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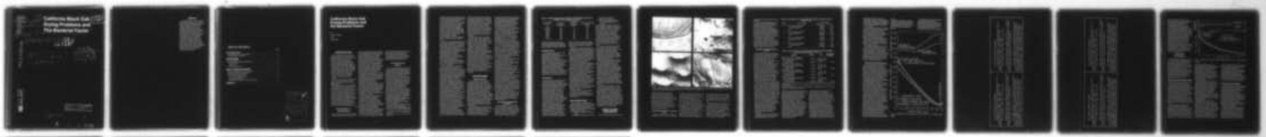

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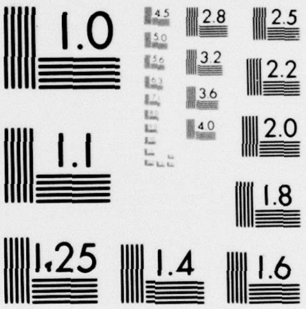

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California Black Oak Drying Problems and The Bacterial Factor.

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Abstract

It is often difficult to kiln dry California black oak lumber green from the saw without developing excessive degrade from honeycomb, ring failure, and collapse. Results from this study indicate that defect-prone lumber contains heartwood that was infected and weakened by anaerobic bacteria in the living tree. Green, bacterially infected boards should be segregated and dried to 20 percent moisture content (MC) under mild air-drying conditions or by low temperature, forced air-drying schedules. The 20 percent MC lumber can then be kiln dried to end-use MC without additional defect. Boards with normal, noninfected heartwood can be successfully kiln-dried green from the saw under conventional schedules.

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California Black Oak Drying Problems and the Bacterial Factor

By

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INTRODUCTION

A strong demand for kiln-dried oak lumber is evident on the west coast, especially by the furniture, millwork, and cabinet industries in southern California. Most of the oak lumber consumed there is imported from the eastern United States, but a ready market exists for kiln-dried lumber from native western oaks. One Los Angeles lumber dealer says he could easily sell one-half million board feet of 4/4-inch California black oak lumber every month of the year, but is unable to locate a mill that can consistently furnish this amount of kiln-dried material.

One main reason California black oak lumber is in short supply is that the green lumber is difficult to dry without costly degrade.

This paper reports on a cooperative study between the U.S. Forest Products Laboratory (FPL) and the Kimberly-Clark Corporation to explore the causes and extent of drying degrade in 4/4 black oak lumber from several different saw timber stands in Shasta County, California. Most drying degrade in this study was traced to heartwood that was weakened by anaerobic bacteria in the living tree. We believe bacterial tree infections may be responsible for most of the unexpected drying degrade in California black oak lumber in general.

Oak Sawtimber in a Softwood Region

Aside from the furniture, cabinet, and millwork industries, there has been little economic impetus on the west coast to utilize California black oak sawtimber in a region predominately covered with softwood sawtimber. The bacteria-related drying problems are easily obscured by more obvious processing and marketing problems with west coast hardwoods. Forest surveys indicate California black oak is represented in sawtimber volume by approximately 1.9 billion board feet in California and 500 million board feet in southwestern Oregon (Smith 1956, Ellwood 1958). Even so, west coast oak timber resources are but a fraction of those in the eastern United States where the net merchantable volume of oak sawtimber is 185 billion board feet with select red and black oaks comprising 39.5 billion feet (Forest Service 1973). Consequently, eastern lumber producers are more experienced in the utilization and marketing of oak lumber. West coast producers are more familiar with softwoods which in California and western Oregon comprise about 600 billion board feet of merchantable sawtimber on commercial timber lands (Forest Service 1973).

California black oak is the only oak species considered potentially important for sustained forest management on commercial forest lands of the west coast (Roy 1962). However, lumber processing problems resulting from improper seasoning and excessive drying defects were considered a serious obstacle to successful management and utilization of California black oak (Edwards 1957, McDonald and Sundahl 1967). Bois (1975) found that the entire philosophy of kiln drying on the west coast must be reexamined if costly degrade in oak is to be avoided at mills accustomed to drying softwoods. It was felt that a successful program of drying research would greatly increase the economic potential of California black oak.

A Persistent Drying Problem

For a single oak species, the drying of California black oak was studied more intensively than were similar problems in some of the more plentiful species of eastern oaks. From the late 1940's until the early 1960's, a series of drying studies was carried out to promote the utilization of California black oak. The earliest drying studies were conducted by the U.S. Forest Service's California Forest and Range Experiment Station (now Pacific Southwest Station) in cooperation with the Diamond-International Corporation at Chico, Calif. These studies, reported by Smith (1949, 1950, 1961), evaluated both the air drying and the kiln drying of green 3/4- and 4/4-inch boards. Additional studies reported by Ellwood (1959a, b) were conducted at the University of California Forest Products Laboratory, Richmond, to develop suitable schedules for kiln drying 4/4 lumber green from the saw.

Drying problems with California black oak lumber were caused by four defects: (1) surface checking and splits, (2) honeycomb or internal checks, (3)

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collapse or excessive shrinkage, and (4) warp. All studies indicated that degrade from these defects would be at a minimum with a combination of careful air drying followed by kiln drying. First it was necessary to air dry the green lumber below 30 percent average moisture content and preferably to 20 percent. Air-dried stock at 20 percent moisture content could then be safely kiln dried to 8 percent moisture content with no additional defects under schedules similar to those recommended by the FPL (Rasmussen 1961) for eastern red oak and black oaks.

Warp can be caused by severe drying conditions, but Wahlgren (1958) found that excessive warp could be related to the presence of tension wood. Ellwood (1959a) was able to keep warp to a minimum when kiln drying green lumber by spacing stickers 18 inches apart and weighting the piles. Initial kiln temperatures were then kept comparatively low until the boards reached 25 percent moisture content. Ellwood (1962) developed a reconditioning treatment to remove much of the collapse and the warp from cup in California black oak and other California hardwoods.

Air drying of green 4/4 California black oak varies from 63 days to 5 months depending on the time of year (Smith 1950, 1961). Much shorter drying times can be realized by kiln drying the lumber green from the saw, but the risk of economic losses is also greater. By west coast softwood standards an initial dry bulb temperature of 120° F is considered mild, yet it was severe enough to completely spoil most of a charge of 4/4 California black oak from collapse and excessive warp (Smith 1950). The recommended kiln schedule for drying green 4/4 California black oak developed at the California Forest Products Laboratory by Ellwood (1959a) specifies that the initial dry bulb temperature must not exceed 110° F with a wet bulb depression of 4° F. The wet bulb temperature should not be reduced until after the lumber has dried below 54 percent moisture content, otherwise surface checking will be excessive. To control development of honeycomb and warp, the dry bulb temperature should not be substantially increased until at least 29 percent moisture content is attained.

West coast lumber manufacturers agree that past research developed sound drying techniques, yet the drying problem persists. According to sawmill operators producing California black oak lumber, this species will generally yield about 30 percent No. 1 Common and Better grades of lumber. Yet only about 20 percent of the lumber may be used for factory lumber, while 80 percent is used for pallets and other lower value products. This 10 percent loss (from 30 to 20 pct) is attributed to drying degrade; as one mill operator puts it "California black oak is a tricky species to dry even under the best *conditions.*"

The Kimberly-Clark Corporation at Anderson, Calif., has considerable volumes of black oak sawtimber on its timber lands in northern California and is aware of the drying problems. Don Prielipp, production manager at Anderson, was familiar with the utilization of eastern oaks from the Company's sawmill operations in Georgia and wondered if bacterial tree infections might not be responsible for some of the drying problems in California black oak. Ward, at the FPL, had found that heartwood infections by anaerobic bacteria in red and black oak trees can result in development of honeycomb and ring failure in 4/4 lumber under normally mild kiln-drying conditions (Ward 1972, Ward *et al.* 1972). When Kimberly-Clark initiated a study to utilize its California black oak sawtimber, FPL evaluated the sawtimber and lumber for bacterial infections.

PROCEDURES

Milling and Drying

A major portion of the study was concerned with sawing woods-run grades of sawlogs into 4/4 lumber at the Kimberly-Clark sawmill in Anderson. The logs came from black oak timber growing in Shasta County, California, at elevations of 2,400 to 3,800 feet. All green lumber was graded under the rules of the National Hardwood Lumber Association (1971) after sawing. Boards grading No. 1 Common or Better were piled on stickers for kiln drying while the lower grade boards were bulk piled and sold for green pallet lumber. The No. 1 Common and Better lumber was kiln dried green from the saw in kilns at the Anderson mill.

Three samples were involved in the milling and drying part of the study. The first sample of oak sawtimber was harvested in May and kiln drying of the lumber was completed by July. A second sample of sawtimber was harvested late the following September and the lumber kiln dried by November. The final sample was harvested in December and the lumber kiln dried during late January and February. All kiln charges were dried to a final moisture content of 5 to 6 percent.

The first and second lumber samples were kiln dried according to the California Forest Products Laboratory schedule for 4/4 flatsawn California black oak (Ellwood 1959a). This schedule calls for an initial dry bulb temperature of 110° F with wet bulb depressions of 3° to 4° F. It was impossible to maintain the required initial drying conditions for the first kiln run. Dry bulb temperatures rose to 120° to 125° F during the day despite being set at 110° F. These high temperatures are due to the hot, dry summers in the Anderson area and to adjacent kilns drying softwood lumber at temperatures of 170° to 190° F. It was much easier to follow the California Forest Products Laboratory schedule for the second run in October and November.

The final kiln charge was dried under a milder schedule that can be maintained during the winter months. This schedule outlined in table 1 was designed according to the recommendations of Smith (1961) for low-temperature drying and the FPL schedule for lowland eastern red oak (Rasmussen 1961). One reason for using a milder schedule was that, under the California Forest Products Laboratory schedules, Ellwood reported rough lumber degrades of 4.8 to 6.3 percent while Smith (1961) found a corresponding degrade of 3.6 percent when the initial drying temperatures did not exceed 100° F. It was apparent that bacteria were responsible for much of the degrade in the first two kiln charges and it was decided that a kiln schedule for southern bottomland oaks would be useful for California black oak.

After kiln drying, each charge of oak lumber was regraded and special note made of the reasons for degrade. Any boards that dropped below the No. 1 Common grade were reclassified as dried pallet stock.

Microbial and Wood Quality Evaluations

Three phases were involved in the evaluation of California black oak for bacterial heartwood infections. The first phase was directly connected with the grading of lumber for the sawmill study. The second and third phases were initiated after the sawmill study and

Table 1.—Mild kiln schedule used for drying 4/4 California black oak lumber at Anderson, Calif. during the winter months

Wood moisture content	Kiln conditions		
	Dry bulb temperature	Wet bulb depression	Equilibrium moisture content
Pct	°F	°F	Pct
Above 50	100	4	17.5
50-45	120	15	9.7
45-40	125	15	9.7
40-35	135	20	8.0
35-30	140	25	6.9
30-20	145	30	5.8
20-15	150	30	5.8
15- 6	160	40	4.3

entailed sampling living trees and selected board samples to establish a more precise relationship of bacteria to drying degrade in California black oak.

Sawmill Phase

During the grading of green lumber, special attention was given to heartwood that emitted strong odors of volatile fatty acids which are characteristic of oak infected by anaerobic bacteria (Ward *et al.* 1972). In addition, green boards containing ring shake, or from logs containing ring shake, were considered to be partially or completely infected by bacteria. When the kiln-dried lumber was regraded, a comparison was made between the incidence of drying defects and the presence of fatty acid odors and shake in the logs and green lumber.

Tree Phase

Standing trees growing on Kimberly-Clark forest lands in the Cascade mountains northeast of Anderson were sampled and evaluated for the presence of bacteria in sound heartwood. The procedure first entailed a survey of black oak tree stumps and logs on stands being logged. This survey indicated the quality of wood to be expected in the standing trees on adjacent stands not being logged.

Thirty standing oak trees were first sampled by examining cores taken with an increment borer. These increment cores, taken at 2 to 4.5 feet above ground, indicated by odor and appearance which trees contained normal, noninfected heartwood and which were probably infected by anaerobic bacteria. Three trees were then selected for more intensive sampling. One tree was considered sound with no apparent microbial infection, the second tree appeared to have sound but very rancid-smelling heartwood, and the third tree appeared to be in the early stages of bacterial infection.

Intensive tree sampling consisted of asceptically removing wood cores from the lower trunk at 1.5 to 4 feet above the ground line with a sterilized increment borer. These cores were systematically removed in separate sections; first from the sapwood, and then from the outer, middle, and inner heartwood. Each core section was divided with sterilized forceps into four subsections.

Three core subsections were placed in tubed culture media—one medium for incubating and culturing the wood under strictly anaerobic conditions and the other two media for aerobic conditions. The fourth core subsection, which would eventually be examined under the scanning electron microscope (SEM) at FPL, was fixed at the tree site in 2 percent buffered gluteraldehyde for about 4 hours. Then it was dehydrated through increasing concentrations of ethanol for a total of 48 hours, at which time it was in 100 percent ethanol. Total time for preparation of the four core subsections after removal from the tree did not exceed 4 minutes.

Details of this matched increment core method for evaluating the microbial condition of standing trees are described by Sachs, Ward, and Kinney (1974).

Wood Quality Phase

Wood quality and related drying factors were evaluated from four board samples, 5 feet long, that were sawed from three freshly cut logs. Three heartwood conditions were represented by these boards, namely:

(1) Normal noninfected heartwood—1 board
(2) Bacterially infected with a strong rancid odor—2 boards
(3) Mixed normal heart and bacterially infected heartwood with a strong vinegar odor—1 board.

Immediately after sawing, the boards were wrapped in plastic and shipped to FPL in Madison. At FPL the boards were surfaced on two faces from a rough green thickness of 1.5 inches down to 1.2 inches. They were also edge surfaced so that each board had a uniform width. About 1.5 inches were trimmed from the ends of each board, and each board cut into three sections. From the ends of each board, two sections 24 inches long were cut, leaving a center section 8 to 9 inches long.

The matched 24-inch-long samples were used in small-scale drying experiments; one was air dried while the mate was kiln dried. All matched samples were end coated to retard longitudinal moisture loss. Air drying samples were on stickers in a weighted, covered pile placed outdoors on the shaded north side of FPL.

When these samples had air dried to 15 percent average moisture content, they were transferred indoors to a controlled temperature-humidity chamber and dried to a final moisture content of 6 percent. The matched set of samples was kiln dried from green to 7 percent moisture content in a small experimental drying chamber with controlled temperature, humidity, and air flow. Initial dry bulb temperature was 120° F with a 5° F wet bulb depression. These initial conditions were used because they represented the mildest conditions in which black oak could be kiln dried at Anderson, Calif., during the summer.

Two cross sections about 1.5 to 2.0 inches along the grain were cut from the center board section to be used in determinations of moisture content and specific gravity. The remaining green section about 5 to 6 inches long was tested for resistance to a pulsed electric current with a portable ohmmeter called the Shigometer Model 7950 (Shigo and Shigo 1974). This section was then split. Splinters asceptically removed from the core were cultured under both aerobic and anaerobic conditions to test for the presence of micro-organisms.

RESULTS AND DISCUSSION

We found that the heartwood of living

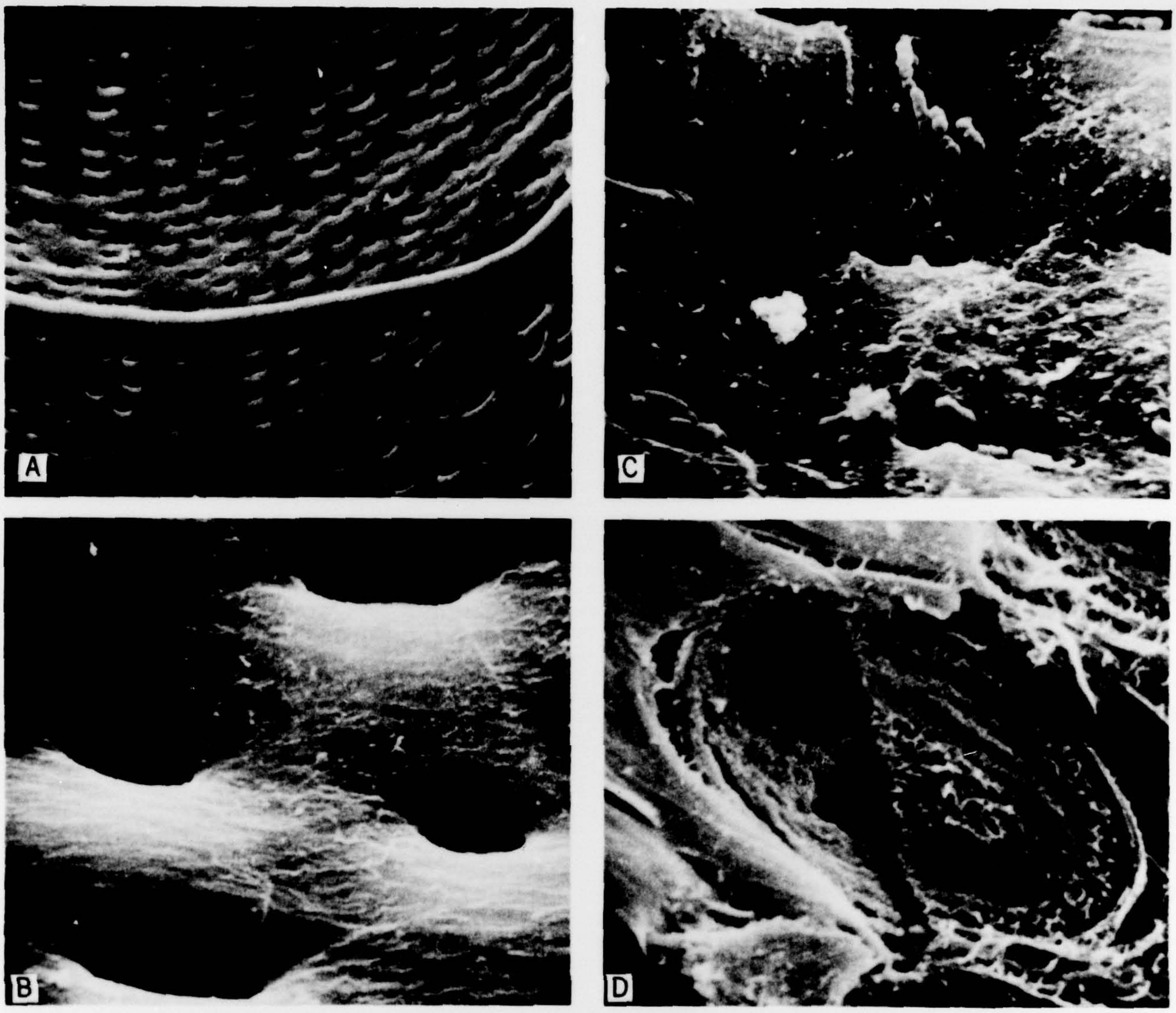

Figure 1.—Scanning electron micrographs of noninfected sapwood (A-B) and bacterially infected heartwood (C-D) from living California black oak trees. Spore of *Clostridium* sp. within the bordered pit in D.
(M 147 430, M 147 428, M 147 429, M 147 428)

California black oak trees can be infected by anaerobic bacteria in a manner similar to that reported for eastern red and black oaks (Ward 1972, Ward *et al.* 1972). Results from both the large-scale mill study and the FPL laboratory study indicate that the bacterially infected heartwood can be related to the unexpected occurrence of drying degrade from honeycomb, ring failure, and collapse.

Microbial Populations in Trees and Logs

Anaerobic bacteria were consistently isolated from sour- and rancid-smelling heartwood of California black oak trees and less often from logs and green lumber. Apparently the survival of these microorganisms depends upon environmental conditions within wood cells, conditions disrupted when the tree is cut. Sapwood and heartwood with a typical oak odor were found to be generally sterile. The scanning electron micrographs (fig. 1) demonstrate that our tissue isolates represent actual conditions within the living tree and are not the result of contamination. Laboratory cultures from the isolates indicate that a mixed population, or more than one species of bacteria, will occur together within sour or rancid heartwood. A favorite niche for these bacteria appears to be in the bordered pits between vessels or between a vessel and an early wood tracheid (fig. 1-C).

Anaerobic bacteria could always be associated with the so-called wind or ring shake frequently encountered in the butt logs of California black oak trees. Culturing of heartwood adjacent to shake zones, together with examination under the SEM, always revealed the presence of bacteria and sometimes fungi. Ring shake was never found in normal, noninfected heartwood of the California black oak in this study.

Fungi were neither isolated from, nor observed in, the bacterially infected heartwood that was sound and clear of dark discolorations. It was not uncommon, though, to isolate fungi from discolored heartwood adjacent to ring shake. Presumably, the anaerobic conditions of sound, bacterially infected heartwood are unfavorable for fungal growth, but the resultant shake may aid the progress of heartwood decay.

Heartwood decay from fungal infections was observed in many of the logs sawed for the mill study, but green boards containing decay were generally not included in the No. 1 Common and Better grades that were kiln dried.

Mill Study and Manufacturing Losses

California black oak logs from three different timber stands were sawed into 4/4 lumber for a total green volume of almost 580,000 board feet. The oak timber was generally mixed with ponderosa pine and both species were harvested in the same logging operation. Table 2 shows that the yield of green No. 1 Common and Better grade lumber from these three stands follows the general grade yields reported by other sawmill operators in northern California. Our green lumber yields also agree with the 30.15 percent yield of No. 1 Common and Better grades reported by Malcolm (1962) for 48,000 board feet of 4/4 California black oak lumber sawed from logs ranging in grade from No. 1 to No. 4.

The No. 1 Common and Better lumber was kiln dried green from the saw while No. 2 Common and lower grade boards were surfaced and sold for green pallet lumber. When the kiln-dried lumber was regraded, there was an average loss in total volume of 15.9 percent, which can be attributed mainly to shrinkage. There were also losses in lumber grade which resulted largely from the formation of collapse, surface checks, splits and ring failure, and to a lesser degree from warp. Kiln-dried boards falling below No. 1 Common grade were sold for dry pallet lumber. Kiln-dried boards with collapse and ring failure usually revealed the internal presence of honeycomb when the boards were crosscut, but honeycomb did not contribute directly to degrade evaluation.

Table 2.—Yield of green 4/4 California black oak lumber from woods-run logs at Anderson, Calif.

Sample	Lumber grades	Volume yield	
		Board foot	Percent
1	No. 1 Common and Better	43,589	30.6
	Green pallet stock	98,650	69.4
	Total	142,239	100.0
2	No. 1 Common and Better	96,063	32.0
	Green pallet stock	204,200	68.0
	Total	300,263	100.0
3	No. 1 Common and Better	40,720	29.7
	Green pallet stock	96,394	70.3
	Total	137,114	100.0
All	No. 1 Common and Better	180,372	31.1
	Green pallet stock	399,244	68.9
	Total	579,616	100.0

Table 3.—Yield and value of 4/4 California black oak No. 1 Common and Better rough lumber kiln dried green from the saw

Samples	Green	Dry	Value added by drying
Sample 1 (Kiln time = 29 days)			
No. 1 Common and Better (MBF)	37,959	24,597 (0.65)	
Pallet stock (MBF)		[1]13,362 (.35)	
$/MBF (Dollars)	[2]329.56	[3]311.60	−17.96
Sample 2 (Kiln time = 36 days)			
No. 1 Common and Better (MBF)	76,420	68,850 (.90)	
Pallet stock (MBF)		[1]7,570 (.10)	
$/MBF (Dollars)	[2]324.91	[3]388.55	+ 63.64
Sample 3 (Kiln time = 39 days)			
No. 1 Common and Better (MBF)	37,290	17,787 (.48)	
Pallet stock (MBF)		[1]19,503 (.52)	
$/MBF (Dollars)	[2]328.68	[3]287.25	−41.43
Samples combined			
No. 1 Common and Better (MBF)	151,669	111,234 (.73)	
Pallet stock (MBF)		[1]40,435 (.27)	
$/MBF (Dollars)	[2]326.88	[3]344.38	−17.50

[1] Dry pallet stock degraded from green No. 1 Common and Better lumber during kiln drying by collapse, ring failure, and splits.

[2] Based on green lumber values of: FAS = $450/MBF, Selects = $435/MBF, and No. 1 Common = $275/MBF (Jan. 1978 basis).

[3] Based on dry lumber values of: FAS = $531/MBF, Selects = $516/MBF, No. 1 Common = $356/MBF, and dry pallet = $150/MBF (Jan. 1978 basis).

Careful inspection of the kiln-dried lumber revealed only 1 to 3 percent of the degrade in each of the three samples could be attributed to warp and end splits. Most degrade resulted from defects associated with bacterially infected heartwood. It was possible to detect the characteristic rancid and strong vinegar odors in dry wood sections crosscut from boards containing collapse, ring failure, and honeycomb. Lumber in the kiln charge of sample 2 contained the least amount of bacterially infected heartwood and sample 3 the most. Table 3 shows that 10 percent of the lumber volume for sample 2 fell below No. 1 Common grade because of kiln-drying defects while sample 3 lumber with the most infected heartwood suffered a 52 percent loss in grade.

Undoubtedly less degrade would have developed in the infected heartwood of the first sample of logs if initial drying conditions had been less severe. Hot weather conditions forced daytime kiln temperatures up to 120° to 125° F during the first 10 days of drying and much of the collapse and ring failure developed within this period. Nevertheless, the greatest amount of degrade observed in the third sample developed when the lumber was dried during the cool winter months under a mild, easily controlled kiln schedule.

Monetary losses from drying degrade with bacterially infected lumber can be calculated in various ways, depending on whether the manufacturer owns and harvests the timber or buys logs or rough green lumber. For the purposes of this paper, we assigned average local lumber values for green and dry grades of oak to the yields from this study as shown in table 3.

These values show that the company lost from $17.96 to $41.43 per thousand board feet by not selling all of the boards in samples 1 and 3 as green lumber. Because of the low incidence of bacterial heartwood in the logs of sample 2, a value of $63.64 per thousand board feet was added by kiln drying the No. 1 Common and Better lumber. The added value from drying sample 2 did not offset the losses from drying samples 1 and 3.

These results indicate that any plans to commercially produce kiln-dried lumber from California black oak should consider whether or not the timber contains bacterially infected heartwood. There should also be an awareness that selection of the upper, more expensive grades of green lumber for kiln drying will not guarantee successful drying results if the wood is infected.

Laboratory Drying Experiments

Experimental drying conditions and moisture loss curves for the green boards shipped to FPL are shown in figure 2 for simulated kiln drying and in figure 3 for air drying. Under both drying conditions, surface checking started in about 24 hours in bacterially infected heartwood of the rancid sample and the mixed wood sample. The initial air drying conditions were quite mild but not enough to prevent surface checking in bacterial heartwood. Normal, noninfected heartwood did not develop surface checks under either air drying or kiln drying. Ellwood (1959b) observed that most surface checking occurred in green flatsawn California black oak on the first day of kiln drying.

Ring failure was present in cross sections cut from both the kiln- and air-dried samples of the rancid board, but ring failure was more severe under kiln-drying conditions (fig. 4). Ring failure did not develop in normal, noninfected heartwood or in the infected heartwood of the mixed sample. Honeycomb developed in the kiln-dried rancid sample, but could not be detected in the air-dried sample. The mixed heartwood sample developed a few internal hairline checks in the bacterial heartwood under kiln drying but not air drying. Neither the surface checks which closed during the final drying stages nor the hairline internal checks are visible in figure 4.

Collapse or excessive shrinkage in thickness is evident in all samples containing bacterial heartwood when compared with cross sections from normal, noninfected heartwood samples.

These laboratory drying experiments demonstrate that the normal, noninfected heartwood of California black oak can be kiln dried green from the saw without defects even under an initial temperature of 120° F. This compares with the first test of the large-

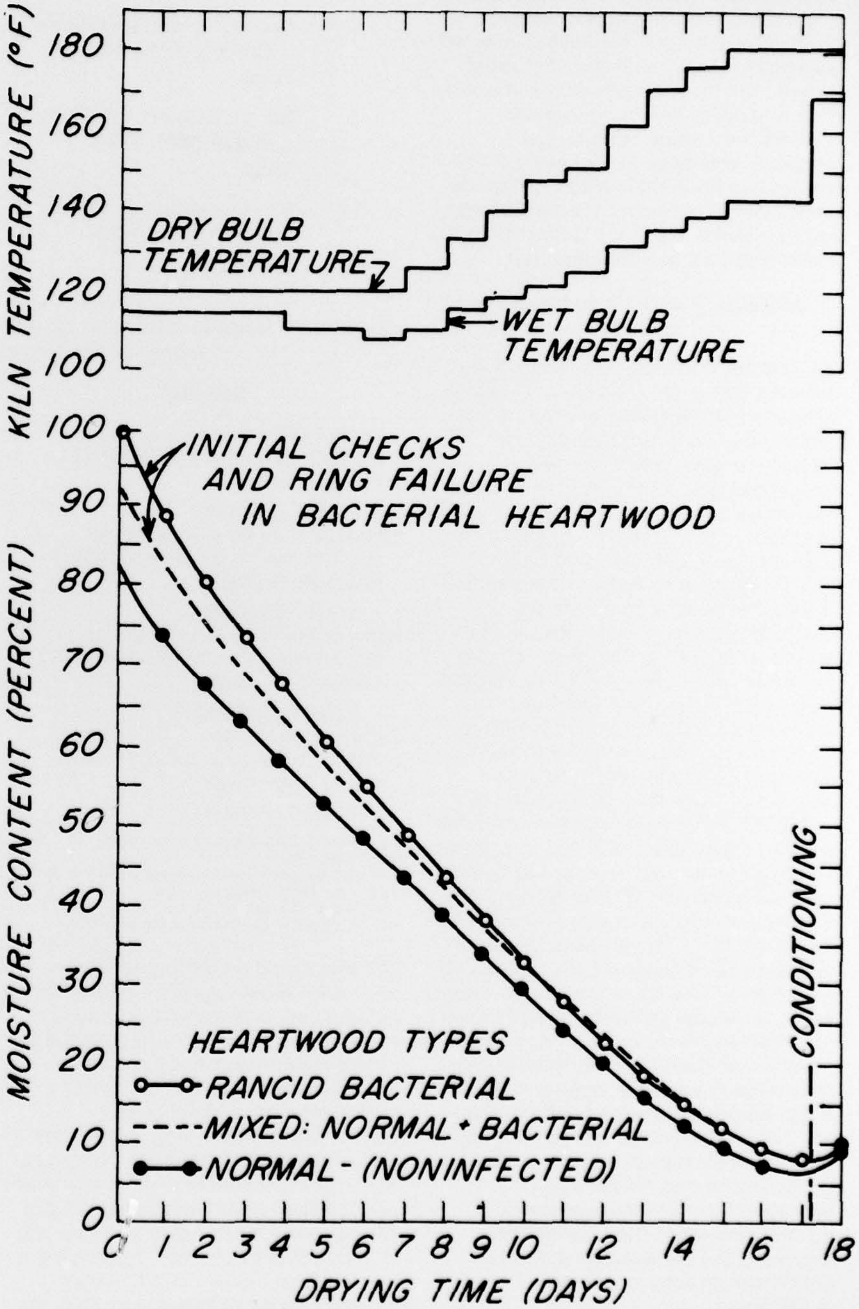

Figure 2.—Experimental kiln conditions and drying curves for 4/4 California black oak.
(M 146 707)

U.S. Forest Products Laboratory.

California Black Oak Drying Problems and the Bacterial Factor, by James C. Ward and Del Shedd. Madison, Wis., For. Prod. Lab., 1979.
15 p. (USDA For. Serv. Res. Pap. FPL 344).

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scale mill study where boards with normal-appearing heartwood remained defect-free even though initial kiln temperatures exceeded 120° F.

The absence of honeycomb in air-dried boards containing bacterial heartwood substantiates Smith's (1961) recommendations that California black oak in general should be predried under temperatures that do not exceed 100° F. However, our laboratory experiments also indicate that some bacterially infected heartwood, particularly the rancid-odor type, cannot be dried defect-free even under the mildest commercial conditions. This is substantiated by the third test of the mill study where over half of the kiln charge was degraded from checking and collapse, even though drying was done in the winter with initial temperatures that did not exceed 100° F.

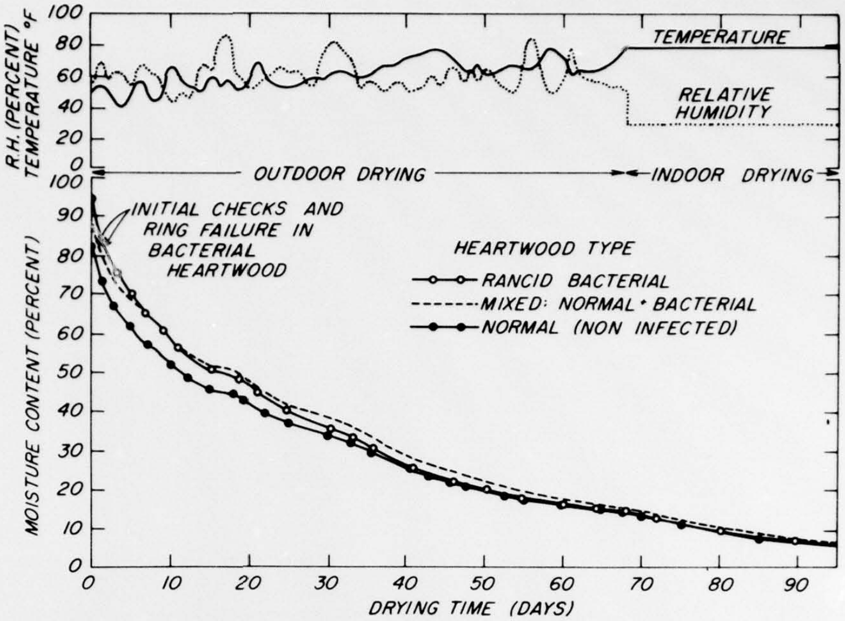


Figure 3.—Atmospheric conditions and air-drying curves for 4/4 California black oak.
(M 146 705)

Wood Quality Considerations

The occurrence of drying defects in bacterially infected heartwood is partly the result of drying conditions and partly due to alteration of the physical and chemical properties of the wood by the bacteria within the living tree. But what are the adverse effects of anaerobic bacteria on the properties of California black oak heartwood? How can some of the salient features of the bacterially infected wood serve to distinguish such defect-prone wood from normal, healthy wood?

Honeycomb and Ring Failure

Examination of boards from both the mill study and the laboratory tests strongly indicates that honeycomb will only develop in the bacterially infected heartwood of California black oak under conventional kiln-drying conditions. Bacterial heartwood that emits strong rancid odors appears to be more prone to develop honeycomb under the milder drying conditions than infected heartwood with a pronounced vinegar odor. This may be attributed to certain types of anaerobic bacteria found in the microbial population of the infected tree trunk.

Strictly anaerobic bacteria in the genus *Clostridium* are prominent members of microbial populations in the heartwood of California black oak and eastern red oaks that emit rancid odors. *Clostridia* produce spores (fig. 1-D) that can remain viable in the soil and oak heartwood for many years. All strains of *Clostridium* spp. isolated from California black oak and eastern red oaks produced pectin-degrading enzymes in culture tests at FPL. These bacteria were not able to cause visible disintegration of wood tissue under laboratory conditions. Microscopic examination of bacterially infected heartwood from living oak trees does not reach a visible disintegration of cell walls as can be seen with wood decayed by fungi.

Until further tests are undertaken, it can be postulated that the compound middle lamella which holds the wood cells together (and is relatively rich in pectic compounds), is weakened by enzymes produced by anaerobic bacteria, particularly in the genus *Clostridium*. When subjected to shrinkage stresses during drying, this bacterially weakened wood will rupture and split apart between cells rather than across cell walls as can occur in wood degraded by fungi.

Observations from this study, together with those from a previous study (Ward *et al.* 1972), suggest that ring failure is an incipient form of ring shake that was initiated in the tree but did not actually rupture until the wood was being dried. This may explain why ring failure developed under both air- and kiln-drying conditions in the laboratory tests, whereas honeycomb developed only with kiln drying. Ring failure was more likely to develop in lumber from logs containing ring shake than in bacterially infected heartwood from logs without ring shake.

Ring shake in logs and ring failure in dried lumber both have characteristic wood separations between cells. This suggests that pectolytic enzymes produced by anaerobic bacteria in the tree are also responsible for weakening of the wood that results in ring shake and ring failure as well as honeycomb.

Shrinkage and Collapse

The shrinkage of California black oak will depend both upon drying conditions and type of heartwood (table 4). Transverse shrinkage was greatest for kiln-dried bacterially infected heartwood and least for air-dried noninfected heartwood. Specific gravity values for these samples (table 5) show the interdependence of shrinkage and density with drying conditions and type of heartwood. These data are apparently in agreement with similar data published by Ellwood (1959a) and Schniewind (1958, 1960).

The type of heartwood and drying conditions apparently can obscure the contribution of annual ring growth to wood density (table 5). For oaks and other ring-porous hardwoods, Paul (1963) found that a faster growth rate generally resulted in higher specific gravity and an increase in mechanical

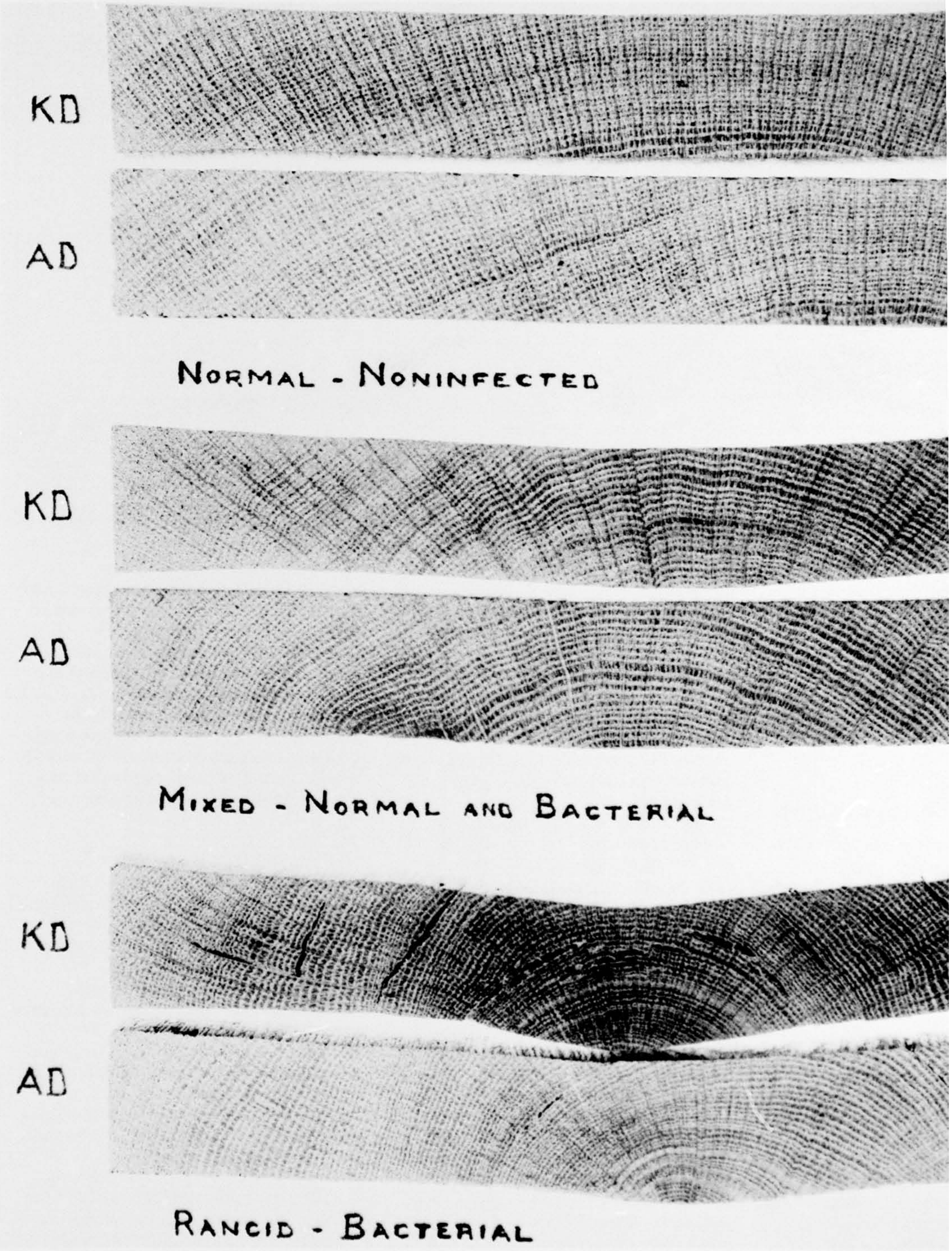


Figure 4.—Cross sections from matched sample boards of 4/4 California black oak—dried under laborat
green to 6 percent moisture content. KD = kiln dried, AD = air dried.
(M 147 113)

strength properties. If density is compared with other wood properties for California black oak, the microbial condition of the heartwood should be considered and specific gravity must be based on green wood volume.

The greater shrinkage of bacterially infected California black oak is largely associated with collapse, especially across the thickness of the board. Collapse seems to be more prominent in California black oak than in most of the eastern red and black oaks. The deep collapse zones in California black oak can be attributed to relatively severe drying conditions, bacterially weakened wood, and plugging of the vessels or pores with tyloses. Moisture movement through the vessels is retarded by the tyloses and bacterial debris. Tensile stresses that are set up are sufficient to cause collapse of the weakened wood tissue.

The presence of tyloses is generally considered a diagnostic characteristic of white oaks rather than the red and black oaks. But California black oak is an exception. All heartwood, both normal and infected, that was examined in this study contained an abundance of tyloses. Furthermore, a comprehensive study of the anatomy of American oaks by Williams (1942) found that tyloses are the rule rather than the exception in California black oak.

The scanning electron micrographs (fig. 5) show that tyloses form in noninfected wood during the transformation from sapwood to heartwood.

The influences of bacterial weakening of the wood and of drying conditions on the dimensional shrinkage of California black oak are illustrated in figure 6.

Table 4.—Influence of drying conditions and type of heartwood on the shrinkage of California black oak (flatsawn 4/4-inch thick)

Drying conditions	Transverse shrinkage[1]—percent loss from green to ovendry dimensions		
	Normal, noninfected heartwood	Mixed: Normal and bacterial heartwood	Rancid, bacterial heartwood
Oven-dried section	9.66	9.92	11.84
Air-dried board	12.33	12.44	17.50
Kiln-dried board	18.03	19.85	20.68

[1] Combined shrinkage of thickness and width.

Board samples with noninfected heartwood followed a conventional pattern of shrinkage, where shrinkage in a direction tangential to growth rings or in width was greater than the radial shrinkage in thickness. Except for the air-dried board with mixed heartwood, all samples containing bacterial heartwood shrank more in thickness or radially, than in width or tangentially.

These shrinkage data in figure 6 suggest a comparsion with Ellwood's (1959a) drying data for flatsawn 4/4 California black oak kiln dried green from the saw. Ellwood's data were grouped in table 6 according to sample boards with honeycomb, without honeycomb but with surface checks, and boards with neither surface checks nor honeycomb. With this arrangement his average shrinkage values exhibit a pattern similar to ours in figure 6. Possibly the excessive radial shrinkage and the formation of honeycomb reported by Ellwood may also be the result of bacterial weakening of the heartwood.

Wood Characteristics for Lumber Presorting

The best solution to the drying problem is to grow California black oak trees without bacterially infected and defect-prone heartwood. Until this can be accomplished, the next best solution is to identify and separate lumber with infected heartwood from noninfected material. Results from this study indicate that segregating bacterially infected logs and lumber offers reduced drying times and energy costs and a reduction in drying degrade. Bacterially infected lumber can be dried under the mild conditions recommended by Smith (1961), while lumber with normal heartwood can be safely kiln dried green from the saw under relatively fast schedules. Effective methods for presorting oak have as yet not been developed.

The rancid or sour odors of bacterially infected California black oak are the most consistent and salient characteristics of the green wood. These odors are due to a combination of volatile fatty acids which include butyric (rancid butter odor), propionic (Swiss cheese odor), valeric (putrid, rancid odor), and caproic (goat odor) acids. Normal oak heartwood will contain small amounts of acetic acid, but infected heartwood will have elevated amounts and emit a strong

Table 5.—Effect of drying conditions, sample volume moisture content and growth rate on the specific gravity of California black oak

Heartwood condition and growth	Specific gravity sample		Specific gravity values					
			This study[2]			Markwardt and Wilson (1935)		California Forest Products Laboratory[2]
	Volume condition	Moisture content at weighing	Normal heart-wood type	Mixed heart-wood type	Rancid bacterial heart-wood type	Oregon	California	
		Pct						
Green	Green	0	0.537	0.538	0.567	0.529	0.491	0.462
Air or low-temperature dried from green	Ovendry	0	0.599	0.594	0.675	—	—	0.503
Kiln dried from green	Ovendry	0	0.666	0.689	0.704	—	—	0.636
Growth rate — rings per inch (green wood)			21	20	22	11.9	20.1	22.6

[1] Data from this study based on matched specimens from the same board sample within each of the 3 types of heartwood.

[2] From Ellwood (1959a) for kiln-dried samples and Schniewind (1958, 1960) for green and air-dried samples.

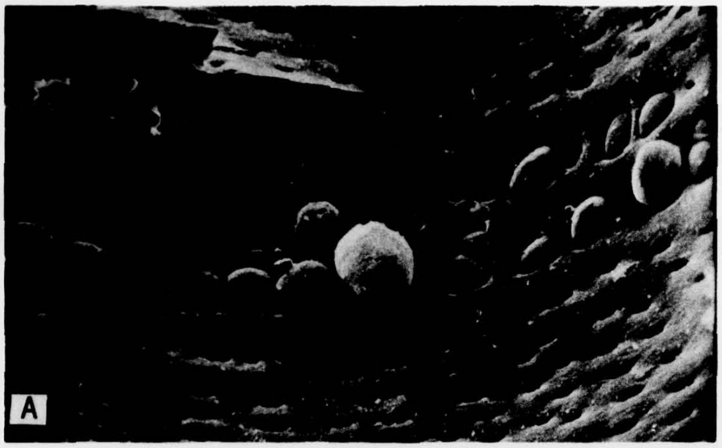
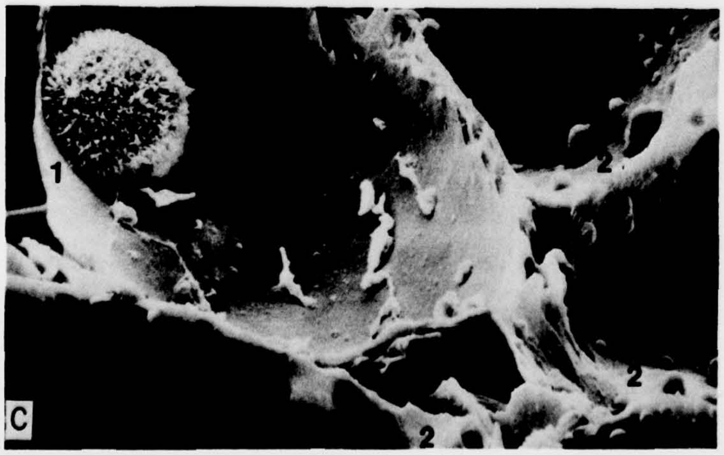


Figure 5.—Scanning electron micrographs of tyloses in living California black oak. A. Vessel from sapwood to heartwood transition zone showing initial tyloses development from ray pits. B. Vessel from noninfected heartwood showing abundant tyloses growth. C. Closeup of tyloses in B showing: (1) Crystal inclusion inside one tyloses and (2) Secondary burgeoning from membranes within adjacent tyloses.
(M 147 433, M 147 431, M 147 434)



vinegar odor. The rancid odors in California black oak are identical to those described by Zinkel *et al.* (1969) in bacterially infected heartwood of eastern red and black oaks. These fatty acid odors were reproduced in potato mash medium with cultures of anaerobic bacteria isolated from California black oak.

Rancid fatty acid odors are a reliable wood characteristic for presorting because they persist in the heartwood long after the bacteria have died and their cells have disintegrated and disappeared. One drawback is that a practical and objective method for detecting these fatty acid odors in green lumber has yet to be developed.

Bacterially infected heartwood can be accurately distinguished from normal heartwood by analyzing steam distillates from the wood with a gas chromatograph, but this procedure is time consuming. Rancid and sour odors are most rapidly identified with the human nose, but the accuracy varies with individuals. Accuracy of odor perception diminishes even with experienced mill workers when many oak boards must be evaluated within a few hours' time.

Electrical resistance of bacterially infected heartwood tends to be lower than the resistance of normal heartwood, but the use of electrical resistance as a detection characteristic does not appear to be promising. There is considerable overlap in the range of resistances for normal heartwood with the resistance ranges for infected heartwood (table 7). We have measured electrical resistances in additional oak boards and find that normal and rancid boards cannot be distinguished with certainty, although rancid heartwood tended to have lower average resistances.

Ellwood (1959a) reported the best indicators of which California black oak boards were most likely to check during drying are: (1) wood with a high initial moisture content and (2) relatively dark-colored wood and wood containing dark streaks or patches.

With our study material we found that green moisture content of bacterially infected heartwood will usually be higher than 85 percent and can range in average from 90 to 100 percent. The green moisture content of normal heartwood averages around 80 percent, but can be as high as 88 to 92 percent. No moisture meter currently available can accurately measure green moisture contents much above 30 percent.

The color of bacterially infected oak may or may not be darker than normal, noninfected heartwood. When the heartwood is darker, it is likely to occur in the lower grades and not in the upper grades dried in this study.

Ring shake in California black oak trees and logs can be a clue to the presence of bacterially infected heartwood. Not all logs with bacterially infected heartwood will have ring shake, but if ring shake is present, it invariably occurs in bacterially weakened heartwood. A considerable reduction in drying degrade can be achieved if logs from trees containing shake are presorted, and the subsequent lumber is dried under mild conditions.

An earlier FPL study found that all of the honeycomb and ring failure in 4/4 No. 1 Common and Better northern red oak occurred in boards sawed from trees containing shake (Ward *et al.* 1972). Neither of these defects developed in No. 1 Common and Better lumber from shake-free trees with noninfected heartwood. Possibly this correlates with the observations of Smith (1961) who found that five logs from only two trees (out of a sample of 47) accounted for 53 percent of the drying degrade in 4/4 rough lumber.

SUMMARY

The heartwood of merchantable and outwardly healthy trees of California black oak can be infected by mixed populations of anaerobic bacteria. The composition of these populations has not been completely defined, but strictly anaerobic bacteria in the genus *Clostridium* were consistently isolated. Fungi were rarely encountered in bacterial heartwood that appears visibly clear and sound. Bacterially infected heartwood emits characteristic rancid or sour odors of volatile fatty acids resulting from bacterial metabolism within the wood.

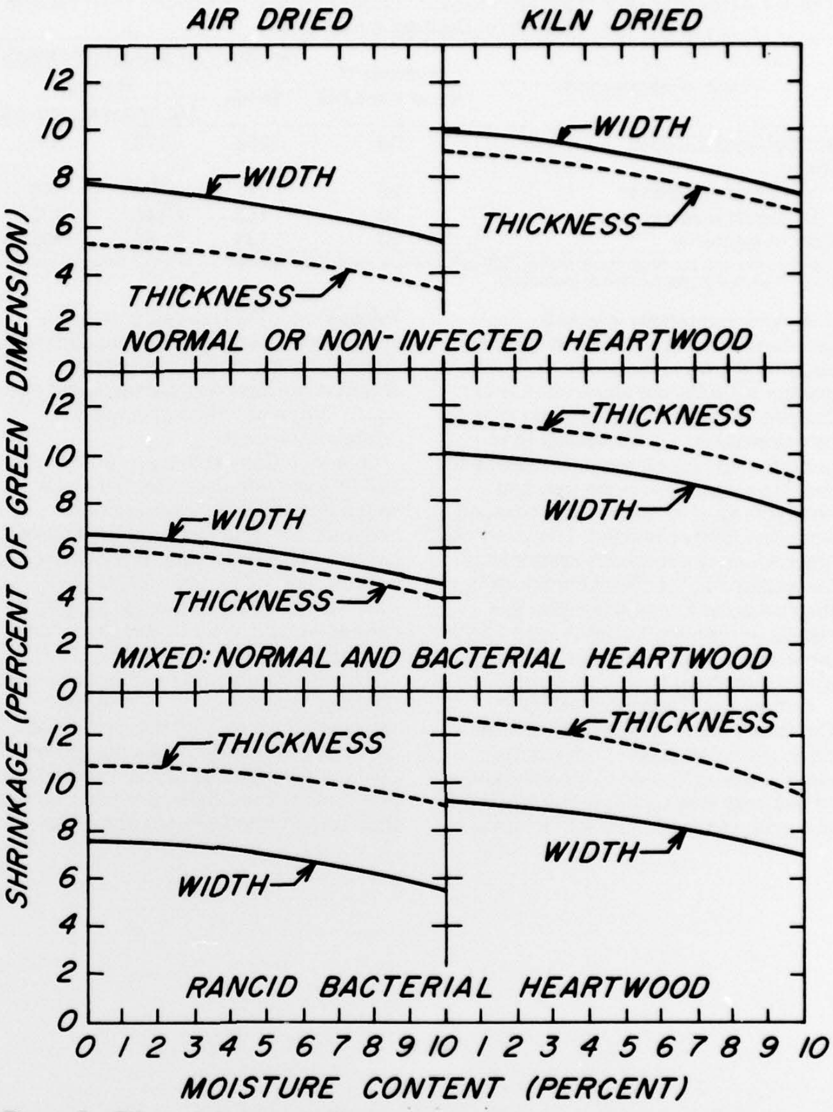


Figure 6.—Effect of drying conditions and bacterial tree infections on the dimensional shrinkage of flatsawn 4/4 California black oak boards. All heartwood contained tyloses.
(M 146 706)

Table 6.—Compilation, according to drying defects, of sample board data from the California Forest Products Laboratory Study (Ellwood 1959a) on the kiln drying of green 4/4 California black oak

Defect group	Part of sample	Green moisture content mean	Specific gravity mean[1]	Total surface checking		Average shrinkage to 8 percent moisture content from green dimension[2]	
				Mean	Range	Width	Thickness
	Pct	Pct		In.	In.	Pct	Pct
Both honeycomb and surface checks	18	95	0.686	31	15-46	8.4	13.6
Only surface checks	52	86	0.650	13	1-50	7.4	8.7
No defects	30	80	0.584	0	—	6.2	5.7
Total sample	100	86	0.636	18	1-50	7.2	8.6

[1] Based on ovendry wood volume and weight.
[2] All flatsawn stock.

Table 7.—Resistance to a pulsed electric current of green heartwood from sample boards of California black oak

Type of heartwood	Number of measurements	Resistance—thousand OHMS[1]		
		Mean	Range	
			Minimum	Maximum
Normal—not infected	30	256	170	380
Mixed:				
Normal wood zones	20	212	140	340
Bacterial wood zones	20	168	140	255
Rancid-bacterial	30	131	95	205

[1] Measured with the Shigometer Model 7950 using needle electrodes, spaced 0.5 in. apart, which were driven 0.25 in. into the surface of the boards.

Rancid, bacterially infected heartwood that is sound and clear can occur in the No. 1 Common and Better grades of California black oak lumber. Despite the sound appearance, rancid oak heartwood will be weaker than noninfected heartwood and is prone to develop ring shake in the tree and honeycomb, ring failure, and collapse when the lumber is dried. The anaerobic *Clostridium* is apparently responsible for weakening the chemical bonds in the compound middle lamella; this results in ruptures between wood cells when the boards are subjected to shrinkage stresses during drying.

Collapse is a common defect in California black oak lumber that has been kiln dried green from the saw. Collapse is attributed to a combination of bacterial weakening of the wood and plugging of the vessels with tyloses. Tyloses were the rule rather than the exception in both the normal and the infected heartwood, but were not observed in sapwood. Collapse did not occur in noninfected heartwood containing tyloses.

One-inch California black oak lumber can be kiln dried green from the saw with a minimum of degrade from collapse, honeycomb, and ring failure if bacterial heartwood is not present in the boards. Normal heartwood can be safely dried under conventional kiln schedules and possibly with initial dry bulb temperatures of 120° to 125° F.

Bacterially infected heartwood should be dried from green to a 20 percent average moisture content under mild air-drying conditions or by the forced air-drying schedules recommended by H.H. Smith. The 20 percent material can then be kiln dried without additional defect. Collapse and honeycomb can be greatly reduced by first air drying bacterial heartwood, but ring failure is an incipient form of ring shake and cannot be adequately controlled with milder drying conditions.

Because of the bacterial infections in California black oak heartwood, this species cannot always be profitable for kiln-dried factory grade hardwood lumber. Presorting green lumber with bacterial heartwood from lumber with noninfected heartwood before drying would greatly enhance the prospects for economic utilization. Effective presorting under commercial conditions cannot be undertaken until rapid and accurate methods are developed for measuring volatile fatty acids and moisture content in green lumber.

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Figure 4.—Cross sections from matched sample boar
green to 6 percent moisture content. KD = kiln dried
(M 147 113)