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Cold Temperature Effects on Stress-Laminated Timber Bridges

A Laboratory Study

James P. Wacker

Abstract

Stress-laminated bridges perform well if adequate bar force is maintained to provide the interlaminar friction and load transfer between adjacent deck laminations. Stress-laminated decks are made of both wood and steel components; therefore, different material thermal properties may cause bar force to change as the temperature changes. In response to concerns about the performance of stress-laminated bridges in extremely cold climates, a cooperative research project between the University of Minnesota, the USDA Forest Service Forest Products Laboratory, and the Federal Highway Administration was initiated to evaluate system performance at temperatures ranging from 21.1°C to –34.4°C. Stress-laminated bridge deck sections, constructed of red pine lumber and high-strength steel stressing bars, were placed in cold temperature settings of –12.2°C, –17.8°C, –23.3°C, –28.9°C, and –34.4°C, while bar force measurements were collected. Testing was completed at three different moisture contents: >30%, 17%, and 7%. At –34.4°C, bar force losses were high when the deck moisture content was above fiber saturation and were moderate to low when the moisture content was below 18%. In all cases, bar force loss was fully recovered after temperatures rose to 21.1°C.

Keywords: stress-laminated, bridge, timber, red pine, temperature, bar force

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Cover Photo—Moose River bridge located on the Chequamegon–Nicolet National Forest in northern Wisconsin.

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Cold Temperature Effects on Stress-Laminated Timber Bridges

A Laboratory Study

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Introduction

Stress-laminated bridge decks consist of a series of wood laminations that are placed edgewise between supports and compressed together with high-strength steel bars (Ritter 1992). The bar force, which typically ranges between 89 and 356 kN (see Table 1 for conversion factors), squeezes the laminations together so that the stressed deck acts as a solid wood plate. Stress-laminating technology was originally developed in Ontario, Canada, in 1976 as a means of rehabilitating nail-laminated lumber decks that delaminated as a result of cyclic loading and variations in wood moisture content. In the 1980s, stress-laminating technology was adapted for the design and construction of new bridges, and several structures were successfully built in Ontario using the stress-laminating concept. The first stress-laminated bridges in the United States were built in the late 1980s. Since then, several hundred stress-laminated timber bridges have been constructed throughout the United States, primarily on low-volume, rural roads. Because of the experimental nature of the new bridge system, extensive field evaluations were implemented by the USDA Forest Service, Forest Products Laboratory (FPL), and the Federal Highway Administration (FHWA) to evaluate long-term field performance (see Appendix A for timber bridge performance reports).

Preliminary data collected from a stress-laminated bridge in northern Minnesota indicated large bar force decreases during the cold winter months. Since several stress-laminated bridges are located in northern climates where sustained cold temperatures are not uncommon, concerns were raised that bar forces may temporarily drop below safe levels during the winter months. To further investigate this cold temperature effect on stress-laminated bridges, laboratory studies were necessary to evaluate the effect of subfreezing temperatures on bar force levels. Results of this study will indicate if stress-laminated bridges should require special design considerations in cold climates.

Table 1—Factors for converting metric units of measurement to inch–pound units

Metric unit	Conversion factor	Inch–pound unit
millimeter (mm)	0.0393	inch (in.)
meter (m)	3.2808	foot (ft)
Newton (N)	0.2248	pound (lb)
Pascal (Pa)	0.001451	pounds per square inch (lb/in^2)
°C	1.8 (°C) + 32	°F

Background

Thermal effects are usually not a consideration in the design of wood highway bridges. However, some bridge designs utilize materials that have unique thermal properties. If not compensated for, any differential between material thermal properties can lead to performance problems when the bridge is exposed to large temperature changes. In these cases, the design needs to compensate for differential movement of bridge components while preserving structural integrity.

Because wood laminations are compressed together with steel bars to form the stress-laminated deck, bar force levels could be adversely affected by large temperature fluctuations. The materials expand and contract at different rates. Since the thermal coefficient of contraction–expansion for wood is approximately twice that of steel, temporary temperature-induced bar force losses may occur as both materials contract under cold temperature conditions. This thermal interaction is complicated by the thermal properties of wood, which are dependent upon many factors including grain orientation. For stress-laminated decks, grain orientation is randomly mixed between radial and tangential directions, which prevents a simplified mechanical analysis.

Thermal contraction of small clear wood specimens has been previously investigated (Kubler and others 1973). An accelerated rate of thermal contraction was observed for moist samples at temperatures below 0°C. Below 0°C, a type of internal drying occurs and moisture diffuses out of the wet cell walls and condenses as ice crystals in the cell cavities. This internal drying causes additional shrinkage that superimposes with pure thermal contraction due to temperature change. Although these tests were not performed on wood members in a stress-laminated configuration, the results give important information about moist wood behavior at cold temperatures.

Other laboratory studies have investigated the effect of cold temperatures on stress-laminated bridge configurations. Pilot studies initiated at the University of Minnesota (Erickson and others 1990) and at FPL (Kainz 1994) shortly after this phenomenon was suspected in field bridges both found that bar force decreased as the temperature dropped below 0°C. Additionally, moisture content of the wood laminations seemed to influence the magnitude of bar force loss.

Based on these laboratory and field studies, stress-laminated bridges located in regions of the United States where extreme cold temperatures are common were suspected to encounter temporary bar force loss. In response to these concerns, a cooperative study was initiated between the University of Minnesota, FPL, and FHWA to evaluate stress-laminated deck bar forces across a wide temperature range and to further investigate this phenomenon and its possible design implications for cold climates. Further effects of preservative, wood species, and moisture content on stress-laminated bridges in cold temperatures have also been evaluated (Kainz and Ritter 1998; Kainz and others 2001).

Objective

The objective of this research was to determine how bar force levels in stress-laminated decks change when exposed to temperatures between 21.1°C and –34.4°C at three different equilibrium moisture content levels.

Test Methods

Testing was completed in the laboratory under controlled temperature and moisture content conditions. Deck sections were sequentially placed from 21.1°C into cold temperature settings of –12.2°C, –17.8°C, –23.3°C, –28.9°C, and –34.4°C and were monitored with load cells (bar force) and thermocouples (temperatures). To detect any moisture content effect, three different wood moisture content levels were used. The deck section configuration and testing procedures are described as follows.

Deck Section Configuration

The general configuration of the stress-laminated deck section used for testing is shown in Figure 1. Deck sections

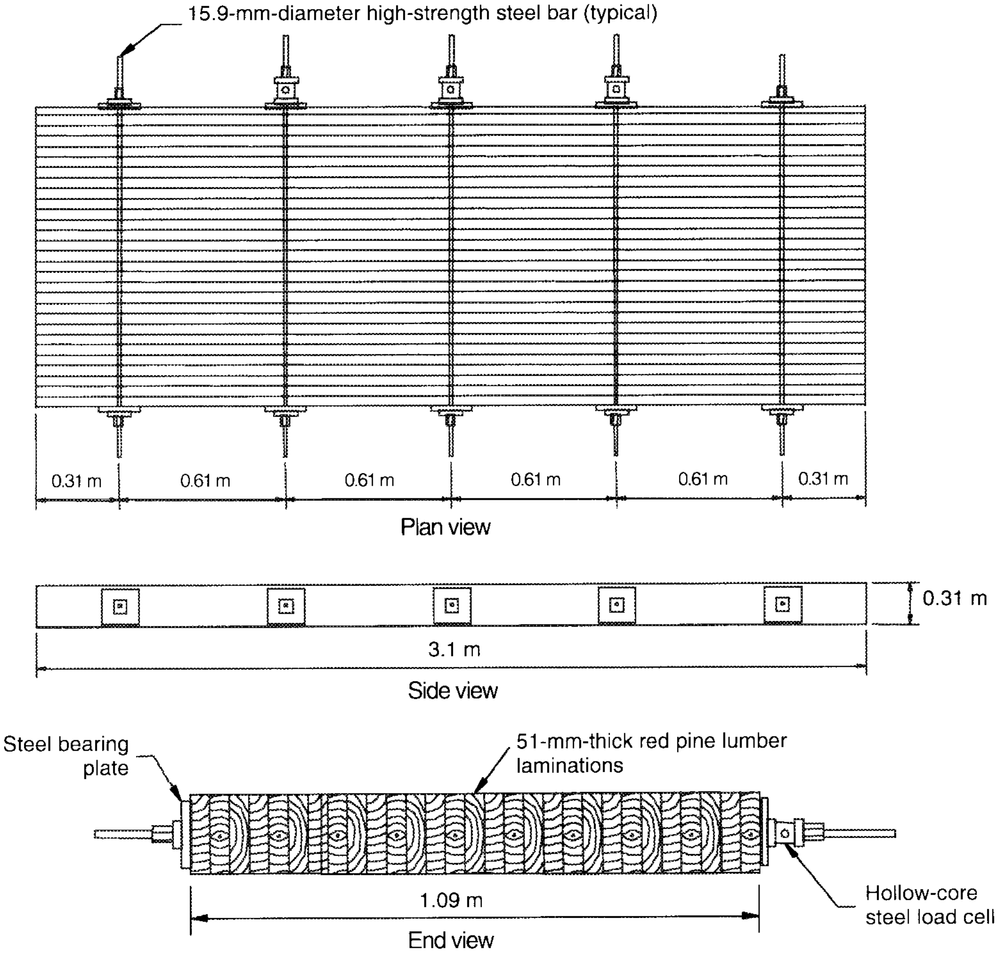

Figure 1—Typical configuration of stress-laminated deck section used in testing.

were constructed to the following dimensions: 3.05 m long, 1.07 m wide, and 305 mm deep. The untreated lumber laminations were full-length red pine (grade no. 2) measuring 51 by 305 mm. Red pine was chosen because a stress-laminated bridge in Minnesota that originally exhibited bar force losses in cold temperatures had deck laminations made from this species. The pre-stressing elements were ASTM A722 high-strength steel bars measuring 15.9 mm in diameter and were spaced at 610-mm intervals beginning 305 mm from the ends. Bars were anchored with rectangular steel bearing plates and flat hex nuts. To measure bar force levels, three steel hollow-core load cells were placed at the interior bar locations of each deck section, between two steel anchor plates.

Testing Procedures

Testing was completed in three phases, each with similar procedures (Table 2). The moisture content of the deck laminations differed in each phase: "green" for Phase I, approximately 17% for Phase II, and approximately 7% for Phase III. For each of the three phases, the same five temperature runs were conducted at increasingly lower temperatures down to –34.4°C. All tests were initiated with bar forces at approximately 120 kN, which is equivalent to an interlaminar compression level of 690 MPa. The procedures used during each phase were repetitive and are described as follows.

Load Cell Calibration

A total of nine steel hollow-core load cells were fabricated in accordance with previously developed specifications (Ritter and others 1991). The cells were designed to compensate for temperature-induced strain variations and were verified at cold temperatures prior to testing. Before the load cells were installed, they were calibrated for compression loads up to 133 kN. In addition, the load cells were recalibrated with the data acquisition system prior to beginning each test phase.

Table 2—Moisture content and temperature conditions used during study[a]

Phase	MC (%)	Temperature runs		
			°C	°F
1	>30	1	21.1 to –12.2	70 to 10
		2	21.1 to –17.8	70 to 0
2	17	3	21.1 to –23.3	70 to –10
		4	21.2 to –28.9	70 to –20
3	7	5	21.1 to –34.4	70 to –30

[a] During each test phase, the moisture content (MC) of the test decks was approximately constant, while all three deck sections were put through each of the five temperature runs listed.

Wood Conditioning

The red pine laminations were purchased in green condition with a high variability in moisture content, between 40% and 70%. The laminations were air-dried for several weeks in an attempt to condition them to approximately 40% moisture content for Phase I. Kiln-drying was not used initially because of concerns that some laminations would drop below the fiber saturation moisture content level, which is approximately 30%. Therefore, the actual moisture content of the laminations during Phase I testing varied between 40% and 60%. For Phases II and III, kiln drying was used to reduce the lamination moisture content to the desired level and to provide more uniform moisture content levels. Throughout testing, an electrical resistance moisture meter (when reliable) and individual lamination weights were used to measure wood moisture content. To prevent fluctuations in moisture content within each phase, the deck laminations were wrapped with polyurethane plastic.

Deck Assembly and Stressing

After the laminations were conditioned to the desired moisture content for each test phase, the deck sections were assembled and the bars were tensioned with hydraulic equipment. To assemble the deck sections, the laminations were placed on edge and stressing bars were inserted through 19-mm-diameter predrilled holes in the laminations. Thermocouples were embedded at several locations within the deck to provide interior wood temperatures. Bearing plates and anchor nuts were then attached. At the completion of Phase I testing, the laminations were numbered and the grain orientation was noted so they could be reassembled in the same manner for future test phases.

After assembly, the stressing bars were tensioned using a hydraulic pump and a single hollow-core ram. Beginning at one end, each bar was tensioned to 120 kN in a sequential manner until the entire deck was stressed together. Plate crushing into the outer laminations was a concern, especially at the high moisture contents used in Phase I, because it would cause bar force loss and dilute any temperature effect data. To detect wood crushing, the outside laminations were visually inspected after removing bearing plates at the completion of each phase.

Data Collection

After the decks were compressed together, data collection was initiated. A data acquisition system was used to monitor bar force, ambient air temperature, and interior wood temperature at 1-h intervals during all temperature runs. Data collection typically began several hours before the decks were placed into the freezer room to ensure that the bar force was stabilized at a constant level. By ensuring constant bar force prior to initiating temperature runs, bar force would be influenced solely by temperature effects. For each temperature run, the decks remained in the freezer until the embedded thermocouples indicated temperature equilibrium. Each temperature run was terminated several hours after removal from cold temperatures when the temperature equilibrated to 21.1°C.

Results and Discussion

The results from all temperature runs during the three phases are summarized in Figure 2. Measured bar forces from all three deck sections were approximately equal and were averaged for each test phase. To aid interpretation, data plots were normalized to the same initial bar force level and test duration. For all test phases, the initial bar forces were within 10% of the target level (120 kN), which corresponds to 690 MPa interlaminar compression. The test duration for the individual tests varied between 500 and 800 h, with more time required to cool the decks to lower temperatures. In addition, no crushing was detected on the exterior laminations. Raw data summaries are also provided in Appendix B for all temperature runs.

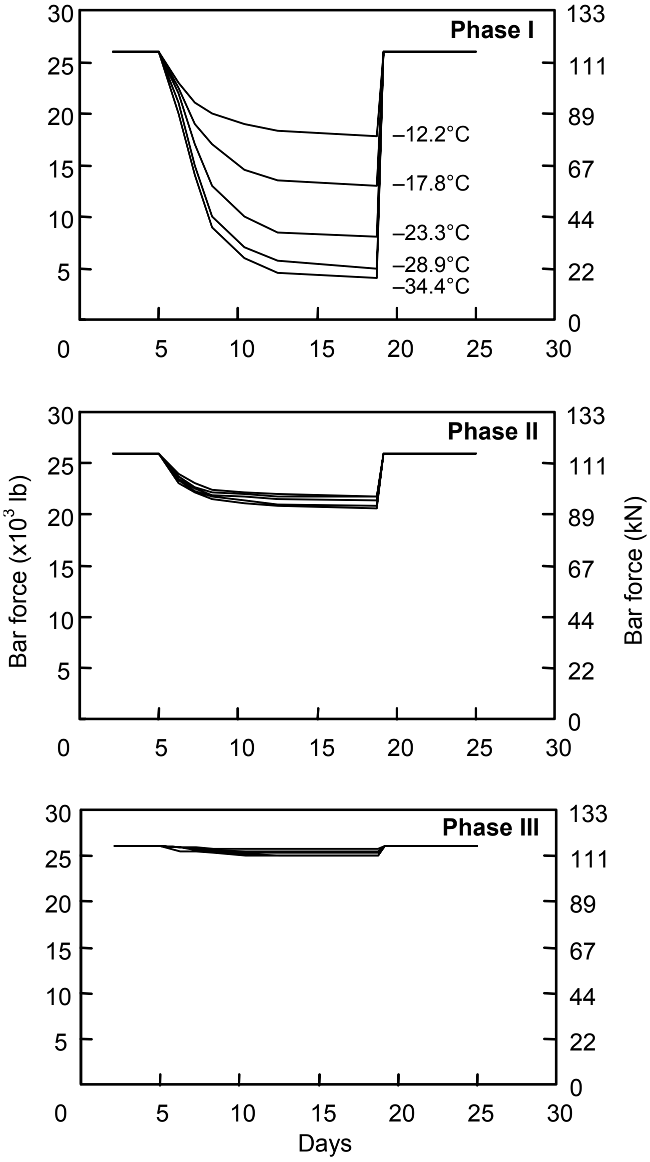

Figure 2—Normalized bar force histories from the three test phases. Each temperature run is denoted with a line, but only phase I is labeled with the lowest temperature for each run because the bar force was so similar for each temperature run in phases II and III.

Phase I

Bar force losses were high during Phase I at a moisture content above fiber saturation. These losses became significantly greater as temperature settings decreased from –12.2°C to –34.4°C. For the first temperature run to –12.2°C, bar force losses totaled approximately 40 kN, or 33% of the original bar force. Bar force losses for intermediate temperature runs to –17.8°C, –23.3°C, and –28.9°C were 52%, 70%, and 81% of the original bar force, respectively. For the last temperature run to –34.4°C, bar force losses were approximately 102 kN, or 85% of the original bar force.

Phase II

Bar force losses were moderate during Phase II at a moisture content of approximately 17%. The losses became only slightly greater as the temperature decreased from –12.2°C to –34.4°C. For the first temperature run to –12.2°C, bar force losses were approximately 22 kN, or 19% of the original bar force. For the last temperature run to –34.4°C, bar force losses totaled approximately 29 kN, or 22% of the original bar force. Bar force losses for temperature runs to –17.8°C,–23.3°C, and –28.9°C were intermediate to these values.

Phase III

Bar force losses were low during Phase III at a moisture content of approximately 7%. The losses were essentially constant as the temperature decreased from –12.2°C to –34.4°C. For the first temperature run to –12.2°C, bar force losses totaled approximately 6.7 kN, or 6% of the original bar force. For the last temperature run to –34.4°C, bar force losses were approximately 8.9 kN, or 7% of the original bar force. Bar force losses for temperature runs to –17.8°C, –23.3°C, and –28.9°C were intermediate to these values.

Phase Comparison

Percentage bar force loss for each phase is compared with the magnitude of temperature decrease in Figure 3. Temperature start and end points were normalized to aid in interpretation. At the moisture content of 7% used in Phase III, the bar force loss was less than 5% and increased slightly as temperature decreased. At the intermediate moisture content of 17% used in Phase II, the bar force loss was less than 20%

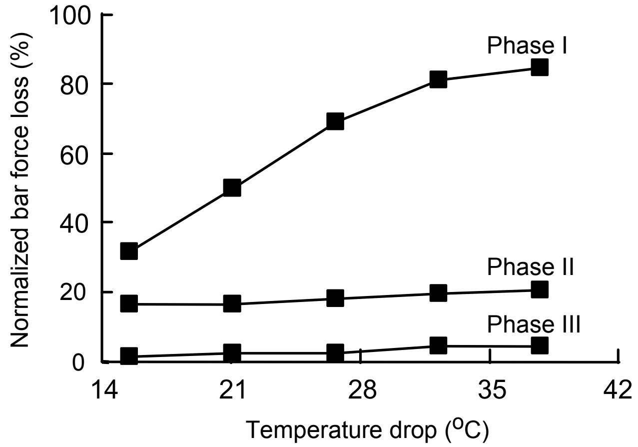

Figure 3—Average bar force loss for each test phase.

and increased slightly as temperature decreased. At a moisture content higher than 30% (green) in Phase I, the bar force loss ranged from 33% to 85% as the temperature decreased. Similar results (Kubler and others 1973) with small wood samples also indicate an accelerated rate of thermal contraction at higher moisture content.

These results indicate that large bar force losses are possible in stress-laminated bridges located in cold-temperature climates. The magnitude of bar force loss depends on a number of factors including the temperature drop, the duration of cold temperature, and the moisture content. Short-term temperature declines, periods of 24 h or less, seem to have little effect on bar force because thermal conductivity of wood is very low. This cold temperature effect appears to be fully recoverable, and the bar force returns to the original level when the temperature increases. In addition, results from monitoring stress-laminated bridges located in cold temperature climates have not detected substantial bar force losses due to temperature effects. (Specific monitoring results from a stress-laminated bridge in northern Minnesota are found in Wacker and others (1998) in Appendix A.)

Discussion

This cold temperature effect has not been a serious problem for bridges in service because of two factors. The first factor is that inspections of several stress-laminated bridges across the United States found the average deck moisture content to be less than fiber saturation in service (see Appendix A). Current AASHTO bridge specifications (AASHTO 1996) require that all lumber be conditioned to a maximum moisture content of 19%, after preservative treatment and at installation. The second factor is the conservative nature of the initial design force in the tensioning bars. Current AASHTO guide specifications (AASHTO 1991) require a conservative factor of safety to offset potential bar force losses. This conservative design approach has limited cold temperature effects on stress-laminated decks to moderate levels, as noted in phases II and III.

Summary and Conclusions

Bar forces were monitored on three stress-laminated deck sections as they were placed in cold temperature settings of –12.2°C, –17.8°C, –23.3°C, –28.9°C, and –34.4°C. Testing was completed at moisture content levels of 7%, 17%, and green condition. Based on the bar force measurements, the following conclusions are presented:

- Bar force loss observed at all cold temperature and moisture content conditions was fully recovered at the completion of each temperature run.
- At any given moisture content level, the maximum bar force loss was observed during the coldest temperature drop to –34.4°C.
- The moisture content of the laminations had a significant effect on the magnitude of bar force loss. Maximum bar force loss totaled 85% of the original bar force at >30% moisture content (Phase I), 22% at 17% moisture content (Phase II), and 7% at 7% moisture content (Phase III).
- Although there was a significant reduction of bar force at temperatures below –17.8°C and moisture content in excess of fiber saturation, field studies conducted at a bridge site in northern Minnesota (Wacker and others 1998) show that this phenomenon has not been a problem for bridges in service.
- These results do not warrant development of special thermal design considerations for stress-laminated bridges to be built in the lower 48 states. However, some thermal design considerations may be warranted in colder climates such as Alaska and Canada. The results also emphasize the importance of specifying and inspecting lumber to be dry (less than 19%) at installation, especially for stress-laminated bridges.

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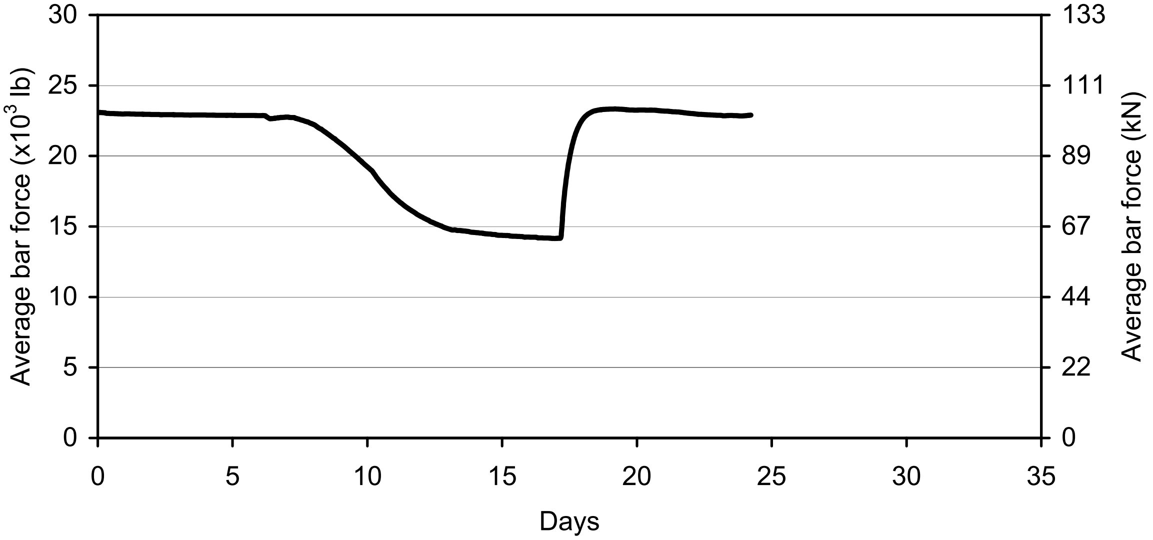
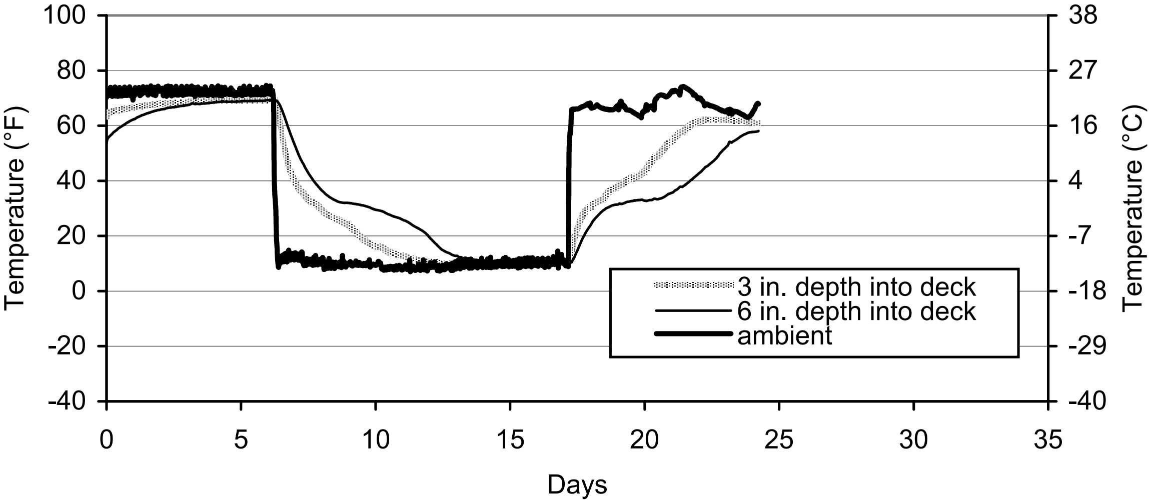
Appendix B—Raw Data Summary





Phase I — Decks at >30% moisture content
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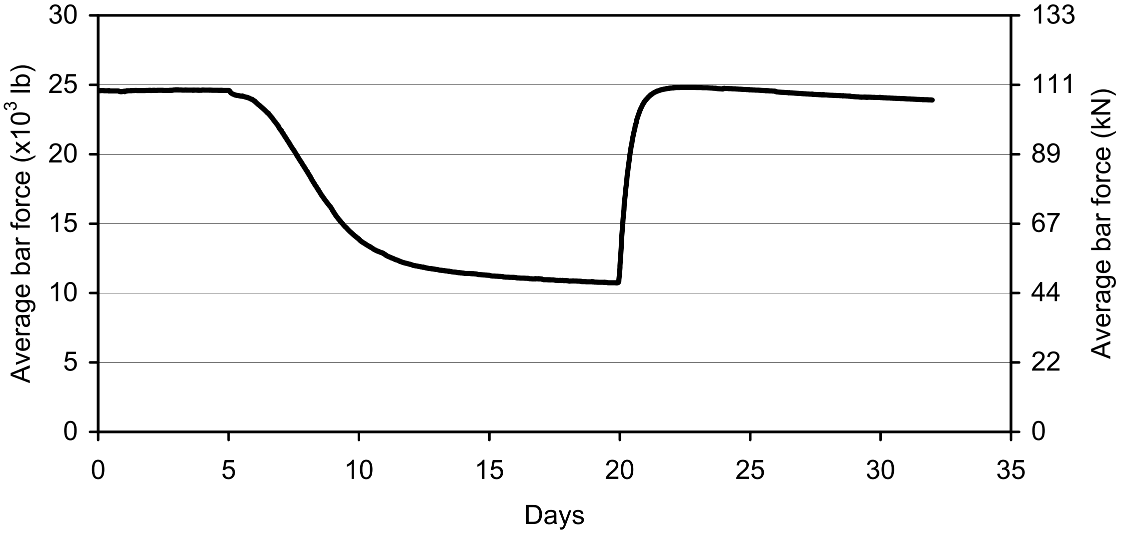

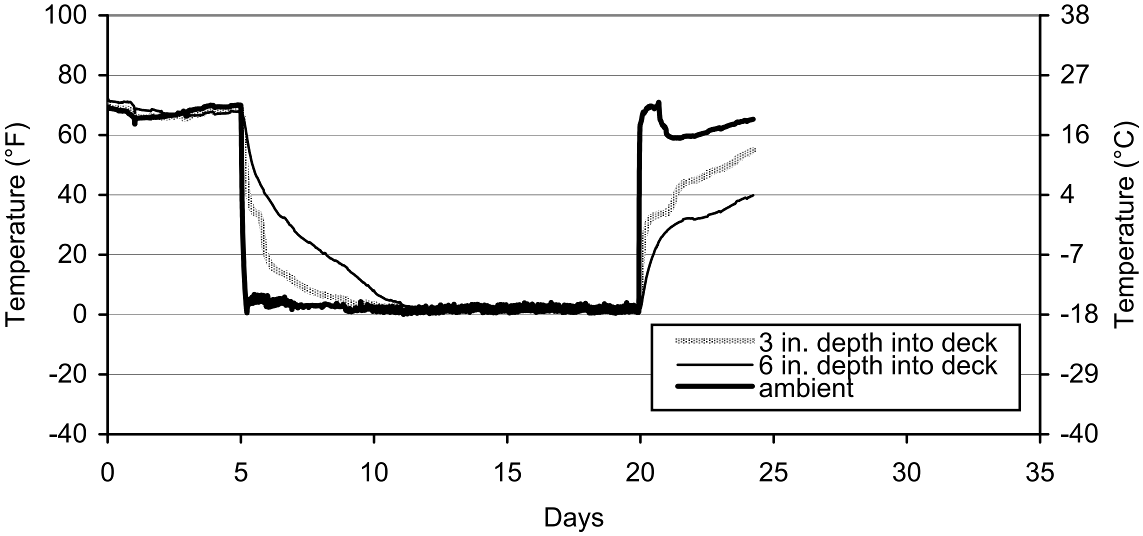

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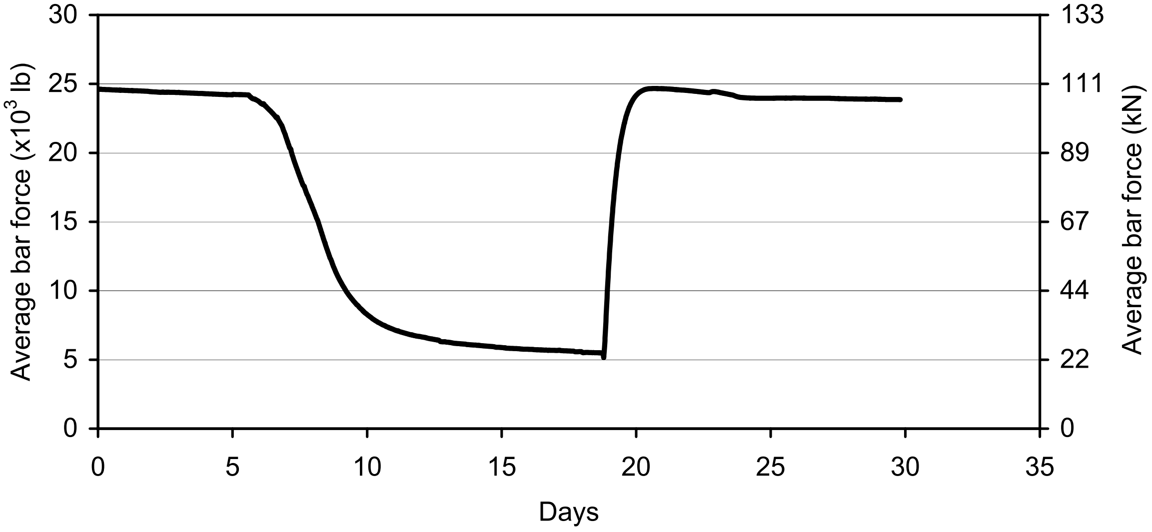

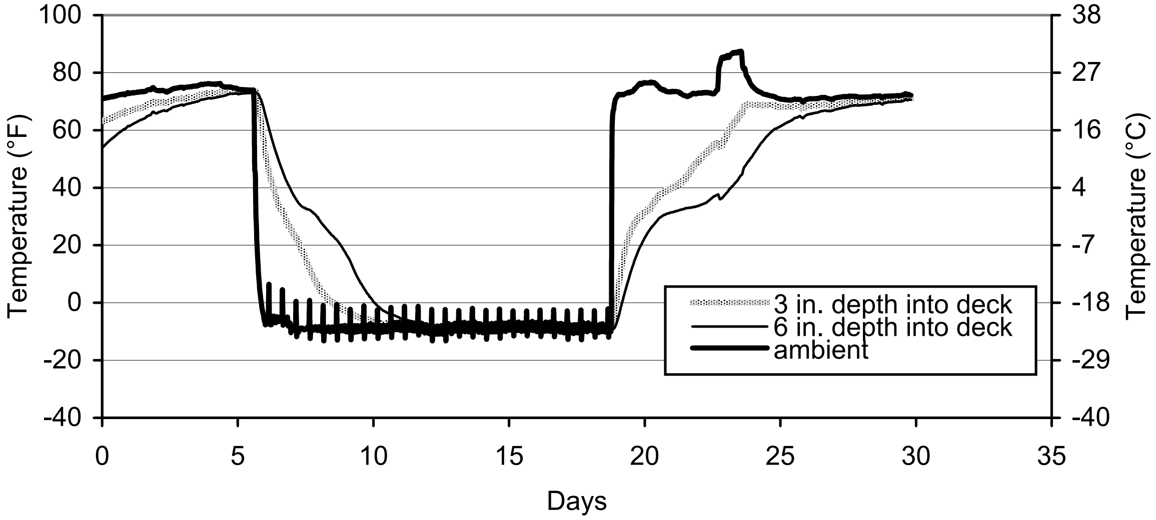

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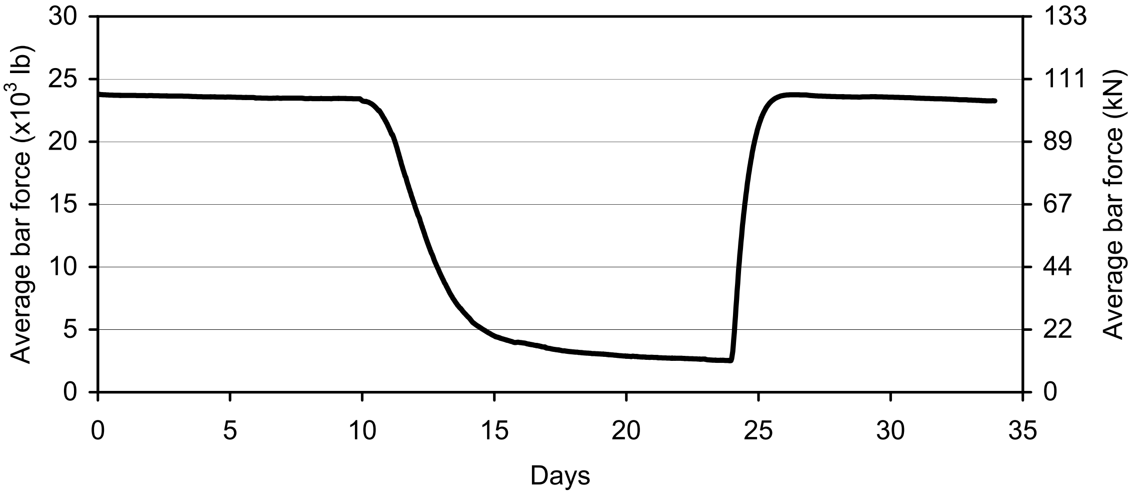
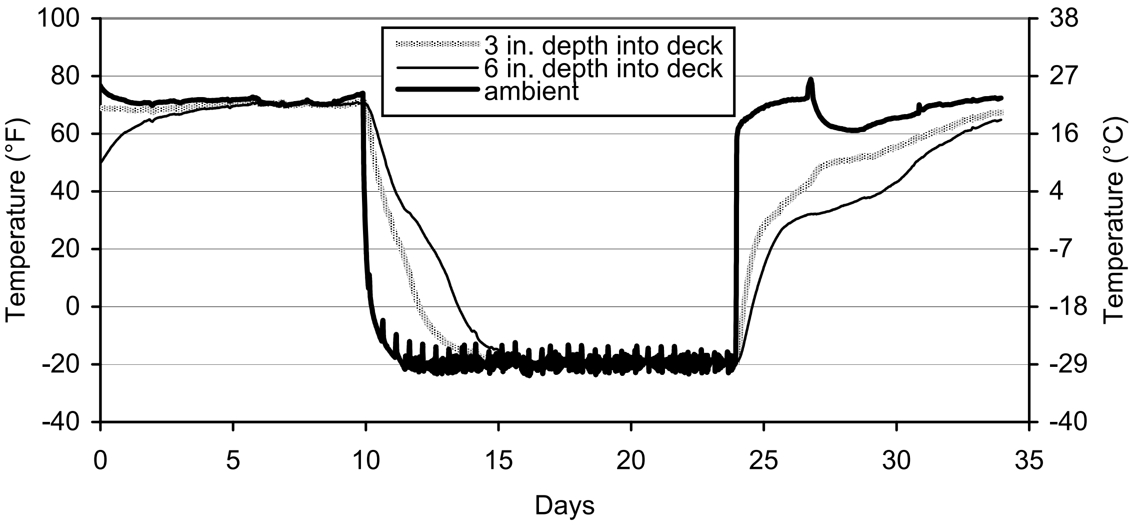
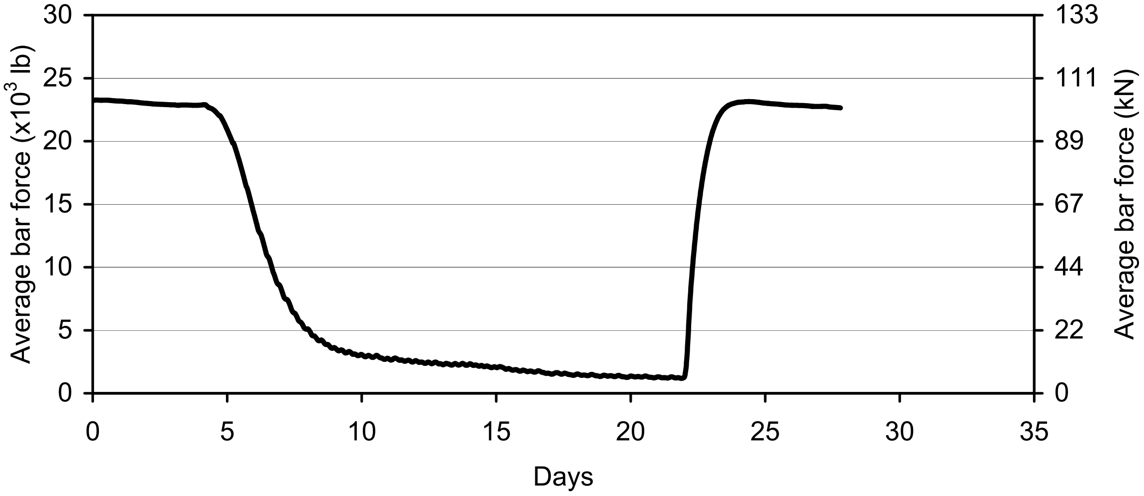
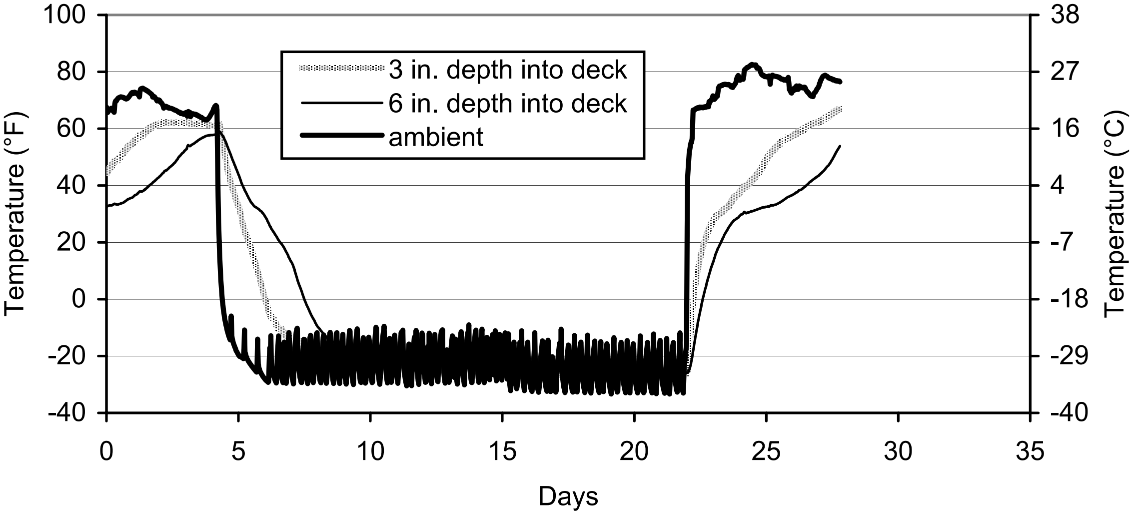


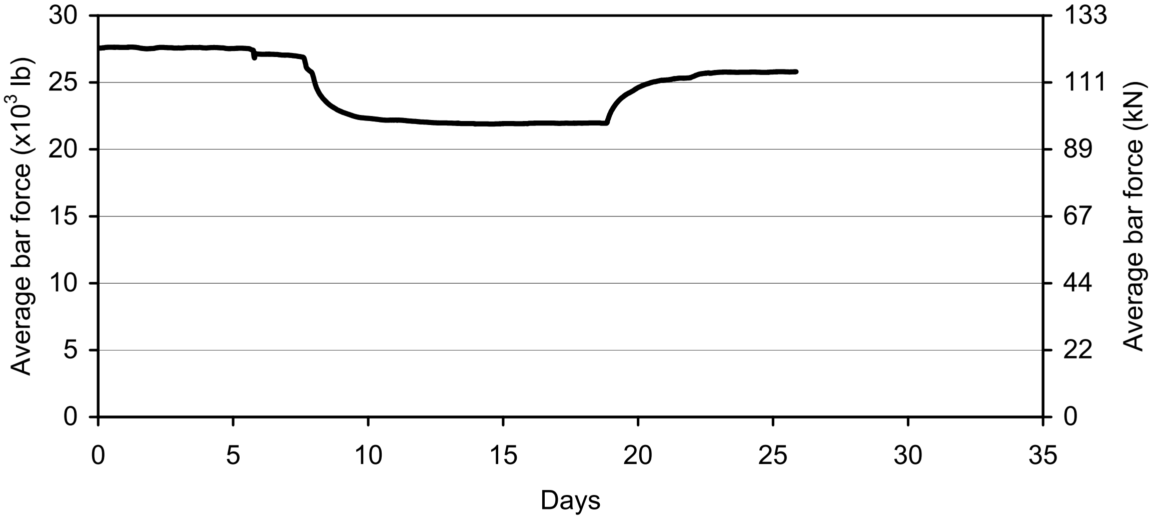


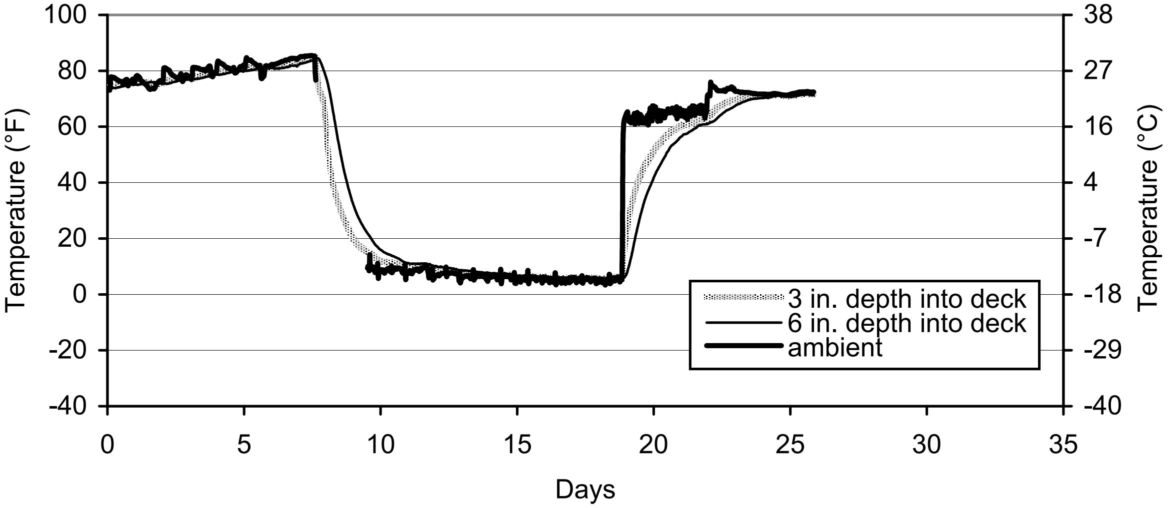
Phase I — Decks at >30% moisture content
Temperature Run — 21.1°C (70°F) to -28.9°C (-20°F)



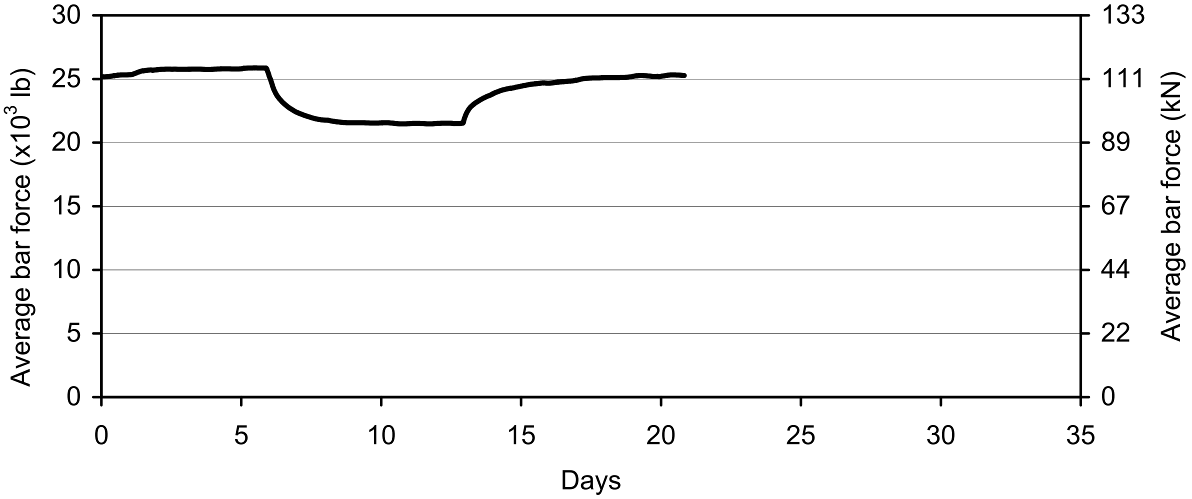


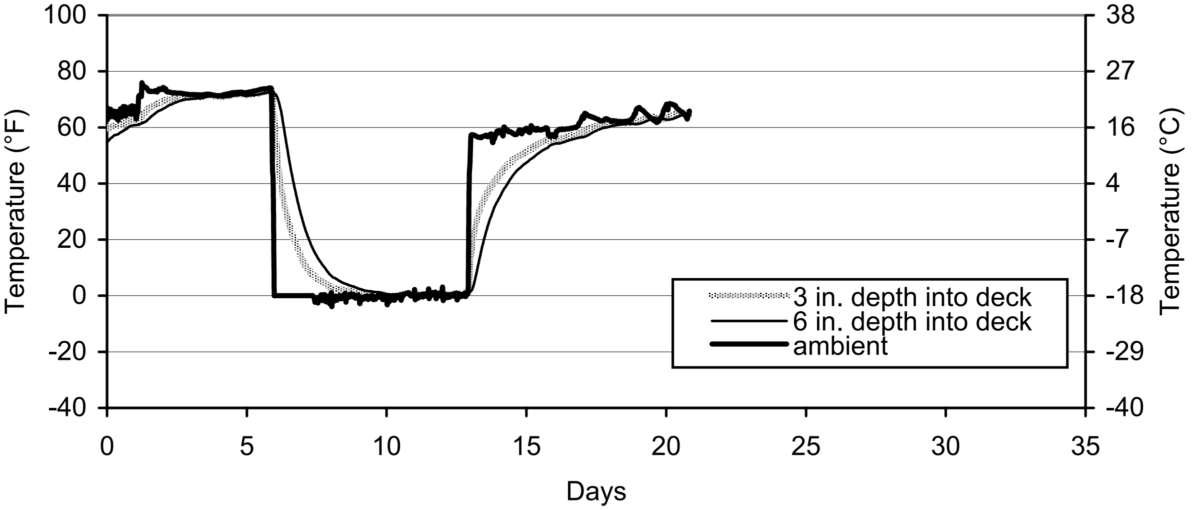
Phase I — Decks at >30% moisture content
Temperature Run — 21.1°C (70°F) to -34.4°C (-30°F)



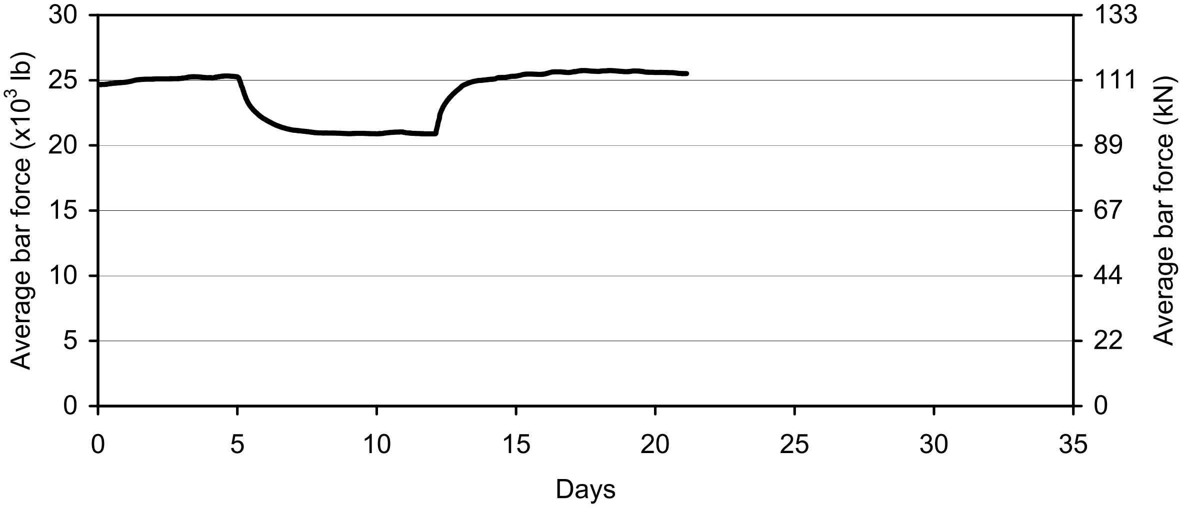


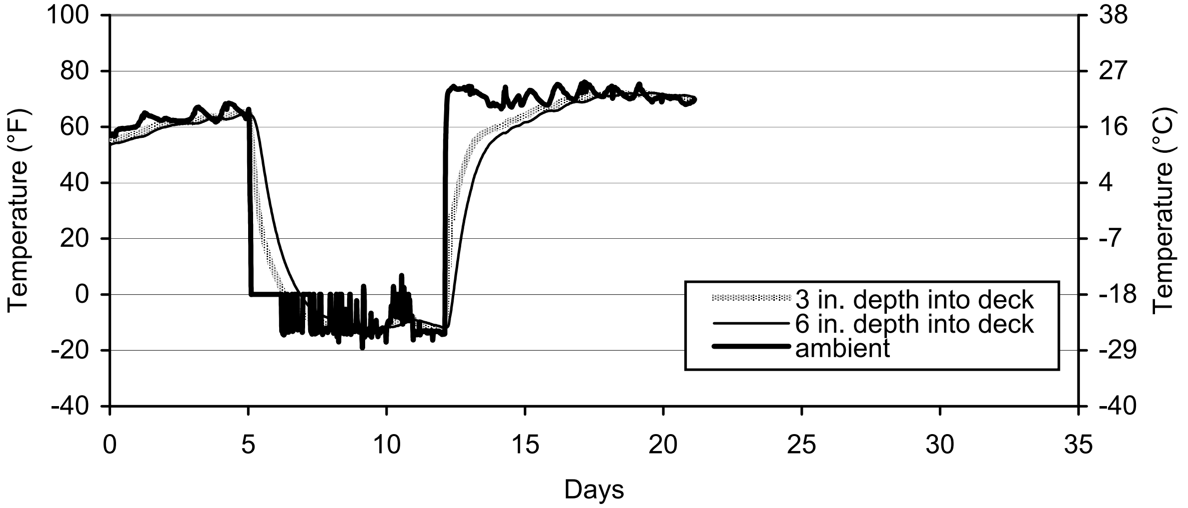
Phase II — Decks at ~17% moisture content
Temperature Run — 21.1°C (70°F) to -12.2°C (10°F)



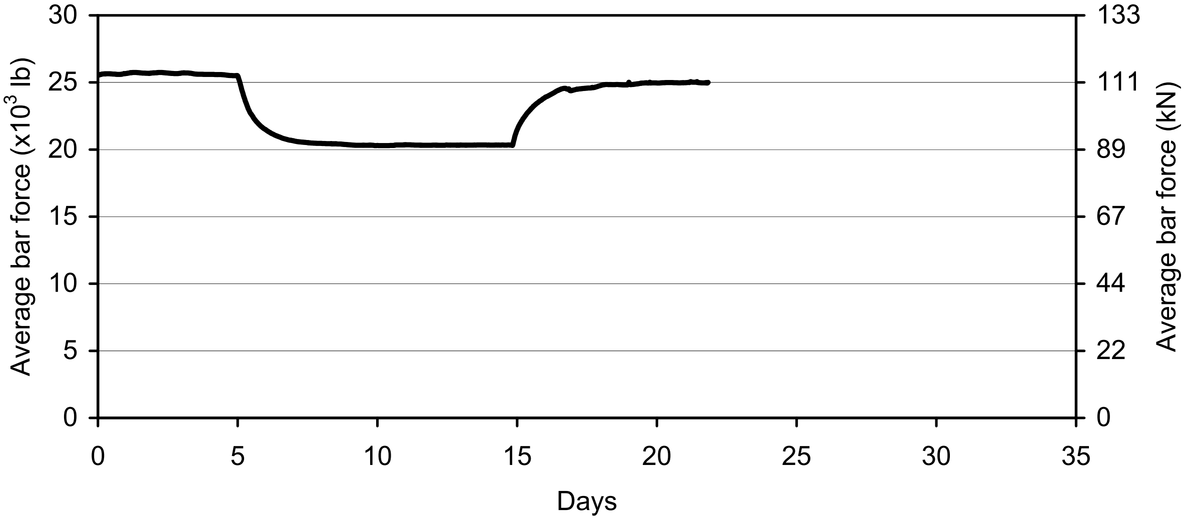


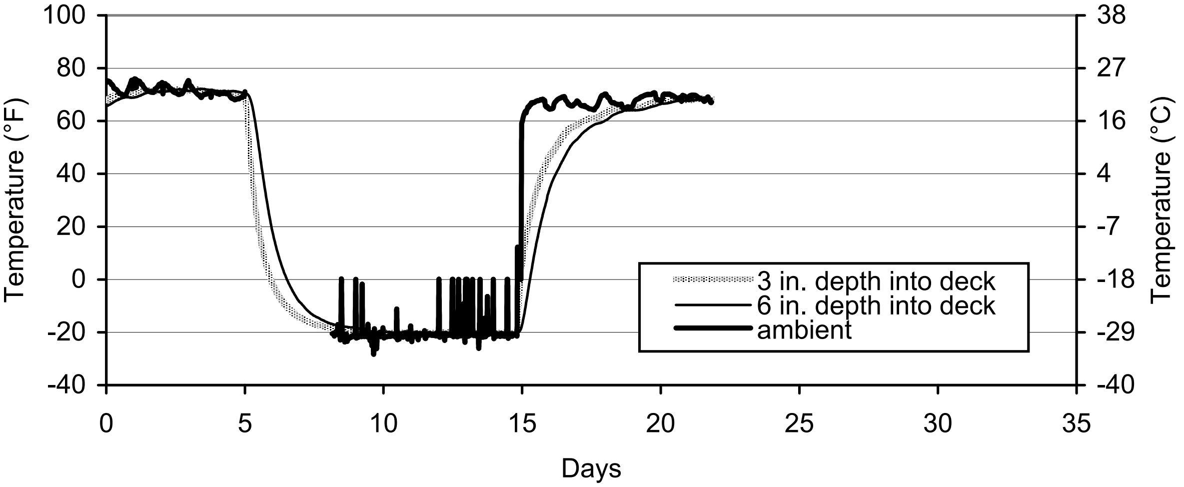
Phase II — Decks at ~17% moisture content
Temperature Run — 21.1°C (70°F) to -17.8°C (0°F)



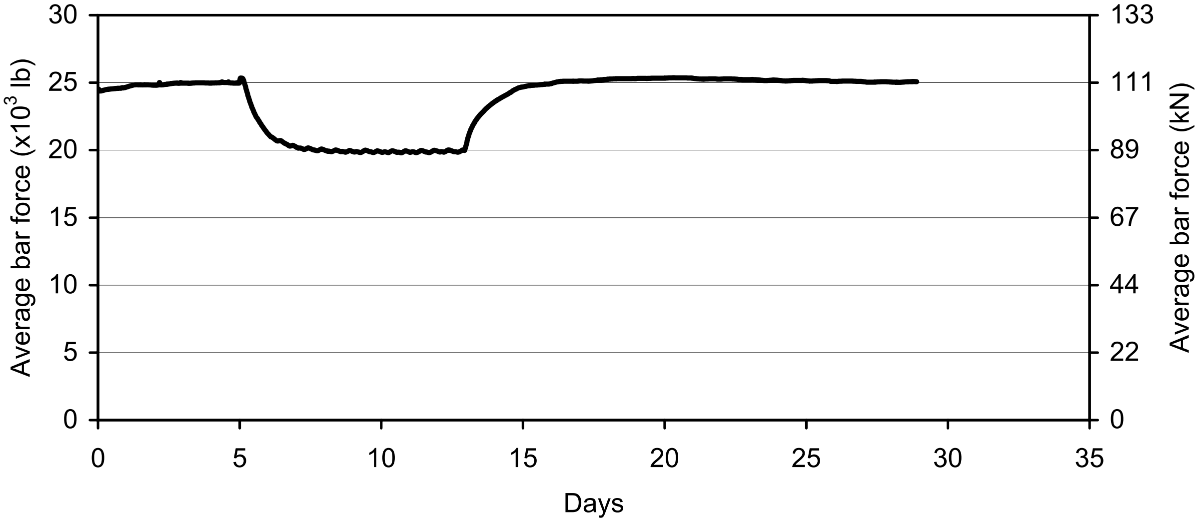


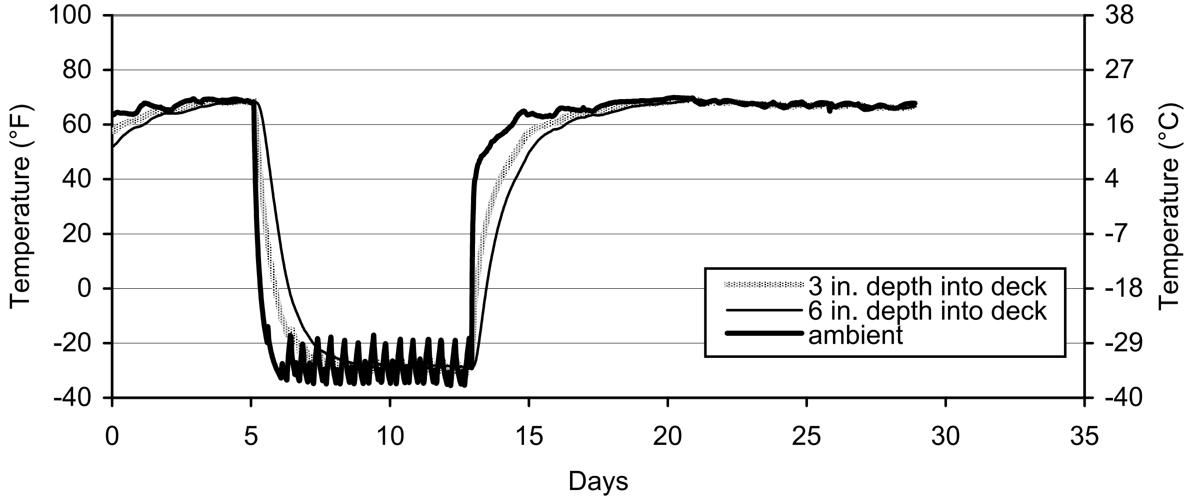
Phase II — Decks at ~17% moisture content
Temperature Run — 21.1°C (70°F) to -23.3°C (-10°F)



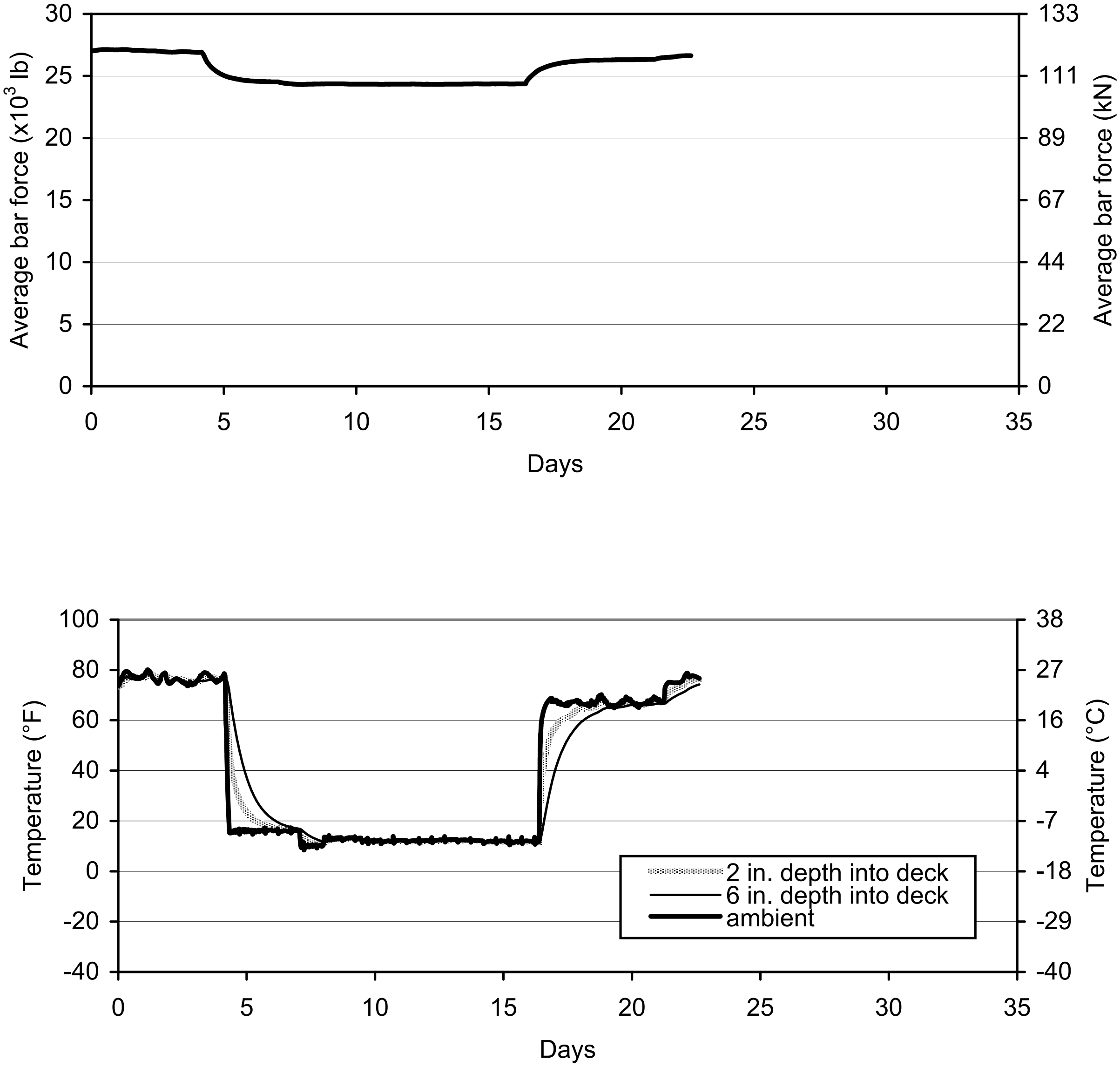


Phase II — Decks at ~17% moisture content
Temperature Run — 21.1°C (70°F) to -28.9°C (-20°F)

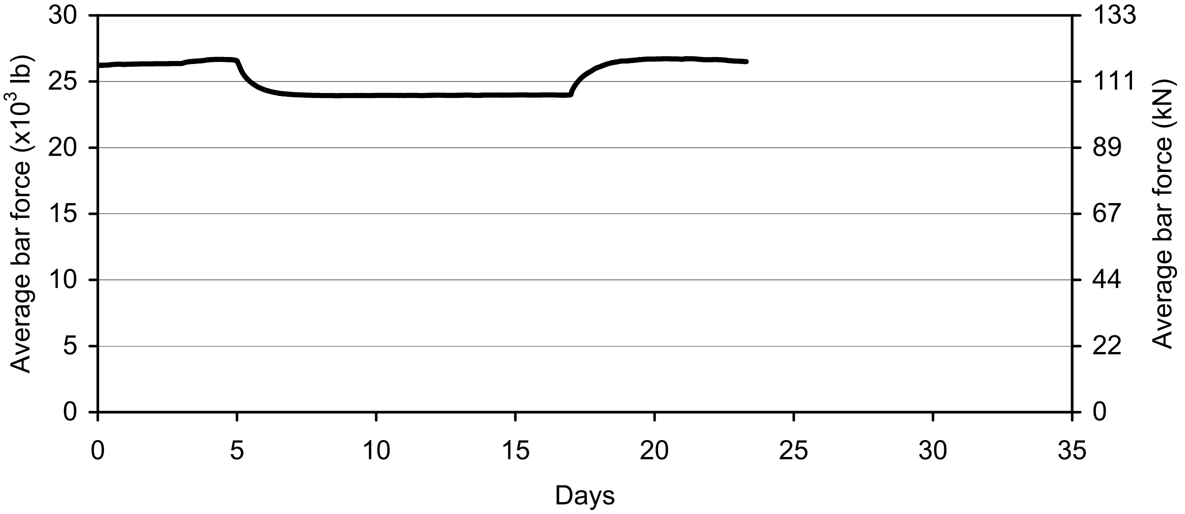


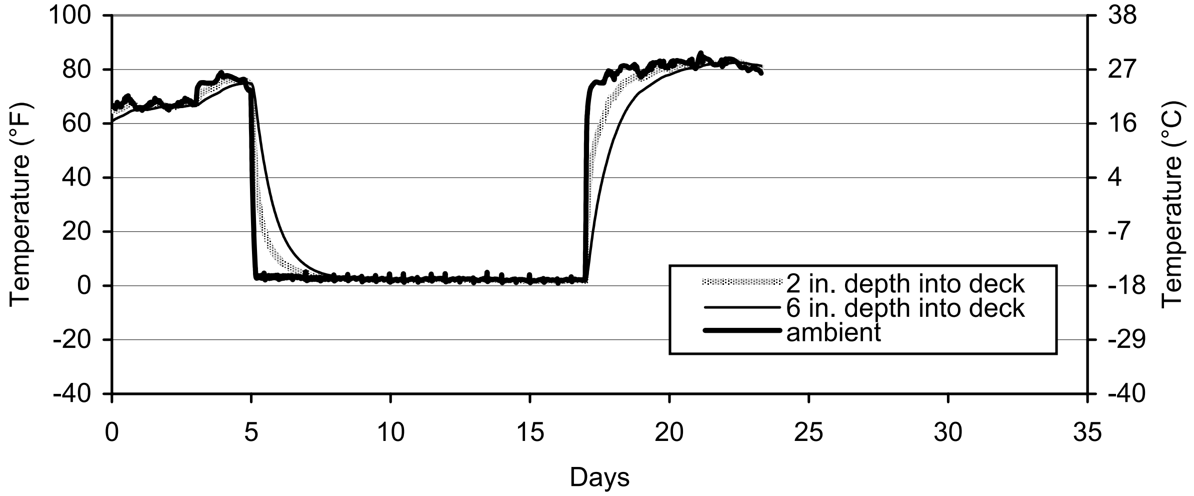


Phase II — Decks at ~17% moisture content
Temperature Run — 21.1°C (70°F) to -34.4°C (-30°F)

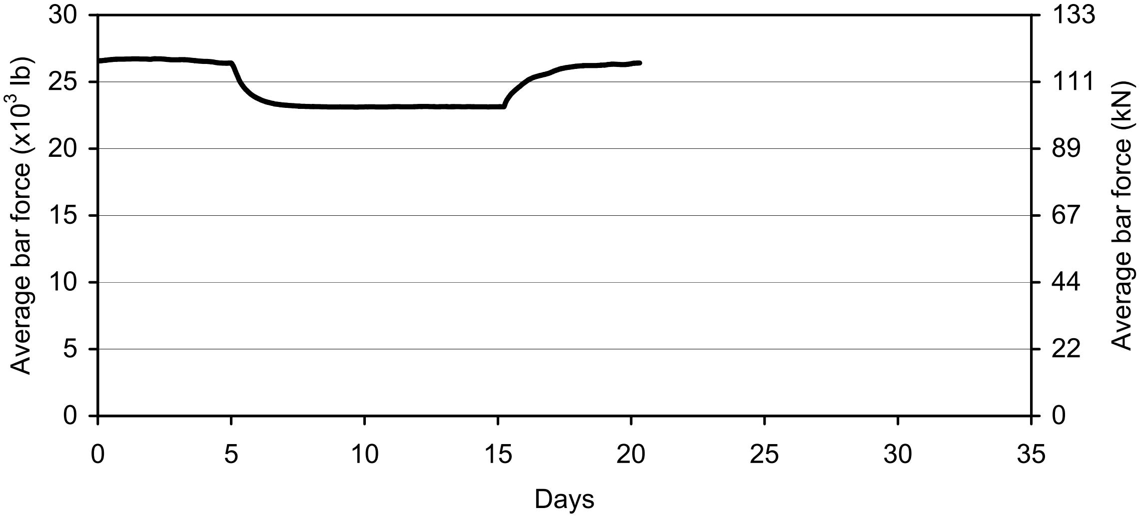


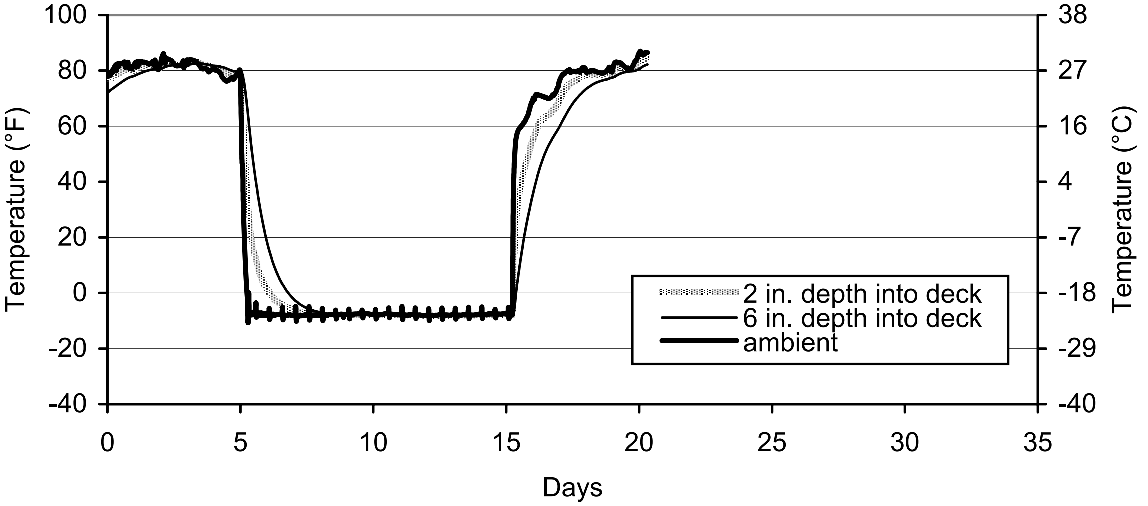
Phase III — Decks at ~7% moisture content
Temperature Run — 21.1°C (70°F) to -12.2°C (10°F)
(3-in.-depth temperature data were not collected in Phase III.)



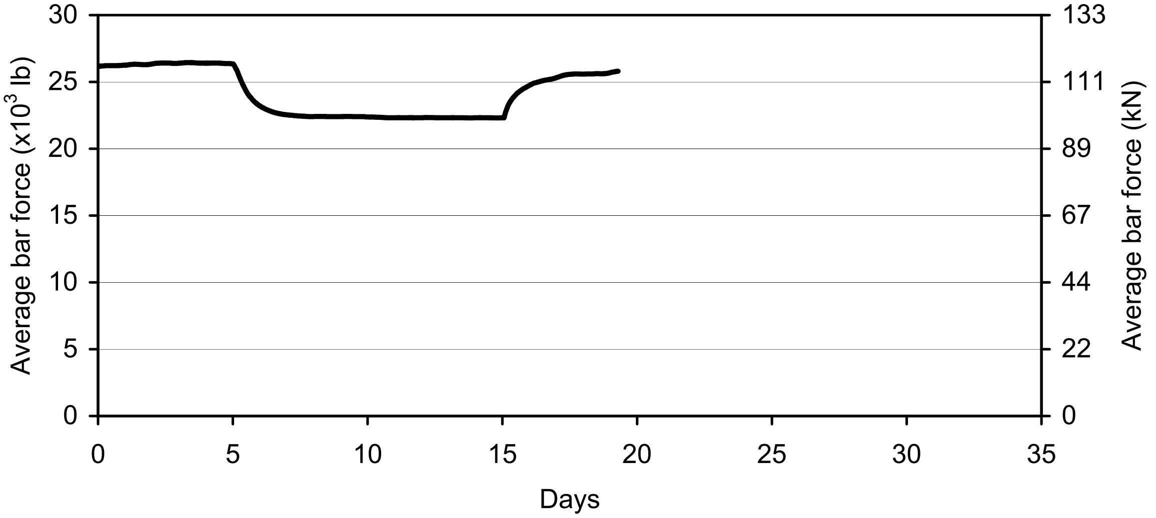


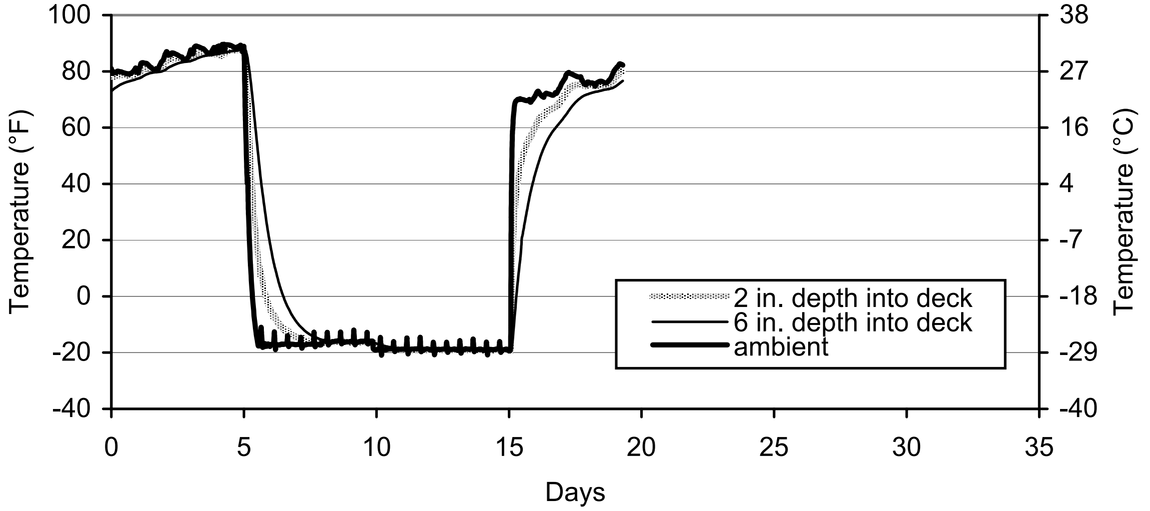
Phase III — Decks at ~7% moisture content
Temperature Run — 21.1°C (70°F) to -17.8°C (0°F)
(3-in.-depth temperature data were not collected in Phase III.)



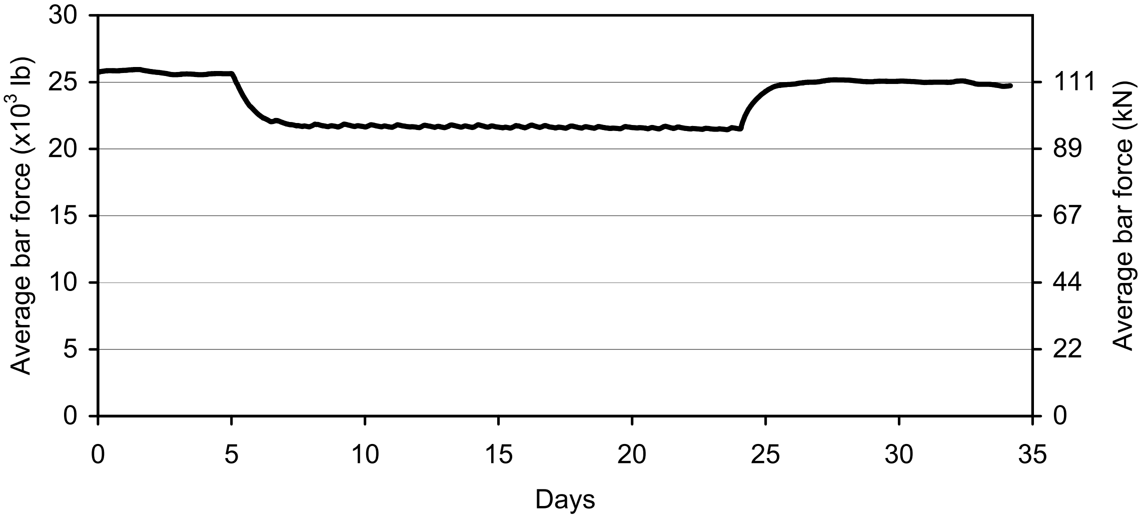


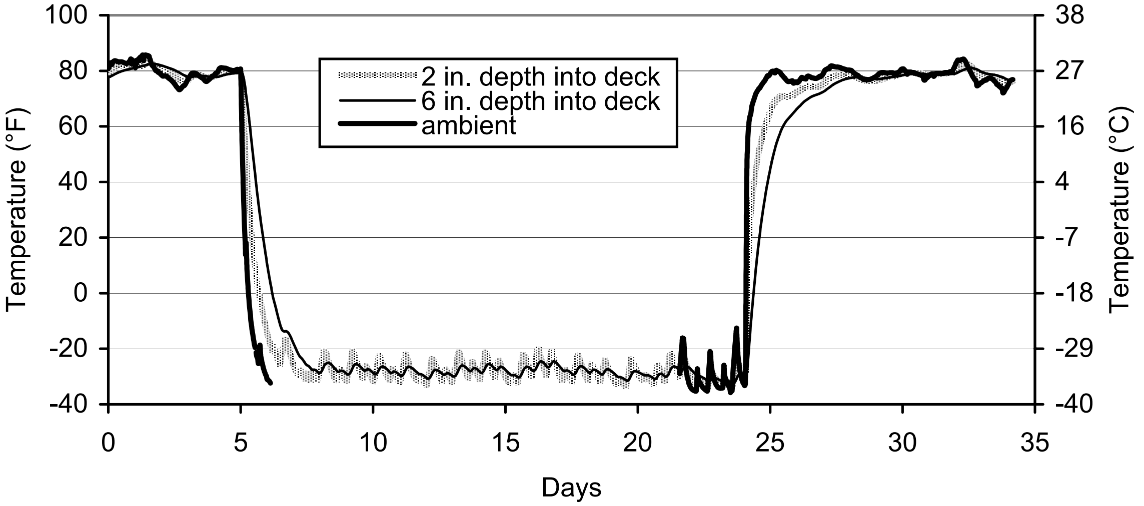
Phase III — Decks at ~7% moisture content
Temperature Run — 21.1°C (70°F) to -23.3°C (-10°F)
(3-in.-depth temperature data were not collected in Phase III.)





Phase III — Decks at ~7% moisture content
Temperature Run — 21.1°C (70°F) to -28.9°C (-20°F)
(3-in.-depth temperature data were not collected in Phase III.)





Phase III — Decks at ~7% moisture content
Temperature Run — 21.1°C (70°F) to -34.4°C (-30°F)
(3-in.-depth temperature data were not collected in Phase III.)