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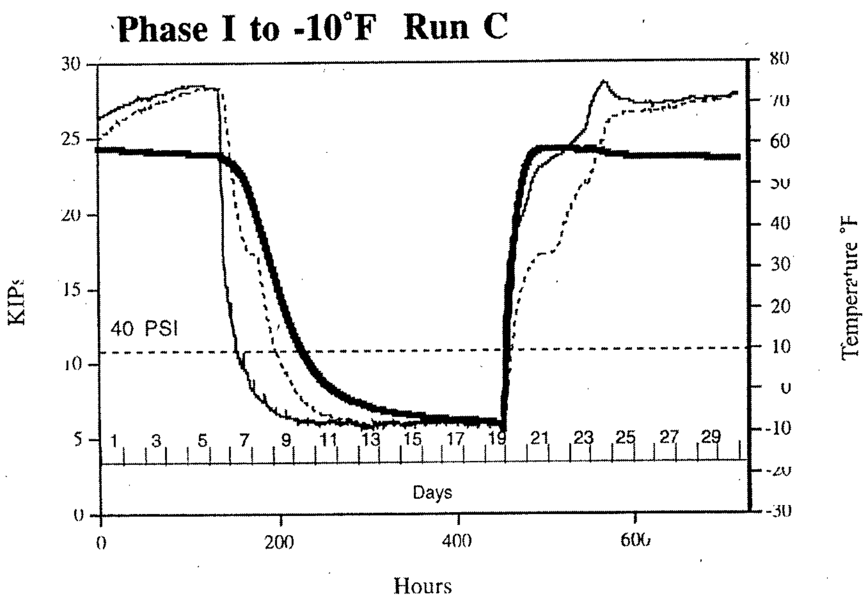

Cold Temperature Effects on Stress Laminated Bridge Decks

Local Road Research Board

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16. Abstract (Limit: 200 words)

This study evaluated the thermodynamics of stress-laminated bridges under laboratory conditions.

After assembling three timber laminated bridge deck panels of 120" x 43" x 12", high tension rods were used to form "stress-laminated" panels. Researchers placed the panels in a laboratory freezer, with cold temperature settings of 10°, 0°, -10°, -20°, and -30° Fahrenheit and repeated the process three times, each with the wood at a different moisture content--a "green" moisture content greater than 30 percent, a 17 percent moisture content, and a 7 percent moisture content (mc).

The results showed that the bar force reduction in the green moisture content sample was significantly greater than in either the 17 percent or 7 percent mc tests. The study concluded that the moisture content levels and temperature fluctuations cause variations in rod stressing levels; that the tensioning losses occur within a few hours of the temperature drop; that the green moisture content levels have a severe adverse effect on the stressing levels; and that tensioning levels somewhat stabilize with moisture contents below 17 percent.

Based on this study, it would appear that any existing stressed bridge decks should be closely monitored until the moisture content of the members is less than 19 percent. Further study may be needed to determine the behavior of bridge decks with a moisture content above 17 percent and below the fiber saturation point.

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Cold Temperature Effects on Stress Laminated Bridge Decks

Final Report

Prepared by:
Robert T. Seavey
Robert W. Erickson
Department of Wood and Paper Science
University of Minnesota

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Published by:
Minnesota Department of Transportation
Office of Research Administration
200 Ford Building
Mail Stop 330
117 University Avenue
St. Paul, MN 55155

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Executive Summary

Stress-laminated timber bridge decks perform well as long as the stressing bars maintain their tensioning force and hold the timber laminated planks tightly together. When the bar force is reduced, the load carrying capacity of the deck is reduced. This phenomenon was observed on a bridge built in northern Minnesota in 1989 where it was noticed that the prestressing levels significantly declined during periods of low winter temperatures and then returned to original levels as the temperatures warmed. Subsequent studies determined the loss was related to the moisture content of the wood and cold temperatures.

The purpose of this study is to further quantify the thermodynamic characteristics of timber over a wide temperature range and a variety of moisture content levels.

Three timber laminated bridge deck panels (120" x 43" x 12") were assembled and then stressed with high tension rods to form "stress-laminated" panels. The panels were then placed in a laboratory freezer where prescribed temperatures could be maintained for extended periods of time. Cold temperature settings were 10, 0, -10, -20, and -30° Fahrenheit. This process was repeated three times, each time with the wood at a different moisture content. The first time was a "green" (moisture content greater than 30%), then at 17% moisture content (mc), and finally at 7% mc.

The results showed that the bar force reduction in the green moisture content sample was significantly greater than in either the 17% mc or 7% mc tests. At 0° F, the pressure between laminae in the green sample reduced to the 40 psi pressure typically used for design of stressed laminated decks. Lower temperatures showed even greater reductions and at the lowest temperatures, it is unlikely that the panels were acting as a stress-laminated panel. The results for the 17% mc and 7% mc samples showed only moderate levels of bar force reduction with the 7% having the least reduction. Even when the 17% mc sample was held at -30° F., the pressure between laminates, although reduced by as much as 16%, was still twice the design pressure of 40 psi. At the end of each test, the samples were allowed to return to the ambient temperature again. Load cells were continuously monitored through cooling and warm-up. In every case the bar force returned to approximately the same level as before the test.

The conclusions of this study are: 1) that moisture content levels and temperature fluctuations cause variations in rod stressing levels, 2) that the tensioning losses occur within a few hours of the temperature drop, 3) that the green moisture content levels have a severe adverse effect on the stressing levels, and 4) tensioning levels somewhat stabilize with moisture contents below 17%.

Based on this study, it would appear that any existing stressed bridge decks should be closely monitored until the moisture content of the members is less than 19%. Further study may be needed to determine the behavior of bridge decks with a moisture content above 17% and below the fiber saturation point. Stress-laminated bridges should be built in compliance with the American Association of State Highway and Transportation Officials (AASHTO) Design Guide for stress-laminated bridges (1990), which prescribes a moisture content of less than 19%.

Introduction

This study evaluated the thermodynamics of stress-laminated bridges under laboratory conditions. Previous studies have shown that wood shrinks when subjected to freezing temperatures, and that the amount of shrinkage is related to moisture content (mc). The load capacity of stress-laminated bridge decks is affected by shrinkage. Ritter states that for the bridge deck to function as an orthotropic plate with sufficient horizontal load distribution, the pressure between laminates should be at least 40 pounds per square inch (psi).

The value of 40 psi has been chosen as a design guideline for stress-laminated bridge decks. The choice of this guideline includes a substantial safety factor because it is noted that "Research at UW/FPL found that a stress-laminated deck would perform acceptably at a compressive prestress level as low as 24 lb/in^2" (USDA Forest Service Engineering Staff EM 7700-8). Finally even without load sharing between laminates, the rods serve as dowels that will support some of the load and distribute it to adjacent laminae.

Our laboratory testing imposed the conditions at the outer limits of those observed in the field. The study plan called for testing the bridge decks at three stages: with the wood fully green, at 15% mc and at around 9% mc. This range of mc is large, but is intended to amplify the effect of moisture content on cold-induced shrinkage. (Although it is not uncommon for timber decks in nail-laminated and stringer bridges to have a moisture content of up to 25% mc, the AASHTO Design Guidelines for stress-laminated bridges prescribes a moisture content of less than 19%.) Also, freezing temperatures of 10°F, 0°F, -10°F, -20°F, and -30°F were maintained for extended periods at each level until the bar force in the decks had stabilized. Once again, this simulation is at the outer limits of natural weather patterns, but was designed to show the limits of stress loss.

Literature Review

Cold-induced shrinkage was first observed by Hans Kubler in 1962. Kubler found that when wood samples were frozen while prevented from drying, they suffered greater shrinkage than was predicted from the thermal coefficient. He postulated that the freezing temperatures caused moisture to migrate from the cell walls into the cell lumens because of a vapor pressure differential. Kubler performed studies relating cold-induced shrinkage to other phenomena such as frost cracks in trees and thermal effects within wood (Kubler, 1988). In one article he describes the phenomenon as follows: "...during cooling below 0°C, moisture diffuses out of cell walls and condenses on ice crystals in cell cavities. This represents a kind of internal drying that caused the very high coefficients of wood below 0°C. The process is again reversible; during reheating, moisture diffuses out from the ice back into the cell walls and reswells the wood." (Kubler et. al. 1973).

At the University of Minnesota, the effect of cold-induced shrinkage was first observed by Dr. Bruno Franck and Dr. Robert Erickson as they tried to explain the unexpected prestress losses on the Cypher Bridge, a stress-laminated bridge in Roseau County, Minnesota. They noted from the Cypher Bridge that prestress levels were reduced during periods of extreme cold, and would return to normal levels after the temperature rose.

Franck and Erickson devised a laboratory test using small, laminated-block model bridge decks (24 inch x 19 inch x 10 inch). The blocks were tested at two mc levels: 30% and 8%. They observed that the model deck at 30% mc showed a prestress loss more than 2 $^1/_2$ times greater than the model deck at 8% mc when the temperatures were dropped from 70°F to -20°F (Erickson et. al., 1990).

Objectives

Previous research shows that the combination of high moisture content and extreme cold temperature will result in lower bar force. Therefore, the objectives of this study were:

- To determine the thermodynamic characteristics of stress-laminated decks made of red pine sawn lumber within the temperature range of 70°F to -30°F.
- To determine how mc levels in wood affect its thermodynamic performance.
- To determine if there is a threshold temperature below which the thermodynamic characteristics of wood become more significant.

Protocols and Procedures

Red pine was used for this study. The individual laminates were 120 inch long, 2 inch thick and 12 inches deep. After the lumber had partially air dried, the decks were assembled and rolled into the freezer unit. Figure 1 shows a schematic of the individual decks. The decks were 10 feet long and 3-1/2 feet wide. Five tensioning rods were used, placed 2 feet on center.

Three decks were used, to maximize the information collected for a single data run within the freezer. A support structure was constructed to accommodate the three decks (Figure 1). It was designed so that each deck rested on a transverse support beam and was unrestrained by the weight of the decks above it. The structure was set on a modified kiln car on tracks which allowed the three decks to be rolled in and out of the freezer as one unit.

Figure 1 Test Frame Assembly

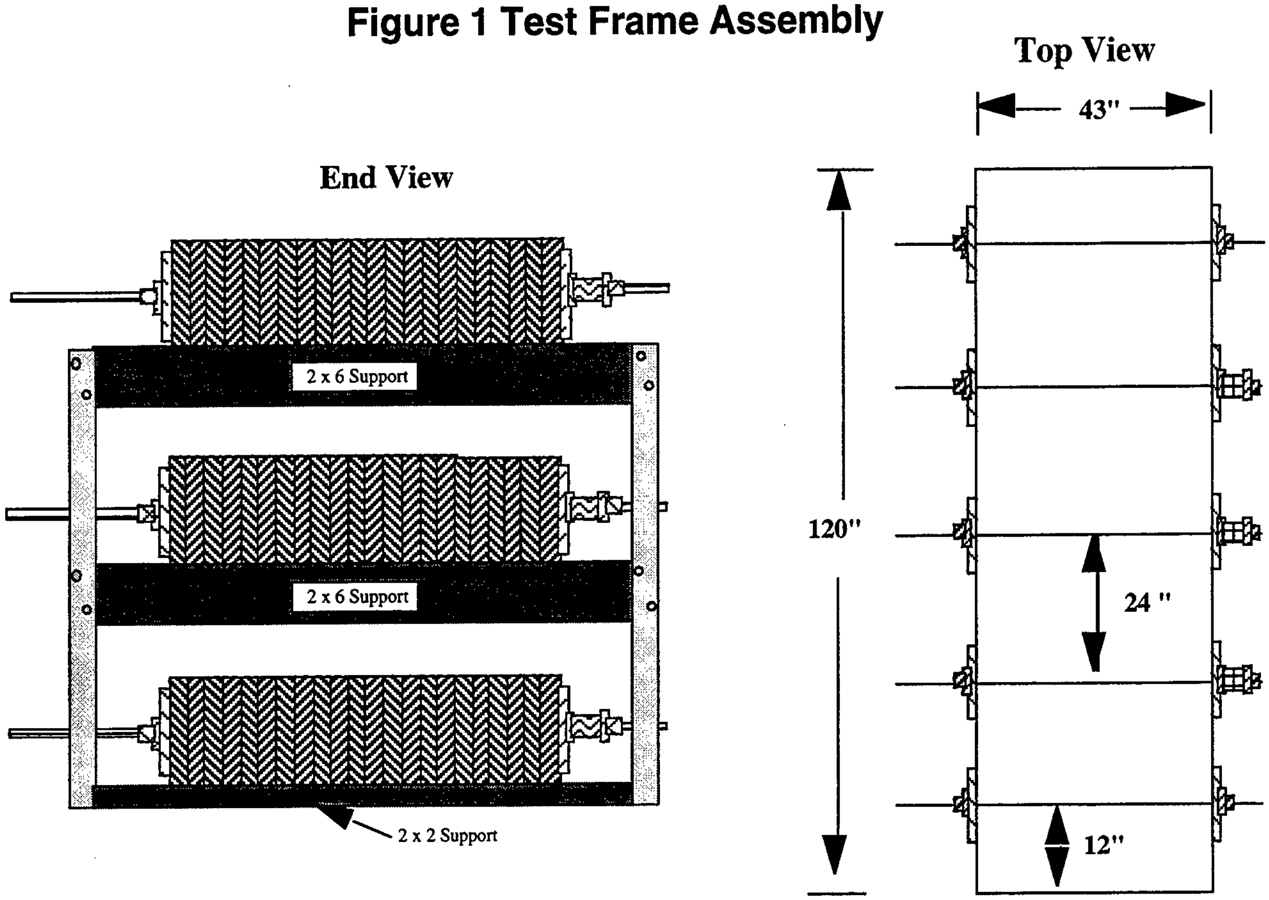
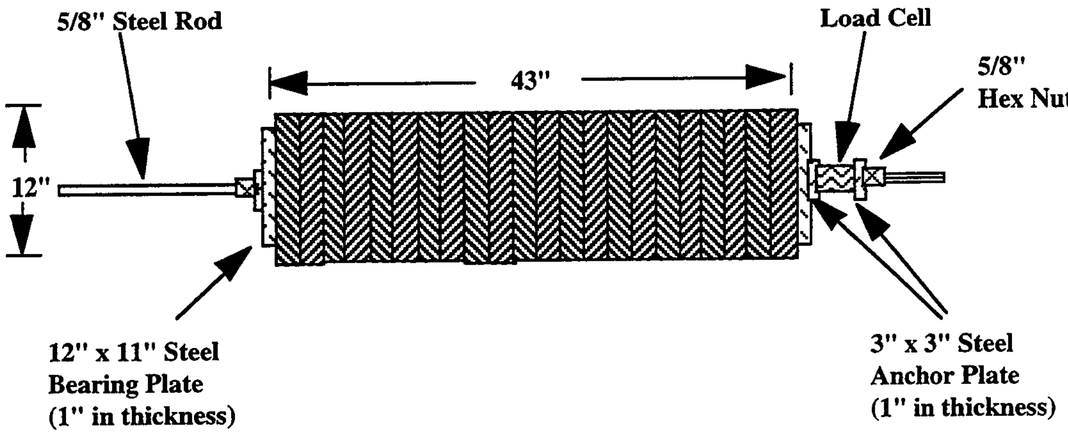


Figure 2 Tensioning Rod Detail



A diagram of an individual rod, with plates and load cell is shown in Figure 2. The tensioning rods were $^5/_8$ inch steel rod 6 feet 6 inch in length, supplied by Dywidag. The load cells were supplied by the USDA Forest Products Laboratory. Maximum pressure per plate was set at 26,200 lb. To reduce excessive crushing under the plates, the following tensioning sequence was used to jack the bridge decks:

1. Tension each rod in sequence to 17,475 lb. (two-thirds of maximum).

2. Tension each rod in sequence to 26,200 lb.

3. Repeat the procedure twice more.

4. After one week, tension each of the rods in sequence again to within 10% of the target value (26,200 lb.).

5. Monitor the decks for four or five weeks, and tension each of the rods in sequence again to within 10% of the target value (26,200 lb.).

The perpendicular-to-grain compression strength of red pine at green mc is 260 psi. After jacking to 26,200 pounds, the pressure immediately under the bearing plates is about 200 psi. This causes some perpendicular-to-grain creep in the wood, and rejacking is needed. It was found after each test phase that by limiting the stress to 200 psi this minimized creep and eliminated crushing under the plates.

For the first run, the mc of the three test decks was above the fiber saturation point. To keep the test decks at this mc they were wrapped with 6 mil polyurethane. The decks were tested under the five test scenarios of temperature variations.

Table 1 - Moisture Content and Temperature Variation During Testing

<table>
<tr><th></th><th>Average Moisture Content</th><th>Temperature Changes (Fahrenheit)</th></tr>
<tr><td>Phase I</td><td>>30%</td><td rowspan="3">A) 70° to 10°
B) 70° to 0°
C) 70° to -10°
D) 70° to -20°
E) 70° to -30°</td></tr>
<tr><td>Phase II</td><td>17%</td></tr>
<tr><td>Phase III</td><td>7%</td></tr>
</table>

During the experimental runs, stress loss was datalogged as the temperature was lowered. Thermocouples placed within the middle deck were monitored to evaluate the rate of cooling. The rate of cooling within the deck lagged the changes in the outside temperature

After completing Phase I, the decks were disassembled, each 2x12 was weighed, then kiln dried to an estimated 17% mc. After drying to 17% mc, they were weighed again and reassembled in preparation for Phase II. This procedure was again followed for Phase III, but with drying to 7% mc. The same datalogging procedure for monitoring temperature and bar force was used for all Phases. For each phase, the decks were wrapped with polyurethane to minimize mc changes. After completing Phase III, the decks were disassembled and selected 2x12s were cut up and tested for mc.

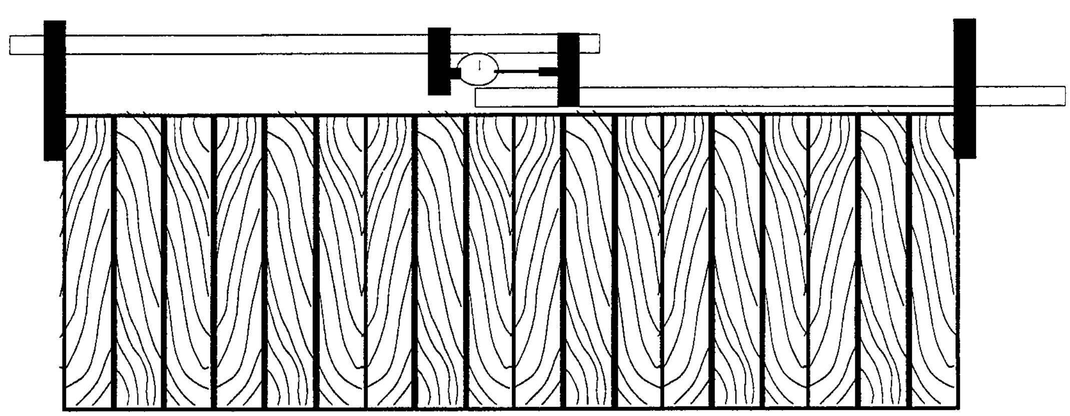
A DT100 datalogger was used for Phases I and II. A Campbell datalogger was used for Phase III. The dataloggers recorded freezer temperatures, bar force (9 load cells) and temperatures within the decks. The load cells and dataloggers were calibrated using an Instron 4200 Testing Machine. The Campbell datalogger was substituted for the DT100 datalogger after technical problems with the DT100 were noted following Phase II. Services to repair the DT100 were not readily available and the Campbell was used as a substitute.

A caliper device was also fabricated and attached to the bridge decks (Figure 3). The design and specifications for this device were developed at the USDA Forest Products Laboratory. The calipers used for this study were fabricated at the University of Minnesota Scientific Apparatus Shop following guidelines and recommendations provided by the Forest Products Laboratory. Two calipers were used, one caliper was mounted to the wood as shown in Figure 3, while the other caliper was mounted to the interior 12 inch x 11 inch bearing plates.

Load cells provided by the USDA Forest Products Laboratory were used on the interior rods for each of the decks. Prior to any testing, the load cells were assembled and loaded on a single rod and placed in a freezer at -20°F. Subsequent readings showed no apparent temperature effect. It is therefore assumed that all changes in load cell readings were accurately reflecting changes in the actual bar force.

Figure 3

Caliper and Dial Gage Detail



Phase I Results

The results from Phase I are shown in Table 2 and Figures 4 through 8. During Phase I the decks were all in the green condition with mc well above the fiber saturation point. Each of the trial runs showed stress loss. After the freezer was shut off, bar forces returned to levels close to their original settings. When temperatures went from 69.2°F to 10.5°F, bar force dropped from 22.861 KIPs to 14.176 KIPs, a decline of 38%. Caliper results followed a similar pattern: the front caliper (mounted to the plates) measured a decrease of 0.086 inches while the rear caliper measured a decrease of 0.106 inches. Caliper readings returned to nearly their original values after the freezer was shut off.

Subsequent runs in Phase I showed a similar pattern with greater magnitude shrinkage and stress loss as the decks were dropped to lower and lower temperatures. The results at 0°F showed a stress loss of 55% (23.892 KIPs to 10.752 KIPs at 1.7°F). Shrinkage, as measured by the calipers, was 0.136 inches front (plates) and 0.140 inches rear (wood). The results at -10°F showed a 75% decline in bar force (23.902 to 5.975) and shrinkage of 0.176 inches front (plates) and 0.193 inches rear (wood).

The greatest stress losses for Phase I are at -20°F and -30°F. The stress loss at -20°F is 89% (23.423 to 2.526). Shrinkage was 0.204 inches front (plates) and 0.244 inches rear (wood). At -30°F the stress loss was 94.6% (22.892 KIPs to 1.242 KIPs) and shrinkage was 0.232 inches front (plates) and 0.252 inches rear (wood).

Figure 4

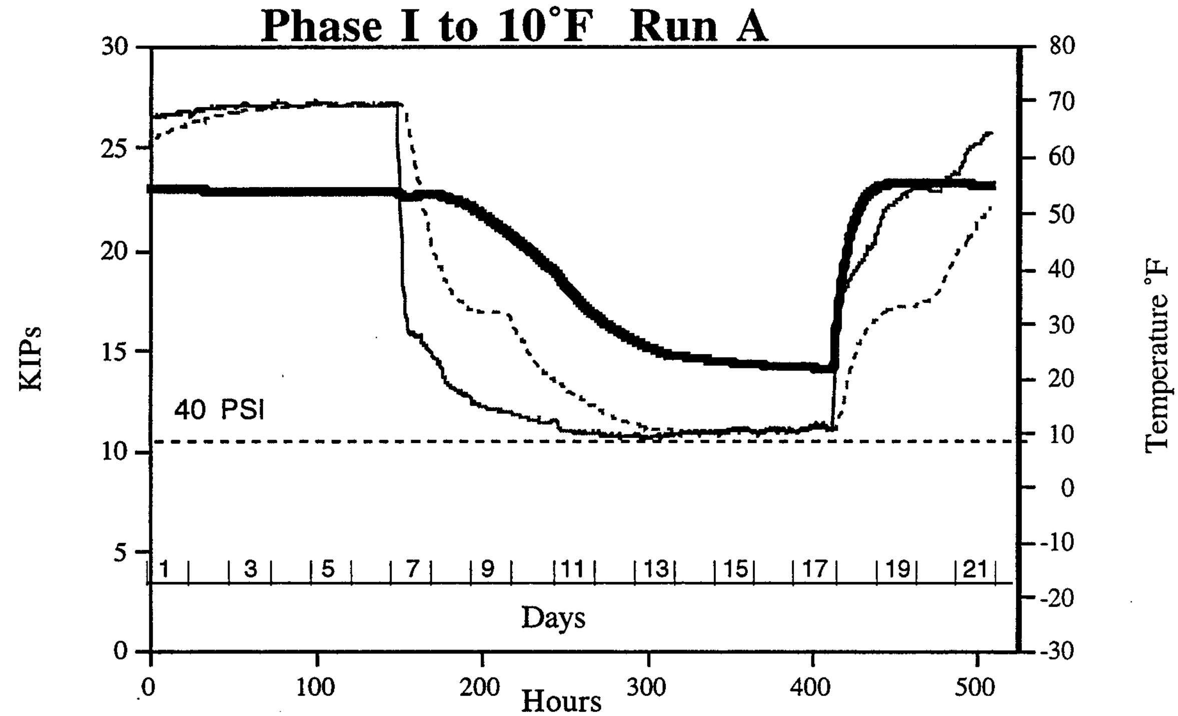


Figure 5

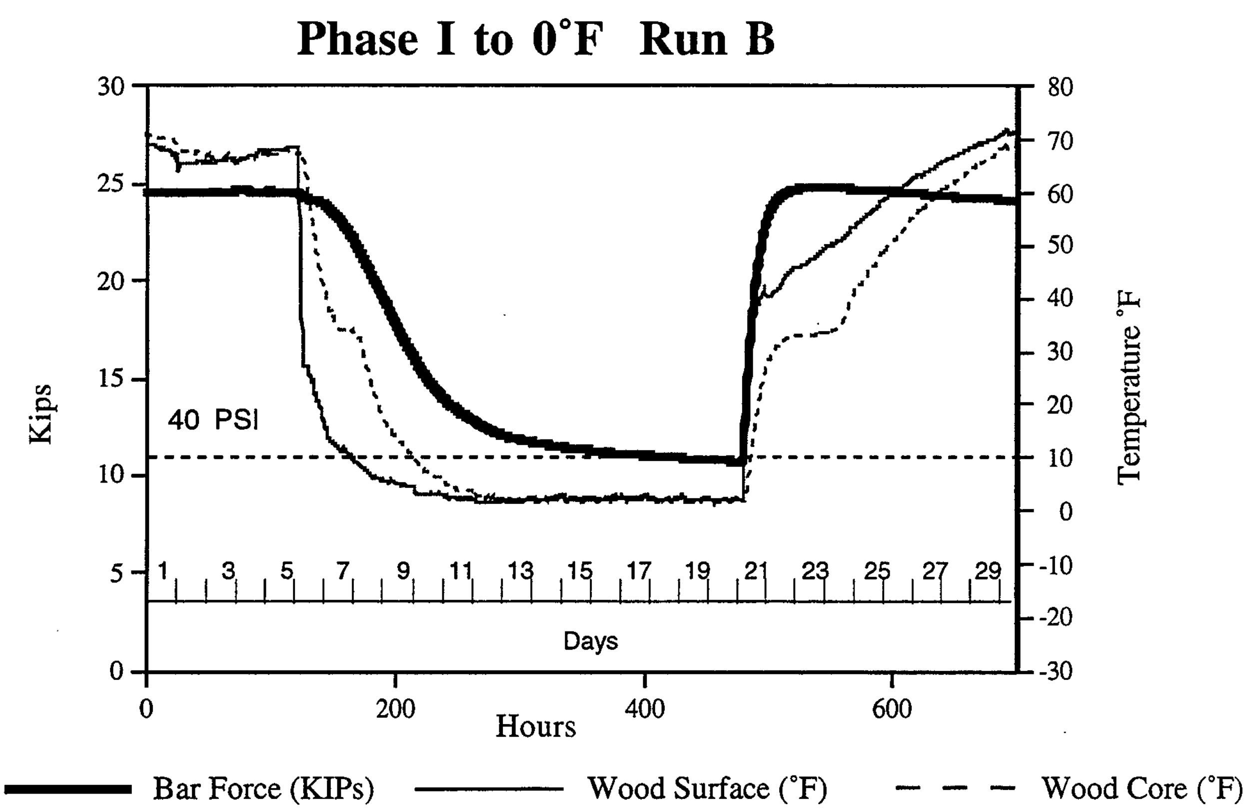


Figure 6

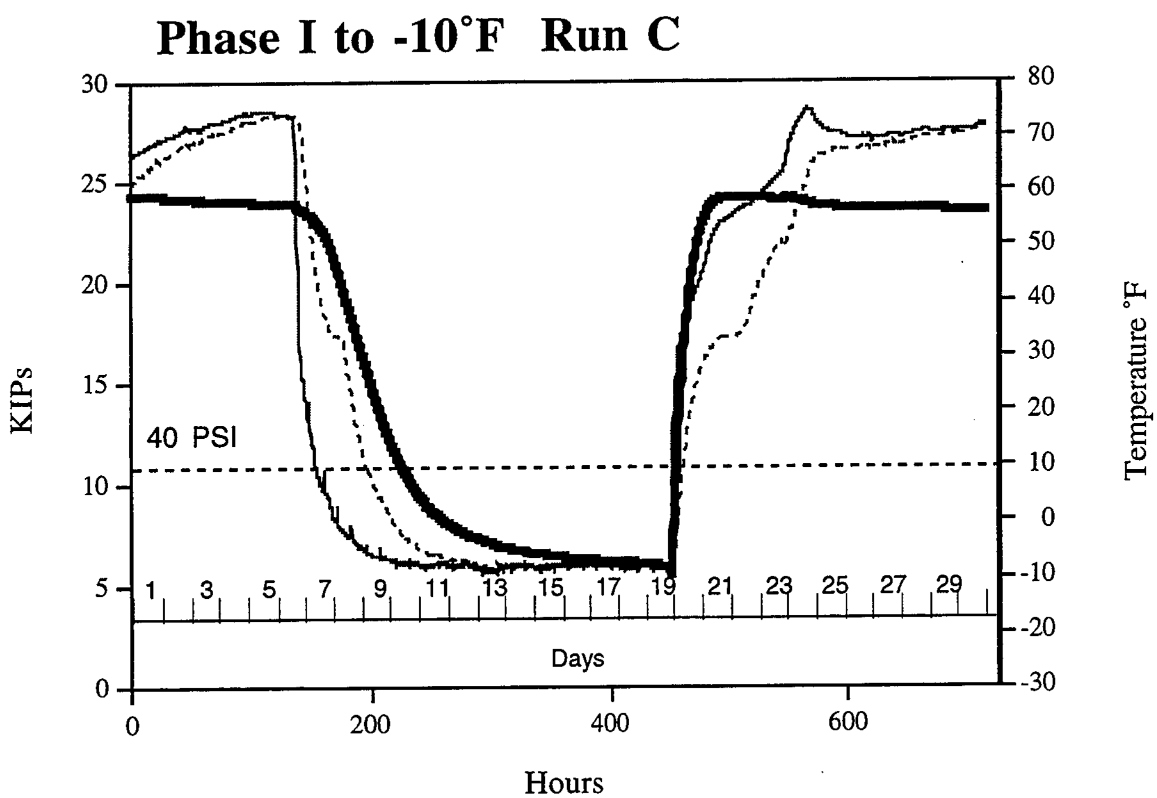


Figure 7

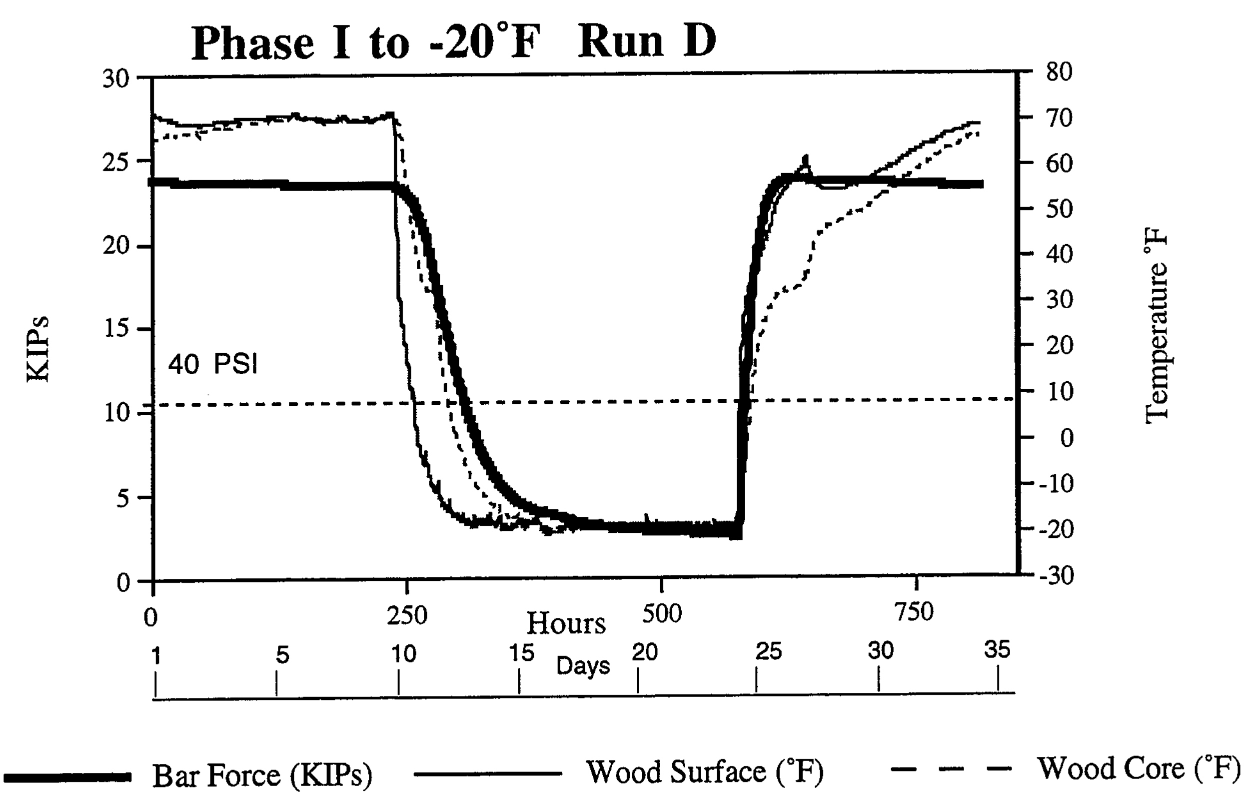


Figure 8

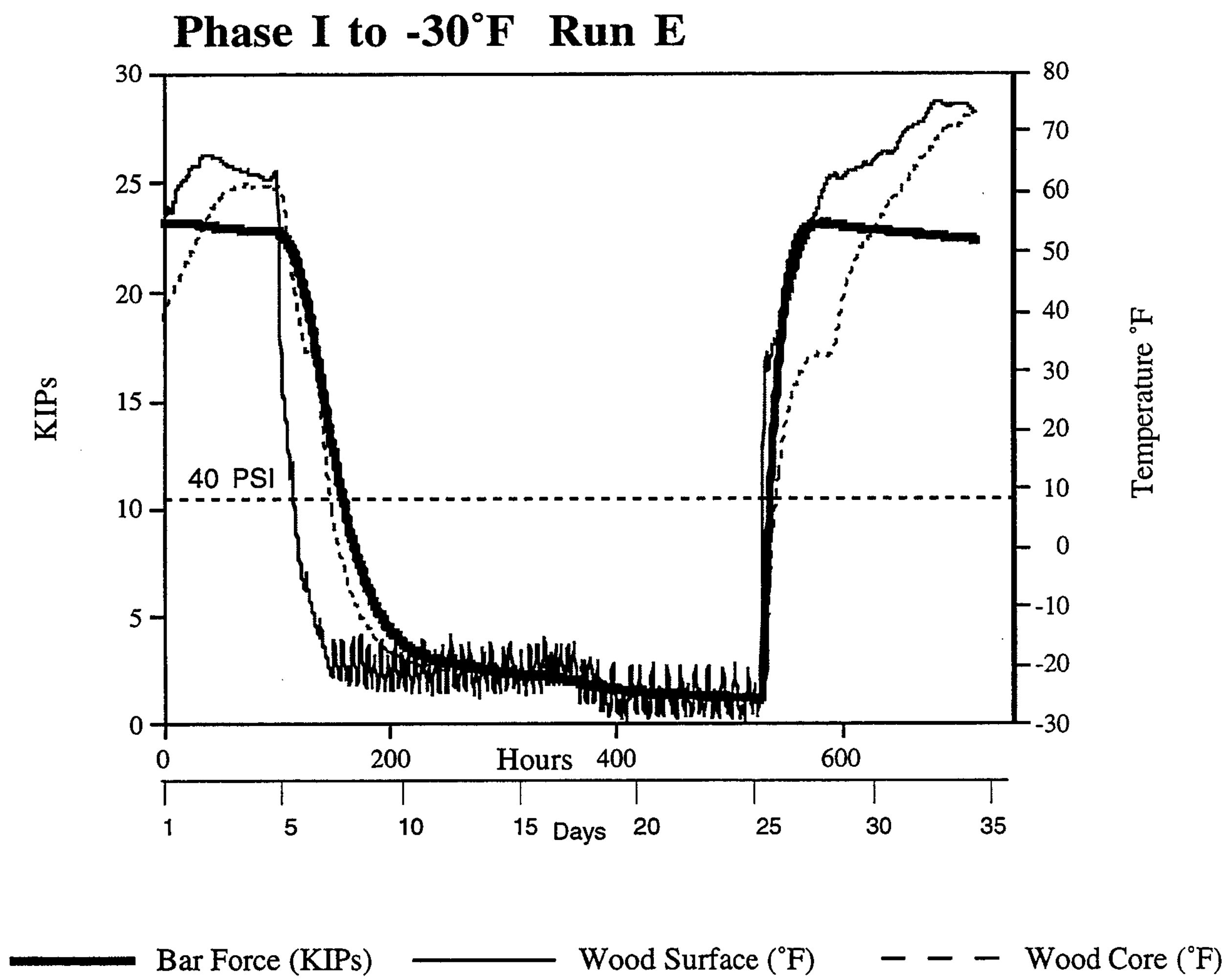

Phase I to -30°F Run E
KIPs
Temperature °F
40 PSI
0
5
10
15
20
25
30
80
70
60
50
40
30
20
10
0
-10
-20
-30
0
200
Hours
400
600
1
5
10
15
Days
20
25
30
35
Bar Force (KIPs)
Wood Surface (°F)
Wood Core (°F)

Table 2 Phase I Results Decks in Green Condition

Phase I to 10°F Run A

	Hours	Temperature	KIPs	Front Caliper	Rear Caliper
Freezer Started	149.0	69.2	22.861	0.185	0.165
Freezer Stopped	412.0	10.5	14.176	0.271	0.271
End of Run	581.5	60.8	22.892	0.182	0.168
Decrease		-58.7	-8.685	-0.086	-0.106
Increase		50.3	8.716	0.089	0.103

Phase I to 0°F Run B

	Hours	Temperature	KIPs	Front Caliper	Rear Caliper
Freezer Started	120.0	68.1	23.892	0.162	0.131
Freezer Stopped	478.5	1.7	10.752	0.298	0.271
End of Run	767.5	73.6	23.908	0.174	0.132
Decrease		-66.4	-13.140	-0.136	-0.140
Increase		71.9	13.156	0.124	0.139

Phase I to -10°F Run C

	Hours	Temperature	KIPs	Front Caliper	Rear Caliper
Freezer Started	134.0	73.5	23.902	0.174	0.131
Freezer Stopped	450.5	-8.7	5.975	0.350	0.324
End of Run	715.5	71.3	23.518	0.176	0.144
Decrease		-82.2	-17.927	-0.176	-0.193
Increase		80.0	17.543	0.174	0.180

Phase I to -20°F Run D

	Hours	Temperature	KIPs	Front Caliper	Rear Caliper
Freezer Started	237.5	71.1	23.423	0.176	0.145
Freezer Stopped	574.5	-18.8	2.526	0.380	0.389
End of Run	814.5	66.9	23.264	0.179	0.169
Decrease		-89.9	-20.897	-0.204	-0.244
Increase		85.7	20.738	0.201	0.220

Phase I to -30°F Run E

	Hours	Temperature	KIPs	Front Caliper	Rear Caliper
Freezer Started	100.5	61.3	22.892	0.179	0.169
Freezer Stopped	527.5	-27.0	1.242	0.411	0.421
End of Run	667.0	62.1	22.649	0.183	0.168
Decrease		-88.3	-21.650	-0.232	-0.252
Increase		89.1	21.407	0.228	0.253

Phase II Results

Phase II results, shown in Table 3 and Figures 9 through 13, are most representative of actual field conditions. The estimated mc was: 17.9% (top deck), 18.2% (middle deck) and 16.1% (bottom deck). The stress loss for Phase II was much less than that observed for Phase I. For Run A (to 10°) stress loss was 18% (26.881 to 21.954). Shrinkage, as measured by the calipers, was 0.043 inches front (plates) and 0.048 inches rear (wood). For Run B (to 0°) stress loss was 16.7% and shrinkage 0.039 inches front (plates) and 0.018 inches rear (wood). While these values may seem confusing compared to Run A, note that stress loss and shrinkage are related to ΔT. For Run A, the initial temperature was 83.5° and the ΔT was 78.1° because the temperature in the decks when the freezer was shut off was 5.4°. For Run B, the ΔT was only 72.5° and a lesser change in bar force would be expected. Run C (to -10°), showed a stress loss of 20.7% (25.224 to 20.883 with a 77.6°ΔT). Deck shrinkage results were similar to Runs A & B (0.039 inches front and 0.038 inches rear).

The greatest stress loss is observed for Runs D and E. Run D (to -20°) shows a stress loss of 20.3% (25.515 to 20.328) and a shrinkage of 0.039 inches front and 0.050 inches rear. Run E (-30°F) had a stress loss of 21.2% and a shrinkage of 0.041 inches front and 0.053 inches rear.

Figure 9

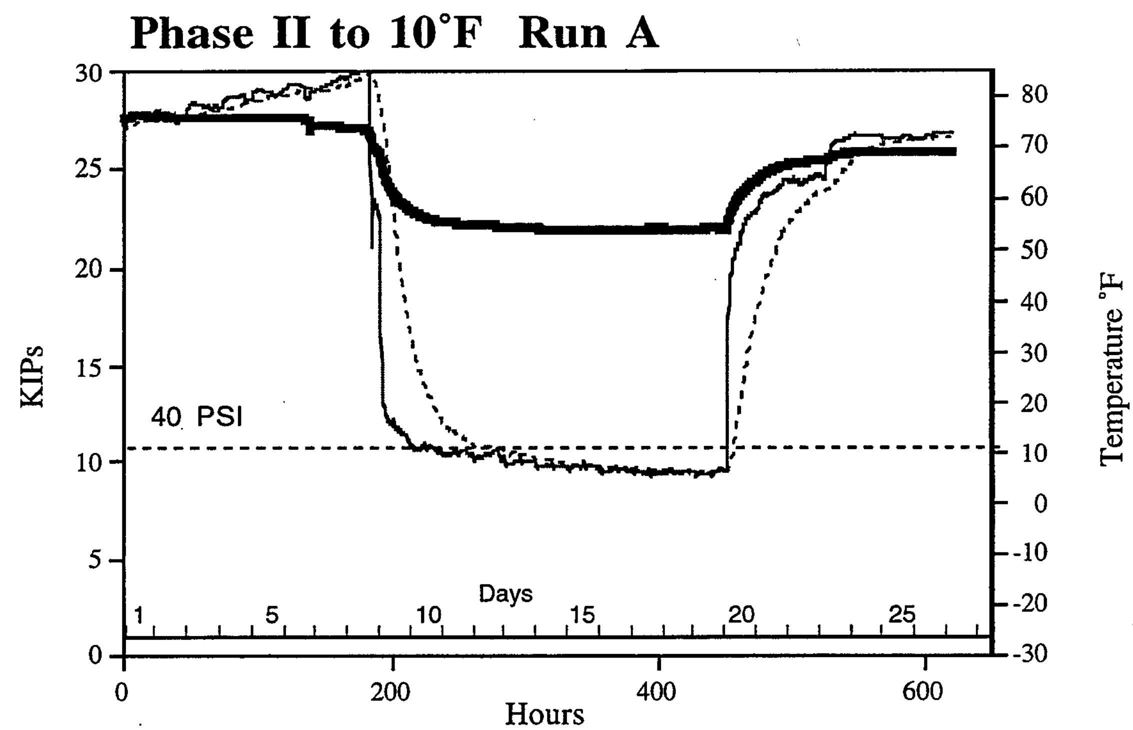
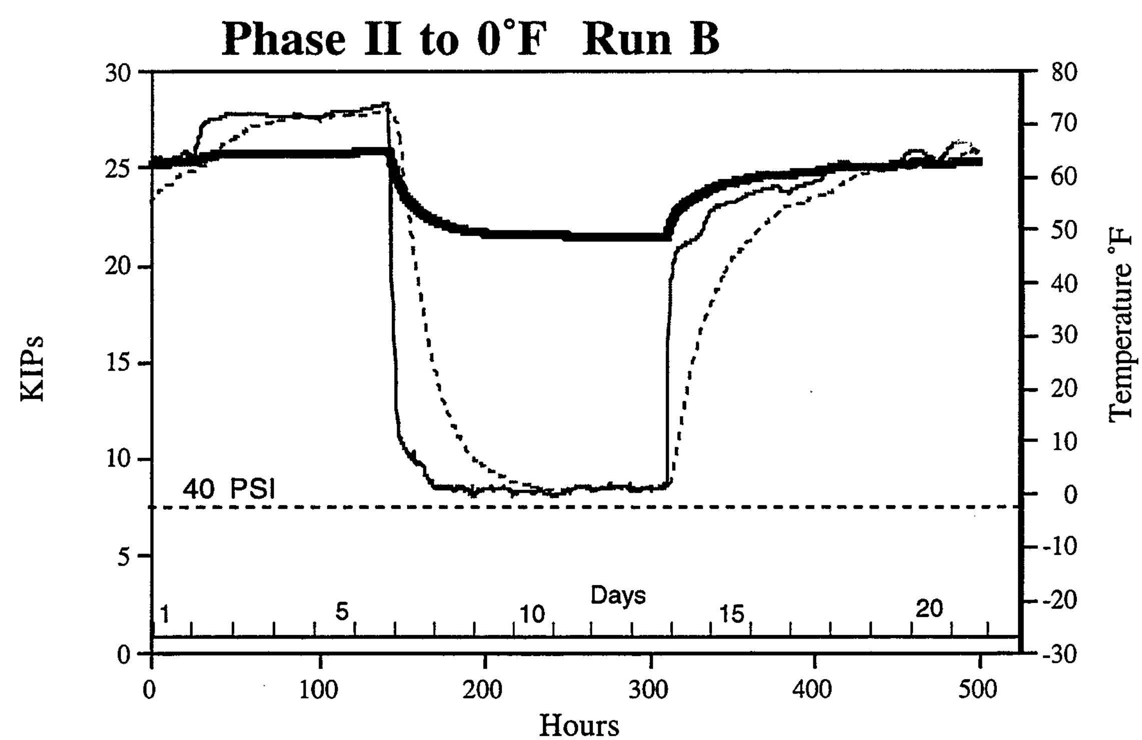


Figure 10



Bar Force (KIPs) — Wood Surface (°F) — Wood Core (°F)

Figure 11

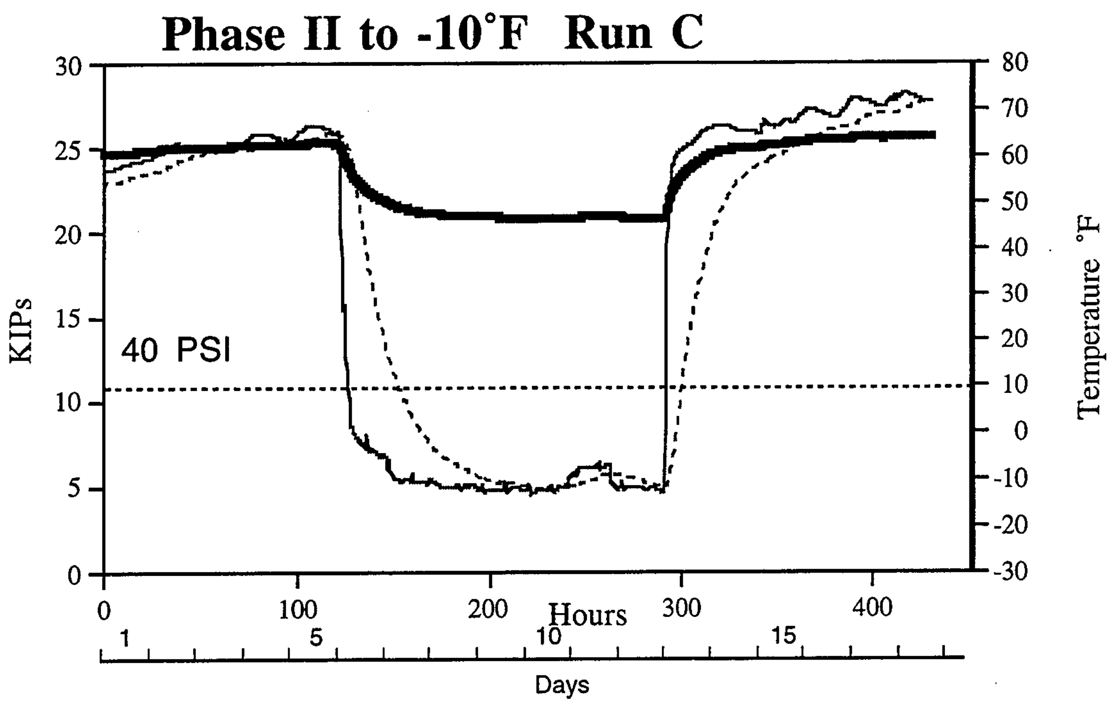
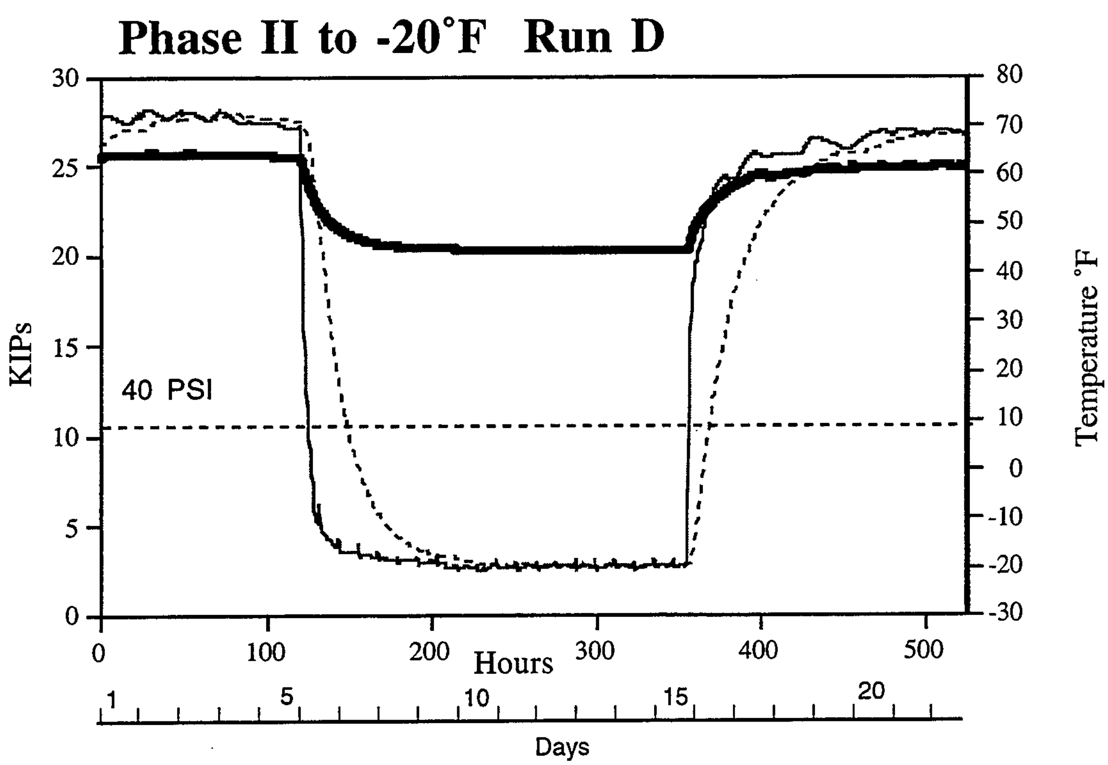


Figure 12



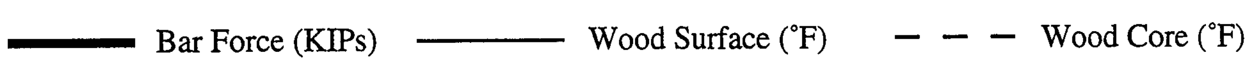
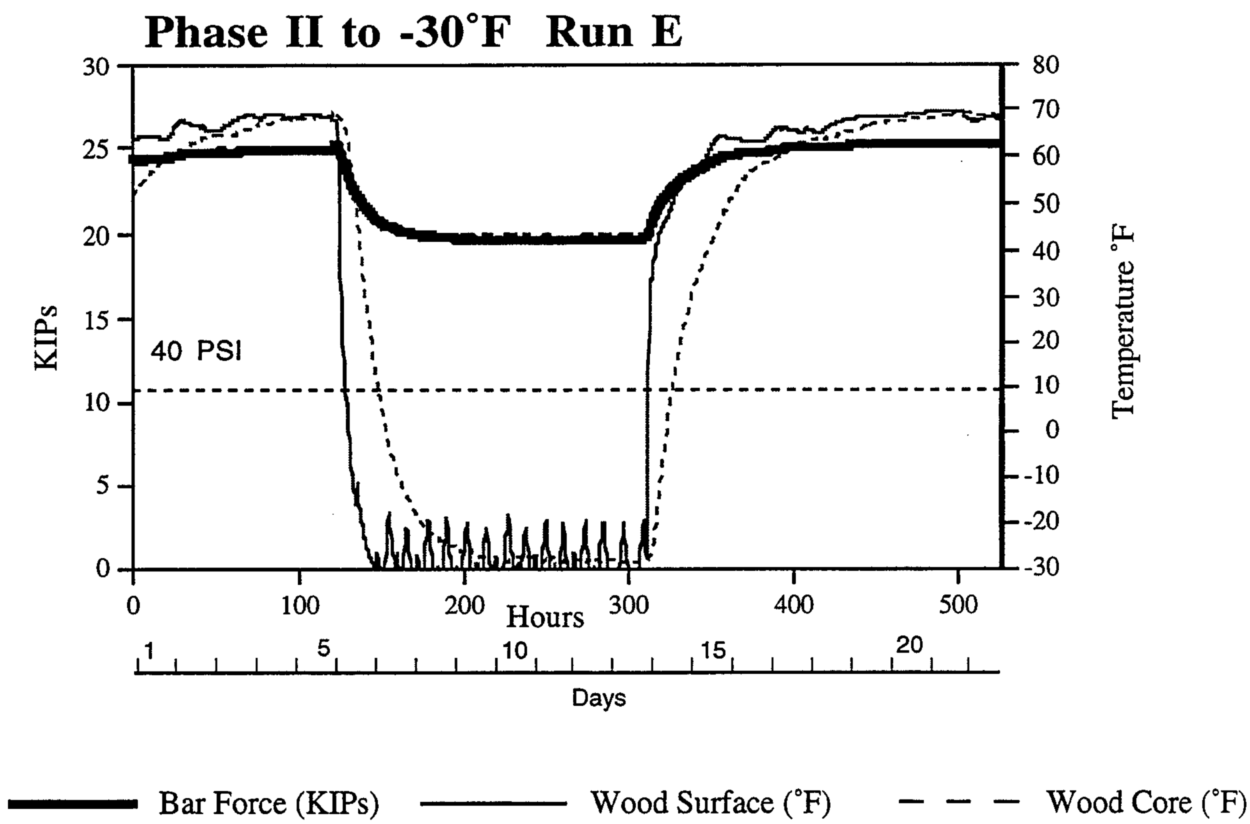


Figure 13



Phase II to -30°F Run E
30
25
20
15
10
5
0
KIPs
40 PSI
80
70
60
50
40
30
20
10
0
-10
-20
-30
Temperature °F
0
100
200
300
400
500
Hours
1
5
10
15
20
Days
Bar Force (KIPs)
Wood Surface (°F)
Wood Core (°F)

Table 3 Phase II Results Decks at 17% mc

Phase II to 10˚F Run A

	Hours	Temperature	KIPs	Front Caliper	Rear Caliper
Freezer Started	182.5	83.5	26.881	0.212	0.202
Freezer Stopped	452.0	5.4	21.954	0.255	0.250
End of Run	620.5	71.8	25.803	0.225	0.216
Decrease		-78.1	-4.927	-0.043	-0.048
Increase		66.4	3.849	0.030	0.034

Phase II to 0˚F Run B

	Hours	Temperature	KIPs	Front Caliper	Rear Caliper
Freezer Started	141.0	73.1	25.857	0.225	0.216
Freezer Stopped	310.0	0.6	21.525	0.260	0.234
End of Run	500.0	65.1	25.268	0.233	0.203
Decrease		-72.5	-4.332	-0.039	-0.018
Increase		64.5	3.743	0.035	0.045

Phase II to -10˚F Run C

	Hours	Temperature	KIPs	Front Caliper	Rear Caliper
Freezer Started	120.5	64.8	25.224	0.233	0.203
Freezer Stopped	290.5	-12.8	20.883	0.272	0.241
End of Run	507.0	70.1	25.004	0.237	0.196
Decrease		-77.6	-5.220	-0.039	-0.038
Increase		82.9	4.121	0.039	0.045

Phase II to -20˚F Run D

	Hours	Temperature	KIPs	Front Caliper	Rear Caliper
Freezer Started	119.5	69.9	25.515	0.237	0.196
Freezer Stopped	355.5	-20.5	20.328	0.276	0.246
End of Run	524.0	68.1	25.004	0.237	0.193
Decrease		-90.4	-8.187	-0.039	-0.050
Increase		88.6	4.676	0.039	0.053

Phase II to -30˚F Run E

	Hours	Temperature	KIPs	Front Caliper	Rear Caliper
Freezer Started	122.5	67.4	25.212	0.237	0.193
Freezer Stopped	310.5	-29.9	19.862	0.278	0.246
End of Run	693.5	66.8	24.972	0.200	0.194
Decrease		-97.3	-5.350	-0.041	-0.053
Increase		96.7	5.110	0.078	0.052

Phase III Results

The mc of the decks in Phase III ranged from 6.7% to 7.5%. Cold-induced shrinkage was observed even at these lower moisture contents. The amount of stress loss in Phase III was significantly less than in Phase II. For Run A (to 10°), stress loss was 9.4% (26.923 to 24.397). Shrinkage was 0.019 inches front and 0.023 inches rear. For Run B (to 0°) stress loss was 9.8% and shrinkage was 0.034 inches front and rear calipers.

Stress loss for Run C (-10°F) was 11.3% (26.393 to 23.134). The shrinkage was 0.022 inches front and 0.034 rear. Run D (to -20°) and had a stress loss of 15.3%. Shrinkage was 0.025 inches front and 0.034 rear. The final run, Run E (to -30°F) showed a stress loss of 16.2% and shrinkage of 0.022 inches (front) and 0.033 inches (rear).

Figure 14

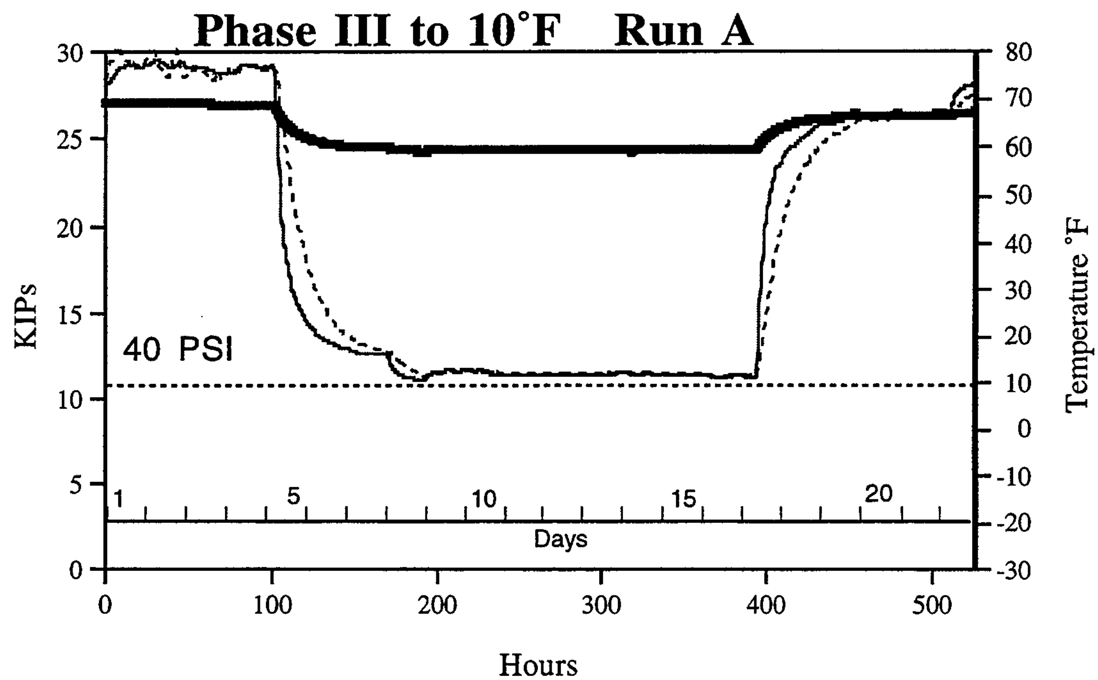
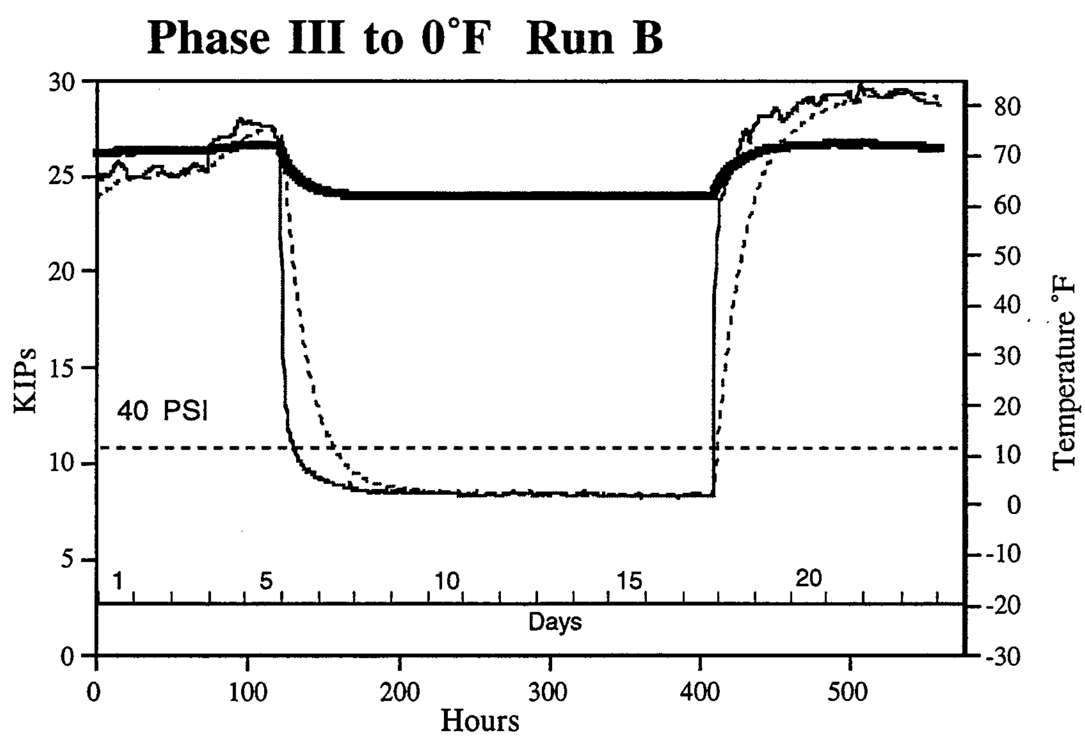


Figure 15



Bar Force (KIPs) Wood Surface (°F) Wood Core (°F)

Figure 16

Phase III to -10°F Run C

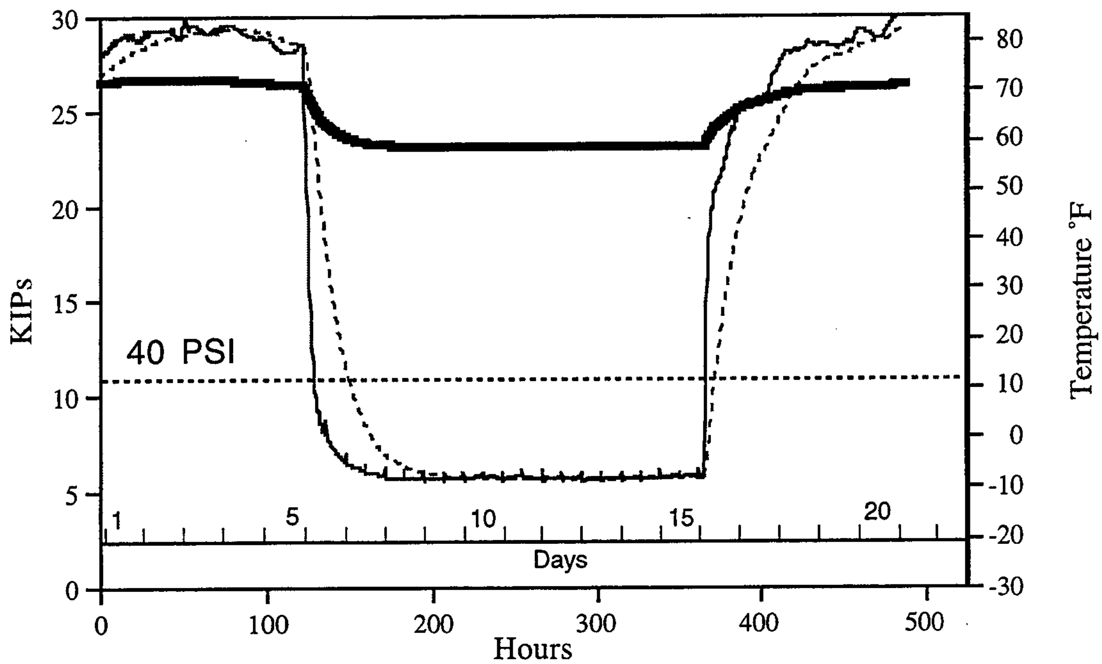
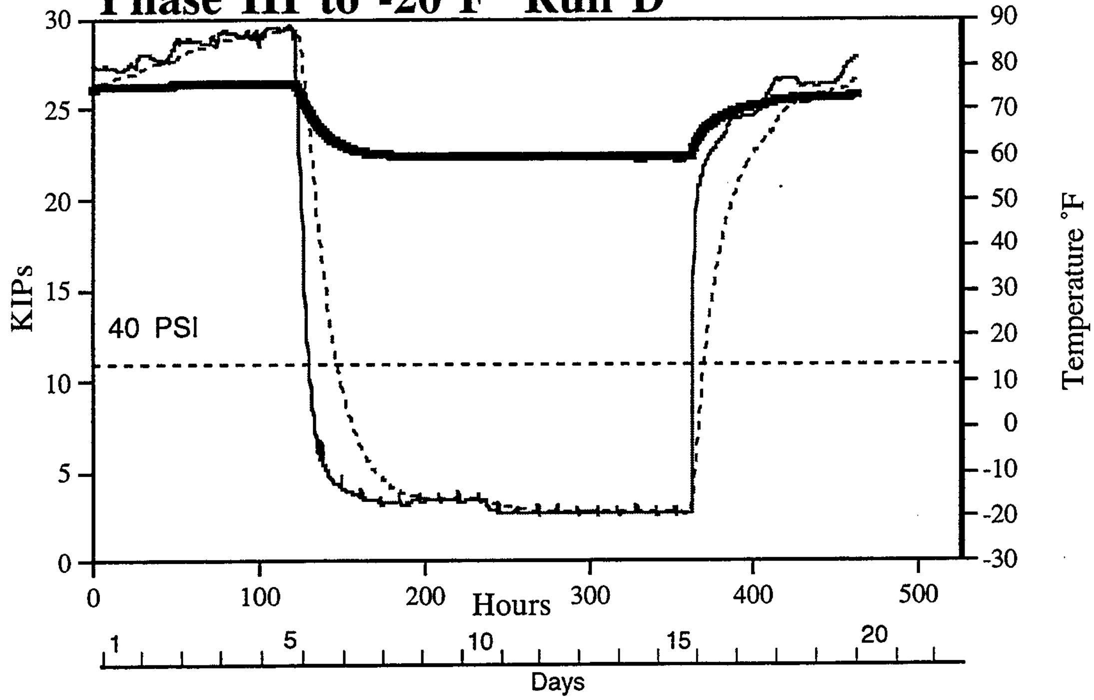


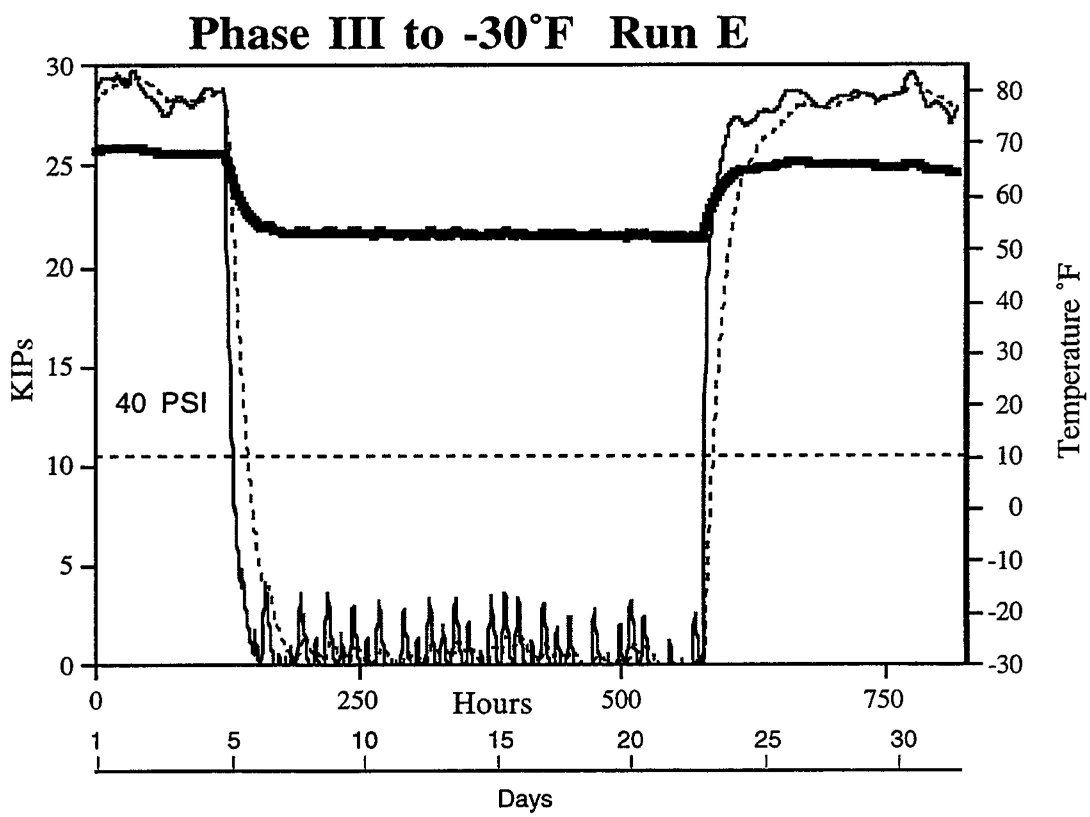
Figure 1

Phase III to -20°F Run D



Bar Force (KIPs) — Wood Surface (°F) - - - Wood Core (°F)

Figure 18



Bar Force (KIPs) ——— Wood Surface (°F) – – – Wood Core (°F)

Table 4 Phase III Results Decks at 7% mc

Phase III to 10°F Run A

	Hours	Temperature	KIPs	Front Caliper	Rear Caliper
Freezer Started	100.5	76.7	26.923	0.515	0.525
Freezer Stopped	393.5	11.4	24.397	0.534	0.548
End of Run	543.0	75.4	26.634	0.518	0.527
Decrease		-65.3	-2.526	-0.019	-0.023
Increase		64.0	2.237	0.016	0.021

Phase III to 0°F Run B

	Hours	Temperature	KIPs	Front Caliper	Rear Caliper
Freezer Started	119.5	73.8	26.599	0.518	0.527
Freezer Stopped	407.0	1.9	23.986	0.552	0.561
End of Run	559.0	81.1	26.498	0.525	0.529
Decrease		75.7	-2.613	-0.034	-0.034
Increase		83.0	2.512	0.027	0.032

Phase III to -10°F Run C

	Hours	Temperature	KIPs	Front Caliper	Rear Caliper
Freezer Started	120.0	79.3	26.393	0.525	0.529
Freezer Stopped	365.5	-7.9	23.134	0.547	0.558
End of Run	487.5	82.8	26.414	0.523	0.528
Decrease		-87.2	-2.979	-0.022	-0.034
Increase		90.7	3.280	0.024	0.031

Phase III to -20°F Run D

	Hours	Temperature	KIPs	Front Caliper	Rear Caliper
Freezer Started	120.0	87.6	26.354	0.524	0.527
Freezer Stopped	361.0	-19.4	22.322	0.549	0.561
End of Run	463.0	78.5	25.797	0.528	0.530
Decrease		-107.0	-4.032	-0.025	-0.034
Increase		97.9	3.475	0.021	0.031

Phase III to -30°F Run E

	Hours	Temperature	KIPs	Front Caliper	Rear Caliper
Freezer Started	120.0	79.9	25.627	0.528	0.530
Freezer Stopped	577.5	-31.6	21.488	0.550	0.563
End of Run	820.0	78.0	24.727	0.529	0.532
Decrease		-111.5	-4.139	-0.022	-0.033
Increase		109.6	3.239	0.021	0.031

Discussion

The most significant results are those in Phase II because Phase II most closely replicates actual field conditions. Moisture contents of about 18% are representative of what can be expected in a stress-lam bridge installation. Each rod is considered to be acting over a 2' x 1' section of the bridge. The lowest recorded bar force for Phase II was 19.862 KIPs. This corresponds to an inter-laminae pressure of 69.0 psi. During Run A of Phase II the stress between laminae dropped from 87.5 psi to 69.0 psi. This decrease in pressure occurred after keeping the decks at -30°F for 188 hours (7.83 days). These results show that properly dried, stress-laminated bridge decks will perform adequately in extremely cold temperatures. A value of 40 psi was noted earlier as the benchmark for when bridges need to be rejacked. As our Phase II tests show, even with several days at -30°F, the inter-laminae pressure was well above this mark.

Excessive moisture is a problem for many wood products and timber bridges are not exempt. During Phase I, with its high mc, the decks needed rejacking part way through the run. Such stress loss is primarily due to perpendicular-to-grain creep which occurs at a higher rate when the lumber is green.

Timber bridges, even those starting with excessively high or low mc, will eventually adjust to a moisture content that is in equilibrium with ambient conditions. Creosote treated bridge decks will not dry as quickly because creosote slows the diffusion of water to the surface. However, after a few years the decks dry out and shrink. Bridge decks that were constructed green will need rejacking after drying, due to shrinking of the laminae.

Results from Phase III (low mc) show the least effect from cold-induced shrinkage. Over-drying bridge laminae to 7% mc will reduce cold-induced shrinkage but will cause problems as the laminae take up moisture and equilibrate to their environment. A consequent swelling of the deck could result in localized crushing under the plates. Our recommendation is to dry the wood to the moisture content that it would normally have in service.

Conclusions

1. Timber bridge laminae that are dried to 19% or less should not be adversely effected by cold-induced shrinkage. Note that AASHTO 1996 and AASHTO LRFD 1996 both contain wording that allows the moisture content to be greater than 19%. Mn/DOT spec also allows the mc to be greater than 19%. The AASHTO Guide Specifications for the Design of Stress-laminated Wood Decks specifies an mc of 19% or less (Section 13.11). For prestressing, the entire piece needs to be at or less than 19% mc.

2. Green lumber (lumber that has not been dried below the fiber saturation point) is significantly effected by cold-induced shrinkage and the greater the temperature variant, the greater the stress loss. Bridge decks exposed to -30°F in the high-mc conditions of Phase I, had stress losses of more than 90% after 20 hours exposure. At high-mc conditions, the rate of stress loss is very fast at the very cold temperatures.

3. Bridge decks dried to 7 - 8% mc showed the least effect from cold temperatures. Furthermore, the percentage of stress loss does not increase appreciably with lowered temperatures (9.4% at 10°F and 16.2% at -30°F).

4. When the freezer was shut off, bar force rebounded to about pre-test levels which indicates that cold-induced shrinkage does not affect the gradual loss of stress over time.

5. Results of this study show that careful monitoring of stress-laminated bridges in cold climates is needed until the mc of the bridge laminae is less than 19%.

6. Further study of the thermal affect on bridges at above 20% mc would be helpful.

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