The objective here was to examine the literature on high-temperature kiln-drying of hardwoods and to evaluate the advantages, problems, and probable cost of this type of drying in the United States. High-temperature drying in current literature refers to drying wood at temperatures above 212° F. (100° C.). The drying may take place in the absence of air, but more commonly, an air-steam or moist air mixture is used. Only processes operating at atmospheric pressure are considered here.

EMC Relationships

For high-temperature drying, the first need is to establish the relationship between vapor pressure, temperature, and equilibrium moisture content (EMC). Although numerous reports deal with this relationship, the most noteworthy and reliable report is that by Grumach (6) (fig. 1). Work by Kollmann (12) and Kauman (9) substantiates that of Grumach.

It should be noted, fig. 1 that the maximum EMC possible at high temperatures is quite low (for example, only 7 percent at 230° F.). Therefore, no matter what the relative humidity is in a high-temperature kiln, the drying conditions (both temperature and EMC) are severe. As a result, a high-temperature kiln, as the temperature increases above 220° F., can be operated without concern for the wet-bulb temperature until the conditioning period. Of course, steaming or high humidities might be used initially to increase warm-up speed.

Species

Green from the Saw

There are more than 25 published studies on high-temperature drying of hardwoods green from the saw; for most of these, kiln temperatures used ranged between 220° and 240° F. High-temperature drying, primarily in Canada and Europe, was reported fairly successful with beech, yellow-poplar, birch, and mahogany (Table 1). Scientists in other countries have also reported good results with several of their native woods. Generally, a slight increase in defects was assumed offset by the 50 per cent or more reduction in drying time. However, most of the species in Table 1 had more drying defects if dried by high temperatures than if dried at conventional temperatures.

Air-Dried

If a species will not dry satisfactorily when green from the saw, the next logical step is to try drying at high temperatures after some air-drying or normal-temperature kiln-drying.

Calvert (3) reported that yellow birch dried well at high temperatures if the moisture content was below 50 per cent (or if just the shell was dry). Cech (5) also reported superior results with yellow birch if it was partially air-dried before being subjected to high-temperature drying. Hartwig (7) reported good results with beech, walnut, ramin and mahogany that were partially air-dried. Hill (8) reported excellent results for well air-dried [below 20 per cent moisture content (M.C.)] yellow-poplar and red gum. However, Keylwerth (10) reported that 8/4 oak air-dried to 30 per cent M.C. before high-temperature drying had excessive degrade when dry. Thinner oak (11) also had degrade when air-dried first (no moisture content level indicated), but there was no degrade with air-dried birch, teak, and iroko (an easily dried hardwood; specific gravity, 0.59; Africa). Malmquist and Noack (18) found that air-dried oak responded well to high-temperature drying, in contrast to reports

*Italic numbers in parentheses refer to literature cited at the end of report.

1Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

Figure 1.—Relationship of equilibrium moisture content for a saturated steam atmosphere at atmospheric pressure (6) to temperature.
of others. Pratt (20) reported excellent results (faster drying and less degrade than normal kiln-drying) for air-dried African mahogany. Malmquist (17) reported that birch and oak, if below 25 per cent M.C., kiln-dried well at high temperatures. He also reported that other researchers found that beech below 25 to 30 per cent M.C. dried well at high temperatures. It appears, therefore, that many hardwood species can be high-temperature dried without increase in degrade if they are first partially air-dried.

Defects

The four defects reported as most prevalent in high-temperature drying of hardwoods were collapse, end-checking, honeycomb, and discoloration. Almost all who are cited here reported these defects.

Collapse is quite prevalent. As a result of collapse, higher shrinkage was noted, an increase in specific gravity (with appropriate increases in strength) was expected, and the hygroscopicity at room temperature was altered in a manner that dimensional stability was improved. Collapse lessened if the initial moisture was reduced by predrying at lower temperatures.

End Checking was frequently observed, but in many experiments short boards that were end-coated did not show excessive end-checking. It is possible that proper end-coating may keep this defect at acceptable levels.

Honeycomb was evident in many species, especially in oak and in material thicker than 1% inches. Lowering the initial moisture content prior to high-temperature drying seemed to reduce the amount of this defect, although the optimum initial moisture content level indicated that this was dependent on species.

Discoloration, usually a toast-brown, was reported by many (12,15,18,22). With some species, this colored layer was very thin, and could easily be planed off. However, with oak, the color was reported throughout (17).

In one study, reduced cup and bow was reported from high-temperature drying when the material was first air-dried (20).

Energy

In three studies (2,4,15), the researchers attempted to measure the energy required in high-temperature drying. They reported that high-temperature drying requires 25 to 60 per cent less energy than does normal kiln-drying. This reduction in energy is attributed primarily to better heat transfer to the wood and less heat loss through the kiln walls because drying time is shortened. These figures are very dependent on species, kiln, initial moisture content, and temperature, but indicate that a major part of the cost of kiln-drying can be reduced.

Stress Relief

Stress relief is mandatory in high-temperature-dried material that is to be resawn, turned, or otherwise worked, because, due to fast drying, stresses are greater than in normal-temperature-dried material. However, stresses can be relieved as easily from high-temperature-dried material as from that dried at normal temperature (2,21). Of course, the lumber and the air temperature in the kiln must be lowered below 212° F. so that the high humidities and necessary EMC's can be obtained.

High-Temperature Kiln-Drying For U. S. Hardwoods

High-temperature drying is definitely a very promising method of drying hardwoods. However, drying schedules have not been investigated or detailed for the major hardwood species of the United States. A few trial schedules for high-temperature drying have not been successful. However, the success of the Canadians and Europeans in drying their hardwoods gives us confi-

Table 1.--Species kiln-dried with high temperatures

<table>
<thead>
<tr>
<th>Species</th>
<th>Source</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beech</td>
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<td></td>
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<td>USA</td>
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<td>Canada</td>
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</tr>
<tr>
<td>Hard maple</td>
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<tr>
<td></td>
<td>Canada</td>
<td></td>
</tr>
<tr>
<td>Walnut</td>
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<td></td>
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<td></td>
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<tr>
<td>Ramin</td>
<td>SE Asia</td>
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<tr>
<td>Mahogany</td>
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<td>7, 19, 20, 24</td>
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<td></td>
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<td>Yellow-poplar</td>
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<tr>
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<tr>
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<tr>
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<tr>
<td>Teak</td>
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<tr>
<td>Bakli</td>
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</tbody>
</table>

1 Drying not always satisfactory due to excessive degrade.
2 See Literature Cited.
dence that high-temperature drying can be used in the United States with great benefits.

Economics-Kiln-Operating Costs
Perhaps the major factor for successful high-temperature drying of hardwoods is favorable economics. From the work in Canada and Europe, what can we expect of the economics here?

Capital Investment
The design of the kiln structure is the same for drying at normal or at high temperatures. Extra insulation and extra resistance against corrosion might be added for high-temperature kilns. Also, a large-capacity heating system and many fans are usually necessary. Therefore, there is an increase in capital investment. However, one manufacturer notes that the increase is generally less than $2,000 for either a new kiln or a modification of an existing one.

Maintenance
Maintenance costs for the kiln may be higher because corrosion has been reported to be a problem (12,15,19). However, because most kilns manufactured in the United States are of aluminum or concrete-block, the main item that might corrode will be the heating system.

Labor
It is likely that labor costs will initially be higher with a high-temperature kiln because frequent surveillance will be needed to avoid danger from possible problems with a new system. However, when the kiln operator has familiarized himself with the system, labor costs will be lower because the schedule is much simpler than the schedules commonly used.

General Economic Outlook
Annual operating cost will, undoubtedly, increase initially with a high-temperature hardwood drying operation due to the increases mentioned. However, because of shorter residence time (or faster drying), therefore a higher annual output, the direct cost of drying per MBF (not including degrade) will probably decrease by 20 per cent or more.

Because of increased drying speed, dry kilns can be smaller to handle the same annual volume of lumber as do the larger, conventional temperature kilns. Smaller kilns permit more flexibility in drying (less mixing of species in a single load, faster unloading and loading). Also, less space is required for smaller kilns. Due to faster turnover, inventory can be reduced. This means lower insurance, lower taxes, and decreased space requirements. Thus, the economics becomes quite favorable.

Viewpoint Of Industry
The hardwood drying industry has viewed high-temperature drying with skepticism. A major reason is that many have tried high-temperature drying but, because they used green wood, the results were unsatisfactory due to excessive degrade. Data in the maximum safe initial, or entering, moisture content are needed for various species to control the degrade.

Perhaps another reason is that the small operators, who comprise most of the drying industry, cannot afford the risk of trying something new—they have neither the financial advisors nor the backing necessary to pioneer.

Another reason is that during the last few years conservative drying practices have been considered sufficient; there has been no impetus to improve the existing methods. However, in recent months the demand for many hardwoods has been increasing (shortages and price increases for hard maple are an example). Capital expenditures may be necessary to accommodate higher demands and to replace older equipment. The trend is toward larger companies with larger drying operations. Reductions in cost of drying are being sought. The drying industry would like (or needs) to know more precisely the procedures for high-temperature drying U.S. hardwoods that will reduce losses from degrade.

Literature Cited