BASIC AND APPLIED RESEARCH IN WOOD DRYING AT THE UNIVERSITY OF MINNESOTA COLLEGE OF FORESTRY

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The College of Forestry is located on the St. Paul Campus of the University of Minnesota along with several other colleges devoted to plant and animal science. The combined undergraduate and graduate student enrollment in Forestry is about 500 students.

The College is situated at the north end of the campus in what might be called a "forestry complex". This complex consists of the 2 College units, Green Hall and the Forest Products Laboratory, plus the U. S. Forest Service North Central Forest Experiment Station. The three buildings are immediately adjacent to each other.

The Department of Forest Products carries out both teaching and research functions, and there are 5 full-time faculty whose time is divided between the two responsibilities. In addition to this faculty there is also Dr. Lewis Hendricks, who is extension specialist in forest products. Generally the number of students matriculating in the forest products related curriculums is about 8 to 10 percent of the College total.

The major tree species in the state is aspen, which is harvested mostly as pulpwood to fill the needs of the local pulp and paper industry. It is commonly estimated that the annual net growth of aspen is about twice as great as the annual cut. It is desirable, therefore, that the use of aspen for solid wood products be increased. This has its problems, however, for aspen is both a difficult wood to properly dry and adequately treat. The discolored wood and wet wood, for example, will collapse quite readily during kiln drying. In this respect it is similar to the west coast softwood species of redwood, western red cedar, and incense cedar. In wood treating operations it treats quite irregularly. A fence post can have an adequate total net retention of preservative but practically all of it may be concentrated at one or two locations with only superficial pickup elsewhere. Obviously anything we can learn about the basic wood-liquid relationships and relate to the standard wood drying and treating processes could be of great value, not only for aspen but toward the more efficient processing of our other species as well.

We hope, therefore, to eventually gain better answers to questions such as the following: Why exactly does collapse occur? What factor or factors control the permeability of wood to various liquids? What sort of pretreatments and processing techniques have the ability to reduce or eliminate undesirable results in both wood drying and treating operations?

In 1962 Dr. William Kelso, who is currently director of wood preservation research at the University of Mississippi, completed his Ph.D. thesis research at the University of Minnesota. In his thesis research he conclusively demonstrated the heretofore neglected, or at least not fully appreciated, role of air as a determining factor in the permeability of wood to water. His conclusions were that air, both in liquid solution and entrained in the flowing liquid as bubbles, was largely responsible for previously observed decreasing flow rates over time as well as disproportionate increases in flow with increases in pressure. His research, therefore, focused attention upon the important effects of air in the wood-moisture relationship. He also demonstrated that subjecting the flowing liquid to a large pressure drop, or to mechanical cavitation, [1] will cause air bubbles to grow in the flowing liquid. Such bubbles can become trapped in the fine pore structure of the wood and thereby reduce the permeability. The release of air from liquid solution in the ordinary pressure treatment processes may be a factor that helps to limit both liquid penetration and retention.

It was realized, however, that in accordance with a generally accepted theory of how collapse occurs in wood drying, the generation of air bubbles could be desirable rather than undesirable. The Tiemann liquid tension stress theory of collapse states that collapse of wood cells during drying occurs because the cell lumens are completely filled with

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[1] A process for creating gas filled spaces in a liquid.

liquid and devoid of adequately sized air bubbles. Consequently, if air bubbles were introduced into these liquid-filled cells, collapse would not occur. This is because the collapsing stress, which ordinarily would be transmitted to the cell walls, is now obviated through expansion of the bubbles.

It then became a problem of conceiving a simple, efficient, and inexpensive method of generating the desired air bubbles in collapse susceptible wood. But how to do this? Cavitation was indeed a possibility but it probably would require sophisticated equipment and operational procedures. It was decided to try freezing the wet wood instead, since one can commonly observe the presence of air bubbles in ordinary ice cubes. In fact, special techniques are used to avoid the entrapment of air bubbles in the ice used for bar drinks. The question of whether or not bubbles remain after thawing, (in a size too small for observation by the naked eye) is affirmatively answered in scientific journals of chemistry or physics.

It seemed appropriate to test the idea and preferably on one of our most collapse susceptible woods. Prior to returning to Minnesota for graduate study, I had worked for 3 years at the California Forest Products Laboratory under Dr. Ellwood on the chemical seasoning stain problem in redwood. I had ample opportunity to kiln dry redwood and become familiar with its collapse tendencies. Having a thoroughly wet piece of redwood in my possession, one that was sent to me at Minnesota by Dr. Helmuth Resch for use in undergraduate teaching, I decided to carry out a simple prefrezzing test.

In short, the experiment was successful and it initiated a train of research that has been modified as needed but which has persisted up to the present.

With this brief background of development in the area of wood-moisture research at the University of Minnesota, I will now discuss the results obtained in some of the more recent endeavors.

Prefreezing Related Research

The drying of prefrozen redwood lumber:

The first publication dealing with the effect of prefreezing upon redwood was published in the August 1966 issue of the Forest Products Journal. Subsequently, there was a series of additional studies in which the drying behavior of nominal 1" redwood lumber was studied.

It was learned, e.g., that not all lumber can go directly from the green chain into the freezer. Lumber with too high initial moisture content will suffer damage during freezing because of the water to ice expansion plus some complex cell wall behavior. It is estimated that lumber with less than 125% moisture content could go directly into the freezer, while that in the higher moisture content categories would require perhaps 3 or 4 days of low temperature predrying at 110° F. D.B. and 90° W.B. (10). After freezing, of course, high drying temperatures can be used without the occurrence of collapse and excessive shrinkage. This is the advantage of prefreezing - it takes away the sensitivity to collapse and excessive shrinkage at high drying temperatures and therefore makes it possible to cut drying time to perhaps one-third of the usual. Instead of close to one year of air drying plus 8 days or so of kiln drying, as in comtemporary procedure, heavy segregation could be pre-dried for 3 or 4 days at low temperature, prefrozen in a few hours, and then kiln dried in about 8 days at higher than normal temperatures. This, in effect, eliminates air drying.

Two experiments of the series were conducted at The Pacific Lumber Company, Scotia, California.[2] Each experiment contained 1M bd. ft. of prefrozen 1" redwood lumber and 1M bd. ft. of end- or face-matched unfrozen boards. The second of these experiments, performed in August, 1967, incorporated larger freezing facilities into the experiment. The first experiment was deficient in this respect and resulted in many boards not being frozen. Completion of the phase change is required in order to obtain the effect.

The kiln schedule employed and the results obtained in the August, 1967 experiment at Scotia are summarized in Tables 1, 2, 3, and 4.

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[2] I wish to acknowledge the services and cooperation of The Pacific Lumber Company and the Moore Oregon Dry Kiln Company in the conduct of these studies.

Table 1. Kiln schedule employed in the Scotia experiment.

Drying Time (hours)	Dry Bulb ^{o}F	Wet Bulb ^{o}F
28	151	136
19	157	137
48	166	137
47	170	140
68	177	130
—	—	—
Total = 210		

Table 2. Shrinkage data for boards dried in the Scotia experiment.

Treatment	6" wide boards			8" wide boards		
	No. of bds	Shrinkage (%)		No. of bds	Shrinkage (%)	
		width	thickness		width	thickness
Controls	111	3.40	6.33	65	3.16	7.08
Prefrozen	111	2.43	3.80	65	2.34	3.87

Table 3. Summary of degrade as determined by The Pacific Lumber Company graders.

Treatment	No. of boards	Collapse			Sticker Stain		Skip			Popped
		slight	medium	heavy	slight	very slight	slight	medium	heavy	birds-eye
Controls	176	51	28	34	44	3	43	33	51	25
Prefrozen	176	1	0	1	50	14	16	4	0	21

Table 4. Moisture content data for boards dried in the Scotia experiment.

Treatment	No. of bds.	(%) Avg. initial moisture content	(%) Avg. final moisture content	(%) Range of final moisture content among boards	No. of boards with final avg. content above 12%
Controls	176	116	8.4	5 to 18	7
Prefrozen	176	116	7.7	4 to 12	0

Without going into the details of the results it is apparent that prefreezing allowed rapid, high temperature drying of this 1" redwood without the usual development of excessive shrinkage and collapse. Thickness shrinkage of prefrozen boards was about 45 percent lower than that for the controls, while the reduction in width shrinkage was about 25 percent. There also was a slightly improved final moisture content picture. The results from this Scotia experiment are representative of those obtained in all prefreezing experiments on redwood.

Prefreezing has the same effect on dimension redwood as well. Unfortunately, we have not had sufficient opportunity to investigate it to the extent of 1" lumber.

We are satisfied that the treatment has great commercial potential and that the next step in this direction should be an expanded pilot plant study.

Basic studies on the prefreezing effect:

At the College of Forestry we have pursued studies of a fundamental nature in hopes of isolating the mechanism by which prefreezing improves subsequent drying behavior. The original theory, of course, was that the freezing generated air bubbles in water-filled cell lumens which eliminated the collapsing stress during drying. In many cases, however, it is found that collapse and excessive shrinkage occur in unfrozen boards of comparatively low moisture content. In other words, it appears unlikely that the cells in redwood need to be completely saturated in order for them to collapse. Our awareness of this situation has been instrumental in promoting the search for other causative factors.

An especially interesting factor is the extractives which can occur in redwood heartwood in amounts equal to 25% or more of the ovendry weight of the wood. Several other collapse susceptible species such as western red cedar, incense cedar, and tanoak are also noted for high extractive contents. It seems possible, therefore, that the extractives may be involved some way in the problems of collapse and excessive shrinkage during high temperature drying.

Figure 1 relates board shrinkages to percent of hot-water-soluble extractives for face-matched prefrozen and control boards. Note the strong association between thickness shrinkage and extractive content for unfrozen boards. As extractive content increased, so did shrinkage, with the correlation coefficient highly significant. For the face-matched prefrozen boards, however, this association did not exist since with increases in extractive content there was no corresponding increase in shrinkage. In the case of width shrinkage the situation was somewhat different, with the correlation between shrinkage and extractives being significant for both prefrozen and control boards.

The information contained in Figure 1 incriminates the extractives in the problem of excessive shrinkage at high drying temperatures, such as the 175° F. employed in this experiment. The absence of a correlation between thickness shrinkage and extractive content for prefrozen boards suggests further that prefreezing reduces shrinkage and eliminates collapse by nullifying some normal contribution of the extractives to dimensional change.

It has also been found that the localized areas of collapse in redwood boards contain a higher percentage of extractives than do adjacent areas which do not collapse. A comparison of the extractive content of collapsed streaks and adjacent non-collapsed wood is given in Table 5.

Table 5. Comparison of the hot-water-soluble extractive content of collapsed streaks with that of adjacent non-collapsed tissue.

	Paired comparisons of percent extractive content inside and outside the streak									
Tissue Type	1	2	3	4	5	6	7	8	9	Avg.
Within the collapsed streak	13.16	17.55	16.20	14.38	13.62	14.79	13.10	17.25	15.43	15.05
Adjacent to the collapsed streak	13.08	14.41	13.58	13.04	10.99	12.34	11.86	12.73	12.60	12.74

Note that the collapse streak is always higher in extractive content, with the averages being 15.05 and 12.74 percent respectively for the collapsed and non-collapsed areas.

Since the above analysis was made at the end of drying it was impossible to make a comparison of the original moisture content of the collapsed and non-collapsed areas. Currently one of our Ph.D. candidates is characterizing these types of redwood tissue with respect to extractive content, initial moisture content, and bulk specific gravity of the extractive-free wood. He is consistently finding that the extractive content of the collapse susceptible area is higher than that outside the area. Generally the moisture content is also higher within the area than without, but there have been exceptions.

Three experiments were conducted in which we evaluated the effect of combined presteaming and prefreezing upon the drying behavior of redwood. Since presteaming has been shown (2) to accelerate the drying of redwood heartwood we anticipated that the combination of the two would be better than using prefreezing alone. Table 6, which gives data that is representative of all 3 experiments, shows that this is not the case. Samples subjected to prefreezing alone have the least shrinkage of all 5 treatments. The next best treatment was presteamed and prefrozen, followed by prefrozen and presteamed. The order of treatment effectiveness shown in Table 6 was the same in all 3 experiments, and indicates that the presteaming treatment has the ability to reverse as well as prevent a portion of the prefreezing effect.

It should be noted that the samples were of 2 color types, light and dark. The 2 types were of about the same bulk specific gravity but the dark samples contained a larger quantity of extractives. In view of the higher initial moisture content for the light colored samples (see Table 6), it is perhaps surprising that they ended up with the lowest final shrinkage and moisture content values. It is believed that the dark-colored samples dried the slowest (11) and shrunk the most because they had the higher extractive content. Figure 2 graphically illustrates the comparative drying rates and shrinkage values for the light- and dark-colored samples. The results of this study give further evidence that the amount of water-soluble extractives is instrumental in determining the high temperature drying behavior of redwood heartwood.

Table 6. Summary of the data from one of the 3 experiments designed to evaluate the effect of combined prefreezing and presteaming upon the subsequent drying behavior of redwood heartwood.

	Specific[1] [2] Gravity	Thickness[1] Shrinkage (%)	Extractive[1] Content (%)	Initial[1] Moisture Content (%)	Final[1] Moisture Content (%)
Controls:					
light[3]	0.37	4.68	11.3	153.5	8.4
dark[3]	0.39	15.66	18.1	101.1	14.2
Prefrozen:					
light	0.37	2.28	9.2	128.8	6.9
dark	0.37	2.26	18.9	115.9	26.2
Presteamed:					
light	0.37	5.43	10.0	110.0	6.6
dark	0.38	9.11	18.3	99.0	15.6
Presteamed and Prefrozen:					
light	0.36	2.70	10.4	136.9	6.6
dark	0.37	3.83	18.3	111.3	16.8
Prefrozen and Presteamed:					
light	0.36	3.16	10.5	134.6	6.8
dark	0.37	4.00	19.3	96.5	13.9

[1] Each value is the average of two samples.

[2] Based on ovendry weight and green volume.

[3] Refers to sample color.

Armstrong and Kingston (1) have measured the effect of moisture content changes upon the deformation of miniature beams cut from several Australian species. These beams were statically loaded during drying from the green state down to well below the fiber saturation point. Their results show the dependence of beam deformation upon moisture content change.

It seemed desirable, therefore, for us to test the effect of prefreezing upon the deformation of miniature redwood beams. After all, during drying a board is subject to creep deformation as a result of the drying stresses present. Since prefreezing can reduce the amount of deformation under this type of stressing, perhaps it could also reduce the amount of creep deflection in a statically loaded beam.

Miniature redwood heartwood beams, 1.0" wide, 0.5" thick, and 13" long were prepared from naturally wet wood (3). These beams were simply supported over a 12" span and dead-weight loaded to about 20 percent of the short-term stress at the proportional limit for old-growth air-dried redwood. A dial gauge was used to measure the deflection of each beam as it dried from the original green condition to approximately 5% moisture while under this constant load. Both low (106° F.) and high (150° F.) drying temperatures were used in individual tests, as well as being combined into the same test.

Figure 3 illustrates the effect of drying temperature and treatment upon relative creep[3] in a test employing both low and high temperature. The creep at 106° F. is comparatively low for both prefrozen and controls. When the temperature was raised to 150° F. the rate of beam deflection, i.e., relative creep, accelerated greatly. When the temperature was returned to 106° F. the creep curves for both prefrozen and controls became nearly horizontal. At the conclusion of the test the relative creep value for the prefrozen was approximately one-half of that for the control. Note that the lower creep for the prefrozen is almost entirely accounted for by summing the reductions obtained during the high temperature periods of the test.

This effect of prefreezing upon flexural creep is most interesting by comparison with the effect the prefreezing upon shrinkage in lumber drying. In high temperature drying of redwood lumber the pretreatment eliminates collapse and excessive board shrinkage. In the testing of redwood beams it eliminates excessive deformation during the high temperature portion of the test. Prefreezing is obviously reducing, in each situation, the amount of deformation coincident with dehydration of the wood. Since prefreezing does not reduce the so-called true shrinkage of redwood (4) it must achieve these results by reducing the creep deformation that accompanies dehydration.

In a drying board it is extremely difficult to separate creep in tension from creep in compression because of the constantly changing moisture gradient and the complex interaction of tensile and compressive stresses. It is equally difficult to identify creep in compression or tension in a drying beam. The top half of the beam is in compression while in the bottom half of the beam the fibers are being stressed in tension. Since all surfaces of the beam are drying simultaneously, creep deflection of the beam is a moving average of the creep occurring in fibers stressed in compression as well as in tension.

Is there some way to overcome this problem? It occurred to us that in the case of beam deflection we could perhaps isolate the effect on fibers dehydrated while stressed in compression from that of fibers dehydrated while stressed in tension. To do this we would simply cover all faces of the miniature beam with aluminum foil, except the face through which we wished drying to occur. In other words, if we wanted most of the drying to occur through fibers stressed in compression we would leave the top face of the sample open. Conversely, if we wanted fibers stressed in tension to be the first ones to dry out we would leave the bottom face of the beam open. This technique, which we refer to as unidirectional diffusion (5), was combined with prefreezing in an extended series of tests. The culmination of this series, and the most important data to arise from it, are summarized in Figure 4.

You will note that for samples with no covering, the reduction in flexural creep due to prefreezing develops early in the test. However, as mentioned previously it is impossible to say anything about creep other than "creep was reduced by prefreezing".

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[3] Relative creep is defined as creep deflection divided by the deflection at one minute after loading.

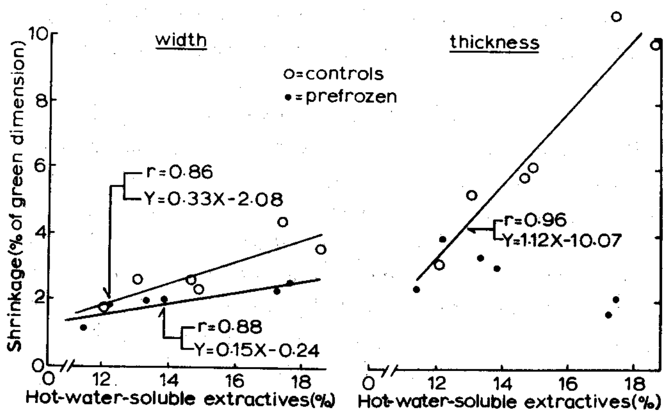

Figure 1. Scatter diagrams showing the relationship between quantity of hot-water-soluble extractives and shrinkage for 6 pairs of face-matched 1" redwood heartwood boards. One board of each face-matched pair was frozen prior to drying. Drying was in an experimental kiln at a constant temperature of 175° F. The r values express the simple correlation coefficients.

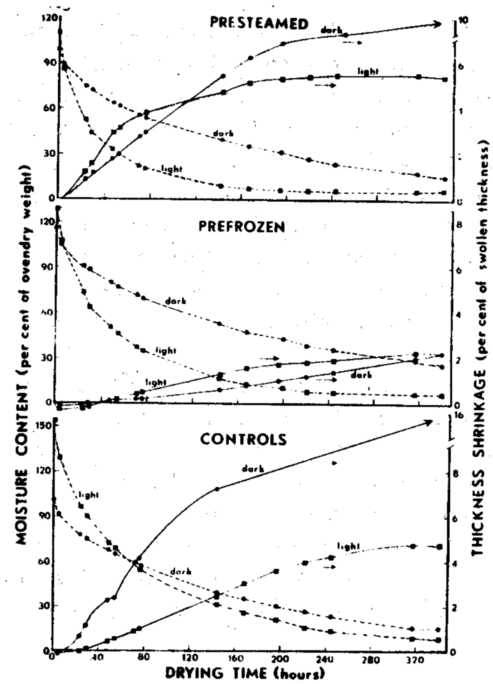

Figure 2. The comparison of drying rates and shrinkage results for light-and dark-colored redwood heartwood samples by treatment. The extractive content, moisture content, and bulk specific gravity values for the 2 sample types are given in Table 6.

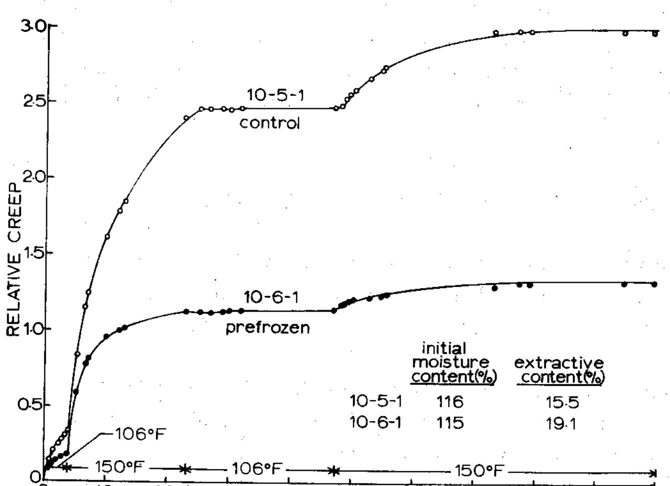

Figure 3. The effect of drying temperature and prefreezing upon the creep of miniature redwood beams. The end-matched prefrozen and control beams were dried out while supporting a constant static load. The 2 beams had essentially the same final moisture content.

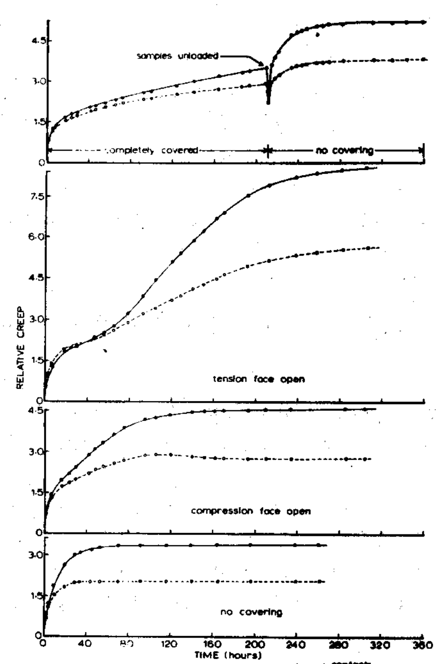

Figure 4. Relative creep of miniature redwood heartwood beams during drying from the green condition while under static load. Aluminum foil was used to completely cover the sample or to leave just the tension or compression face open. The test was carried out at 150° F. and 50 percent relative humidity. Each curve for prefrozen and controls is the average for 3 samples.

Samples in the curves immediately above, those with compression face open, also show the reduction due to prefreezing in the first one-third or so of the test. Thereafter, as with the curves for samples with no covering, the curves become parallel and remain so to the end of the test. In other words, the reduction in creep due to prefreezing developed during that period of time in which the principal dehydration was of fibers above the neutral axis of the beam and consequently stressed in compression.

Going next to samples with the tension face open, we see that the reverse is true. The creep curves for prefrozen and controls coincide during the first part of the test, and the reduction due to prefreezing develops over the latter part of the test. Since the compression face was covered, its drying was delayed. Therefore, as with the compression-face-open samples, the effect of prefreezing upon creep is again coincident with the drying of fibers stressed in compression.

The last set of curves is for samples that were completely covered, unloaded and weighed, completely uncovered and tested to equilibrium moisture content. The relatively small divergence of the curves prior to unloading is believed due to the drying that occurred through the aluminum foil. The foil is not a perfect vapor barrier and after 210 hours exposure to a temperature of 150° F. and a relative humidity of 30 percent, the samples had lost an average of 17 percent moisture content. The rapid divergence of the curves after unwrapping and reloading, however, pretty well proves that the mechanism by which prefreezing reduces deformation comes into being when the moisture begins to separate from the solids in the system. The data in Figure 4 is therefore interpreted to mean that the principal effect of prefreezing upon deformation during drying is to reduce the amount of creep in fibers dehydrated while under compressive stress.

It is theorized that the water-soluble extractives, through their association with the wood and water, help to impart characteristic deformation behavior to redwood heartwood. Prefreezing modifies the subsequent drying behavior possibly by modifying the nature of the extractives and their contribution to the system. Figure 5 shows that relative creep was correlated with initial moisture content and extractive content in samples dried without covering at 150° F. (3). We also found, in the same study, that the initial moisture content of the samples was strongly correlated with the extractive content, i.e., the higher the extractive content the higher the initial moisture content.

We have also conducted a series of flexural creep tests using aspen samples. The results from samples with either the tension or compression face open are given in Figure 6. The curves are roughly similar with those of redwood but there are two important differences. First, the variation in relative creep for individual samples was much greater than that encountered in redwood. (Note that the one compression-face-open sample is plotted at only one-tenth of actual value.) Second, all of the samples of Figure 6 were prefrozen, and though it was difficult to tell because of the extreme variation between samples, they appeared to have the same flexural creep behavior as unfrozen samples. This is in agreement with our aspen lumber research where we have found only small and inconsistent reductions in shrinkage due to prefreezing.

Incising Dimension Lumber to Reduce Drying Time and Moisture Content Variability[4]

Mr. Robert Thompson, who is on the staff of the College of Forestry, has been experimenting with the use of aspen (*Populus tremuloides*) for studs. He has recognized, as part of the problem, that aspen is quite variable in original moisture content and is most difficult to dry to a uniform final moisture content in a reasonable length of time.

It occurred to him that for many years the treating industry has used incising to facilitate the movement of preservative liquids into impermeable species. He reasoned that perhaps incising would be equally beneficial in the movement of moisture out of green wood during drying. The literature made only casual mention of the use of incising as a pretreatment for drying, and that was in conjunction with air drying. He decided, therefore, to test the idea in kiln drying.

Aspen was used for the initial experiment with the incising being done at the Andersen Corporation, Bayport, Minnesota. They have an incising machine that they use regularly to incise wooden window parts for subsequent

[4] This is the title of a publication being prepared by Mr. Robert Thompson and under whose leadership the incising research is conducted.

preservative treatment. The results of this first experiment were encouraging and indicated the desirability of further incising research.

No commercial incising machines of a size and type appropriate to the proposed research were available. Using ideas furnished by Mr. Thompson and his fellow researchers, a private engineering firm in Minneapolis was employed to manufacture the machine. To some extent the University of Minnesota Scientific Apparatus Shop was also involved in the design.

This design resulted in a unit that is capable of incising all 4 sides of a 2 by 4 in one pass through the machine. The incising pattern that results is a series of slashes, 1 1/2" on center, and in rows about 1/2" apart. The depth of the incisions can be either 1/4, 3/8, or 1/2 inch.

This machine was first used on full length aspen 2 x 4 studs. The drying results, once again very encouraging, were reported in "The Proceedings of the Aspen Stud Seminar" (9). Due to the success in this study Mr. Thompson decided to investigate the effect of incising upon the drying behavior of some commercially important softwood species.

Several western as well as local softwood species were included in this study. As the 100 to 125 rough green studs of each species were received, each of the studs was cut into 2 equal lengths with the taking of a moisture content section in the process. One of the lengths was given a 3/8" deep incising treatment while the other length was left unincised. The various species were kiln dried essentially in accordance with the schedules recommended by the Madison Forest Products Laboratory.

At the conclusion of kiln drying about 25% of the end-matched pairs of pieces were randomly selected for use in checking the variability of final moisture content. Both the incised and unincised pieces were cut into 3" lengths, and their moisture contents determined individually. A statistical analysis was made of the variation in moisture content along the length of each 4' piece as well as between pieces of each type.

Table 7 summarizes the end-of-drying moisture content data. With the exception of red pine all species show a lower final moisture content for the incised rather than for the unincised. The F1 statistical values are a measure of moisture content variation within each piece while F2 is a measure of variability in average moisture content between pieces of the sample.

Table 7. Moisture Content Analysis of Matched Sample Sets with the Results of Statistical Tests for Moisture Content Variability.

Species	No. Pc. in Sample	Final Av. Incised	M/C of Sample Unincised	Stat. Values F1	Stat. Values F2	Confidence F1	Confidence F2
W. C. Douglas Fir	25	8.5%	10.5%	*	*	*	*
W. C. Hemlock	24	8.5%	11.2%	2.21	2.72	.95	.99
Balsam Fir	25	9.7%	16.6%	2.75	2.00	.99	.95
W. White Fir	25	14.0%	18.6%	1.86	0.82	.90	.25
W. Larch (Boise)	25	15.8%	19.3%	1.10	1.28	.50	.75
Ponderosa Pine	25	14.5%	15.5%	0.58	0.57	.10	.10
Red Pine	31	15.9%	15.5%	2.22	0.64	.975	.10
Inland Douglas Fir	31	15.5%	16.6%	1.49	0.83	.25	.25
W. Larch (Libby)	32	13.6%	18.2%	1.40	1.47	.75	.75
Aspen	32	13.4%	16.1%	1.42	1.41	.75	.75

* Variability data not valid because samples for incised and unincised weren't matched sets.

A high confidence level indicates a difference in drying due to incising. Several of the species, therefore, show a reduction in both types of moisture content variation because of incising.

Table 8 gives the results of another type of statistical test, which is the "t" test. The significance level in this case indicates the confidence with which you can make the statement, "incising is of benefit in reducing drying variability." Based upon this sample, and with the exception of ponderosa pine and red pine, this statement can be made with an 80 percent degree of confidence or more.

Table 8. Results of the Statistical t Test Used to Measure Reduction of Variability of M/C by Incising.

Species	Two Sided t Value	Significance Level
W. C. Douglas Fir	2.579	98%
W. C. Hemlock	2.059	95
Balsam Fir	1.918	90
W. White Fir	2.191	95
W. Larch (Boise)	1.520	80
Ponderosa Pine	0.643	40
Red Pine	0.478	20
Inland Douglas Fir	2.683	98
W. Larch (Libby)	3.852	98
Aspen	1.599	80

Table 9 shows the estimated savings in drying time by species. It indicates that for certain species incising not only improves the uniformity of final moisture content but also causes a significant reduction in drying time. For certain wood products, at least, the concept of improved permeability in wood drying through incising would appear to be both practical and useful.

Table 9. Estimated Savings in Drying Time by Incising.

Species	Hours in Kiln to Dry	Estimated Extra Hours to Dry Unincised	Per Cent of Kiln Time Saved by Incising
W. C. Douglas Fir	96	3	3.0%
W. C. Hemlock	68 1/2	8	13.2
Balsam Fir	135 1/2	18	15.3
W. White Fir	94 1/2	7	8.0
W. Larch (Boise)	80	18 1/2	30.1
Ponderosa Pine	58 1/2	2	3.5
Red Pine	139 1/2	--	--
Inland Douglas Fir	92 1/2	4 1/2	5.6
W. Larch (Libby)	118 1/3	20	20.3
Aspen	111 1/2	12	12.1

The Effect of Swelling Upon Wood Permeability

Wood permeability research at the College of Forestry, over about the past decade and one-half, has developed under the guidance of Dr. Ralph Hossfeld. One area of interest has been the swelling of wood by organic solvents, or by mixtures of organic solvents. In 1960 Oberg and Hossfeld (8) published a paper describing the swelling of wood in the dioxane-water system. External swelling was found to reach a maximum at 0.8 mole fraction water. This study, along with subsequent permeability research at Minnesota, prompted Dr. Hossfeld to ponder the relationship between the degree of swelling and permeability. Recently such a study was completed (6), and the following is a very brief summary of this research.

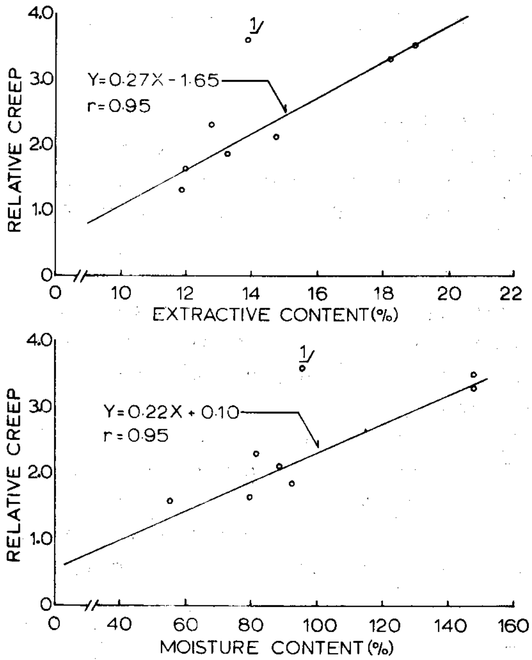

Figure 5. Scatter diagrams showing the relationship between relative creep, hot-water-soluble extractive content, and initial moisture content for miniature redwood heartwood beams dried at 150° F. The regression equations and correlation coefficients are based upon seven samples.

1/ This sample developed a severe collapse streak during the test.

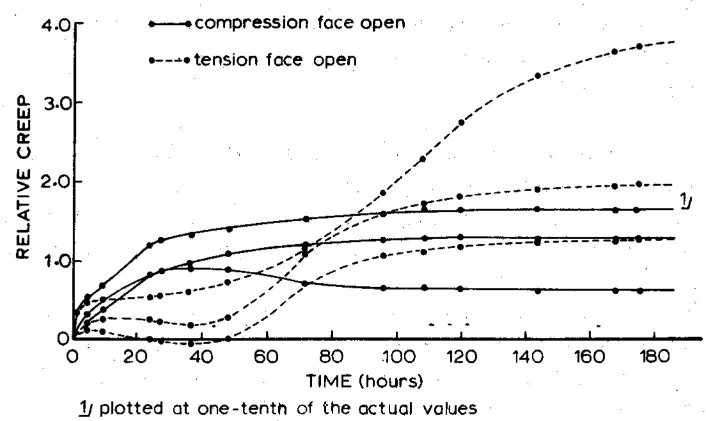

Figure 6. Relative creep curves for miniature aspen beams drying from the green condition while under static load. Aluminum foil was used to cover all but the compression or tension face of the samples. Each curve is for an individual sample. The test was carried out at 130° F. and 50 percent relative humidity.

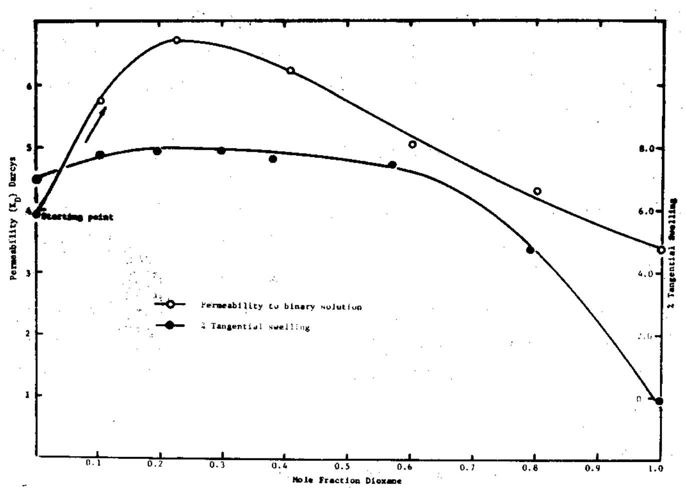

Figure 7. The relationship between the percent swelling of a northern white cedar sapwood specimen and its permeability to a water-dioxane solution.

Northern white cedar sapwood was selected for the study primarily because of its permeability and the lack of resin canals or a torus in the pit membrane. Samples were mounted in the permeability apparatus in the manner described by Megraw (7). The samples were in the form of a right cylinder 1.27 cm in diameter and 0.65 cm in the longitudinal direction, the direction of fluid flow.

The degree of swelling of the permeability sample was determined by making measurements on small specimens from the matching material. This measurement was accomplished by using electronic equipment that sensed an increase in dimension and then translated this change into a voltage that was plotted against time on a strip chart recorder, resulting in a swelling rate curve. Therefore, for a given binary solution, it was possible to determine both the extent and rate of external swelling.

Much of the previous research by Dr. Hossfeld and his students has served to show the influence of air upon wood permeability results. In the process of carrying out this research techniques have been developed for deaerating the permeating fluids prior to use, and also for obtaining constant rates of flow. These highly developed techniques, which insure the collection of meaningful data, were employed in the study under discussion.

In a typical permeability determination the selected concentrations of the binary system were placed in the storage tank and then deaerated. The wood sample, after mounting in the permeability cell, was evacuated and then impregnated with the initial permeating fluid of the series contained in the tanks. The permeability cell was then installed in the permeability apparatus, and the sample was permeated with the various solutions by manipulation of appropriate valves in the permeability apparatus.

Several binary solutions have been employed, and all of them show that liquid permeability tends to be maximum when the amount of swelling is at a maximum. This is graphically shown in Figure 7, where the permeability is plotted as a function of mole fraction dioxane. Both maximum permeability and tangential swelling occur at about 0.2 mole fraction dioxane. With subsequent increases in the concentration of dioxane in the permeating liquid, permeability decreases almost uniformly. The minimum permeability was obtained with pure dioxane, which also gives the minimum value for swelling.

The results with some of the other binary solutions have not been as straightforward as with the dioxane-water system. In the tertiary butyl alcohol-water system, e.g., maxima in permeability and swelling did not occur at the same solution concentration. Further study and interpretation have shown, however, that the basic direct relationship does exist for these other binary solutions as well. At the present time Dr. Hossfeld is in the process of preparing a manuscript that extends and clarifies the important interactions between liquid permeability and degree of swelling.

Closing Comments

In this summary I have attempted to give some meaningful insights as to the nature of current research in the area of wood-moisture relationships at the College of Forestry, University of Minnesota. I have not, of course, included any great degree of detail as to scientific data or procedure. Also, it is not an all-inclusive coverage with respect to individual research projects. It is, hopefully, a fairly representative sampling of the types of things we are involved with and thusly gives a sense of the direction in which we are attempting to move. With some luck, plus considerable help and challenges from research going on at other forestry related institutions, we are hopeful of continuing and meaningful progress in the future.

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