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Evaluating Shrinkage of Wood Propellers in a High-Temperature Environment

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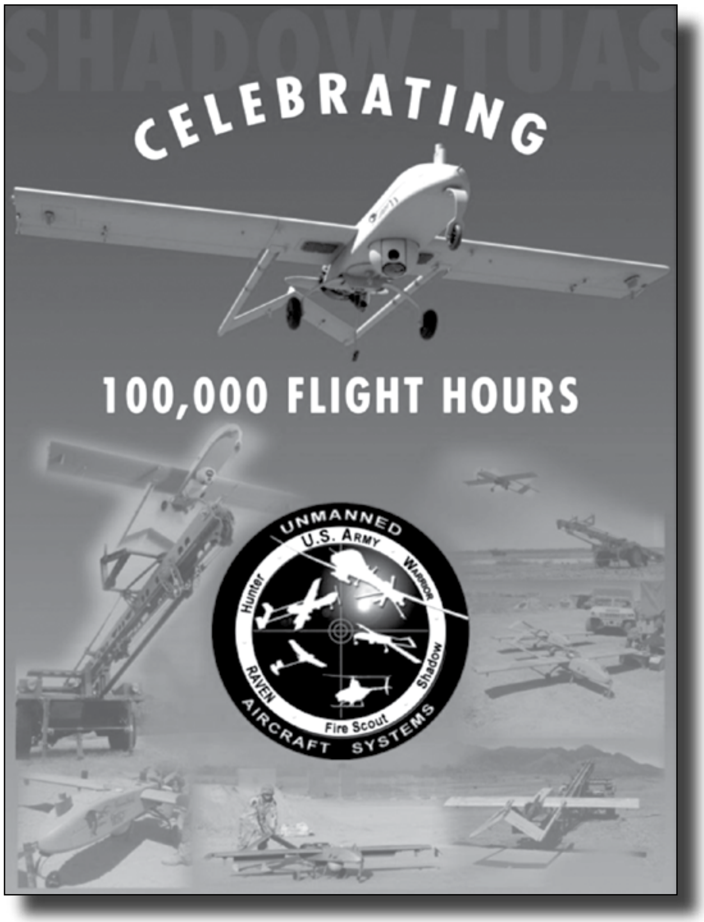

Abstract

Minimizing wood shrinkage is a priority for many wood products in use, particularly engineered products manufactured to close tolerances, such as wood propellers for unmanned surveillance aircraft used in military operations. Those currently in service in the Middle East are experiencing performance problems as a consequence of wood shrinking during long-term storage at low equilibrium moisture content conditions prior to installation. To evaluate the extent of shrinkage, seven sugar maple (*Acer saccharum*) veneer propellers were dried from 11% to 3% moisture content in a controlled environment of 150°F (65°C) for 3 days. Two of these wood propellers were encased in polyethylene bags. Results showed 5 to 20 times more shrinkage for the thickness of the propeller hub and the hub face perpendicular to the propeller blades (across the grain), respectively, compared with the hub face parallel to the blades (along the grain). Two hubs, coated with aluminum oxide paint, showed dimensional changes similar to those observed for uncoated hubs. For the two wood propellers encased in polyethylene bags, moisture loss was slowed during the course of the experiment by roughly 46%. Wrapping the wood propellers prior to shipping would slow moisture desorption, thereby minimizing shrinkage during short-term storage. Processing the propellers at a lower equilibrium moisture content would minimize shrinkage during long-term storage.

Keywords: wood, propeller, shrinkage, sugar maple, veneer, equilibrium moisture content, EMC

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To convert item	To	Multiply item by
Inches	Centimeters	2.54

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Evaluating Shrinkage of Wood Propellers in a High-Temperature Environment

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Introduction

The Forest Products Laboratory (FPL) has played a major role in wood propeller research since 1917. During World War II, FPL published two significant publications about its work on the manufacture and design of wood aircraft (including propellers). Wood continues to play a significant role in military operations around the world (Risbrudt and others 2007) in a wide variety of applications, from portable structures to propellers for unmanned surveillance aircraft.

Knowing the temperature and relative humidity conditions a wood product will be exposed to in service is essential for maintaining the product's dimensional stability, whether it is used for decking applications or wood propellers for military aircraft. The equilibrium moisture content (EMC) of wood is a function of the temperature and relative humidity conditions of its surroundings. Table 1 (Simpson 1998) illustrates typical EMC values for wood at various combinations of temperature and relative humidity (RH).

Sugar maple (*Acer saccharum*) is a hardwood tree species whose wood is typically kiln-dried to a moisture content (MC) of 6% to 8% prior to use in interior applications. When freshly cut, sugar maple wood can have MC values as high as 72% (green condition). As it dries, wood shrinks considerably. As shown in Table 2, sugar maple wood shrinkage is greatest in tangential and radial directions (perpendicular to the longitudinal axis of the wood's fibers). Longitudinal shrinkage from freshly cut green condition to a dry condition (approximately 0% MC) is small (roughly 0.2%) compared with both radial and tangential shrinkage values (Alden 1995, FPL 1999).

Recently, a supplier of wooden propellers to the U.S. Department of Defense contacted FPL with a question regarding the shrinkage of their product during storage in the Middle East. Specifically, their wood propellers, which are used on unmanned surveillance aircraft in Iraq and Afghanistan, are experiencing fitting problems because of excessive shrinkage. Excessive wood shrinkage of the hubs of these propellers causes misalignment of hub-bolt holes, which can cause installation problems and subsequent performance issues. The study summarized in this report was designed and conducted to quantify the amount and location of wood shrinkage of the hubs in response to the high temperature and low relative humidity conditions encountered during storage.

Materials and Methods

Seven wood propellers were supplied to FPL for experimental evaluation by Sensenich Wood Propellers, Plant City, Florida. Each propeller was machined from a 16-ply sugar maple veneer blank (Fig. 1) manufactured by Burkel, Inc., of Oconto Falls, Wisconsin. Moisture content of the blanks varied from approximately 5% to 7%. Wood propellers 29 in. (73.7 cm) tip-to-tip were machined from the blanks by Sensenich at their Plant City facility. Moisture content of the finished propellers was approximately 9% to 10%. These seven wood propellers were not coated with any finish.

The following testing protocol was used to prepare and evaluate shrinkage of the propellers:

Upon receipt, the uncoated propeller specimens were initially inspected and allowed to come to equilibrium at 74°F (23°C) and 65% RH (roughly 12% EMC). The procedure after conditioning was as follows:

1. Each specimen was labeled.
2. Two specimens had their center hole coated with aluminum oxide paint.
3. Two specimens were sealed in polypropylene bags during the entire 3 days of the experiment to examine the efficacy of the plastic for minimizing moisture loss.
4. The weight of each propeller was determined.
5. The hub and bolt hole dimensions of each specimen were measured.
6. Each specimen was dried in a testing oven at approximately 150°F (65°C) for 3 days.

Figure 1—An unfinished wood propeller provided to the Forest Products Laboratory for evaluation.

Table 1—Typical equilibrium moisture content values for wood at various temperature and relative humidity (RH) combinations

Temperature (°F (°C))	Equilibrium moisture content (%) at various percentage RH values																		
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
30 (–1.1)	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.4	13.5	14.9	16.5	18.5	21.0	24.3
50 (10.0)	1.4	2.6	3.6	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.3	11.2	12.3	13.4	14.8	16.4	18.4	20.9	24.3
70 (21.1)	1.3	2.5	3.5	4.5	5.4	6.2	6.9	7.7	8.5	9.2	10.1	11.0	12.0	13.1	14.4	16.0	17.9	20.5	23.9
90 (32.2)	1.2	2.3	3.4	4.3	5.1	5.9	6.7	7.4	8.1	8.9	9.7	10.5	11.5	12.6	13.9	15.4	17.3	19.8	23.3
110 (43.3)	1.1	2.2	3.2	4.0	1.9	5.6	6.3	7.0	7.7	8.4	9.2	10.0	11.0	12.0	13.2	14.7	16.6	19.1	22.4
130 (54.4)	1.0	2.0	2.9	3.7	4.5	5.2	5.9	6.6	7.2	7.9	8.7	9.4	10.3	11.3	12.5	14.0	15.8	18.2	21.5
150 (65.6)	0.9	1.8	2.6	3.4	4.1	4.8	5.5	6.1	6.7	7.4	8.1	8.8	9.7	10.6	11.8	13.1	14.9	17.2	20.4

Table 2—Shrinkage of sugar maple wood (*Acer saccharum*)

	Shrinkage (%) at three MC levels		
	0 %	6 %	20 %
Tangential	9.9	7.6	3.2
Radial	4.8	3.9	1.6
Volumetric	14.7	11.9	5.0

[a] Green condition to indicate final moisture content value.

Steps four and five were repeated during each specimen's exposure in the drying oven. For each of the five specimens, 62 points were measured seven times over a period of 3 days to evaluate the shrinkage. An example of the points measured for Propeller No. 1 is listed in the Appendix. Grain orientation was also determined through physical inspection of the blade tips. Horizontal direction (along the grain) corresponded to No. 2 to No. 4 (side-to-side) bolt holes, and the vertical direction (across the grain) corresponded to No. 1 to No. 3 (top-to-bottom) bolt holes (Fig. 2).

The following were recorded:

1. Average diameter values for all bolt holes, the bore hole, and counterbore holes
2. Specimen length measurement from the edge of the hub to the blade tip
3. Specimen width and thickness measurements 6 in. from the hub

Note that a temperature of 150°F (65°C) was chosen for testing in an attempt to simulate the environmental conditions that would be expected during long-term storage in a metal pole building in Iraq and Afghanistan. After 3 days, all seven specimens were oven-dried and their oven-dried mass determined.

Results

The sugar maple veneer wood propellers dried from 11% to 3% MC showed significant shrinkage differences for both the hub thickness and hub face perpendicular to the blades compared with the hub face parallel to the blades. Figures 3 and 4 indicate shrinkage values for various sections of the propeller hub.

The two wood propellers that were sealed in polyethylene bags decreased only 3.7% compared with the non-bagged propellers' moisture loss of 8%. Encasing the wood propellers in polyethylene bags slowed the drying rate by roughly 46%.

Two of the wood propeller hubs coated with aluminum oxide on the hub bore and counterbore showed dimensional changes similar to the three uncoated hubs.

Using tangential and radial dimensional change coefficients of 0.00353 and 0.00165, respectively, and longitudinal shrinkage of 0.2%, the tangential, radial, and longitudinal shrinkage values were calculated for an MC change from 11% to 3% (Table 3). These results were used along with physical inspection to determine approximate grain orientation of the wood propeller (FPL 1999).

Figures 5, 6, and 7 illustrate plots from actual measurements demonstrating the shrinkage of different sections including the hub counterbore and the top and side bolt holes.

Discussion

Very close tolerances are required for wood propellers used in military operations; therefore, any dimensional changes may affect the engine performance. Knowing the extent of shrinkage from long-term storage in high-temperature environments is required for the safe operation of these unmanned military aircraft. Based on dimensional changes calculated for these wood propellers in the tangential, radial, and longitudinal directions during drying, the following points were noted. The longitudinal, radial, and tangential shrinkages mostly occurred along the length of the propeller (along the grain), along the thickness of hub (across the plies), and along the face of the propeller perpendicular to the blades, respectively. For any direction, the amount of shrinkage is affected by changes in temperature and relative humidity. In Iraq, temperatures of 150°F (65°C) may

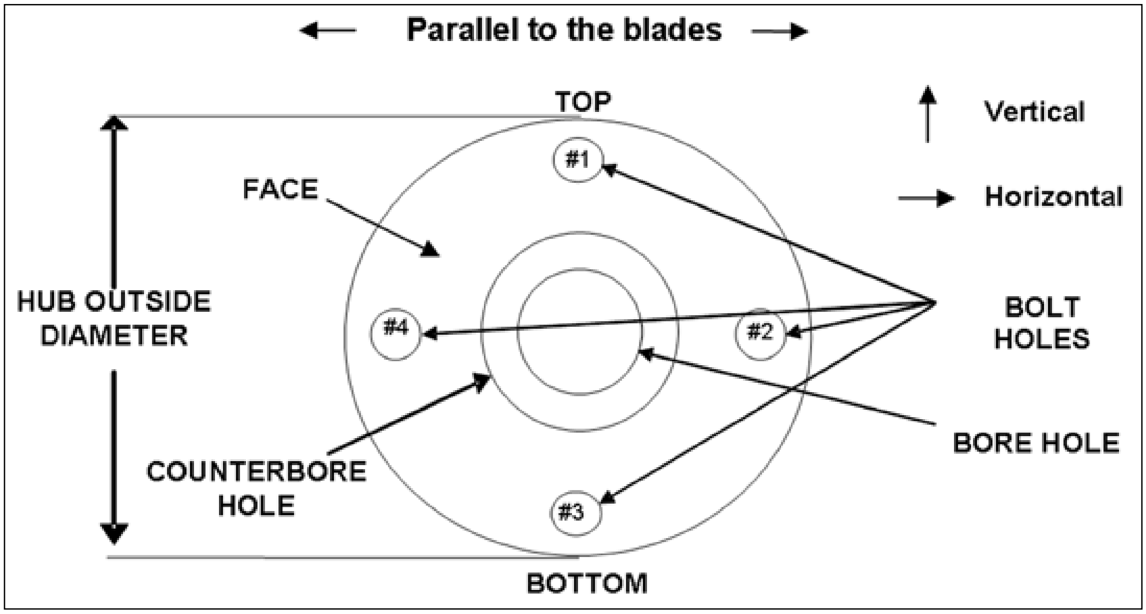


Figure 2—Wood propeller hub.

Table 3—Comparing shrinkage for tangential, radial, and longitudinal directions

Distance	Initial reading (in.)	Expected tangential change (in.)	Expected radial change (in.)	Expected longitudinal change (in.)	Actual change (in.)
Top to bottom bolt holes	2.168	0.061	0.029	0.004	0.057
Side to side bolt holes	2.166	0.061	0.022	0.004	0.006
Hub thickness	1.634	0.046	0.022	0.003	0.030

be reached in closed metal storage facilities during July and August. This increase in temperature significantly lowers the EMC, causing shrinkage up to 20% more than expected.

As found in use, the distance between the top and bottom bolt holes (across the grain) shrank significantly more than the side-to-side bolt holes (along the grain) because of the different grain orientation. Wood is an orthotropic material; therefore, wood has different properties depending on grain orientation. For most species, tangential shrinkage is approximately twice the radial shrinkage. Therefore slightly altering the grain orientation by 10 degrees for subsequent veneer plies during veneer blank manufacturing may reduce the difference in shrinkage between the vertical and horizontal directions.

Coating only the bore and counterbore holes of the hubs with aluminum oxide did not retard moisture loss; therefore, this minimal level of coating is not useful as a moisture barrier. Aluminum paint has been shown to significantly reduce moisture sorption in wood products (FPL 1999). Even though aluminum oxide coating did not slow the rate of moisture loss, it does provide a hard protective coating for the hub, thus reducing wear.

Recommendations

The following recommendations can be made to address engine performance problems from shrinkage of wood propellers stored in high-temperature environments:

- Maintain the MC of the wood propeller at 6% during the entire manufacturing process for both sugar maple veneer blanks and wood propellers to limit the effect of in-use shrinkage. This percentage is less than the median of 6.9% EMC that the propellers would be exposed to during the summer and winter months in Baghdad, Iraq. A lower MC than the median would be prudent because of the uncertain length of time the wood propeller may be stored in a high-temperature environment.
- Vacuum pack both the veneer blank and the finished wood propeller in an airtight polyethylene bag for transport and storage. Encasing the propeller would limit shrinkage during short-term storage in high-temperature environments.
- Remove the propellers from dry storage and unwrap at least 2 to 4 weeks prior to installation. This will give the

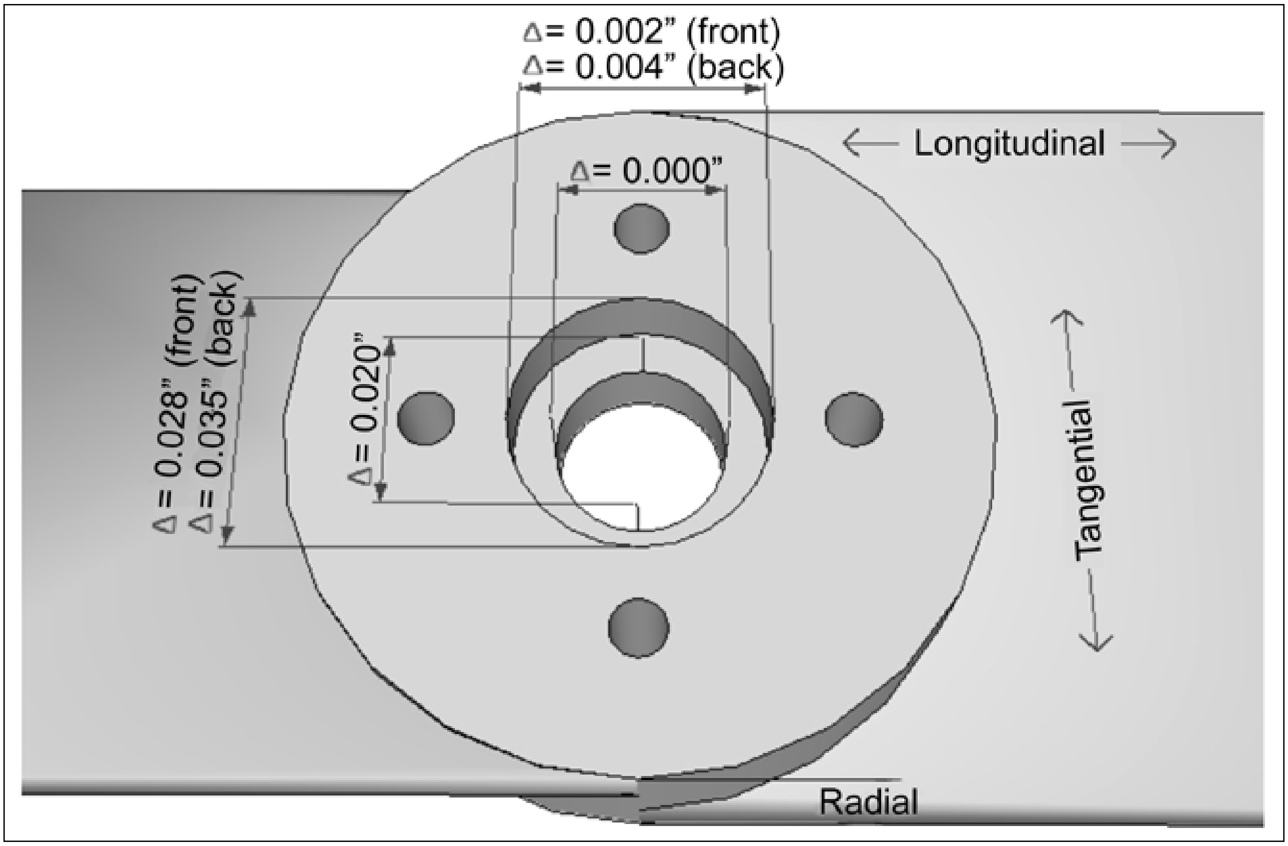


Figure 3—Dimensional change Δ for the propeller hub bore and counterbore.

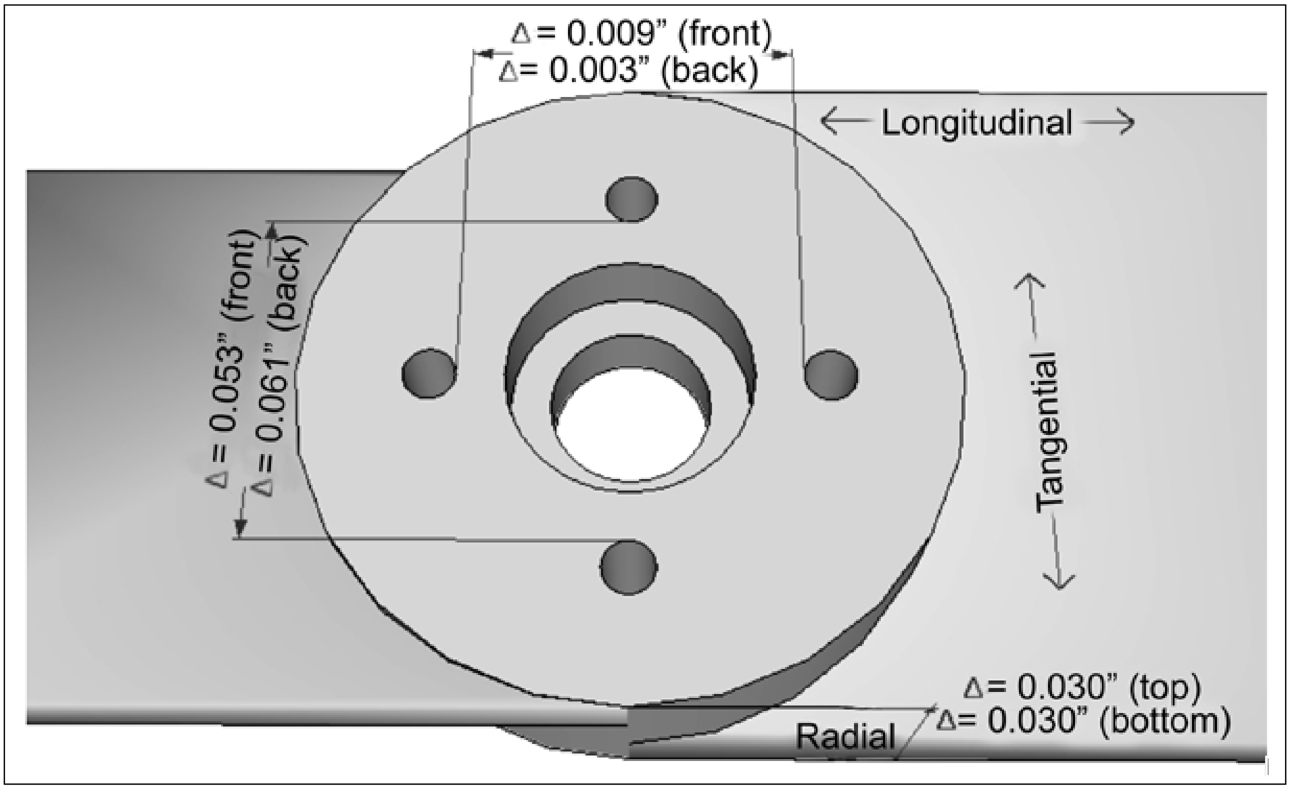


Figure 4—Dimensional change Δ of the spacing of the bolt holes.

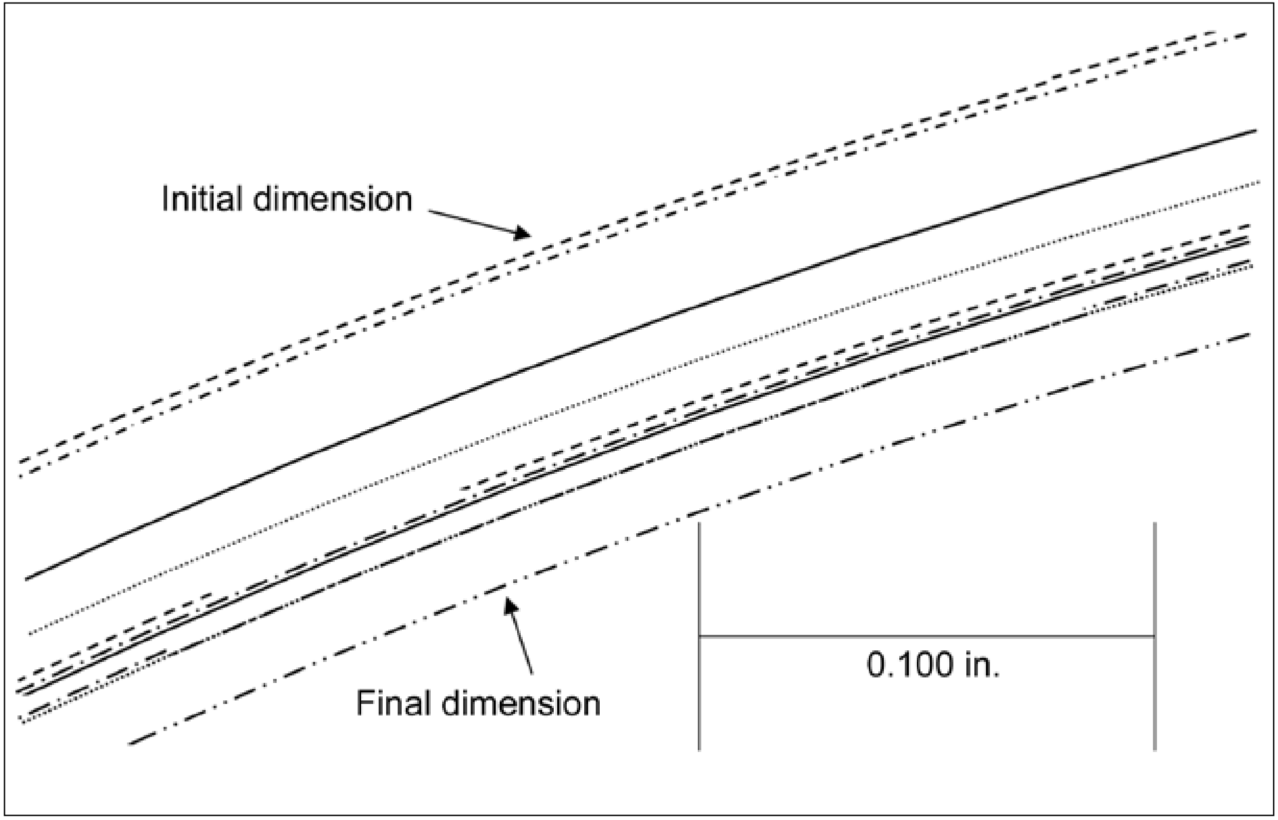


Figure 5—Dimensional change of an outer hub section during evaluation.

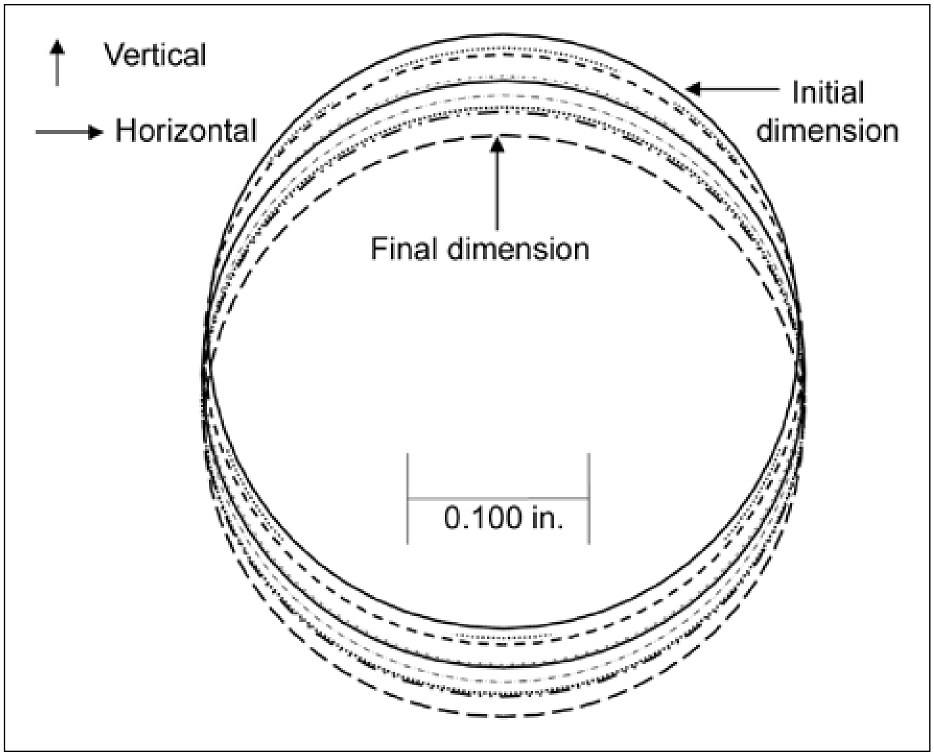


Figure 6—Dimensional change of the top bolt hole during evaluation.

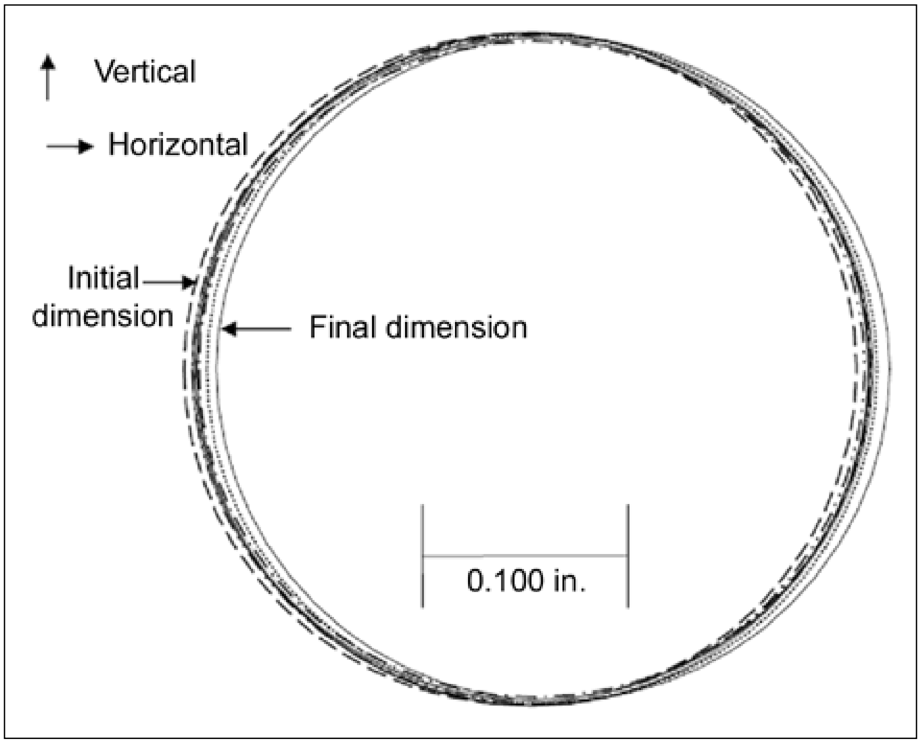


Figure 7—Dimensional change of the side bolt hole during evaluation.

wood time to equalize to the surrounding in-service EMC, thus minimizing performance problems caused by shrinkage.

- Track dates of manufacturing, transportation, and storage of the wood propellers. Better tracking will allow the use of the first-in first-out method to minimize the storage time of wood propellers and to also help resolve any potential problems in the future.

References

Alden, H.A. 1995. Hardwoods of North America. General Technical Report FPL–GTR–83. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 140 p. http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr83.pdf.

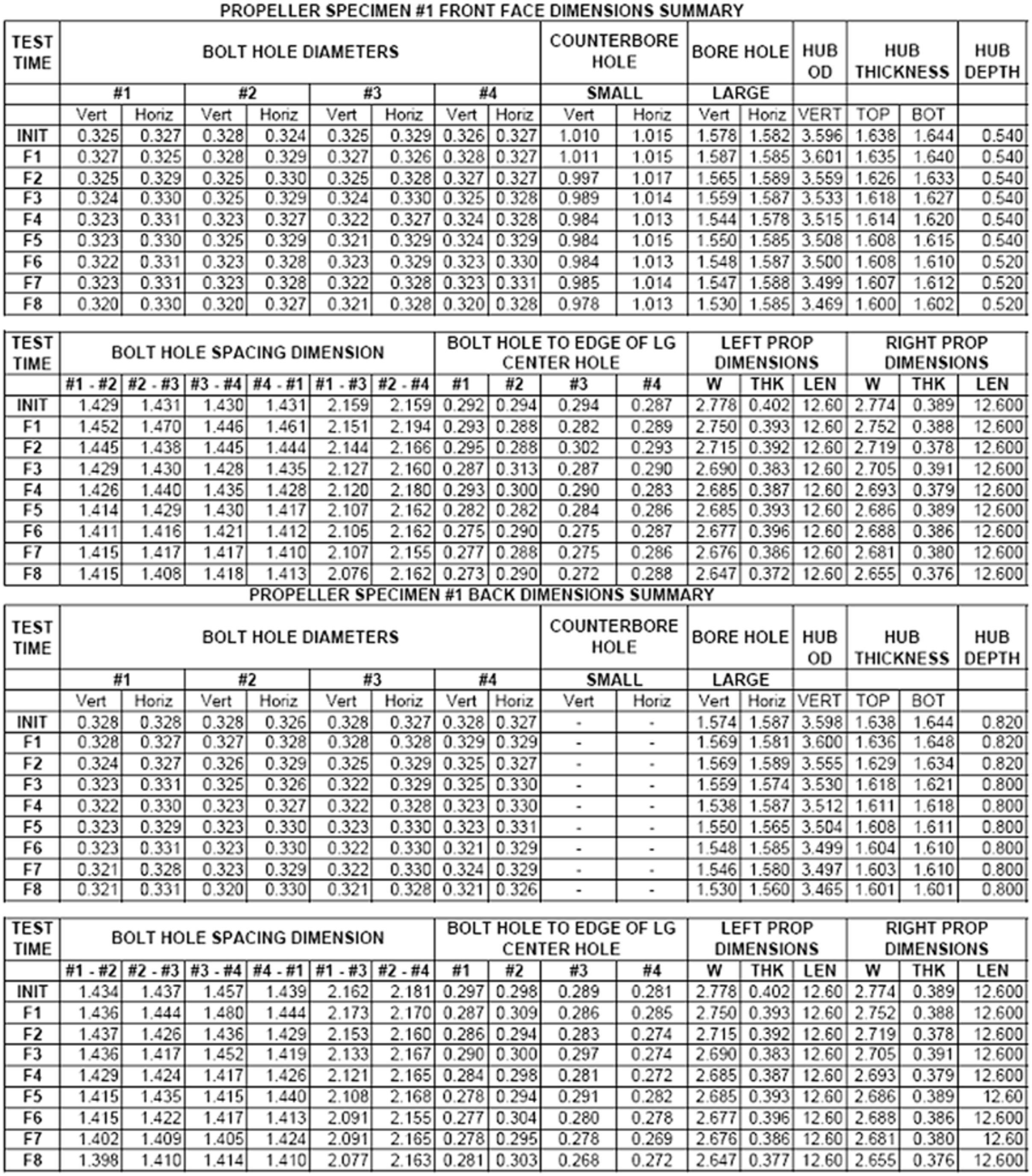
FPL. 1999. Wood handbook: wood as an engineering material. General Technical Report FPL–GTR–113. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr113/fplgtr113.pdf.

Risbrudt, D.R.; Ross, R.J.; Blankenburg, J.J.; Nelson, C.A. 2007. Forest Products Laboratory supporting the nations' armed forces with valuable wood research for 90 years. Forest Products Journal 57(1/2):6–14. http://www.fpl.fs.fed.us/documnts/pdf2007/fpl_2007_risbrudt001.pdf.

Simpson, W.T. 1991. Dry kiln operator's manual. Agriculture Handbook AH–188. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. http://www.fpl.fs.fed.us/documnts/usda/ah188/.

Simpson, W.T. 1998. Equilibrium moisture content of wood in outdoor locations in the United States and worldwide. Research Note FPL–RN–0268. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 14 p. http://www.fpl.fs.fed.us/documnts/fplrn/fplrn268.pdf.

Appendix—Wood Propeller Dimensions for Propeller No.1



PROPELLER SPECIMEN #1 FRONT FACE DIMENSIONS SUMMARY

TEST TIME	BOLT HOLE DIAMETERS								COUNTERBORE HOLE		BORE HOLE		HUB OD	HUB THICKNESS		HUB DEPTH
	#1		#2		#3		#4		SMALL		LARGE					
	Vert	Horiz	Vert	Horiz	Vert	Horiz	Vert	Horiz	Vert	Horiz	Vert	Horiz	VERT	TOP	BOT	
INIT	0.325	0.327	0.328	0.324	0.325	0.329	0.326	0.327	1.010	1.015	1.578	1.582	3.596	1.638	1.644	0.540
F1	0.327	0.325	0.328	0.329	0.327	0.326	0.328	0.327	1.011	1.015	1.587	1.585	3.601	1.635	1.640	0.540
F2	0.325	0.329	0.325	0.330	0.325	0.328	0.327	0.327	0.997	1.017	1.565	1.589	3.559	1.626	1.633	0.540
F3	0.324	0.330	0.325	0.329	0.324	0.330	0.325	0.328	0.989	1.014	1.559	1.587	3.533	1.618	1.627	0.540
F4	0.323	0.331	0.323	0.327	0.322	0.327	0.324	0.328	0.984	1.013	1.544	1.578	3.515	1.614	1.620	0.540
F5	0.323	0.330	0.325	0.329	0.321	0.329	0.324	0.329	0.984	1.015	1.550	1.585	3.508	1.608	1.615	0.540
F6	0.322	0.331	0.323	0.328	0.323	0.329	0.323	0.330	0.984	1.013	1.548	1.587	3.500	1.608	1.610	0.520
F7	0.323	0.331	0.323	0.328	0.322	0.328	0.323	0.331	0.985	1.014	1.547	1.588	3.499	1.607	1.612	0.520
F8	0.320	0.330	0.320	0.327	0.321	0.328	0.320	0.328	0.978	1.013	1.530	1.585	3.469	1.600	1.602	0.520

TEST TIME	BOLT HOLE SPACING DIMENSION						BOLT HOLE TO EDGE OF LG CENTER HOLE				LEFT PROP DIMENSIONS			RIGHT PROP DIMENSIONS		
	#1 - #2	#2 - #3	#3 - #4	#4 - #1	#1 - #3	#2 - #4	#1	#2	#3	#4	W	THK	LEN	W	THK	LEN
INIT	1.429	1.431	1.430	1.431	2.159	2.159	0.292	0.294	0.294	0.287	2.778	0.402	12.60	2.774	0.389	12.600
F1	1.452	1.470	1.446	1.461	2.151	2.194	0.293	0.288	0.282	0.289	2.750	0.393	12.60	2.752	0.388	12.600
F2	1.445	1.438	1.445	1.444	2.144	2.166	0.295	0.288	0.302	0.293	2.715	0.392	12.60	2.719	0.378	12.600
F3	1.429	1.430	1.428	1.435	2.127	2.160	0.287	0.313	0.287	0.290	2.690	0.383	12.60	2.705	0.391	12.600
F4	1.426	1.440	1.435	1.428	2.120	2.180	0.293	0.300	0.290	0.283	2.685	0.387	12.60	2.693	0.379	12.600
F5	1.414	1.429	1.430	1.417	2.107	2.162	0.282	0.282	0.284	0.286	2.685	0.393	12.60	2.686	0.389	12.600
F6	1.411	1.416	1.421	1.412	2.105	2.162	0.275	0.290	0.275	0.287	2.677	0.396	12.60	2.688	0.386	12.600
F7	1.415	1.417	1.417	1.410	2.107	2.155	0.277	0.288	0.275	0.286	2.676	0.386	12.60	2.681	0.380	12.600
F8	1.415	1.408	1.418	1.413	2.076	2.162	0.273	0.290	0.272	0.288	2.647	0.372	12.60	2.655	0.376	12.600

PROPELLER SPECIMEN #1 BACK DIMENSIONS SUMMARY

TEST TIME	BOLT HOLE DIAMETERS								COUNTERBORE HOLE		BORE HOLE		HUB OD	HUB THICKNESS		HUB DEPTH
	#1		#2		#3		#4		SMALL		LARGE					
	Vert	Horiz	Vert	Horiz	Vert	Horiz	Vert	Horiz	Vert	Horiz	Vert	Horiz	VERT	TOP	BOT	
INIT	0.328	0.328	0.328	0.326	0.328	0.327	0.328	0.327	-	-	1.574	1.587	3.598	1.638	1.644	0.820
F1	0.328	0.327	0.327	0.328	0.328	0.328	0.329	0.329	-	-	1.569	1.581	3.600	1.636	1.648	0.820
F2	0.324	0.327	0.326	0.329	0.325	0.329	0.325	0.327	-	-	1.569	1.589	3.555	1.629	1.634	0.820
F3	0.323	0.331	0.325	0.326	0.322	0.329	0.325	0.330	-	-	1.559	1.574	3.530	1.618	1.621	0.800
F4	0.322	0.330	0.323	0.327	0.322	0.328	0.323	0.330	-	-	1.538	1.587	3.512	1.611	1.618	0.800
F5	0.323	0.329	0.323	0.330	0.323	0.330	0.323	0.331	-	-	1.550	1.565	3.504	1.608	1.611	0.800
F6	0.323	0.331	0.323	0.330	0.322	0.330	0.321	0.329	-	-	1.548	1.585	3.499	1.604	1.610	0.800
F7	0.321	0.328	0.323	0.329	0.322	0.330	0.324	0.329	-	-	1.546	1.580	3.497	1.603	1.610	0.800
F8	0.321	0.331	0.320	0.330	0.321	0.328	0.321	0.326	-	-	1.530	1.560	3.465	1.601	1.601	0.800

TEST TIME	BOLT HOLE SPACING DIMENSION						BOLT HOLE TO EDGE OF LG CENTER HOLE				LEFT PROP DIMENSIONS			RIGHT PROP DIMENSIONS		
	#1 - #2	#2 - #3	#3 - #4	#4 - #1	#1 - #3	#2 - #4	#1	#2	#3	#4	W	THK	LEN	W	THK	LEN
INIT	1.434	1.437	1.457	1.439	2.162	2.181	0.297	0.298	0.289	0.281	2.778	0.402	12.60	2.774	0.389	12.600
F1	1.436	1.444	1.480	1.444	2.173	2.170	0.287	0.309	0.286	0.285	2.750	0.393	12.60	2.752	0.388	12.600
F2	1.437	1.426	1.436	1.429	2.153	2.160	0.286	0.294	0.283	0.274	2.715	0.392	12.60	2.719	0.378	12.600
F3	1.436	1.417	1.452	1.419	2.133	2.167	0.290	0.300	0.297	0.274	2.690	0.383	12.60	2.705	0.391	12.600
F4	1.429	1.424	1.417	1.426	2.121	2.165	0.284	0.298	0.281	0.272	2.685	0.387	12.60	2.693	0.379	12.600
F5	1.415	1.435	1.415	1.440	2.108	2.168	0.278	0.294	0.291	0.282	2.685	0.393	12.60	2.686	0.389	12.60
F6	1.415	1.422	1.417	1.413	2.091	2.155	0.277	0.304	0.280	0.278	2.677	0.396	12.60	2.688	0.386	12.600
F7	1.402	1.409	1.405	1.424	2.091	2.165	0.278	0.295	0.278	0.269	2.676	0.386	12.60	2.681	0.380	12.60
F8	1.398	1.410	1.414	1.410	2.077	2.163	0.281	0.303	0.268	0.272	2.647	0.377	12.60	2.655	0.376	12.600