A procedure for testing the effect of finish coatings on the moisture buffering capability of wood

Nicholas Rawlings <norawlin@uncc.edu>

Just as thermal mass can mitigate diurnal temperature swings by absorbing heat during the day and releasing it at night, hygroscopic materials such as wood can smooth out short-term variations in humidity by absorbing water vapor when the air is wet and releasing it when the air becomes dry. This moisture buffering ability means that wood can be used as a passive strategy for maintaining human comfort inside buildings — a strategy that does not require the use of energy-intensive equipment such as fans or air conditioning units.

However, wood is seldom left exposed once construction is complete. Typically, it covered in or treated with some other kind of material, such as paint, oil, or varnish. These materials alter the physical properties of the wood to which they are applied in ways that may diminish its moisture buffering capabilities. This paper introduces a low-cost system for testing the effect of finish coatings on the moisture buffering capability of wood.

1. Introduction

The hygroscopic properties of wood — its ability to absorb moisture from the surrounding air — have been intuitively understood by humans for thousands of years. However, it has only been in the last century that we have learned how to quantify this capability, and even more recently that architects and building science researchers have begun to investigate its effects on the climate of indoor spaces.

Just as thermal mass can mitigate diurnal temperature swings by absorbing heat during the day and releasing it at night, hygroscopic materials such as wood can smooth out short-term variations in humidity by absorbing water vapor when the air is wet and releasing it when the air becomes dry. This moisture buffering ability means that wood can be used as a passive strategy for maintaining human comfort inside buildings — a strategy that does not require the use of energy-intensive equipment such as fans or air conditioning units.

However, wood is seldom left exposed once construction is complete. Typically, it covered in or treated with some other kind of material, such as paint, oil, or varnish. These materials, referred to here as finishes, alter the physical properties of the wood to which they are applied, including its hygroscopic capabilities. The question of how these finishes affect wood's natural moisture buffering abilities remains an open question.

Finishes can be applied for their aesthetic effects, altering the color, brightness, luster, or reflectivity of the wood underneath. More often, though, they are said to protect the wood from physical or cosmetic damage. Different types of finishes offer varying levels of protection from:

- Mechanical damage, such as dents and scratches.
- Chemical damage from spills and skin oils, which can permanently stain the wood.
- Radiative damage from heat and sunlight, which can darken or fade the wood.
- Biological damage from bacteria and fungi, which can cause the wood to rot.
- Moisture damage from contact with both water vapor and liquid water, either of which can cause wood to swell and crack.

Protecting wood from moisture damage, while a necessary and worthwhile objective, would seem to be at odds with the goal of using wood for moisture buffering. Indeed, one might even question whether a piece of wood so protected would be left with any moisture buffering capacity at all.

Fortunately, not all finishes protect from moisture intrusion equally, and few, if any, can block it completely. It is logical to assume that those finishes designed to be most resistant to moisture will have the greatest impact on the moisture buffering capabilities of wood. Shellac, for example, is quite permeable and can be expected to preserve a significant amount of the wood's ability to absorb and release water vapor. Spar varnish, on the other hand, is used for sealing wooden boats and can be expected to negate most, if not all, of the underlying wood's moisture buffering potential.

2. Prior Work

Well before the building science community became interested in wood for its moisture buffering capabilities, the forest products industry was studying ways of preventing moisture from being absorbed by wood. A 1985 report from the National Forest Products Laboratory details the experimental procedure used to determine the moisture-excluding effectiveness (MEE) of 91 different finishes. The finishes were brushed onto 3”×5”×⅝” samples of ponderosa pine sapwood, which were hung in a rack and placed in a room in which the air was kept at 80°F and at 90% relative humidity. The samples were weighed before being placed in the room and re-weighed one, seven, and fourteen days after the experiment had begun to determine how much moisture had been absorbed by each sample.

Figure 2. A rack of ponderosa pine samples that were tested for the Forest Products Laboratory report. (Feist 1985, 3)

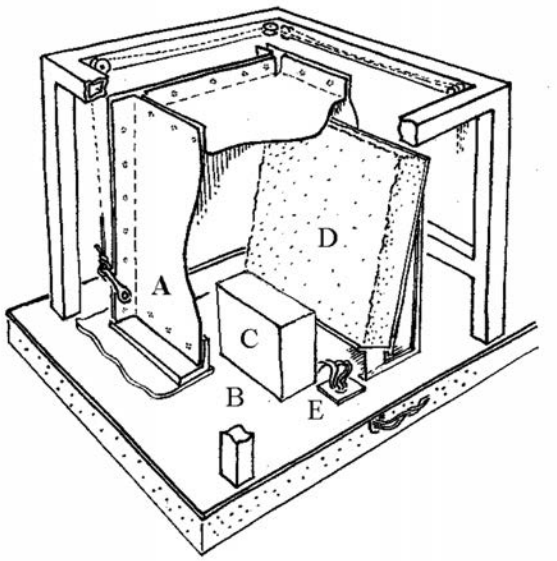

Figure 1. A cutaway diagram of Padfield's flux chamber. (Padfield 1998, 23).

Tim Padfield, a conservation scientist, was among the first to suggest that buildings should take advantage of the absorptive properties of their materials to passively regulate their internal humidity. In his doctoral thesis, he describes the design and construction of a "flux chamber" for studying "the moisture absorbent properties of porous walls" (Padfield 1998, 23). It was important to Padfield that his chamber be capable of replicating the same kind of variations in humidity (which he refers to as "water vapor flux") that would occur in an actual interior environment over time. This requirement necessitated a significantly more complex setup than a traditional humidity box.

Carsten Rode was one of Tim Padfield's advisors during his doctoral research at the Technical University of Denmark. In the mid 2000s, Rode saw "a need for a robust definition of a term for the moisture buffer effect of materials," and set out to define such a term as well as a testing protocol to measure its value (Rode 2005, 2). His team developed the Moisture Buffer Value (MBV), which "indicates the amount of moisture uptake or release by a material when it is exposed to repeated daily variations in relative humidity between two given levels" (Rode 2005, 3). The MBV of a material is expressed in kilograms of water per square meter of surface area and per percent change in relative humidity.

The testing procedure for MBV specifies that material samples should be sealed on all but one or two sides and exposed to a minimum of three cycles consisting of 8 hours of high humidity followed by 16 hours of low humidity. This asymmetric cycle is meant to replicate the conditions observed in a "typical" room, such as a bedroom or office, in which the respiration and perspiration of its human occupants increases the humidity for approximately 8 hours each day. The test should be carried out at 23°C with the high portion of the cycle at 75% relative humidity and the low portion at 33% relative humidity.

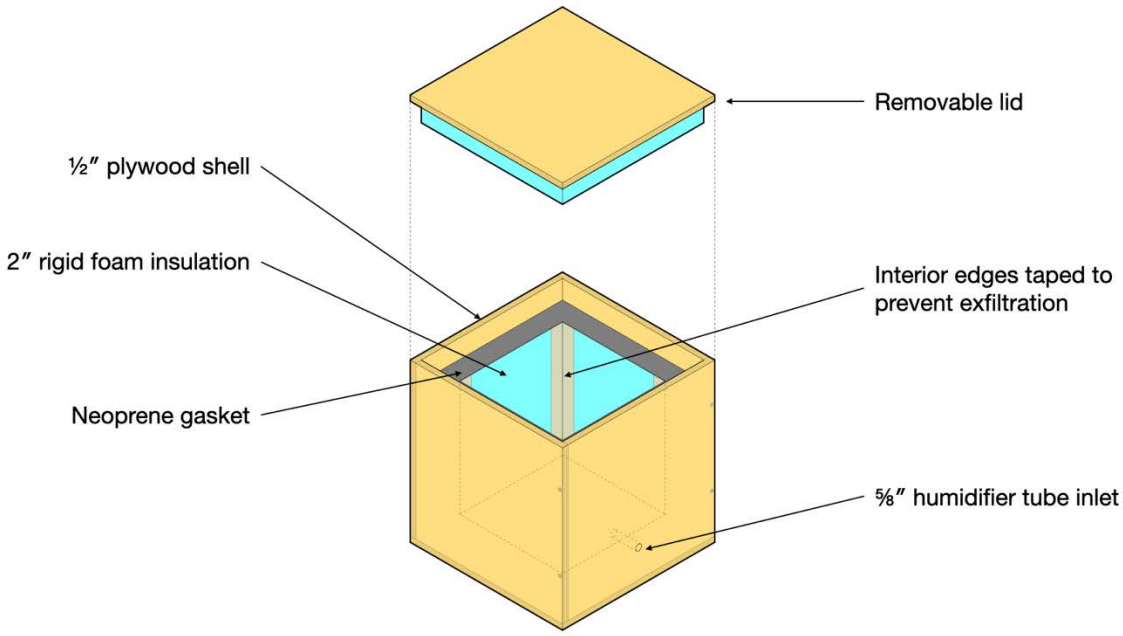

Figure 3. A schematic diagram of the test enclosure.

3. Strategy

Tests will be conducted on samples of southern yellow pine, a class of softwood species that are cheap, readily available, and already common in construction. The moisture buffering capabilities of these woods is expected to become increasingly important as mass timber products gain greater acceptance among architects and building professionals. All samples will be cut to equivalent lengths and sanded to minimize surface effects.

The tests will be conducted within a cubical enclosure consisting of rigid foam insulation surrounded by a plywood shell. Rigid foam insulation is effective both as thermal insulation and as a moisture barrier; joints between adjacent pieces will be sealed with flashing tape in order to prevent vapor exfiltration during the experiment. Water vapor will be introduced into the interior environment through a tube passing through the side of the box, the other end of which is connected to a humidifier.

Two sensors will be attached to the underside of the lid of the box. A DHT11 temperature and humidity sensor will be used to monitor the ambient conditions inside the box. The wood samples will be suspended from a 1kg straight bar load cell, which will record changes in the mass of the sample as it absorbs moisture from the air. Readings from these two sensors will be collected by an Arduino microcontroller and transmitted to a nearby laptop for storage and analysis.

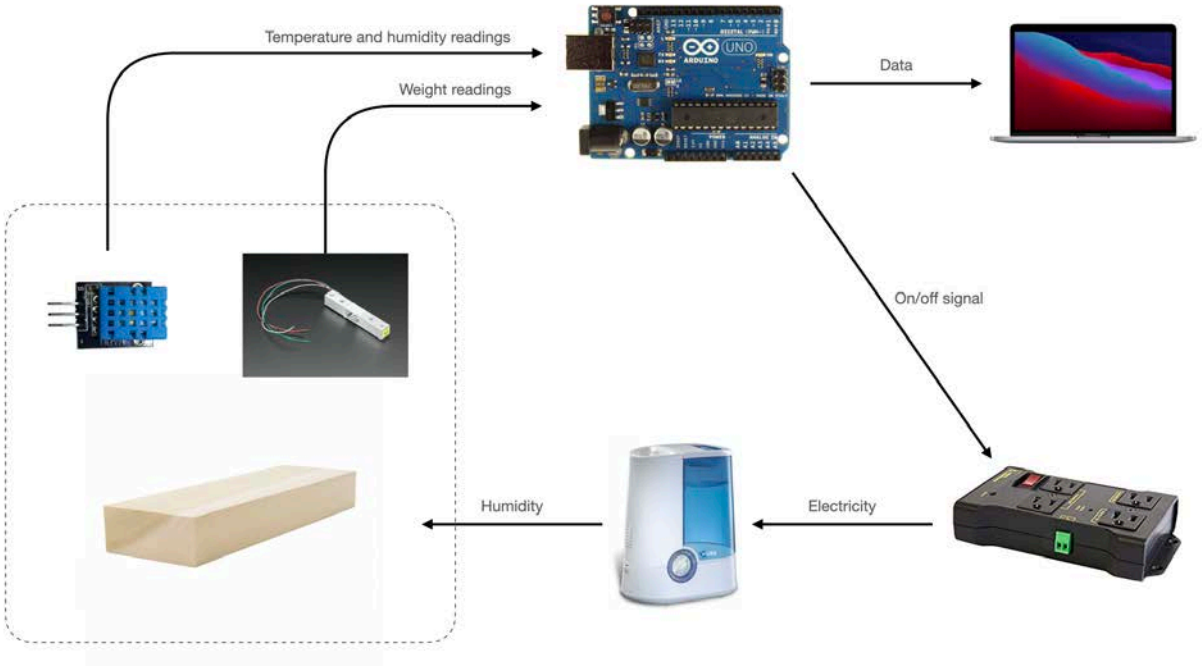

Figure 4. A diagram depicting the relationships between the components of the testing system. The dashed region to the left represents the test enclosure.

The Arduino is also responsible for maintaining a consistent humidity level within the box for the duration of the experiment. The microcontroller will be able to turn the humidifier on and off by means of a relay that the humidifier will be plugged into. When the DHT11 sensor detects that the relative humidity inside the box has risen above 75%, the Arduino will send a signal to the relay to cut power to the humidifier in order to prevent over-humidification of the box. When the relative humidity inside the box falls below 75%, another signal is sent to restore power to the humidifier.

Each test will begin by suspending a dried sample from the load cell. After the lid has been replaced and the box sealed, the humidifier will begin to pump water vapor into the box. Over the next several hours, the sample will absorb moisture from the humid air inside the box. That absorbed moisture will increase the mass of the sample, hopefully causing the readings from the load cell to increase over time. The amount and rate of increase are expected to be a useful indication of the moisture buffering capability of the sample.

4. Fabrication

4.1. Plywood Shell

The first step of constructing the test enclosure involved cutting and assembling the pieces for the plywood shell. In order to minimize waste, the pieces were sized to take advantage of the

Figure 5. The plywood shell prior to the installation of the rigid foam insulation.

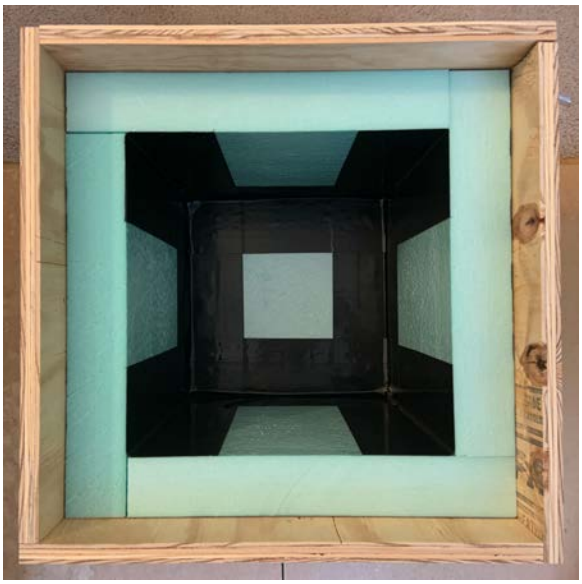

Figure 6. The interior of the test enclosure.

entire width of a standard 4 foot by 8 foot sheet of plywood. The plywood itself was surplus material held by the school's fabrication lab, and was obtained at no cost.

The plywood pieces were assembled using simple butt joints and held together with two countersunk screws on each edge. Holes for the screws were pre-drilled to avoid splitting the plywood during assembly. A 5/8 inch hole (below right) was also drilled through one of the sides of the shell for the tube that would carry water vapor from the humidifier into the test enclosure.

4.2. Rigid Foam Insulation

Waste was unavoidable when sizing the pieces of rigid foam insulation, which provides thermal insulation for and a vapor barrier around the test environment. The pieces were cut on a table saw from a surplus sheet obtained from the fabrication lab at no cost. Prior to installation, a 5/8 inch hole was drilled through one of the side pieces to match the water vapor inlet hole in the plywood shell. The side pieces were installed first, and then the bottom piece was pushed through the space between them. The fit was tight, so no adhesive was required.

Flashing tape, which is commonly used to seal vapor barriers around doors and windows during building construction, was applied to the interior edges of the rigid foam insulation. This tape prevents water vapor from escaping the test environment through the gaps between adjacent pieces of insulation and being absorbed by the plywood shell instead of the wood sample under test.

Figure 8. The 3D-printed sensor mount.

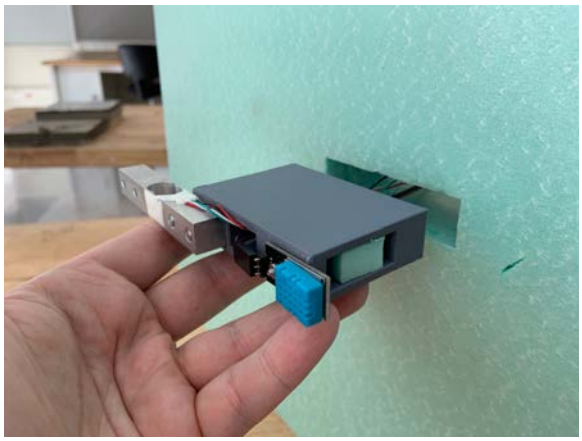

Figure 7. The sensor mount being inserted into the lid of the test enclosure.

4.3. Sensor Mount

A mount was designed to securely and rigidly attach the load cell and the DHT11 temperature and humidity sensor to the plywood shell of the lid of the test enclosure. The load cell was attached to the mount with a pair of M5 machine screws, and the DHT11 with a single M2.5 machine screw. The mount was then attached to the plywood with a pair of 1/4" machine screws. Two small pockets were included in the design of the mount to hold the nuts in place while it was being secured to the plywood. The mount is 3 inches long, 3/4 inch wide, and 2 1/8 inches tall and was 3D printed in the fabrication lab at a cost of $3.

4.4. Control System

The control system for the test enclosure consists of the following electronic components:

- An **Arduino Uno** microcontroller that reads data from the sensors and regulates the humidity. The Arduino was included in the electronics kit provided to each student at the beginning of the semester.
- A **DHT11 temperature and humidity sensor** that measures the dry bulb temperature and relative humidity inside the test environment. The DHT11 was included in the electronics kit provided to each student at the beginning of the semester.
- A **1kg straight bar load cell** that measures the weight of the wood sample under test. Liz obtained the load cell for approximately $4.
- An **HX711 load cell amplifier** that makes the signals from the load cell, which are too weak to be read directly by a microcontroller, easily readable by the Arduino. This tiny board was packaged with the load cell.
- An **IOT Relay** that controls the flow of electricity to the humidifier. This product, on load from Liz, contains single-pole double throw (SPDT) relay that allows digital control of a standard 120V power supply.

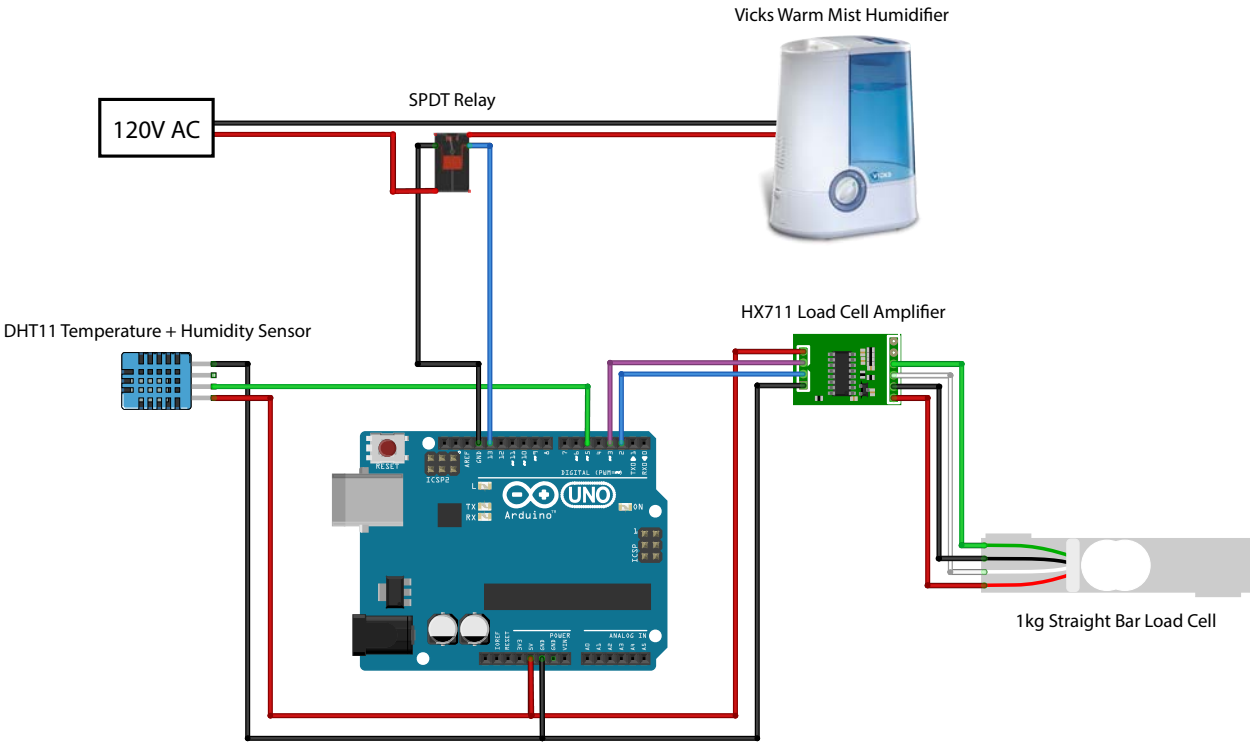

Figure 9. Wiring diagram of the control system.

- A **Vicks Warm Mist Humidifier** that produces water vapor to increase the humidity of the test environment. The humidifier was borrowed from Liz's collection of such devices.

Once pin connectors were soldering to the HX711 board and the ends of the load cell wires, the components were connected via jumper cables according to wiring diagram shown in Figure 9.

The code loaded into the Arduino collects readings from the sensors and outputs them to the serial monitor as a line of tab-separated values approximately every 5 seconds. The load cell is powered down between readings to mitigate thermoelectric effects that could distort the load cell's readings.

The code also tracks an exponential running average, which minimizes random fluctuations, of relative humidity readings in the test environment. When the average drops below 75%, the humidifier is turned on to increase the moisture level of the test environment. When the average rises above 75%, the humidifier is turned off to prevent over-humidifying the environment, which could result in condensation and damage to the sensors.

Figure 10. The setup used for the first baseline test. The Arduino and relay are sitting on top of the test enclosure. The humidifier is on the floor to the right of it.

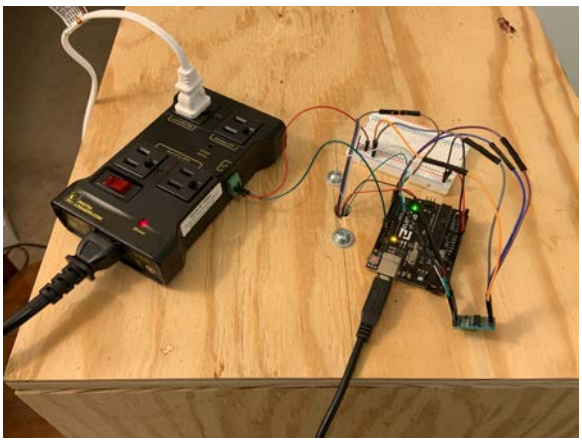

Figure 11. The control system as it appeared just prior to the first baseline test.

5. Methodology

While the Arduino is running, it sends readings over the attached USB cable roughly every 5 seconds. These readings were captured on a MacOS laptop and saved to a file that could later be imported into an application such as Excel or Tableau for analysis.

Because each test could last for hours, or even days, it was necessary to conduct them in the author's home where the laptop could remain unattended for extended periods of time without the threat of theft or tampering. The enclosure was elevated above the humidifier so that condensation that formed in the plastic tube connecting the two would flow back into the humidifier instead of to the test enclosure. The humidifier itself was placed in a dishpan to contain any leaks.

Before each test, the lid was removed for 5–10 minutes to allow the air inside the enclosure to match the air in the room, which averaged 45% relative humidity. During these few minutes, the text box had to be closely guarded to prevent feline infiltration. Once the interior conditions in the box had reached equilibrium, a test sample was hung from the load cell and the lid was replaced. Additional weight was placed on top of the lid in hope of more effectively sealing the test environment. The enclosure then sat idle for 15 minutes while the sample settled before the USB cable was plugged into the laptop to begin the test.

6. Results

Only one complete test has been conducted as of the time of this writing, so there is insufficient data to either prove or disprove the initial hypothesis. However, this test does demonstrate the viability of the overall method. During this test, an unfinished sample block was placed in the test enclosure for 96 consecutive hours to collect baseline data.

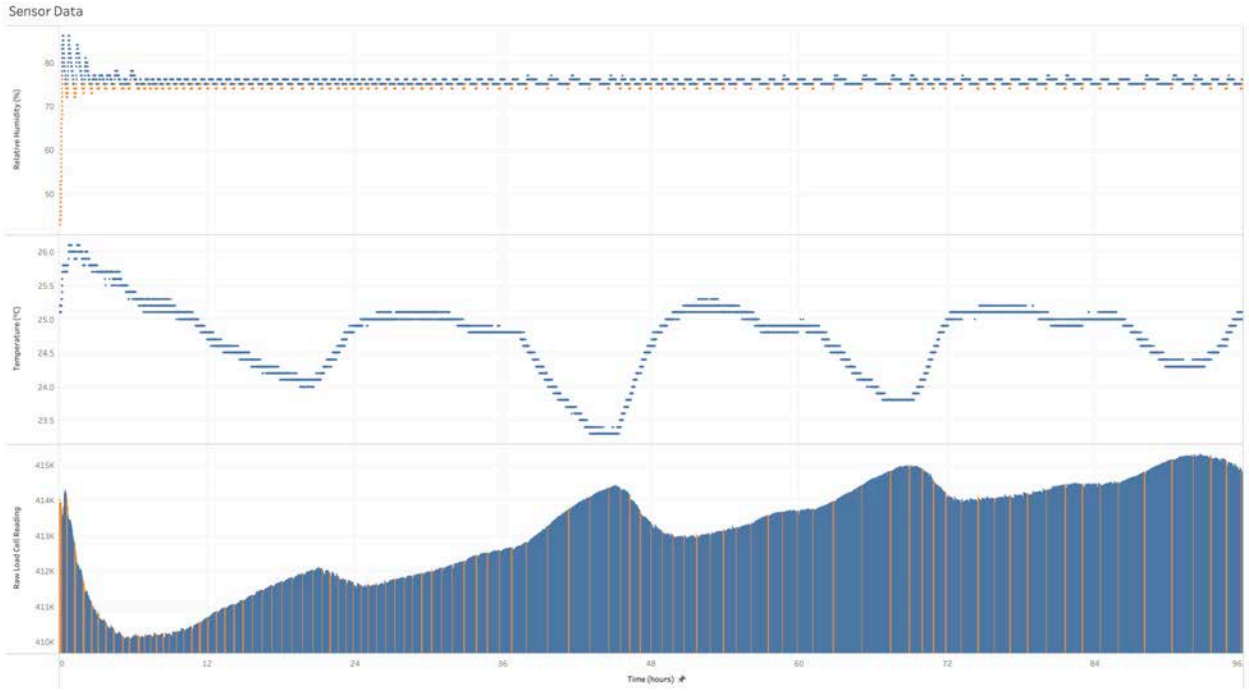

Figure 13. Raw sensor data collected during the first baseline test. Orange regions indicate times when the humidifier was powered on.

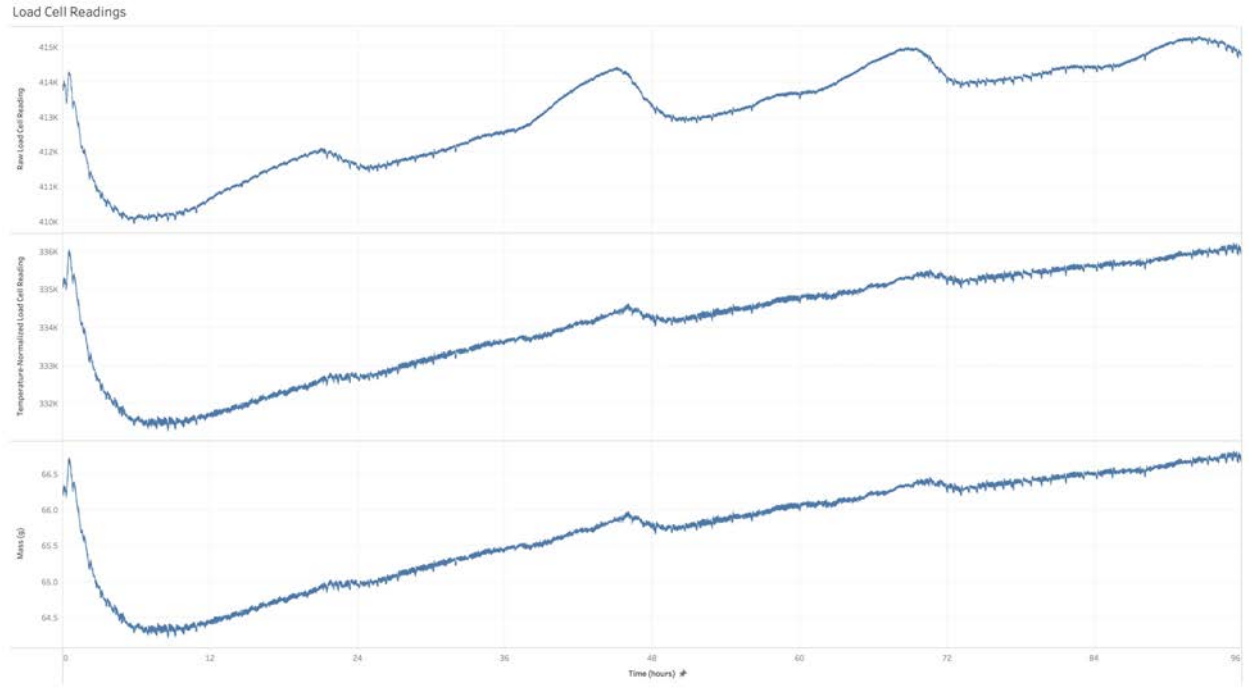

Figure 12. Raw load cell readings, temperature-normalized load cell readings, and calculated mass during the first baseline test.

Once normalized to compensate for the effect of variations in temperature on the load cell readings, the data revealed that the mass of the sample block increased by approximately 2.5 grams (3.9%) between the 8-hour mark and the end of the test period.

Two aspects of this initial dataset are troubling, however. The marked decrease in load cell readings during the first few hours of the test is unexplained and may indicate a need for more extensive preconditioning. Also, the readings weren't completely smoothed by the temperature normalization process. The local maxima at the 46- and 70-hour marks likely indicate that the normalization coefficients are not completely accurate, but could also point to changes in rate at which moisture is absorbed by the test block due to variations in temperature.

7. Conclusions

The testing procedure outlined here shows promise as a low-cost method of evaluating the effect of finish coatings on the moisture buffering capability of wood. Making such a method available to architects and students who are interested in humidity buffering (regardless of material) but lack the resources to purchase industrial-grade testing equipment is highly desirable. However, there remain several significant issues related to calibration and methodology that must be resolved before this procedure can become truly effective.

The test enclosure could be significantly improved by adding a means of regulating the internal temperature. The need for normalization of load cell readings demonstrates that temperature is a non-trivial variable in this experiment, and therefore needs to be more carefully monitored and controlled.

The system could also benefit from a means of removing humidity from the test environment in a controlled way. Adsorption of water vapor is only half of the behavior of a moisture buffering material; the ability of that material to release vapor back into the environment is also critical. It should not be assumed that a finish will affect the adsorption and desorption rates of a wood surface equally.

Finally, the system must eventually be validated by comparing the results it produces to an established procedure such as Rode's MBF. Validation will prove the accuracy of this procedure and help establish its error rate and confidence intervals.

Acknowledgements

The author would like to thank Liz McCormick both for her guidance and for providing many of the parts used in the construction of the testing system, as well as Alex Cabral and Robbie Sachs for their invaluable assistance during the fabrication process.

References

Feist, William C, James K Little, and Jill M Wennesheimer. December 1985. “The Moisture-Excluding Effectiveness of Finishes on Wood Surfaces.” https://www.fpl.fs.fed.us/documnts/fplrp/fplrp462.pdf.

Padfield, Tim. 1998. “The role of absorbent materials in moderating changes of relative humidity.” PhD Thesis, Technical University of Denmark. https://www.conservationphysics.org/phd/phd-indx.html.

Rode, Carsten, Ruut Peuhkuri, Kurt K. Hansen, Berit Time, Kaisa Svennberg, Jesper Arfvidsson, and Tuomo Ojanen. June 2005. “Moisture buffer value of materials in buildings.” *Proceedings of the 7th Symposium on Building Physics in the Nordic Countries* 1 (June 2005): 108–115.