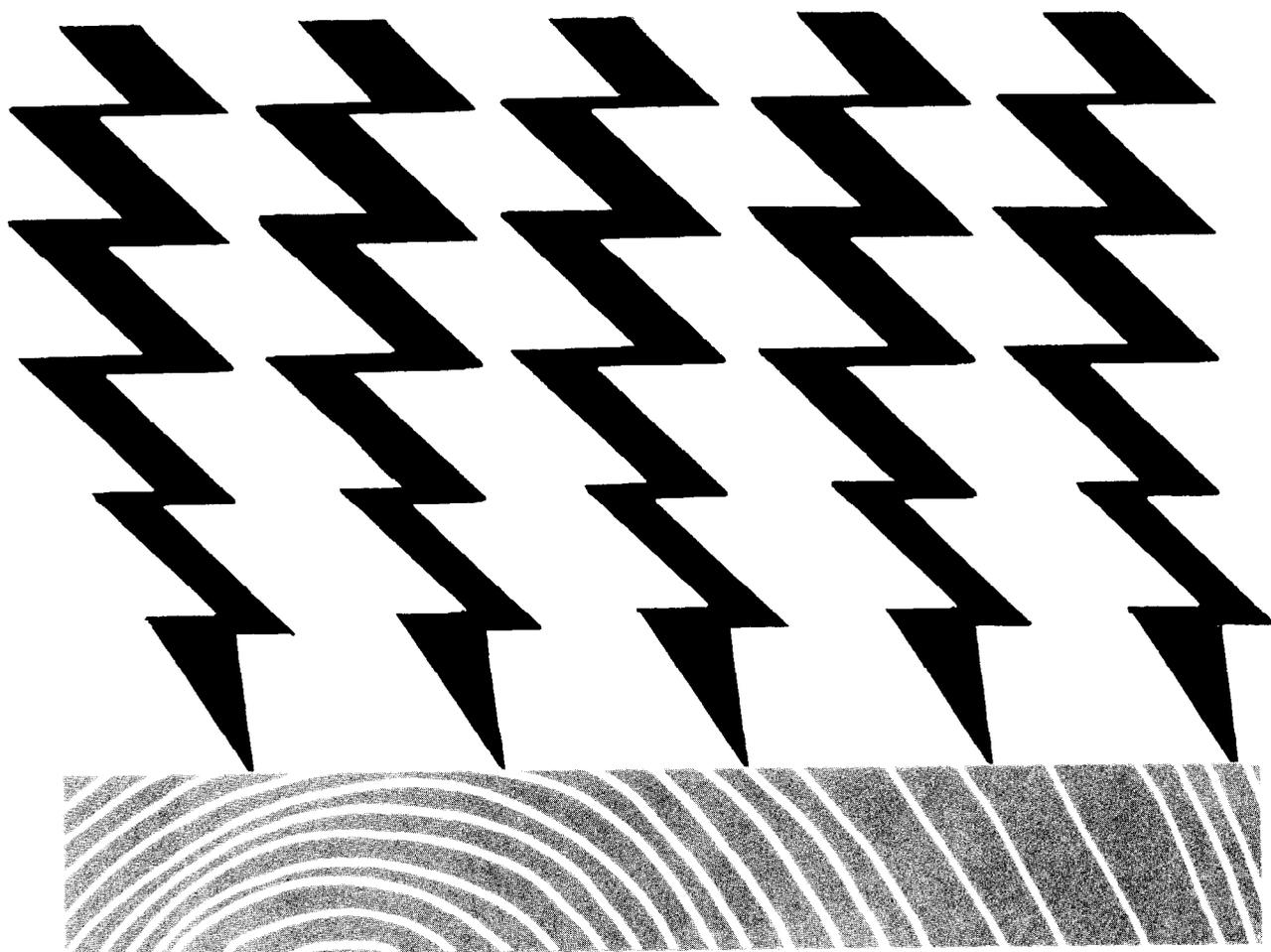


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Radio-Frequency Dielectric Drying of Short Lengths of Northern RedOak



Abstract

For most uses hardwoods are dried as entire boards that include all defective portions discarded after drying. The United States has a large resource of low-quality hardwoods and the potential exists for significant savings in energy and in dryer capacity by cutting out defects before drying. One approach could use radio-frequency drying. In this investigation short lengths of northern red oak were dried rapidly, but energy consumption and honeycomb were excessive in drying to low moisture levels. However, rapid radio-frequency dielectric drying to 25 to 30 percent moisture content followed by more conventional finish drying may hold technical promise.

Radio-Frequency Dielectric Drying of Short Lengths of Northern Red Oak

By
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Introduction

Drying Hardwood Cuttings

Hardwoods for use in furniture stock, millwork, flooring, and similar uses, are traditionally dried as entire boards that range from 8 to 16 feet long and that vary in width. Depending on grade, a certain percentage of the volume of these boards is defective and unsuitable for a high-quality end product. The eastern part of the United States has an abundance of low-grade hardwoods, and advances in processing efficiency could lead to increased utilization of this resource. Low-grade boards have a significant percentage of fiber unusable for a final furniture-type product. To dry this unusable wood only to discard later is a waste of energy and of dryer capacity. If the defective volume could be cut out before drying, significant savings may be possible.

The idea of drying clear hardwood cuttings instead of entire boards is not new. Torgeson (14)², Rice (11), Caterick (4), and Bingham and Schroeder (1) considered the idea. Rice (11) investigated the idea experimentally and concluded drying dimension parts instead of lumber is technically and economically feasible. Despite Rice's conclusions, drying dimension parts is not practiced commercially to any great extent, probably because in-

dustry is not convinced the advantages outweigh the disadvantages.

The advantages of drying dimension parts instead of whole boards are:

- Reduced energy consumption
- Increased dryer capacity
- Possible reduction in transportation costs

Disadvantages and potential problems are:

- More pieces to handle
- More end checking
- Increased warp
- More wet residue to handle

These major advantages of reduced drying energy and increased dryer capacity are illustrated in table 1, which shows estimates of these savings for hardwood lumber grades (assumes 4/4 red oak). If, for example, No. 2C were used, energy consumption per usable thousand board foot (Mfbm) increases from 4.51 to 7.73 million British thermal units (Btu); required dryer capacity per usable Mfbm increases from 1 to 1.71 million Btu, energy savings by drying only usable cuttings is \$8.05 per Mfbm.

The major disadvantages of drying only usable parts of boards are the

much greater number of individual pieces that must be handled, the increased number of ends exposed and susceptible to end checking, and the possible presence of warp in pieces for which only small machining allowances remain.

This investigation attempted to determine if one particular approach, radio-frequency dielectric drying, has sufficient technical promise for drying hardwood cuttings to be considered a potential drying process of the future when cost, availability, and sources of energy may be considerably different than they are today.

Radio-frequency drying requires electrical energy, which currently is more expensive than most other sources (including oil, gas, and wood residues). Whether the use of electrical energy will increase or decline in the future when the mix of our energy sources may change is unknown. However, a system that could rapidly dry hardwood cuttings, such as radio-frequency drying, has sufficient potential payoff so that technical feasibility should be investigated now in anticipation of the time economic feasibility might be a reality.

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

² Italicized numbers in parentheses refer to literature cited at end of report.

Table 1.—Potential savings in energy and dryer capacity by drying 1-inch northern red oak cuttings instead of entire boards

| Grade | Clear surface required | Energy required per usable 1,000 board feet in drying from 50 to 7 percent ¹ | Required dryer capacity per usable 1,000 board feet | Savings in energy costs (\$2.50 per million Btu) by drying only cuttings |
|---------------------|------------------------|---|---|--|
| | | <u>Pct</u> | <u>Million Btu/Mfbm</u> | <u>Mfbm/Mfbm</u> |
| All clear | 100 | 4.51 | 1.00 | 0 |
| Firsts | 91-2/3 - 100 | 4.71 | 1.04 | .50 |
| Seconds | 83-1/3 - 91-2/3 | 5.15 | 1.14 | 1.60 |
| Selects | 91-2/3 - 100 | 4.71 | 1.04 | .50 |
| No. 1C | 66-2/3 - 83-1/3 | 6.01 | 1.33 | 3.75 |
| No. 2C | 50 - 66-2/3 | 7.73 | 1.71 | 8.05 |
| No. 3A | 33-1/3 - 50 | 10.83 | 2.40 | 15.80 |
| No. 3B ² | 25 - 33-1/3 | 15.46 | 3.43 | 27.38 |

¹ Simpson and Tschernitz (12)

² Requires sound cuttings, not clear.

Radio-Frequency Drying

For many years, wood drying by radio-frequency electrical energy has been investigated, but has not been accepted industrially except for a few specialty items. Some of the past research is described in (2,5,6-9,15,16). There are two general methods of drying wood with radio-frequency electrical energy. In one, the boiling method, the surrounding atmosphere is not controlled and a high level of power is applied to the wood. The free water is driven out of the wood both as vaporized water and as liquid water forced out by steam pressure. Of the two methods, this is the faster; it is generally considered applicable only to short lengths of permeable species that do not permit the build up of high steam pressures that rupture the wood. The other method, the temperature gradient, is slower than the boiling method, but in sensitive species causes less degrade. A lower level of power is applied—just enough to keep the interior of the wood slightly below 100° C. The surrounding atmosphere is maintained cool and humid. The temperature gradient from the inside to the outside moves moisture out of the wood, because of the associated vapor pressure gradient.

Ward and Anderson (16) report that northern red oak is tolerant to the boiling method. They present a drying curve for 1- 3/4- by 2- 1/4- by 24- inch

red oak that shows drying from about 65 to 10 percent moisture content in about 14 minutes produced no serious drying defects. An objective of the present work is to confirm this tolerance and to take advantage of the high longitudinal permeability of red oak to rapidly remove water from the end grain of short lengths by the boiling method of radio-frequency drying. Further objectives are to establish a drying-rate curve, to assess any drying defects that occur, and to determine power and energy consumption characteristics.

Experimental

Material for this investigation was taken from freshly sawed boards of northern red oak. Clear specimens 4 inches wide by 24 inches long were cut from the boards, and surfaced on both sides to 1 inch thickness. The specimens were then randomly assigned to different treatments, 13 drying times (0, 4, 6.5, 9, 12, 15, 18, 24, 30, 45, 75, 120, and 300 min). Seven replicates were dried at each drying time. The lengthwise moisture gradient was determined for each specimen by cutting moisture sections 1/4 inch along the grain at 3-inch intervals over the 24-inch length of the specimen. The average moisture content of the whole piece was estimated from this gradient. These moisture sections also served

as crosscut samples to determine presence or absence of honeycomb.

In addition to drying rate, lengthwise moisture gradient, and degrade assessment, other pertinent information was gathered. The power absorbed by the wood was monitored during the 300-minute drying run. The internal temperatures were measured in four specimens over a 3-hour period. An estimate of the moisture gradient across the 1-inch thickness was also determined, based on six replicates, each dried for 12 minutes. These were obtained from 1/4-inch-long moisture sections similar to the lengthwise moisture gradient sections but cut from the center of the 24-inch-long pieces. Three smaller moisture sections (1116 in. wide) were cut along the 1-inch thickness of each of these 1/4-inch sections, one section was taken from each face and one from the center (fig 1).

The radio-frequency generator was a 5-kilowatt-capacity unit with the load circuit containing the drying wood electromagnetically coupled to the generator circuit. A variable tuning coil was built into the load circuit to maintain tuning for transfer of power as the dielectric properties of the wood decreased during drying (fig. 2). The frequency was 27.12 megahertz (MHz). Aluminum electrodes were held in contact with the wood by a slight pressure. Each sample was dried individually.

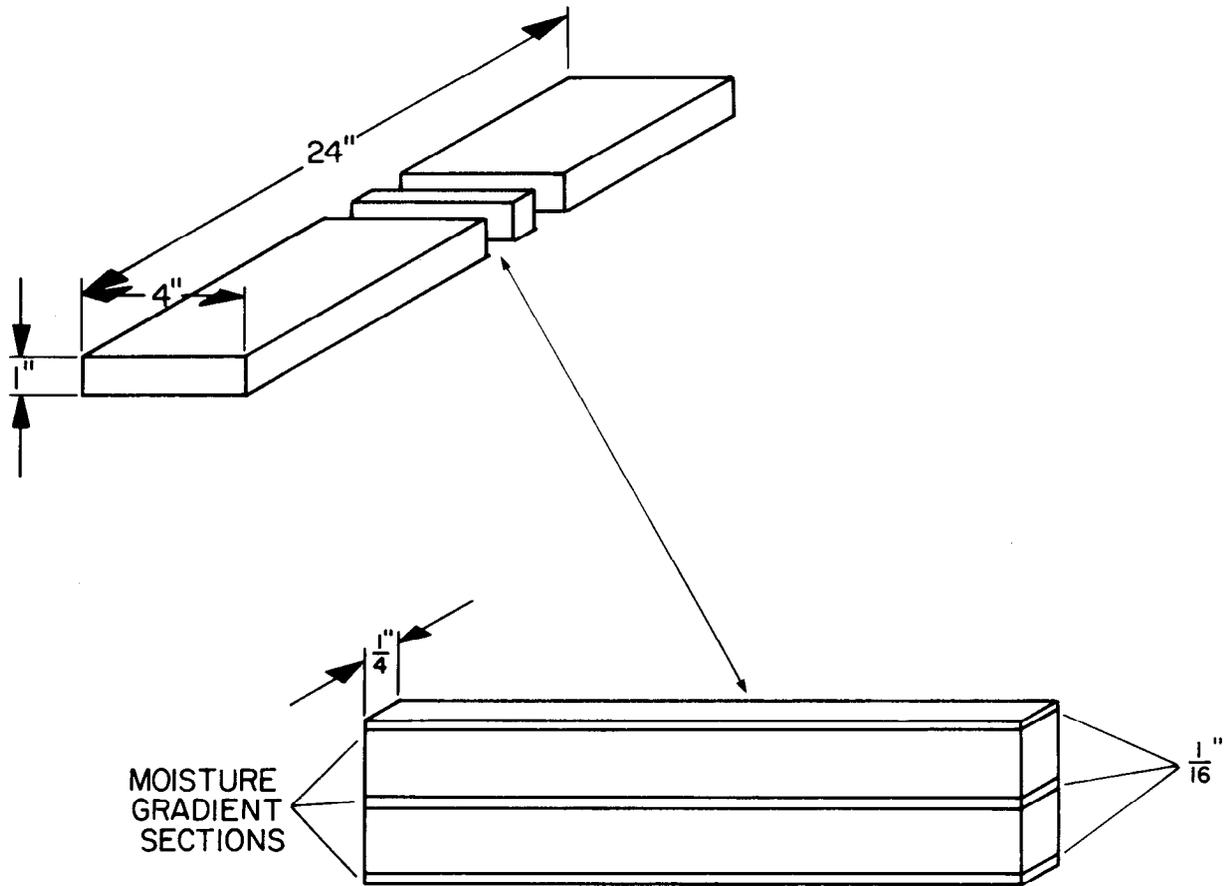


Figure 1.—Method of preparing specimens for moisture gradient in thickness direction.

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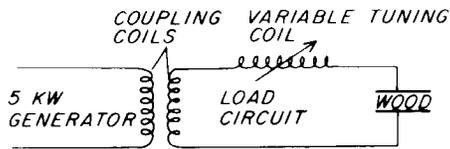


Figure 2.—Schematic of radio-frequency generator and load circuit for drying lumber.

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Results and Discussion

Drying Rate

The average lengthwise moisture gradients at the various drying times are shown in figure 3. The figure illustrates the statement often made for radio-frequency drying—it dries wood from the inside out. The 0- and 4-minute gradients show the effects of normal end drying. The 6.5-minute gradient is almost flat; from then up

to 30 minutes, the gradient is reversed because steam pressure forces free water to the ends of the boards. At 30 minutes, the moisture content has dropped below the fiber saturation point; from this point on, diffusion takes over, and the moisture gradient again reverses. The average moisture content of the boards as a function of time is shown in figure 4; data for moisture content and drying time are listed in table 2, as are statistics showing variation in moisture content. The average moisture content for each specimen was estimated by integrating the moisture-gradient curve. Figure 4 shows that drying is very rapid from the initial 79.2 percent moisture content down to the fiber saturation point of approximately 25 percent; at fiber saturation, the much slower process of diffusion takes over.

The moisture gradient through the thickness, measured when the average moisture content was

38.9 percent, showed the center considerably dryer than the shell. The average moisture content of the outer moisture sections was 41.5 percent; the average of the center sections, 11.7 percent.

The internal temperature is shown as a function of time in figure 5. Initial temperature rise is rapid; in 3 minutes the temperature is up to 100° C, after which it gradually increases to a maximum of approximately 135° C.

Power and Energy Consumption

Any data on power and energy consumption apply only to the radio-frequency generator load system developed for this investigation, and do not apply to other systems except to point out general characteristics. The power absorbed by the load during drying from green to 20 percent moisture content is shown in figure 6.

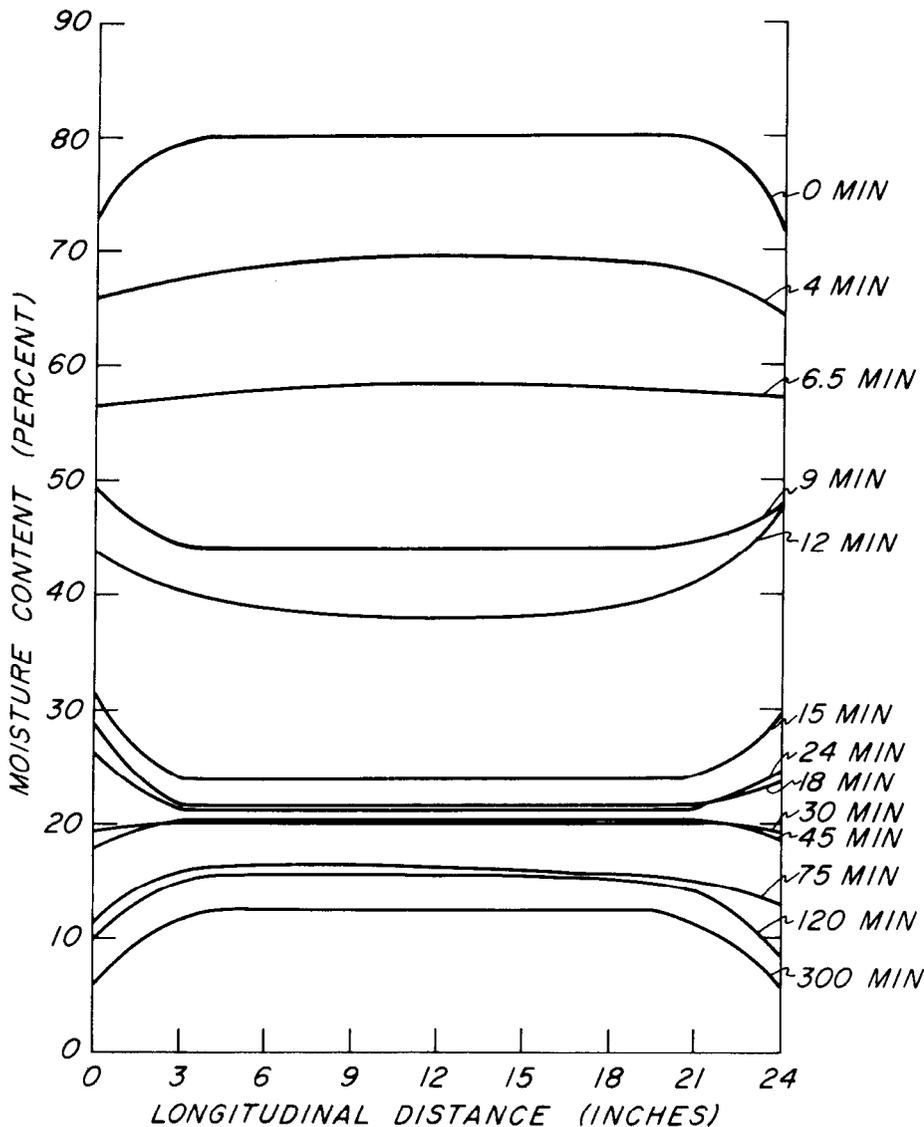


Figure 3.—Lengthwise moisture gradients for 1- by 4- by 24-inch-long red oak lumber during radio-frequency dielectric drying.

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The striking feature shown by figure 6 is the rapid decrease in power consumption as moisture content decreases below 50 percent moisture content. Electric power supplied to a load can be expressed as (2):

$$P = 0.55 f E^2 e \tan d \cdot 10^{-12}$$

where

P = power absorbed (watts/cm³)

f = frequency (hertz)

E = field strength (volts)

e = dielectric constant of load

d = dielectric loss angle

Skaar (13) has shown that the dielectric constant decreases as moisture content decreases. The decrease in dielectric constant is severe, dropping from 30 to 40 for green wood to approximately 2 for oven-dry wood. Thus, as wood dries it can absorb less and less radio-frequency power. The data on thickness-moisture gradient show that, even at fairly high average moisture contents (40 to 50 pct) the center of wood is considerably drier than the outer wood, and can account for the rapid decrease in power absorbed.

Another factor of practical significance in the design of any

radio-frequency system is the impedance matching between generator and load circuit (10). Without proper "tuning," maximum power cannot be transferred between generator and load. As the dielectric properties of the wood decrease during drying, the impedance of the load circuit changes, and some adjustments must be made in the load circuit to maximize power transfer (fig. 2). The variable tuning coil used in this work was an attempt to accomplish this successfully in maintaining maximum power transfer during drying. Any practical radio-frequency drying system will require considerable engineering analysis to maintain optimum power transfer during drying.

The energy required to dry the red oak of this investigation with this radio-frequency system is shown in figure 7 as a function of final moisture content. The actual energy used and the percent efficiency are relevant only to this system and are not as important as the shape of the curve in figure 7. The curve shows a sharp increase in energy required at a final moisture content of about 25 percent. This corresponds to the point in drying at which mass flow of water no longer contributes much to drying, and diffusion, which is much slower, has taken over as the controlling mechanism. The much slower drying rate requires maintaining power to the load for lengthy periods of time, during which energy consumption continues to add up.

Wood Quality

Drying defects are summarized in table 3. Some honeycomb and surface checking occurred in 54 percent of the boards dried 15 minutes or longer. Because of the moisture gradient in the thickness direction (41.5 to 11.7 pct at an average moisture content of 38.9 pct) it is understandable that honeycomb could occur. The drier center was restrained from shrinking by a still-wet shell, and tensile failures occurred.

Severity of honeycomb varied; whether or not it would cause rejection of the piece would depend on its severity and the requirements of the end product. Nevertheless, the honeycomb present is probably too severe for many oak products. As McAlister and Resch (6) noted, one means to overcome the problem of honeycomb is to reduce power input

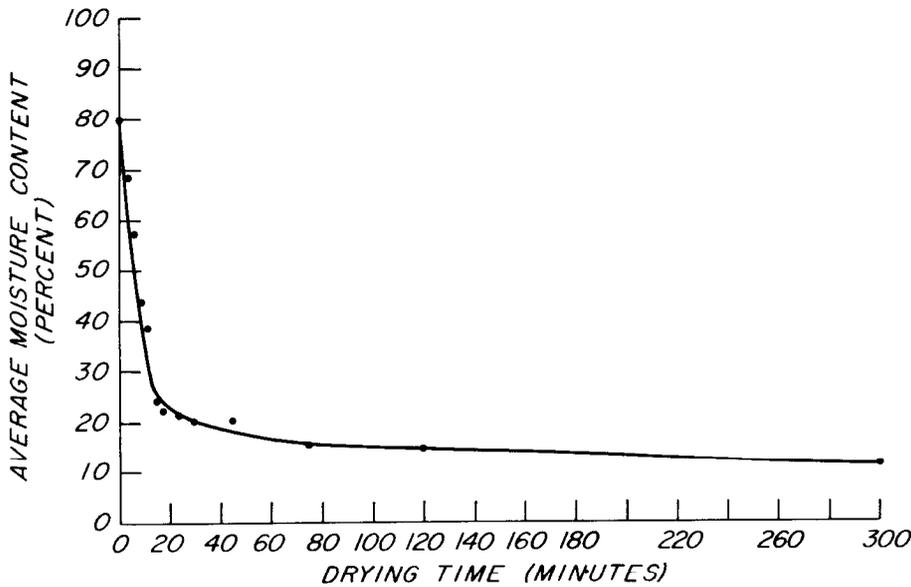


Figure 4.—Relationship of average moisture content to drying time for 1- by 4- by 24-inch-long red oak dried by radio-frequency energy.

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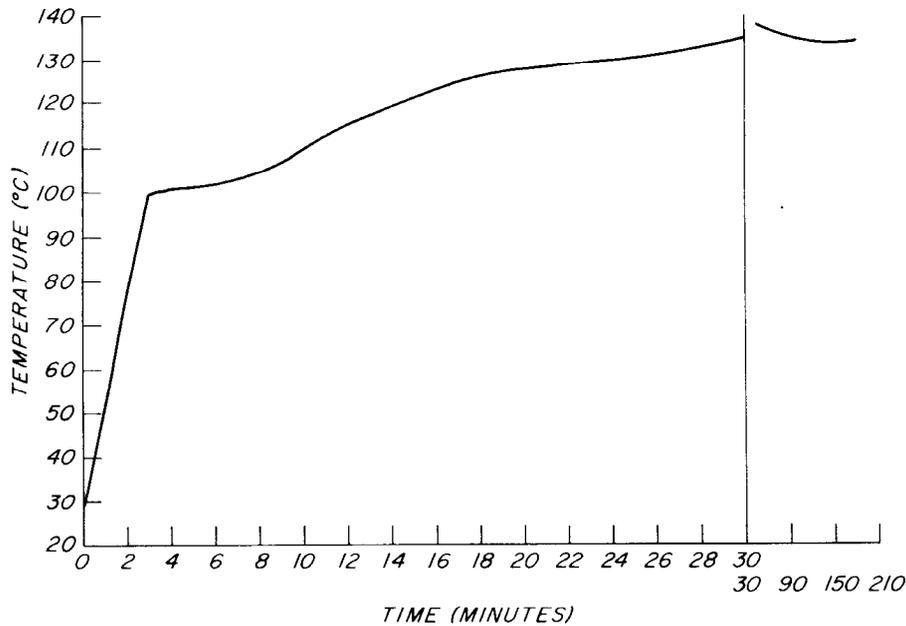


Figure L—Relationship of internal temperature in 1- by 4- by 24-inch-long red oak to time during radio-frequency dielectric drying.

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to the boards. Although this reduces drying rate, it may be possible to develop procedures that will minimize honeycomb yet retain short drying times.

Feasibility of Radio-Frequency Drying

Although the technical feasibility of radio-frequency drying short lengths of red oak has not been established by this investigation, some possibilities for potential applications have resulted. The results of analyzing drying time, energy consumption, and defect development point to the impracticality of using continuous high-power levels in radio-frequency drying oak to low moisture-content levels. The results, however, suggest an application of radio-frequency drying that, if successfully developed, would retain some of the advantages of rapid drying without resulting in excessive defects. Air drying is very slow, and it may be possible to replace months of air drying by short high-frequency cycles of only minutes in drying to moisture contents in the 30 percent range. Conventional kiln drying could then be used in drying to final moisturecontent levels of 6 to 8 percent. It would be necessary to develop moderated radio-frequency cycles that might take longer than the 12 to 15 minutes used in this work, but they would still be relatively short and would upgrade final quality.

This investigation was limited to the response of oak to rapid radio-frequency drying. Many other hardwood species are much more tolerant to rapid high-temperature drying than oak. Since this study was completed, Boone (3) has shown that some hardwood species, particularly those of low density, are tolerant to rapid high-temperature drying. Thus, there are probably species more suitable than oak for which the advantages of rapid radio-frequency drying could be successfully realized. This rapid drying, if coupled with the potential energy and dryer-capacity savings made possible by drying only usable parts instead of entire low-grade boards, could result in a drying process more efficient than the processes now used. Research should be encouraged to determine optimum radio-frequency drying schedules that will maximize drying rate and minimize drying defects.

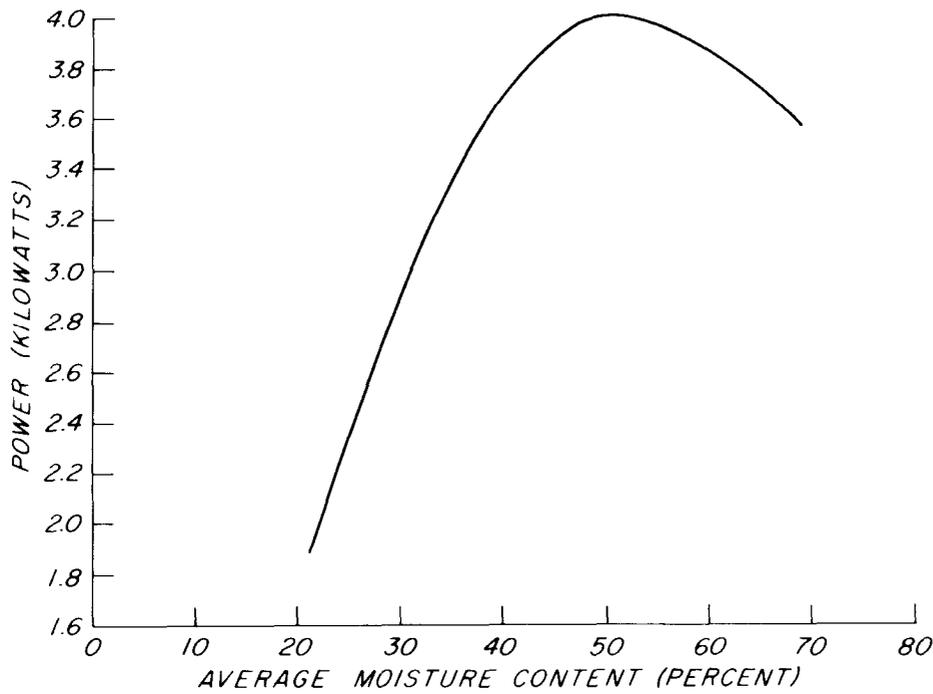


Figure 6.—Relationship of power absorbed during radio-frequency dielectric drying of 1- by 4- by 24-inch red oak from green to 20 percent moisture content.

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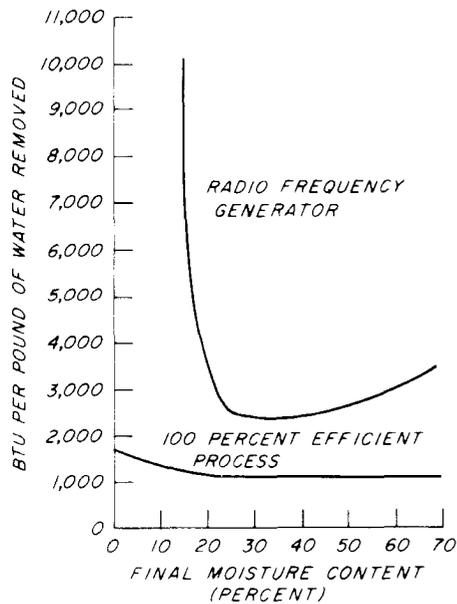


Figure 7.—Relationship of energy required to dry 1- by 4- by 24-inch red oak to final moisture content.

M 148 994

Summary and Conclusions

Northern red oak boards, 1 inch thick by 4 inches wide by 24 inches long, were dried from an initial moisture content of approximately 80 percent to various final moisture contents by radio-frequency electrical energy. Drying occurred rapidly above the fiber saturation point, but slowed down considerably below this moisture content. With the drying system used in this investigation, the average moisture content could be reduced in 15 minutes from 80 to 25 percent. However, the level of degrade in boards dried to 25 percent or below was probably too high for many oak products in which honeycomb is an important defect. The results did suggest that radio-frequency drying has some potential as a predrying process to be followed by lower temperature drying.

Table P.-Average moisture content after 13 radio-frequency drying times for 1- by 4- by 24-inch red oak

| Drying time | Average moisture content | Standard deviation | 95 percent confidence limits |
|-------------|--------------------------|--------------------|------------------------------|
| <u>Min</u> | <u>Pct</u> | <u>Pct</u> | <u>Pct</u> |
| 0 | 79.2 | 10.5 | 69.5 - 88.9 |
| 4 | 68.5 | 8.5 | 60.6 - 76.4 |
| 6.5 | 57.2 | 13.9 | 44.4 - 70.1 |
| 9 | 43.9 | 7.7 | 36.8 - 51.0 |
| 12 | 38.9 | 12.6 | 27.3 - 50.5 |
| 15 | 24.1 | 8.4 | 16.1 - 31.9 |
| 18 | 22.1 | 5.3 | 17.2 - 27.0 |
| 24 | 21.7 | 3.0 | 18.9 - 24.4 |
| 30 | 20.0 | 3.5 | 16.8 - 23.2 |
| 45 | 20.4 | 3.5 | 17.2 - 23.6 |
| 75 | 15.5 | 1.7 | 14.0 - 17.1 |
| 120 | 14.6 | 2.2 | 12.6 - 16.6 |
| 300 | 11.5 | 2.0 | 9.7 - 13.3 |

Table 3.-Summary of drying defects associated with radio-frequency drying 1- by 4- by 24-inch red oak

| Drying time | Average moisture content at end of drying time | Number-of boards | | |
|-------------|--|------------------|-----------------|---------------------------------------|
| | | Honey-combed | Surface-checked | Either honeycombed or surface checked |
| <u>Min</u> | <u>Pct</u> | | | |
| 15 | 24.1 | 6 | 1 | 6 |
| 18 | 22.1 | 3 | 2 | 3 |
| 24 | 21.7 | 2 | 0 | 2 |
| 30 | 20.0 | 3 | 1 | 3 |
| 45 | 20.4 | 4 | 4 | 4 |
| 75 | 15.5 | 5 | 4 | 5 |
| 120 | 14.6 | 5 | 4 | 5 |
| 300 | 11.5 | 2 | 2 | 2 |

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