable quality levels, and correlate these criteria with storage and drying parameters. The project was sponsored by the United States Hop Administrative Committee through the USDA Consumer and Marketing Services and covers the states of Oregon, California, Idaho, and Washington.

Results of the project, of interest to growers and to drier managers interested in general and practical applications, are summarized in this bulletin.

Quality Factors

A generally recognized set of in-bale quality factors was not found. However, the evaluators' prevailing opinions can be summarized as follows:

- **Moisture content** should be approximately 9 percent. A lower moisture content increases potential for shatter. A higher moisture content promotes spoilage unless the bales are placed in cold storage.

- **Shatter** concern varied with individual. Shatter is generally recognized as undesirable but some hop growers and managers show little concern for this factor.

- **Color** is expected to be natural and uniform. Natural color variation between varieties and the effect of suffuring on color were of little concern to some growers and buyers.

- **Aroma** unless unnatural, does not appear to be important, except in a general way. However, it is particularly important to discriminating buyers.

- **Alpha acid index** is important to certain buyers but few drier managers attempt to optimize this factor.

Shatter

Shatter potential was determined by pressing cones firmly between the fingers and by bending individual petals through an arc of 160 to 180°. The observations were made from a drying study. Hops were removed at various moisture content and checked immediately for shatter with the following results:

- **Moisture content:**
  - 45.5 to 19.5 percent — Petal tips shattered.
  - 15.4 percent — Pressed tips shattered, a few stems and petals broke when bent through a 180° arc.
  - 12.7 to 11.7 percent — Tips shattered, a few stems and petals broke when bent through a 180° arc. Petal hinges seemed to fail but did not break loose.
  - 8.8 percent — Tips shattered, a few stems and petals broke when bent through a 180° arc. Petal hinges seemed to fail but did not break loose. Much shatter when pressed.
Hops were then exposed to room conditions for 25 hours and 30 minutes and the moisture content had increased to 10.8 percent. Petal hinges failed but did not come loose when bent. About one-third of petals shattered when bent; much shatter resulted from pressing cones.

Hops were then dried in a laboratory oven at a temperature of about 250° F. for one hour. At 4.5 percent moisture content, all petals shattered.

The air in the room was humidified with steam to elevate air and moisture conditions to 85° F. and 88 percent relative humidity. Air was then passed through the hops for 30 minutes. At 15.4 percent moisture content, the cones were nearly free of shatter when petals were bent through a 180° arc.

A second shatter study was conducted in laboratory by drying a small quantity of hops at 160° F. and a relative humidity of 6 percent. At a moisture content of:

34.0 percent – Light cone pressure produced some petal fracture but no petal loss.

16.9 percent – Minor petal loss when bent through a 160° arc, considerable petal breakage.

11.9 percent – Minor petal loss when bent through a 160° arc, much petal breakage.

5.3 percent – About 20 percent petal loss when bent through a 160° arc, nearly complete shatter when pressed.

1.1 percent – Nearly 100 percent shatter.

The hops were equilized overnight in the room, then humidified with air at 95° F. and 80 percent relative humidity. At a moisture content of:

10.2 percent – About 90 percent petal shatter after 15 minutes.

13.6 percent – Fifty percent petal shatter after 1 hour, 5 minutes of humidification; strig fails frequently.

15.2 percent – About 10 percent of the petals break from the strig after 2 hours 5 minutes of humidification; a few petals shatter when pressed.

Three significant observations can be made.

1. Shatter potential increases as the moisture content is reduced.

2. The process is reversible. When the moisture content is raised by hydration, shatter potential decreases.

3. Shatter potential seems to increase at a faster rate as the moisture content is reduced below approximately 10 to 11 percent.

The results noted above plus observations in the field can be summed up in a list of suggestions that may help minimize shatter.

1. Hydration of dried hops while still in the kiln can be effective (see discussion on hydration, page 10).

2. Maintaining 60 to 70 percent relative humidity in the cooling (tempering) room will keep the moisture content at a higher level (see discussion on equilibrium moisture content on page 7).

3. The handling or dropping of hops should be minimized.

4. A movable conveyor floor in the drier would minimize breakage from handling when the kiln is emptied.
Figure 1. Hop temperatures resulting from drying a 6-inch bed with 160°F air at a rate of 30 cfm/sq. ft.
Hop Temperature During Drying

Six inches of hops were dried with air at 160°F, 7 percent relative humidity, and an air rate of 30 cfm/sq. ft. A medium-sized hop located at the center of the drying bed was fitted with small thermocouples at the center of the strig and in the lupulin area. A second hop with a thermocouple in the lupulin area was placed on the surface of the drying mass. Temperatures observed during the drying period are shown in figure 1.

A second study was conducted to observe the drying response of hops at the point where the air enters the hop mass. A thermocouple was located in the lupulin region for these tests. The results are reported in figure 2.

These results show the cooling effect of moisture evaporating from drying hops and emphasize the opportunity to use a higher air temperature during the earlier part of the drying period without significant heat damage to hops. A reduced total drying time could result from such a procedure, with a second benefit being an improvement in quality.

Alpha Acid vs. Drying Conditions

Studies conducted during the first two years of this project led to the conclusion that drying temperature and time (as utilized in the tests and as used by some kiln managers) did not affect the alpha acid level of dried hops. Differing observations reported in the literature and by some drier managers prompted the extensive investigation reported below.

![Figure 2. Hop temperatures when dried in a 2 1/4-inch depth at an air rate of 60 cfm/sq. ft.](image-url)
A quantity of California Cluster hops dried at 140°F. was secured from a commercial kiln. They were transported in a sealed plastic bag, and stored at 40°F. Approximately 1,000 grams at a time were removed from storage and subjected to heated air for various periods of time at various temperatures to observe the time-temperature effect on the alpha-acid. Hop depth averaged about 2½-inch; air rate was about 60 cfm/sq. ft. The samples were sent to the Washington State Department of Agriculture Laboratory and Hop Division for alpha-acid analysis. The results are reported in table 1. Duplicate samples were developed for a few tests; they are noted by two values.

Note that the alpha-acid tends to decrease with both temperature and time. But also note irregularities in this trend, for example, values in the eight percent range along the right edge and bottom of the table.

Burgess,* in 1931, reported laboratory studies to determine the effect of drying temperature on alpha-acid conducted during the 1925-1929 period. Hops were dried in thin layers, approximately one hop deep to eliminate the deep-bed effect but the variety and drying time were not reported. His results, figure 3, show that higher temperatures generally depress alpha-acid. However, some curves are much steeper than others and some show slope reversals indicating outside or unknown operating factors. Burgess noted that all of the samples dried at ambient temperature, 64°F. in the graph, had a low alpha-acid content. He indicated he had no explanation for the low values but believed they might result from the long required drying period.

*See reference list on page 12.

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**TABLE 1.** Percentage of alpha-acid present in samples after subjecting dried hops to air at different temperatures for various periods of time.

<table>
<thead>
<tr>
<th>Temperature (F.)</th>
<th>Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>150°F</td>
<td></td>
</tr>
<tr>
<td>160°F</td>
<td>7.1</td>
</tr>
<tr>
<td>175°F</td>
<td>7.3</td>
</tr>
<tr>
<td>200°F</td>
<td>7.3</td>
</tr>
<tr>
<td>210°F</td>
<td>8.6</td>
</tr>
<tr>
<td>230°F</td>
<td>8.2</td>
</tr>
</tbody>
</table>

*From green hops dried for 5 hours.
The hop supply had a moisture content of 8.5% and an average alpha-acid of 8.5%.

Numbers in parentheses are moisture contents.
We are now convinced that drying at a high temperature and extended time can depress the alpha-acid level; although depression can not always be expected because of factors that are not yet understood. Without firm proof, we suggest that the following additional factors might affect the indicated average alpha-acid level in a dried hop sample: soil characteristics and amounts of irrigation water as well as temperature, relative humidity, and solar intensity during the growing period, location of hop on plant, time of day harvested, weather condition at time of harvest, level of maturity at harvest, uniformity of drying, breakage and lupulin distribution. Also, the method of sampling affects the ability to duplicate the results of the alpha-acid determination.

No suggestions can be made to minimize the reduction of alpha-acid other than those implied above. Storage of baled hops under refrigeration is recommended to minimize potential reduction of alpha-acid during significant storage periods.

Petal-Strig Moisture Content Relationships

A tray of hops approximately 16 inches square and 2½ inches deep was dried by air at 125°F flowing at a rate of approximately 160 cfm/sq. ft. Drying was started at 9 a.m., five hops were removed for moisture study at 1:30 p.m. The petals were removed from the strigs and moisture content was determined on the strigs and the petals. The process was repeated at every 30 to 40 minutes interval until 5 p.m. when the hops were judged to be overdried to a degree comparable to those at the bottom of an average kiln; the moisture contents of the hops at this time are shown as (1) in figure 4. The hops were sampled after being processed as noted below. Moisture contents were then determined and noted on figure 4 with appropriate numbers as follows:

(2) After being in the drier overnight without heat or air movement.

(3) After drier fan was operated without heat for one hour.

(4) After being in the drier to equalize for three days without heat or air movement.

(5) The tray of hops was then moved to a refrigerator where temperature was 36° to 40° F. and relative humidity 85 to 90 percent. A sample was taken after 6 hours.

(6) After 24 hours in refrigerator.

(7) After 48 hours in refrigerator.

The strig seemed heavy and large at the higher moisture contents and as drying took place it became relatively smaller. It was very thin at the lower moisture levels and the petals could be removed by bending at the point of attachment and breaking them loose.

When the moisture content increased, the strig increased in diameter but did not become as large as when drying from the green condition.

The computed dry weight, petal to strig ratio p/s as shown by dots in figure 4, indicates the existence of a bias since it is physically impossible for this ratio to change significantly during the drying process. Evidently at higher moisture contents, a small portion of the petals remained on the strig. This study did not reveal whether the strig or petal stubs expanded with an increase in moisture content but the experimenters believe that it was mainly the base of the petals that changed in size, rendering the collection of exact data impossible.

In spite of this bias, the results reveal a difference in moisture content of the two parts during drying and indicate a different relationship during hydration, which in turn, indicates a potential for hysteresis in equilibrium moisture relationships.
Equilibrium Moisture Relationships

The moisture content of agricultural crops varies with the relative humidity and temperature of surrounding air. The relationship which is usually presented as a graph or curve is called an equilibrium moisture curve (figure 5). If the moisture content of the crop is above the value indicated by the graph for a specific relative humidity, it will decrease and eventually reach the equilibrium moisture content indicated by the graph. If the moisture content of the crop is below the graph value, it will increase and eventually reach the indicated equilibrium. Air temperature usually does not affect the data significantly and can be neglected in using the chart.

Equilibrium moisture content data were developed from California clusters. The data were checked against single samples of other varieties from Oregon and Washington and against a similar study reported in 1958.* The upper curve of figure 5 is representative of green hops as they are dried. The lower curve represents relationships as the moisture content increases either because of an increase in the relative humidity of the atmosphere (for hops on the cooling floor, for example), or because of desired hydration. (Discussed later in this publication). The lower curve would also be useful for hydrated hops that are redried. The difference between the curves is frequently called hysteresis.

*See list of references on page 12.
Figure 4. Moisture content of petal and strig during drying and subsequent hydration. The ratio of the weight of dry material in the petals to that in the strig, p/s, is indicated by the dotted curve.

If the atmosphere in the cooling floor area has a relative humidity of 30 percent, for example, the hops would eventually equalize to a moisture content of 5.1 percent. But if the air has 60 percent relative humidity, the final moisture content would be 9.0 percent. This provides a clue to the importance of maintaining a desirable relative humidity in the cooling room before baling, a factor not considered at any hop drying facility visited.

Spoilage
Managers are fully aware that pockets or regions of high-moisture-content hops on the cooling floor or in the bale may spoil. Sometimes micro-organism activity causes heating, an indication of possible spoilage or even of significant spoilage. Micro-organisms produce heat, moisture, and carbon dioxide. Heat and moisture may help to accelerate the spoilage process. Carbon dioxide may be used as an index of micro-organism activity.

Micro-organisms associated with bulk-stored crops usually become active when the relative humidity exceeds 80 to 85 percent, approximately, the exact level depending upon crop, temperature, and organisms. Carbon dioxide was observed in the atmosphere surrounding the hops when the equilibrium moisture data were developed. The observations were:

<table>
<thead>
<tr>
<th>Equilibrium Relative Humidity (percent)</th>
<th>CO₂ Percent by Volume</th>
</tr>
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<tr>
<td>69</td>
<td>0.12</td>
</tr>
<tr>
<td>74</td>
<td>0.18</td>
</tr>
<tr>
<td>87.5</td>
<td>0.45</td>
</tr>
</tbody>
</table>

The data show, by using figure 5, that potential for spoilage exists at a moisture content over 10 to 11 percent where the relative humidity is at and above 69%. The potential for spoilage increases as moisture content increases above 11 percent.
Hydration

Extensive observations over three years of research, confirm the general knowledge that the moisture gradient from the bottom to the top of the kiln may be 10 percent, or more in many cases. The bottom hops may be as low as 3 percent in moisture content and the top as high as 15 percent or higher when drying is finished. Variations may exist horizontally in the kiln resulting from a lack of a uniform air flow through the bed, variations in mass density when laying the kiln, and perhaps in hop maturity when harvested.

Excessive shatter will result if the hops are removed from the kiln at too low a moisture content (below 8%) and spoilage on the cooling floor or in the bale will result if the moisture content is too high (above 10%). A uniform moisture content of between 8 and 10 percent is optimum to minimize these problems. The optimum level will depend on the individual grower’s management procedures, and the standards of the broker who buys the hops.

A nearly uniform moisture content can be produced by moving air at a high moisture content through the dried hop mass before removal.
from the kiln. Note from the lower curve of figure 5 that air with a relative humidity of 60 to 70 percent moving through the hops will bring the hop mass to the desired average moisture content. This process, called hydration, can be designed into the system in the following manner.

The relative humidity of the air in the dryer can be raised to the desired level by spraying water into the air discharge from the drier fan after the heat is turned off. A two-fluid (water-air) nozzle is strongly recommended because the two-fluid nozzle produces droplets that are small enough to evaporate before they impinge on the plenum floor or wall and also because small drops continue to be formed when the required water rate is low. This is not the case with single fluid nozzles. Normal average daily weather data for August and September from stations in or near the hop growing areas are listed in table 2.

The water rate to the nozzle(s) must be adequate to bring the relative humidity of the hydrating air up to the 60-70 percent level discussed earlier. Thus, the relative humidities in the table must be raised. Recommended average hourly estimated water rates per 10,000 cfm of drier air to raise the relative humidity to the desired level are: Oregon, 12.5 gallons; Idaho, 22.7 gallons; Washington and California, 20.3 gallons.

Capacities higher than noted may be advisable to insure adequate performance for occasional days of excessively high temperature; a 60 percent increase for days of 110°F., for example.

Note that the normal relative humidity may be high enough at certain times of day or night for hydrating naturally. However, this procedure should not be relied upon because of day to day temperature and humidity variation, and because the heat in the drier and plenum walls will cause a reduction in the relative humidity of plenum air.

System design. One to five nozzles in a bank or manifold are located in the air discharge from the fan where the air rate is high. The spray should be directed in the same direction as the air flow. The nozzle manufacturer or sales engineer can specify the nozzle size, required air pressure, cubic feet of nozzle air per minute, and water pressure needed. The relative humidity of the air in the plenum can be observed by a reliable relative humidity indicator. A manual valve can control the water rate to the nozzle(s) and, in this way, control

<table>
<thead>
<tr>
<th>Location</th>
<th>Month</th>
<th>Maximum Temperature (F.)</th>
<th>Time of Day (hours)</th>
<th>Relative Humidity, Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>04</td>
<td>10</td>
</tr>
<tr>
<td>Salem, Oregon</td>
<td>August</td>
<td>80.8</td>
<td>87</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>September</td>
<td>76.8</td>
<td>87</td>
<td>65</td>
</tr>
<tr>
<td>Boise, Idaho</td>
<td>August</td>
<td>88.7</td>
<td>51</td>
<td>34</td>
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<tr>
<td></td>
<td>September</td>
<td>78.8</td>
<td>59</td>
<td>40</td>
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<tr>
<td>Yakima, Washington</td>
<td>August</td>
<td>86.5</td>
<td>71</td>
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<tr>
<td></td>
<td>September</td>
<td>78.8</td>
<td>76</td>
<td>43</td>
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<tr>
<td>Sacramento, California</td>
<td>August</td>
<td>91.9</td>
<td>76</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>September</td>
<td>88.2</td>
<td>75</td>
<td>50</td>
</tr>
</tbody>
</table>
the relative humidity of the hydrating air. Ranch water pressure will be adequate for the nozzles but the pressure switch for the water pump motor should be adjusted for minimum operating differential, or a pressure control valve in the water supply line may be advisable to minimize pressure fluctuations.

If steam is available, it can be used instead of the nozzle system. The steam rate would be the same as the water rate and it should be introduced through the fan or at the fan discharge. Steam is not preferred over water if a steam source is not available. The boiler and related controls may be too costly if hop hydration were the only use for the equipment.

As an example, assume a drier operation in the state of Washington; assume a drier floor 36 feet square, an area of 1,296 square feet, with an air rate through the floor of 40 cfm/sq. ft. The total air rate would be 40 times 1,296 or 51,840 cfm. The recommended water rate for Washington is 20.3 gallon per 10,000 cfm of air, so the water requirement for this drier would be 5.18 x 20.3 or 105 gallon per hour. If the air rate through the hops is not known, an estimate may be secured by measuring the fan speed and static pressure in the plenum and then securing the fan delivery rate from the fan performance data.

System control is manual by adjusting the water rate to create the desired plenum relative humidity, automatic controls are also available. Inquiry should be directed to a local industrial control specialist for recommendations.

These suggestions on hydration should be followed for optimum results.

1. The hops should be distributed uniformly on the kiln floor to avoid dense areas producing undried or partially dried hops. Mechanical systems are now available for this purpose.

2. The moisture content at the top of the kiln should be close to the optimum in-bale moisture content when drying is completed.

3. The fan should be operated for a few minutes after the heat is turned off to cool the fan, heater, fan housing, and partially cool the plenum walls before turning on the hydrating water. This procedure will reduce the amount of water required to create the desired relative humidity.

4. Hydration at 60 to 70 percent relative humidity should continue until the moisture content is uniform throughout the mass. Thirty minutes to an hour should be adequate for most kilns.

Note that it is not possible to over hydrate the hops because of the limits that result from the equilibrium moisture relationships. Also note that uniformly hydrated hops can be baled directly from the kiln, thus reducing shatter from handling, reducing labor, equipment, and equalizing storage space.

A modified design procedure may be followed if it is not possible or practical to supply water at the rate needed. The entrance to the fan can be partially blocked to reduce the rate of airflow through the hops. The design and management procedures will still apply but the time for hydration may have to be extended.

Drying by Microwave

Personnel of the USDA Western Regional Research Laboratory in Albany, California, conducted some preliminary drying tests in their microwave dryer. Green hops were dried in 10 minutes; and a sample that had been kiln dried to a 30 percent moisture content was finish dried to 10 percent in 2.5 minutes. A sample with 15 percent moisture was reduced by microwave to 7.5 percent moisture content in approximately 1½ minutes.

Drying by microwave did not depress the alpha-acid level; the color was good; and the final moisture content appeared uniform. However, the lupulin appeared to have been agglomerated. Costs of drying which are excessive, were not considered.
Microwave drying is fast but its physical effect on the lupulin and its high operating cost would need to be considered carefully before use can be recommended. Its greatest potential lies as means of producing uniform moisture content and in the removal of surface or spot moisture sometimes existing in nearly dried hops.

Air Rate-Static Pressure Relationships

The data shown in figure 6 were developed during drying tests and may be useful for system design. Note that compaction of the green material as depth increases affects the resistance to air markedly; also note that shrinkage during drying has a comparable reverse marked effect. Due to these factors, it is probable that the data show trends only and should not be used for critical design.

REFERENCES


Figure 6. Pressure-air rate relationships for green hops of various depths. One observation for dry hops is included for comparison.