

# **Developing Innovative Wall Systems that Improve Hygrothermal Performance of Residential Buildings Progress Report**

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## **ABSTRACT**

This document serves as the Topical Report documenting work completed by Washington State University (WSU) under U.S. Department of Energy Grant, Developing Innovative Wall Systems that Improve Hygrothermal Performance of Residential Buildings. This project was conducted in collaboration with Oak Ridge National Laboratory (ORNL), and includes the participation of several industry partners including Weyerhaeuser, APA – The Engineered Wood Association, CertainTeed Corporation and Fortifiber. This document summarizes work completed by Washington State University August 2002 through June 2006.

WSU's primary experimental role is the design and implementation of a field testing protocol that monitored long term changes in the hygrothermal response of wall systems. During the project period WSU constructed a test facility, developed a matrix of test wall designs, constructed and installed test walls in the test facility, installed instrumentation in the test walls and recorded data from the test wall specimens.

Each year reports were published documenting the hygrothermal response of the test wall systems. Public presentation of the results was, and will continue to be, made available to the building industry at large by industry partners and the University.

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Todd Currier  
Margret Thomas

## INTRODUCTION

Washington State University (WSU) and Oak Ridge National Laboratory (ORNL) have implemented a research protocol to analyze hygrothermal response of wall assemblies. The protocol utilizes three primary evaluation methods. These include experimental testing of full-scale walls in the natural environment, characterization of building materials response to moisture, and long term predictive evaluation of heat and moisture transport through building components using advanced computer modeling techniques.

## EXECUTIVE SUMMARY

This document serves as the Topical Report documenting of work completed by WSU under U.S. Department of Energy Grant, Developing Innovative Wall Systems that Improve Hygrothermal Performance of Residential Buildings. This project was conducted in collaboration with Oak Ridge National Laboratory (ORNL), and includes the participation of several industry partners including Weyerhaeuser, APA – The Engineered Wood Association, CertainTeed Corporation, and Fortifiber. This document summarizes work completed by Washington State University August 2002 through June 2006.

This project developed and implemented a unique systems engineering approach to designing wood frame building assemblies that are energy efficient and moisture tolerant in the climate of the Pacific Northwest. The overall impact of successful project completion has been a significantly improved understanding of building component relationships within a wall system and how they influence hygrothermal performance. In addition to developing a system engineering approach to wall moisture evaluation, this project tested the viability of building materials and assembly methods in the field.

This project is unique because it proposes to apply a number of evaluation methods to a specific end result. Laboratory testing of building material hygrothermal properties, field-testing of full-scale wall samples, and evaluation using advanced computer modeling all led to the development of durable wall assemblies for a specific climate. This project was specifically targeted at developing results for wood framed construction in the challenging climate of the Pacific Northwest. The results of the project include:

- an expanded hygrothermal material property data base,
- a fully instrumented natural exposure test facility,
- an implemented systems engineering approach using the most advanced modeling tools and uniform test methods
- specific construction solutions for the Pacific Northwest climate.

WSU's primary role in the project was constructing the building and the test walls, and collecting the data, with ORNL performing the detailed analysis and incorporating the results in its moisture modeling tools. However, the additional analysis performed on the data by WSU did lead to several conclusions about the performance of wall assemblies in the Pacific Northwest marine climate. They are as follows:

- The amount of cavity insulation does not change the moisture performance of walls significantly. Both R-11 and R-21 walls had similar moisture accumulation for the test years examined.
- Walls constructed with R-13 cavity insulation plus R-5 foam sheathing provides better moisture performance than a wall with R-21 cavity insulation only. Combined with a smart vapor retarder, The R-13+5 construction provides excellent performance.
- Cladding ventilation is effective at lowering the wood moisture content of insulated wall cavities. A fully ventilated cladding that includes openings to the exterior both high and low on the wall is critical. Simply providing an air space behind the cladding without openings to the exterior is not effective.
- Vapor retarders with a dry cup perm rating less than 1 are important in the Pacific Northwest climate. The use of a smart vapor retarder provides additional benefits by allowing additional drying to the interior from the wall cavity in the spring and summer. This is likely true for other marine climates.
- Long term study of wall performance under a variety of environmental conditions is needed to provide a reliable performance evaluation.

## **EXPERIMENTAL DESIGN**

### **WSU and ORNL Roles**

WSU has been largely responsible for the testing conducted at the Natural Exposure Test Facility (NET). With input from ORNL and the industry partners, WSU developed the test facility, test wall design, and ran the experiments. ORNL was key in two areas with regard to testing at the NET. They provided the design for instrumentation and were influential in the selection of test wall characteristics.

ORNL's primary work includes material property testing and hygrothermal modeling. WSU supported ORNL efforts by sending materials from the NET to ORNL for testing. WSU also prepared test wall data and provided them to ORNL. ORNL will be using this information to develop reporting on the comparative performance of NET test walls to computer simulations. The primary ORNL activities will be discussed in separate reporting provided by the lab. This reporting is included as an attachment to this report.

### **Natural Exposure Test (NET) Facility**

To facilitate the field tests, WSU constructed the NET. The NET is located at the Washington State University Agriculture Research campus in Puyallup, Washington. The weather conditions of this site are typical of the marine climate in the Pacific Northwest.

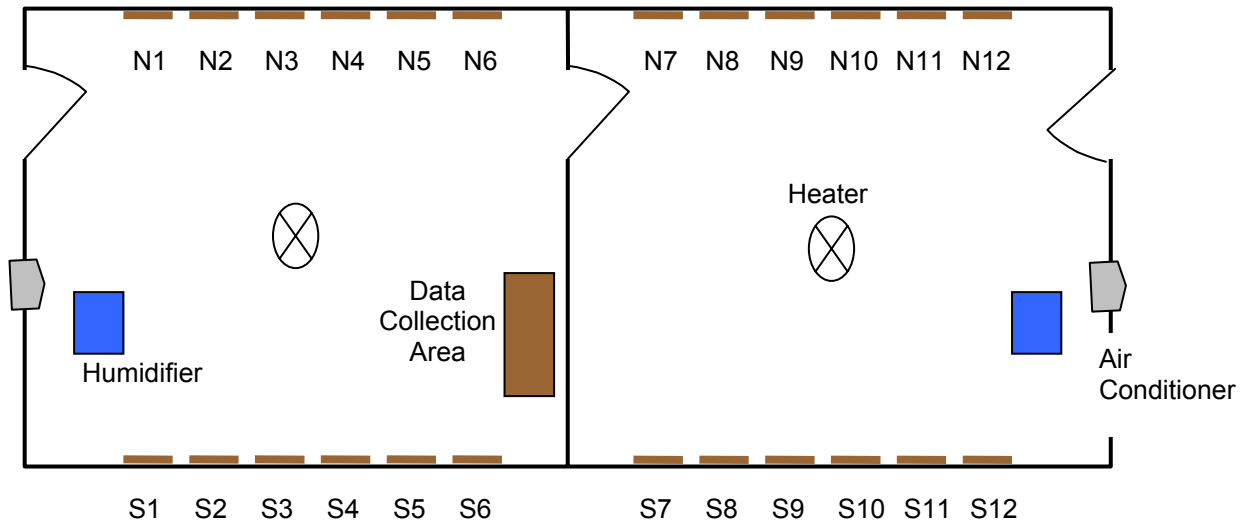
The NET was located on the property to provide maximum exposure of the test walls facing south or north. For south facing test walls, this optimizes exposure to wind driven rainfall, which occurs primarily in the fall and winter. The walls on the north are exposed to little wind driven rain but lack direct exposure to sun in the winter, setting up an alternative critical condition. The NET is in an open field with no obstructions within 400 meters (1312 feet) of the south facing wall. To the north there are a few one story buildings located 60 meters (197 feet) or more away.

The NET is a 4.3x7.3 meter (14x70 foot) building designed using open beam construction to maximize openings for test walls as large as 4.3x 3 meters (14x9.5 feet). A 0.6 meter (2 foot) high insulated knee wall was poured with a slab on grade within. The buildings structural frame was constructed with structural insulated panels (SIP). Two 7.5 meter (35 foot) Parallam™ beams were used to support the roof panels. SIP construction was used to facilitate air tightness and provide good insulation performance.

Roof overhangs were limited to approximately 0.25 meter (10 inches) to allow maximum exposure for the test specimens to the weather. The choice of roofing and sidings materials was a request by the University in an effort to be compatible with campus architecture. Gutters were provided to collect roof run-off.

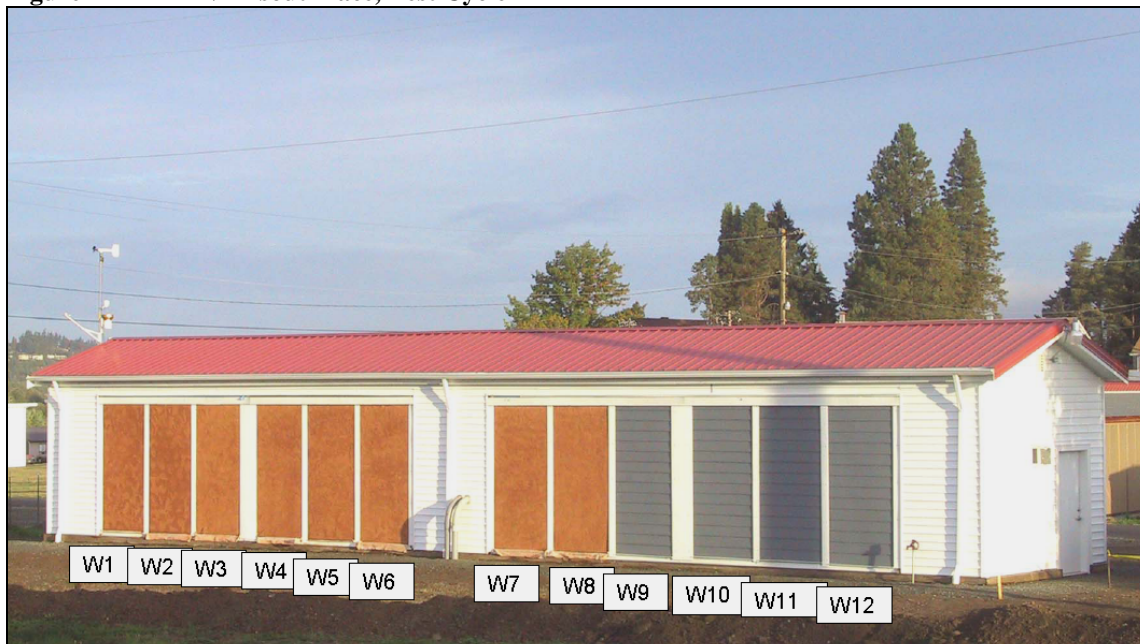
The NET is segmented into two 4.3x10.7 meter (14x35 foot) rooms with HVAC systems for each. This was done to allow creation of different interior environments in each of the two rooms. Each room includes an electric unit heater, wall mount air conditioner and humidifier. A simple plan view of the NET is included as **Figure 1**.

**Figure 1** NET floor plan

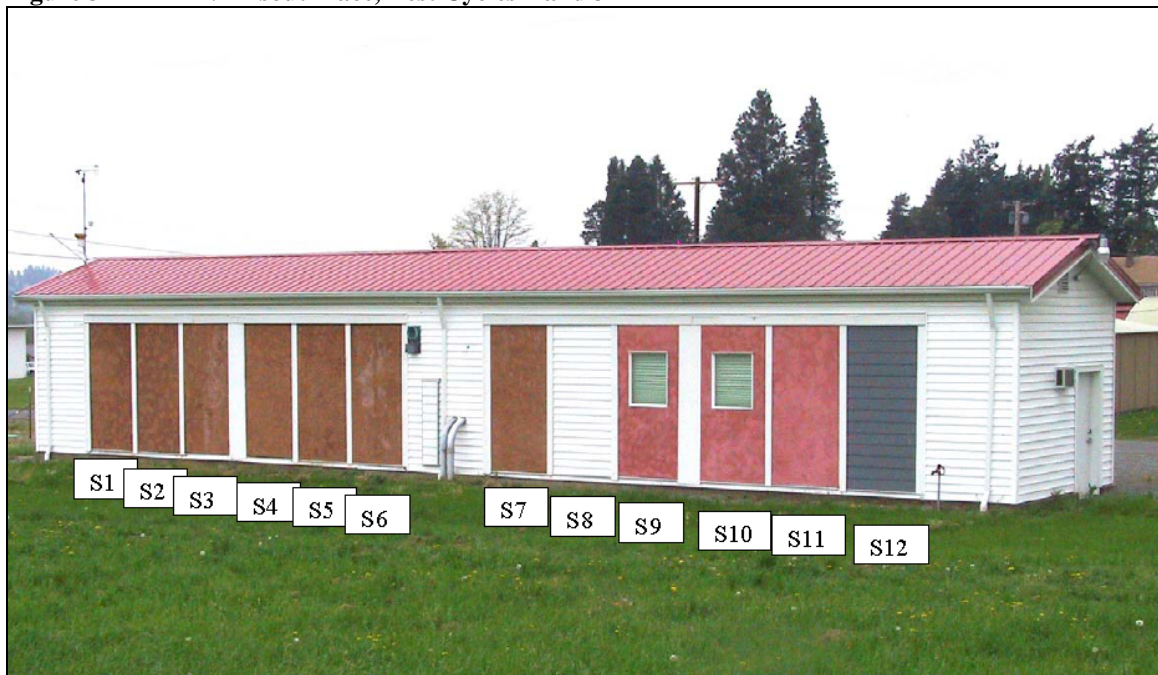


**Figure 2** shows the south facing wall of the completed NET with twelve 1.2x2.7 (4x9 foot) test wall assemblies installed for test Cycle 1. Test Cycle 2 and 3 are shown in **Figure 3** and **Figure 4**. Although not all test walls were the same thickness, it was decided to keep the exterior of the building flush in an attempt to minimize any uneven weather effects on the test specimens.

**Figure 2** NET south face, Test Cycle 1



**Figure 3**      **NET south face, Test Cycles 2 and 3**



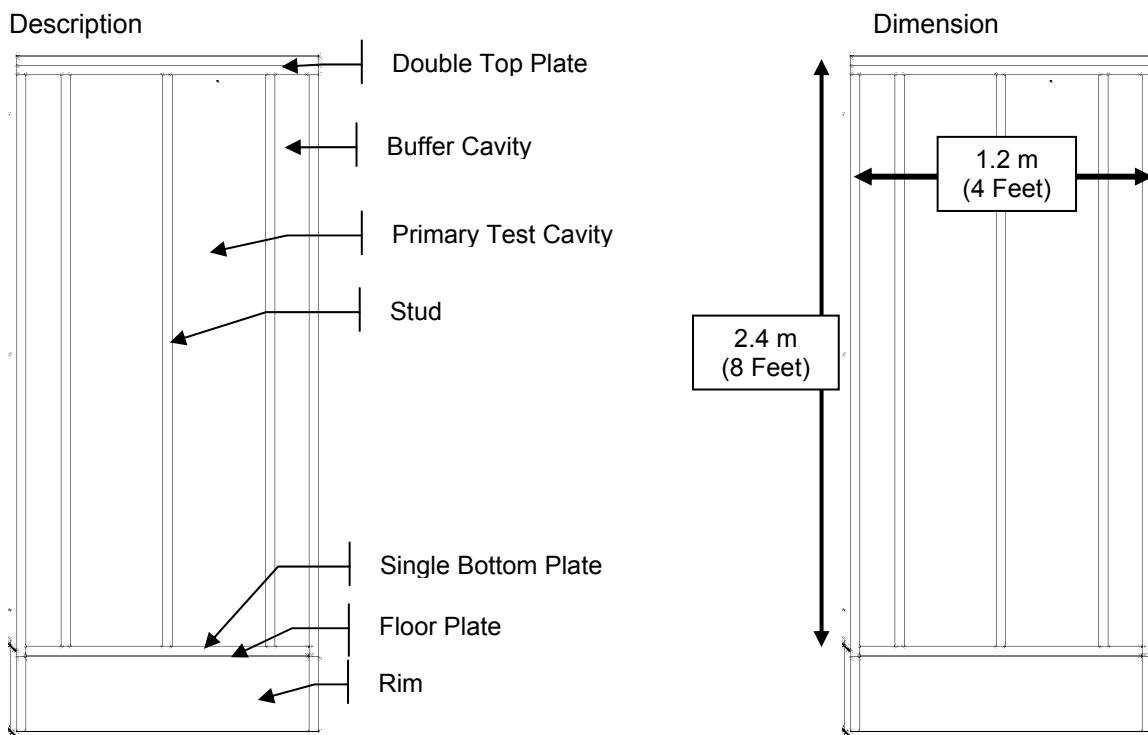
**Figure 4**      **NET north face, Test Cycles 2 and 3**



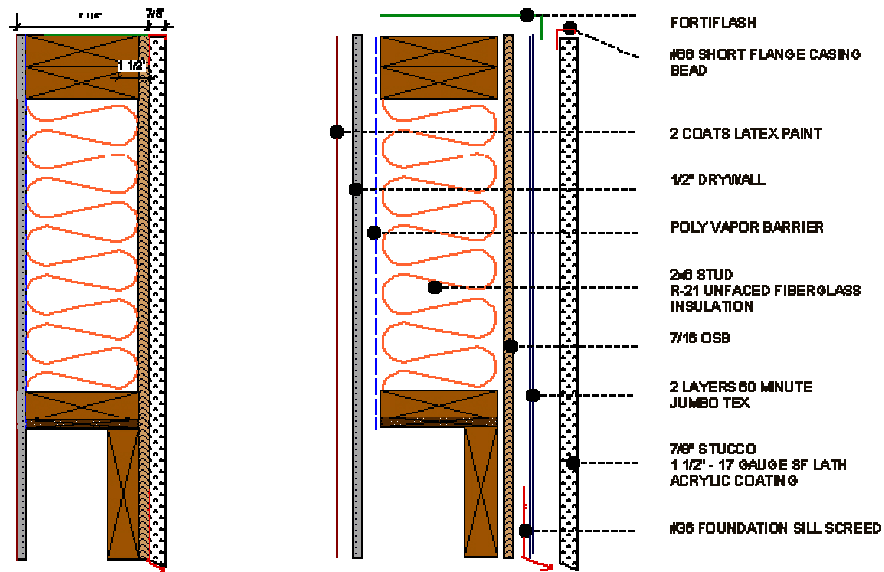
## Typical Test Wall Design

Each test wall is based on a 1.2x2.4 meter (4x9 feet) design. All of the test walls use a standard wood stud frame that includes a double top plate and a single bottom plate placed on a floor plate and rim board. This frame design provides two 39x240 cm (15.5x96 inch) primary test cavities. The test cavity is protected from edge effects by smaller buffer cavities. The floor plate is insulated to the interior to separate the bottom plate of the test from unusual interior loads. The top plate is insulated to expose the frame to both interior and exterior temperature differences that typically occur at the intersection with wood frame roof truss. **Figure 5** provides an illustration of the standard frame. Framing depth varies based on the specific test wall configuration. These details are included in the description of each test wall. **Figures 6-8** provide example sections of three of the test wall designs. In test cycle 2 and 3, walls with windows were included in the matrix. These walls modify the basic configuration to include a window.

**Figure 5** Typical test panel framing



**Figure 6** Schematic representation of Test Wall #S1 – unvented stucco system (not to scale)



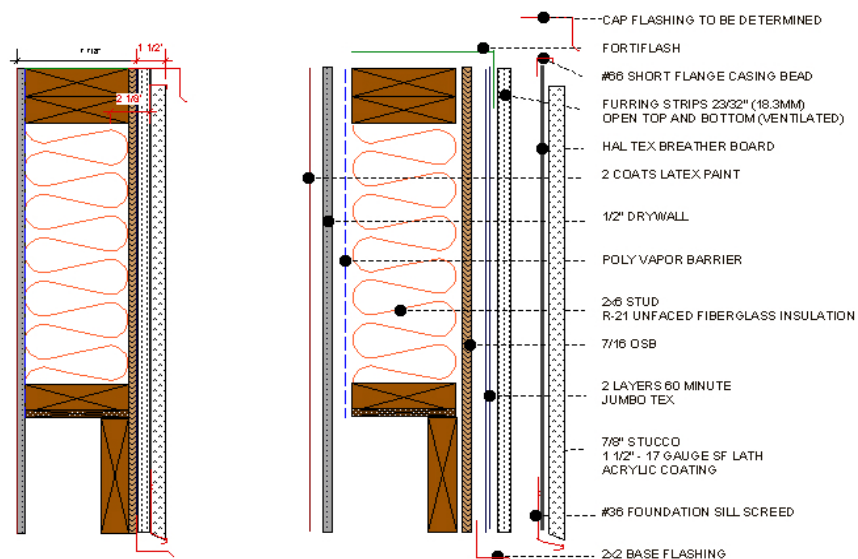
TEST WALL #1  
LOCATION S1

2x6 R-21  
UNVENTED STUCCO WALL WITH POLY VAPOR RETARDER

CHUCK MURRAY  
WASHINGTON  
STATE UNIVERSITY

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**Figure 7** Schematic representation of Test Wall #S4 – ventilated stucco system (not to scale)



TEST WALL #4  
LOCATION S4

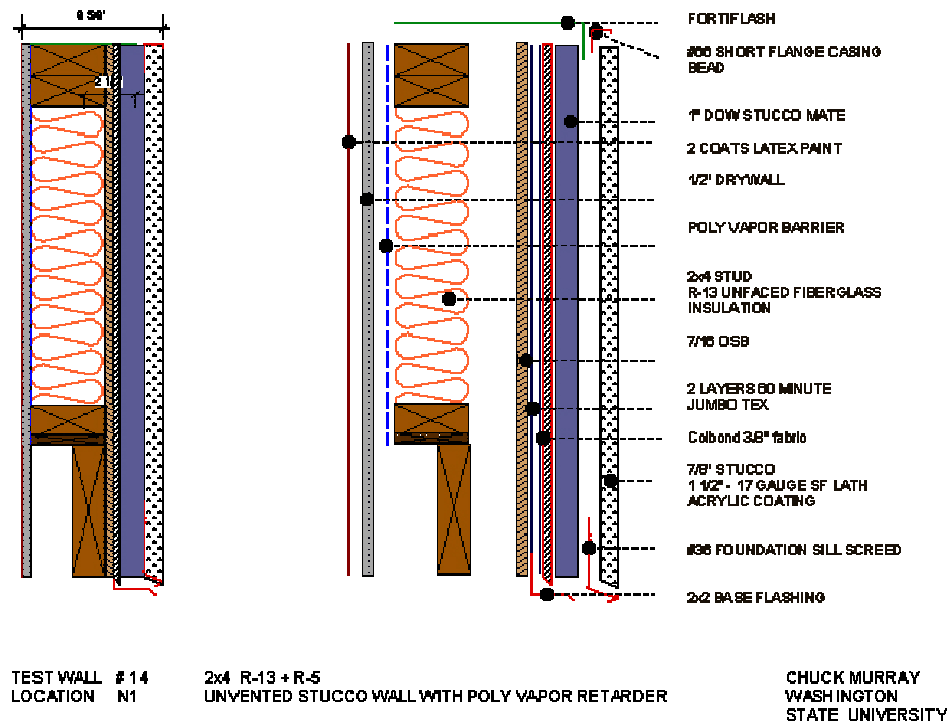
2x6 R-21  
VENTILATED STUCCO WALL WITH POLY VAPOR RETARDER

CHUCK MURRAY  
WASHINGTON  
STATE UNIVERSITY

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Figure 8

Schematic representation of Test Wall S6 1" foam clad system (not to scale)



## Instrumentation

Data collection equipment was installed to continuously monitor the hygrothermal performance of the test walls. Outdoor environmental conditions are monitored by a high quality weather station located on site. Interior environment is monitored using instruments meeting the same standards.

The instrumentation plan for the test facility was developed to meet two requirements. First, to provide direct feedback on the performance of the test walls exposed to Pacific Northwest environment, and second, to provide data for the calibration of advanced computer models being developed by ORNL. Using computer simulations and previous field experience, ORNL defined the best location for each on the instruments. The instrument package includes instruments that document interior and exterior environmental conditions as well as the moisture performance of the test walls.

The instrument package and initial programming was purchased from Balanced Solutions of Waterloo Ontario. This methodology is detailed in the paper by Straube and Onysko in 2002. Balanced Solutions also provided consulting services during installation. This system has since been adopted for use by ORNL at the NET Facility in Hollywood, South Carolina, and by a number of facilities run by the private sector.

## Data Loggers

Measurements are made using 3 Campbell Scientific CR10X Measurement and control modules and 9 Scientific AM 16/32 Relay Multiplexers. Sampling occurs every 5

minutes and is averaged hourly. Logger clocks are set nightly to a computer that is set daily to an atomic clock. The computer and loggers follow daylight savings time. These loggers also control the humidifier and cooling equipment inside the building.

#### Data Logger 1

5 Campbell Scientific AM 16/32 Relay Multiplexer  
Recording Temperature  
Condensation Sensors  
Gypsum Sensors

#### Data Logger 2

4 Campbell Scientific AM 16/32 Relay Multiplexers  
Relative Humidity sensors  
Moisture Content sensors

#### Data Logger 3

Weather Instrumentation  
5S500 Temperature and Relative Humidity Probe  
TE525 Tipping Bucket Rain Gauge  
05103 RM Young Wind Monitor

#### Weather Instruments

The primary weather instruments are located on top of the building at the southwest corner of the NET. Additional pyranometer locations are noted below. Weather instruments are measured every 10 minutes and averaged every hour.

Outdoor Temperature and Relative Humidity – Outdoor temperature and relative humidity is measured using Campbell Scientific CS500 Temperature and Relative Humidity Probe mounted in a radiation shield.

Solar Radiation – Solar radiation (sun plus sky radiation) is measured using Campbell Scientific SP-Light Silicon Pyranometer. It measures the energy received from the entire hemisphere (i.e., 180 degree field of view). One pyranometer is included in the roof mounted weather station and provides vertical measurements. Two additional pyranometers were added to the walls in March of 2004 during the second test cycle. One is mounted facing north, the other facing south.

Wind Speed and Direction –A RM Young Wind Monitor is used to measure wind speed and direction. This the logger programming records hourly average, minimum and maximum wind speed in several standard formats.

Precipitation – Vertically falling rainfall is measured using the Campbell Scientific 525 Tipping Bucket Rain Gage located on the roof.

#### Test Wall Instrumentation

##### **Temperature (T)**

The 240 temperature channels are measured using a simple voltage divider circuit consisting of a Fenwal/Elmwood thermistor (Honeywell# 192-103LET-A01) wired in

series with a 10K precision resistor. The resistor and thermistor form a three wire half bridge. Three wires come from the sensor: ground, excitation, and output **Figure 9**.

The output of the half bridge is

$$v/v_o = R_o / (R_T + R_o) \quad (1)$$

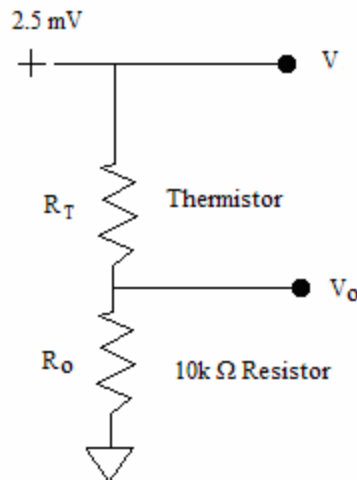
where  $v/v_o$  is the ratio of output voltage to applied voltage for the half bridge,  $R_o$  is the pickoff resistor value (10K, which is also the thermistor resistance at 25 C), and  $R_T$  is the thermistor resistance. Solving for  $R_T$

$$R_T = R_o * (v_o/v) - 1 \quad (2)$$

The relationship between the logarithm of the ratio of thermistor resistance to resistance at 25°C and temperature is well fit by a third order polynomial. Departures of the fit from actual values are less than the thermistor accuracy (0.2°C) from -40 to +60 °C. If we let  $x = \ln(R_T)$  then

$$T = -0.101 x^3 + 4.346 x^2 - 77.18 x + 446.05 \text{ (in } ^\circ\text{C)} \quad (3)$$

The Campbell Scientific CR10X Data logger implements equation 3, giving a temperature output in degrees C. In the logs we apply a range filter:  $20 < T < 150$



**Figure 9** Three wire half bridge for temperature measurement

### Relative Humidity (RHc)

Relative Humidity is measured using a Hycal IH-3610-1 (Honeywell) using a similar circuit to the temperature sensing circuit **Figure 10**. It uses a precision 121k Ω resistor.

$$RH = (V_{out} - 0.958) / 0.03068(4)$$

The Campbell Scientific CR10X Data logger implements equation 4. Then in the log, a range filter is applied:  $0 < RH < 150$

Relative Humidity (temperature correction)

$$RH_c = RH / (1.0546 - 0.00216 * T) \quad (5)$$

In the logs, a correction equation (5) from the Honeywell HIH product sheet is applied. This correction is based on the thermistor, which is coupled with each humidity sensor.

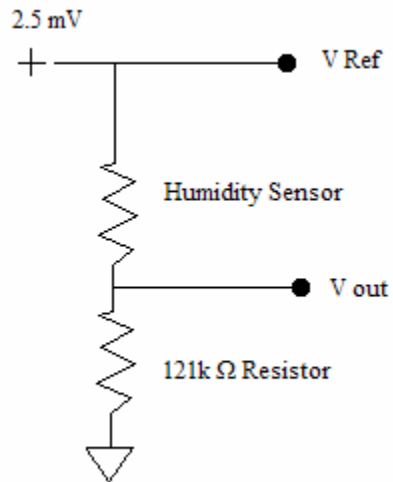


Figure 10

Three wire half bridge for RH measurement

### Wood Moisture Content (MCc)

Wood moisture content is being measured in the framing at the following locations: top plate near the exterior sheathing (MCc1), bottom plate near the exterior sheathing (MCc6), and the center stud, at mid-height, (MCc5).

The moisture content sensor consists of two brass nails wired to the data logger. The nails are coated to assure that the measurement only occurs at the tip of the sensor. The two nails are inserted into the wood 24 mm (1 inch) apart. Sensors are typically at a depth of approximately 3 mm (1/8 inch). The one exception is MCc3, which is inserted to measure the exterior moisture content of the sheathing board. The MCc3 sensor is inserted to a depth to reach within 3 mm (1/8 inch) of the exterior surface of the sheathing.

To make a measurement a voltage is measured across a fixed resistor, which is placed in series with the moisture pins. This provides a reading in millivolts. Every 5 minutes three measurements are taken in quick succession and values that are not negative are averaged and placed in temporary memory of the loggers. Every hour these measurements are averaged and stored as permanent data. A range filter is applied to the final values

$0 \leq MC < 6998$ . Each moisture content sensor is partnered with a temperature sensor described below.

The millivolt readings are then converted to percent wood moisture content as part of data analysis. The following formula is applied to convert the moisture content sensor readings with the temperature sensor readings to provide a temperature corrected moisture content in percent. The post processing values are noted in this report as Moisture Content corrected (MCc).

For each wood product a set of wood species correction factors are applied. The frame lumber and OSB correction factors were provided by Balanced Solutions. Correction values specific to plywood were not available. For this report, the Oriented Strand Board values were used. We believe the moisture content readings listed in this report for plywood may be high.

Frame lumber	a = 0.853	b = 0.398
Oriented Strand Board	a = 1.114	b = 0.36
Plywood	a = 1.114	b = 0.36

Temperature Corrected Moisture Content (percent)

$$MCc = (((10^{(2.99 - 2.113 * \text{Log}10(\text{Log}10(MC * 1000000)))}) + 0.567) - 0.026 * T) + 0.000051 * T^2) / (0.881 * 1.0056^T - b) / a \quad (6)$$

T= temperature

b= wood species function

a= wood species function

The moisture content values are accurate in the range of 10 to 25 percent. In particular, as the moisture content increases above 25 percent the readings are less accurate. It is also important to note, that the moisture content readings are only spot readings, and do not reflect the total moisture content of the entire specimen. For example, the sensors embedded 3 mm (1/8 inch) into framing lumber only reflect the moisture present near the surface of the specimen in the specific location of the sensor. This reading does not indicate that the entire frame is in equilibrium with the sensor reading.

### Experimental Sensors

At the request of ORNL, two additional sensors types have been placed in many of the test walls. The results of these instruments will not be reported at this time. Further work on the calibration of the experimental instruments is needed.

A variation of a leaf wetness sensor developed by Balanced Solutions was placed in the wall cavity. Surface contacts that measure the electrical resistance of a water film on the flat surface of the instrument indicate accumulation of moisture. The instrument was placed in the wall cavity to provide an indication of the incidence of condensation.

A gypsum block moisture sensor designed to measure soil moisture content was used in the stucco cladding and interior drywall. Once again the electrical resistance measured in the gypsum will provide additional information on the moisture content of the building products.

### Ventilated Cavity Pressure

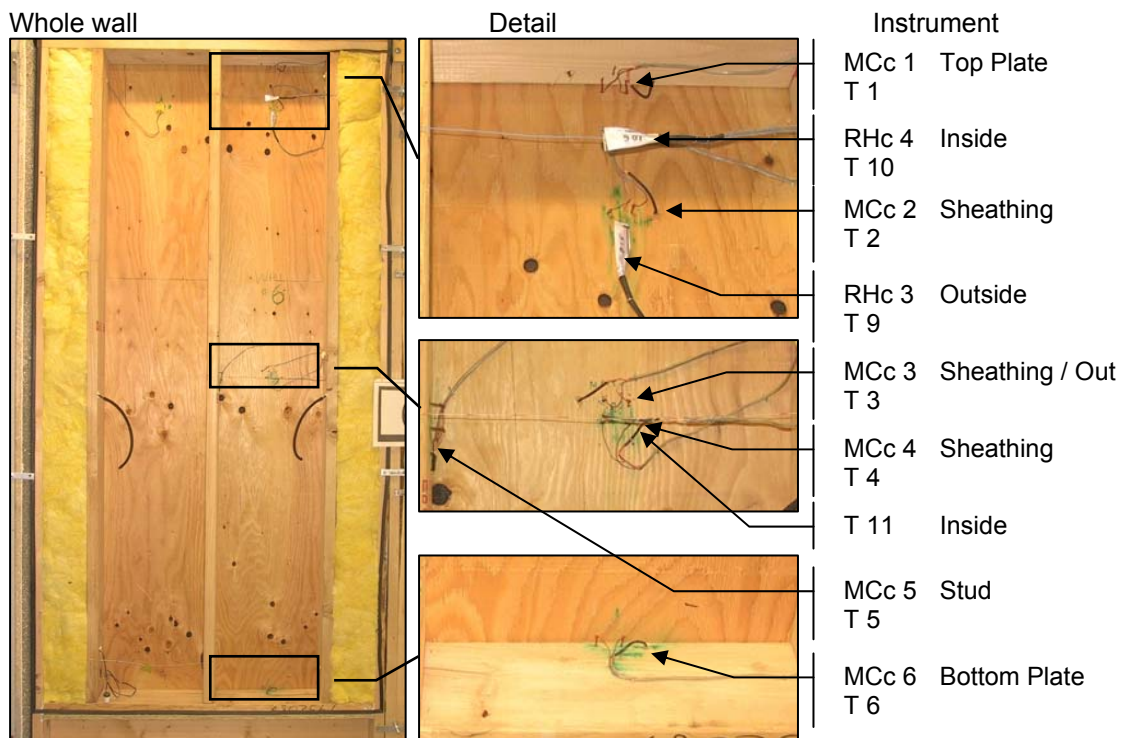
Pressure in several of the vented and ventilated cavities has been measure using a logging differential pressure gauge that provides resolution of 0.1 Pascal. Tubing runs

from the pressure logger to the vented and ventilated cladding cavities. For each wall one pressure reading was recorded low on the wall, one high on the wall. Simple static pressure readings are recorded every minute. The resulting data allowed us to determine the average pressure difference. This allows us to determine whether there is airflow or a static space in the vented or ventilated cavity.

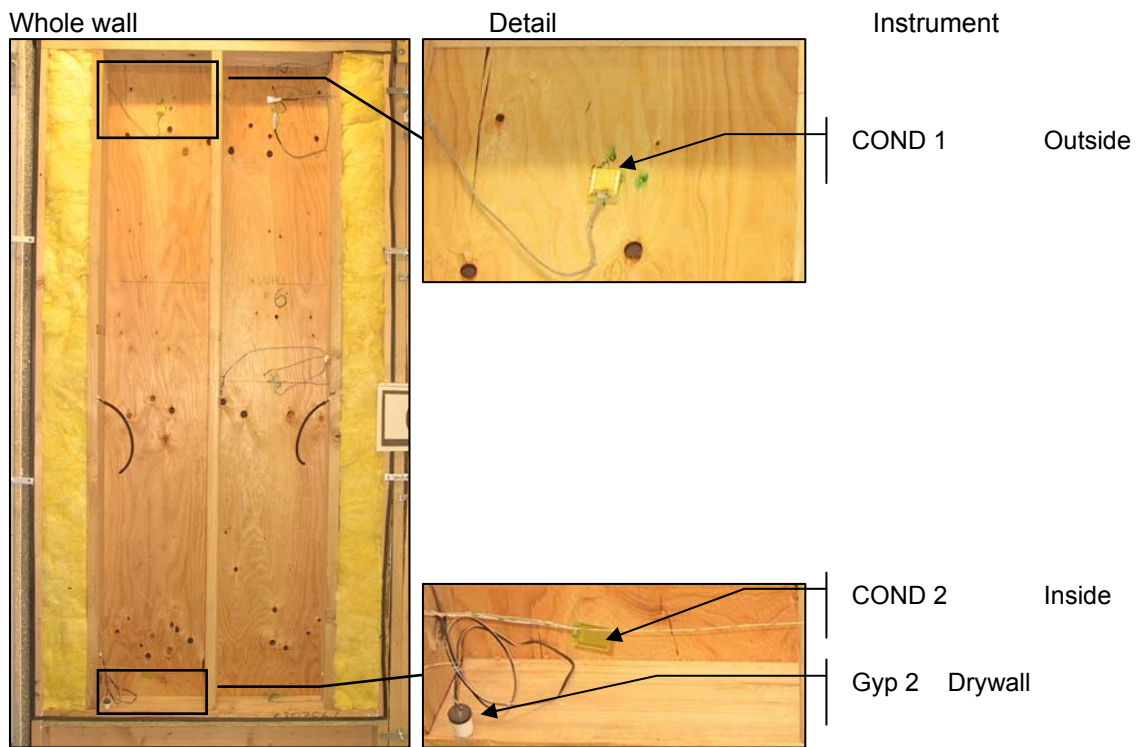
### Sensor Location in the Test Walls

The sensor locations are listed below, and they are illustrated in **Figures 11-13**. It should be noted that the location of the sensors is modified in test walls with windows. There is a partial set installed above and below the window.

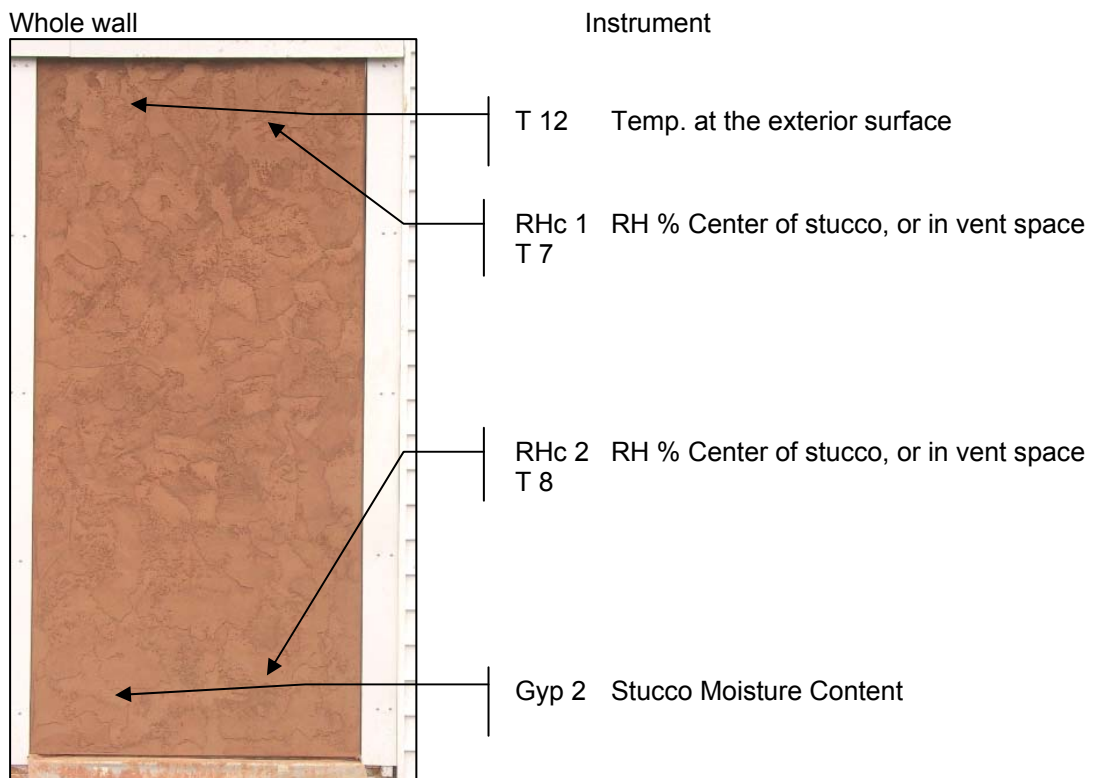
**Figure 11 Instrument location in the right framed cavity**



**Figure 12 Instrument location in the left framed cavity**



**Figure 13 Instruments located on the exterior**



## **Relative Humidity and Temperature**

### **RHc1 and t7**

Relative humidity exterior to the weather resistive barrier.

For test walls with direct applied stucco, this sensor is embedded in the stucco. For walls with a space between the weather resistive barrier and the cladding, the sensor is placed in this space. The sensor is located 30 cm (12 inches) from the top of the test wall.

### **RHc2 and t8**

Relative humidity exterior to the weather resistive barrier

Similar to RHc1, but sensor is located 210 cm (83 inches) from the top of the test wall.

### **RHc3 and t9**

Relative humidity of the insulated cavity next to the exterior sheathing

Located in the framed cavity between the insulation and the exterior sheathing board, 30 cm (12 inches) from the top of the test wall center of a primary test cavity.

### **RHc4 and t10**

Relative humidity of the insulated cavity next to the interior sheathing

Located in the framed cavity between the insulation and the interior gypsum board/vapor retarder, 30 cm (12 inches) from the top of the test wall center of a primary test cavity.

## **Wood Moisture Content and Temperature**

### **MCc1 and t1**

Top plate moisture content

Located in top plate near the exterior sheathing board

### **MCc2 and t2**

Exterior sheathing moisture content

Located in the exterior sheathing board, 30 cm (12 inches) from the top of the test wall.

### **MCc3 and t3**

Exterior sheathing moisture content – placed deep to read exterior influences.

Located in the exterior sheathing board, 120 cm (48 inches) from the top of the test wall.

### **MCc4 and t4**

Exterior sheathing moisture content – placed deep to read exterior influences.

Located in the exterior sheathing board, 127 cm (50 inches) from the top of the test wall.

### **MCc5 and t5**

Center stud moisture content

Located in the center stud, 127 cm (50 inches) from the top of the test wall. The sensor is centered between the interior and exterior sheathing board.

MCc6 and t6  
Bottom plate moisture content  
Located in bottom plate near the exterior sheathing board

### **Additional Temperature Sensors**

T11  
Cladding temperature  
Embedded in the cladding near the exterior surface of the material. The sensor is located 30 cm (12 inches) from the top of the test wall.

T12  
Drywall temperature  
Located 127 cm (50 inches) from the top of the test wall.

### **Testing Schedule**

For this project, WSU monitored the performance of the test walls for almost three years, fully capturing the effects of three full wetting and drying cycles for the test walls. We defined these as three test cycles:

- Test Cycle 1    October 1, 2003 - September 14, 2004 (data presented in **Appendix A**)
- Test Cycle 2    November 7, 2004 - September 20, 2005 (data in **Appendix B**)
- Test Cycle 3    October 1, 2005 to June 30, 2006 (data in **Appendix C**)

For Test Cycles 1 and 3, the test walls were subjected only to exterior and interior environmental loads. Test Cycle 2 used similar test conditions for the first few months. But in the spring and early summer, additional loads were introduced to the framed wall cavity. This schedule modification is detailed in **Appendix B, Figure B 1**.

As wood frame wall systems are subjected to changes in indoor and outdoor environmental conditions, it is typical for there to be changes in the moisture volume and distribution in the building assembly. Walls get wet and dry out with seasonal changes. The actual calendar for this cycle is dependent on the indoor comfort settings selected for the building and the local climate.

For homes in the Pacific Northwest, moisture loading from the exterior and interior environments is most likely to take place in the months of October through January. This is when there is greatest rainfall, highest outdoor humidity, and highest vapor drive from the interior. In the spring, there is a transition period where the driving forces that influence wall moisture volumes and distribution is in flux. There are periods of moisture accumulation followed by drying. There is also redistribution of the moisture from one area in the wall assembly to another. By early summer, wood frame walls will typically be dry. They remain dry until October, when the cycle begins again. To match this cycle, our testing and evaluation begins each fall.

### **Indoor and Outdoor Environmental Conditions**

To provide context for the performance of the test walls, a discussion of the environmental loads is important. The performance of the test walls is influenced by the indoor and outdoor environmental conditions. For outdoor conditions, this is the local weather during the testing period. For indoor conditions, the temperature and interior humidity was controlled to provide an appropriate test condition for the walls. This section will provide a brief summary of both indoor and outdoor environmental conditions that occurred during each test cycle.

### Indoor

Indoor temperature and humidity settings were selected to provide a robust, but realistic, interior load. Target settings for the experiment were a temperature of 20 to 21 degrees C (68 to 69.8 F) and relative humidity of 50 to 55 percent. This set point will result in an interior vapor pressure of roughly 1200 to 1350 Pascals. These settings were maintained throughout the experiment using heating, cooling and humidification equipment. The indoor control settings were selected to provide interior winter design conditions that were higher than average, but within the distribution of indoor temperature and humidity observed by ORNL in apartments and small homes in Seattle, WA. (Aoki-Kramer, 2004) These settings were somewhat variable early in test cycle 1. The relative humidity varied both high and low. On average this was not an issue, except for January of 2004, when the interior vapor pressure was higher than our targets.

In retrospect, the recorded interior conditions were also compared to interior design values using a modification of a formula from ASHRAE Standard 160P Design Criteria for Moisture Control in buildings, working draft, April 2006. Equation 4.1 of this standard provides interior design vapor pressure based on the volume of the occupied space, outdoor vapor pressure, interior moisture production rate based on occupancy, and ventilation rate of the building.

$$p_i = p_{o,24h} + \frac{\dot{c} m}{Q_{ventilation}} \quad (4.1)$$

where

$p_i$  = indoor vapor pressure, Pa (in.Hg)

$p_{o,24h}$  = 24-hour running average outdoor vapor pressure, Pa (in.Hg)

$c$  = 1.36 105 m<sup>2</sup>/s<sup>2</sup> (10.7 in.Hg-ft<sup>3</sup>/lb)

$\dot{m}$  = design moisture generation rate, kg/s (lb/h) (sections 4.3.2.1.1 and 2)

$Q_{ventilation}$  = design ventilation rate, m<sup>3</sup>/s (cfm) (sections 4.3.2.1.3 and 4)

**Figure 14** provides the results of our evaluation. We have used the values for a 2 bedroom home with less 140 square meters (1500 square feet) of floor area and an assumed ventilation rate of 0.35 air changes per hour. These inputs are listed below. **Figure 15** provides interior vapor pressure during the three test cycles. By comparing these design vapor pressure values in **Figure 14** to **Figure 15**, you will note that for most of the testing periods, the interior environment in the NET was kept below the indoor design conditions recommended in ASHRAE 160p.

$p_{o,24h}$  = Vapor pressure measured on site during, or from historical climate data

•  
 $m$  = 12 L/day Design moisture generation rate for 2 bedroom home

Qventilation = 0.35 air changes per hour

### Outdoor

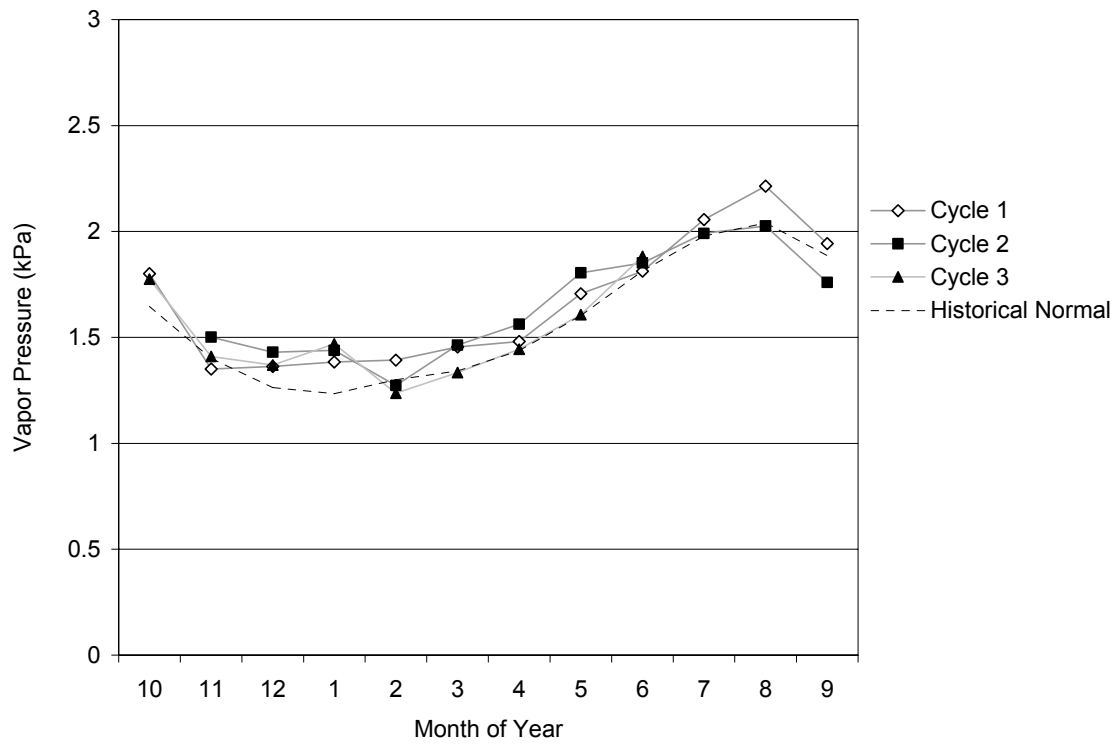
For any give year the outdoor environmental conditions will vary from the historical normal data. The following section provides a few observations to put the research results in context, specifically notes on rainfall. Detailed graphs of the weather data can be found in **Appendix D**.

Test Cycle 1, rainfall exceeded normal for October only. For the rest of the year the rainfall was below normal, resulting in cumulative October - March precipitation that was approximately 70% of normal.

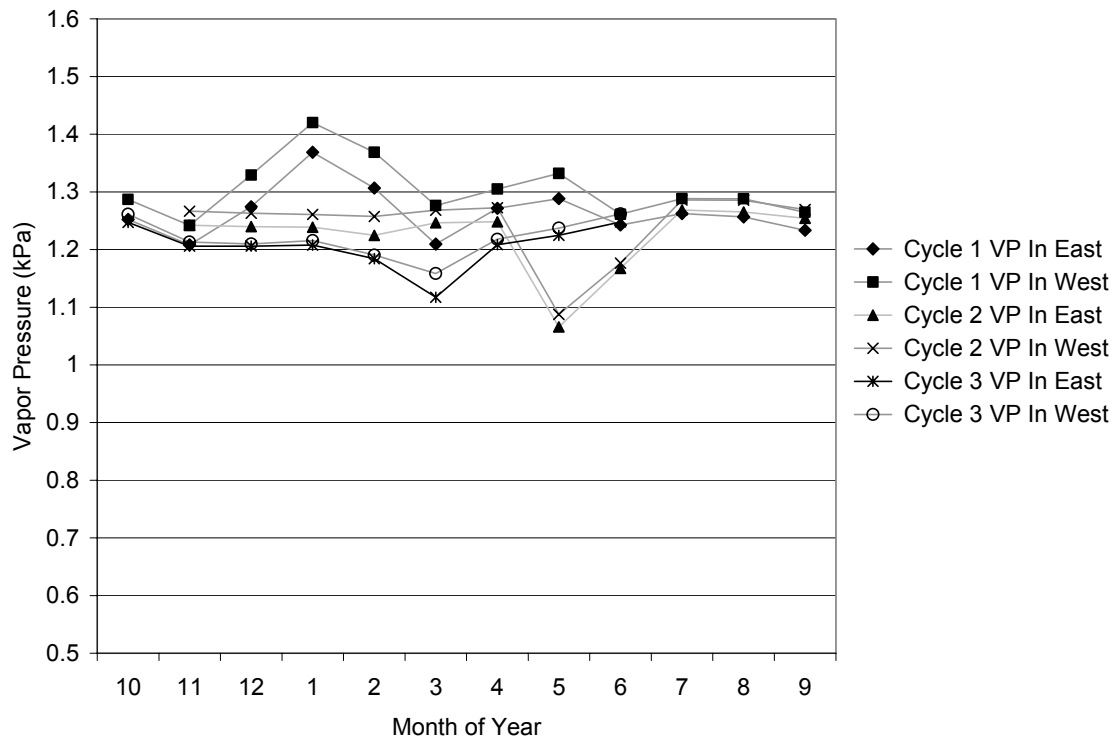
Test Cycle 2, rainfall was again significantly below normal. For October – March, cumulative rainfall was 54% of normal.

Test Cycle 3, Cumulative rainfall for October – March was normal. There was a particularly long period of time in late December – January where there was cloud cover and rain every day, nearly beating historical records for continuous days of rain.

**Figure 14** Design vapor pressure based on Formula 4.1



**Figure 15** Recorded interior vapor pressure



## Wall Wetting Experiment

At the request of ORNL, WSU performed a procedure that introduced an additional load of moisture to the insulated cavity of the wall. This procedure was conducted to determine if the computer simulation work conducted by ORNL could produce similar results to the wall loading that took place during this test. It also provides added field data on the drying performance of the test walls. This procedure was conducted during test cycle 2 in the spring.

To introduce moisture into the walls using a controlled method, WSU installed irrigation tubing and a medium that would hold the moisture in each primary test wall cavity. The medium is located in the wall cavity between the drywall or vapor retarder and the insulation. In theory, the moisture enters the medium and distributes the moisture to the wall through evaporation. There were cases where the medium did not hold all of the water introduced. There were times the water left the medium in a liquid state rather than vapor, and it was distributed in large concentrations to the bottom plate.

Over the test periods measured amounts of water were injected into the wetting medium. The medium in each of the wall's two primary test cavities received an injection of water on the following schedule.

- A single load of 150 cc was injected on February 12, 2005.
- A series of injections were performed from March 15 to April 8, 2005. Injections of water were made every two to three days for this time period. For most walls this resulted in a load of 1075 cc per test cavity. For walls with windows, a smaller amount of water was injected, totaling 607 cc.

After this testing was completed, the walls were monitored to examine the drying rate after the loading. Then the drywall was removed from the walls to allow them to dry prior to the second series of wetting.

- June 2 through July 7, 2005 a second series of water injections were performed. During this time period, walls without windows received a load of 1500 cc per test cavity. For walls with windows, water was injected totaling 835 cc.

## Test Wall Systems

### Selection of Test Walls

The selection of test wall designs was an iterative process. Over several months, input was received from research team members and industry partners. Several decisions on the test wall construction were made early in the process. Others came rather late in the process, as purchasing decisions were made based on input from materials suppliers in the Puget Sound region. One of the most challenging aspects of selecting test wall designs was balancing the almost unlimited number of possibilities with the limited test wall space in the NET. In the end, the research team chose test wall construction methods that would allow analysis of construction methods thought to have significant impact on heat and moisture transport performance.

It is important to note that the wall designs chosen were selected to demonstrate specific heat and moisture transport principles. While detailed comparisons between test walls can be made, the test walls selected can also be used to demonstrate more general heat and moisture transport characteristics. For example, stucco represents a cladding system with potential for moisture storage, and lap siding represents a systems that does not store moisture. Specific comparisons between these systems can be made, while studying more general principles of construction.

In addition, the test wall designs were chosen to meet calibration requirements for the hygrothermal computer models created by ORNL. ORNL will provide more detail on the effects of material and assembly choices in separate reporting.

The following discussion outlines the selection of materials and assemblies. **Table 1** provides a tabular description of the walls tested under cycle 1. **Table 2** provides a matrix of the walls tested in cycles 2 and 3.

**Table 1****Test wall matrix 2003-2004 (Test Cycle 1)****WSU Natural Exposure Test Facility**

Wall	Window	Ext Finish	Siding	Ext. Venting	WRB	Sheathing	Ext Insulation	Cavity Insulation	Frame	Vapor Retarder	Int Board	Int Paint	Location
w1		Cement	Stucco 7/8"	Unvented	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	S1
w2		Cement	Stucco 7/8"	Unvented	2x 60 min	OSB		R-21	2X6	MemBrain	Drywall	Latex	S2
w3		Cement	Stucco 7/8"	Vented	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	S3
w4		Cement	Stucco 7/8"	Ventilated	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	S4
w5		Cement	Stucco 7/8"	Unvented	2x 60 min	Plywood		R-11	2X4	Kraft	Drywall	Oil	S5
w6		Cement	Stucco 7/8"	Unvented	2x 60 min	Plywood		R-21	2X6	Poly	Drywall	Latex	S6
w7		Cement	Stucco 7/8"	Unvented	2x 60 min	OSB		R-21	2X6	None	Drywall	Latex	S7
w8		Cement	Stucco 7/8"	Unvented	2x 60 min	OSB	Foam - 1"	R-13	2X4	MemBrain	Drywall	Latex	S8
w9		Latex	lap	Unvented	2x 60 min	Plywood		R-21	2X6	Poly	Drywall	Latex	S9
w10		Latex	lap	Vented	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	S10
w11		Latex	lap	Ventilated	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	S11
w12		Latex	lap	Unvented	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	S12

OSB 7/16" Aspen

Plywood 15/32" 4 Ply Doug Fir

Unvented Siding direct applied over sheathing and weather resistive barrier.

Vented 3/4" Cavity behind exterior sheathing open at the bottom of the panel only

Ventilated 3/4" Cavity behind exterior sheathing open at the top and bottom of the panel

WRB Weather Resistive Barrier

2x 60 min 2 layer 60 minute building paper.

MemBrain<sup>o</sup> CertainTeed smart vapor retarder

Drywall 1/2" Standard drywall taped and finished

Table 2

**Test wall matrix 2004-2006 (Test Cycle 2 and 3)**  
**WSU Natural Exposure Test Facility**

Wall	Window	Ext Finish	Siding	Ext. Venting	WRB	Sheathing	Ext Insulation	Cavity Insulation	Frame	Vapor Retarder	Int Board	Int Paint	Cycle 1 Name
S1		Cement	Stucco 7/8"		2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	w1
S2		Cement	Stucco 7/8"		2x 60 min	OSB		R-21	2X6	MemBrain	Drywall	Latex	w2
S3		Cement	Stucco 7/8"	Vented	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	w3
S4		Cement	Stucco 7/8"	Ventilated	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	w4
S5		Cement	Stucco 7/8"		2x 60 min	Plywood		R-11	2X4	Kraft	Drywall	Oil	w5
S6		Cement	Stucco 7/8"		2x 60 min	Plywood		R-21	2X6	Poly	Drywall	Latex	w6
S7		Cement	Stucco 7/8"		2x 60 min	OSB		R-21	2X6	None	Drywall	Latex	w7
S8		Cement	Vinyl		1x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	
S9	mech.fla	Cement	Stucco 7/8"		2x 60 min	Plywood		R-21	2X6	Poly	Drywall	Latex	
S10	peal+stick	Cement	Stucco 7/8"		2x 60 min	Plywood		R-21	2X6	Poly	Drywall	Latex	
S11			Stucco 7/8"		1x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	
S12		Latex	lap		2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	
N3		Latex	lap	Ventilated	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	w11
N4		Cement	Stucco 7/8"	Ventilated	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	
N5		Cement	Stucco 7/8"		2x 60 min	OSB	Foam - 1"	R-13	2X4	MemBrain	Drywall	Latex	w8
N6		Cement	Stucco 7/8"		2x 60 min	OSB	Foam+drain	R-13	2X4	MemBrain	Drywall	Latex	
N7		Cement	Stucco 7/8"		2x 60 min	OSB		R-21	2X6	None	Drywall	Latex	
N8		Dryvit	Dryvit		Liquid	Plywood	4" EPS	none	2X4	None	Drywall	Latex	
	OSB	7/16"	Aspen										
	Plywood	15/32"	4 Ply Doug Fir										
	Unvented		Siding direct applied over sheathing and weather resistive barrier.										
	Vented	3/4"	Cavity behind exterior sheathing open at the bottom of the panel only										

Ventilated	3/4"	Cavity behind exterior sheathing open at the top and bottom of the panel
WRB		Weather Resistive Barrier
2x 60 min		2 layer 60 minute building paper.
MemBrain®		CertainTeed smart vapor retarder
Drywall	1/2"	Standard drywall taped and finished
Foam	1"	Extruded Poly Styrene R-5
Mech. Fla		Vinyl window with mechanically attached flashing system
Peal+ stick		Vinyl window with peal and stick flashing system

### Framing

All test walls are constructed with wood framing systems. The lumber used in all test walls was a typical species grouping (Hem-fir) commonly used in the Pacific Northwest for residential construction. The lumber is manufactured kiln dry. The moisture content of the lumber at the time of test wall assembly ranged from 10-14%. The density of Hem-fir is mid-range among construction lumber products with an average specific gravity approximately 0.43 (based on oven dry weight and volume).

In most cases 4.4x14 cm (nominal 2x6 inch) frames were selected as representative of the majority of residential construction in Washington and Oregon. This framing type was selected to accommodate the R-21 insulation typically employed to meet the energy codes in the two states. 4.4x8.9 cm (nominal 2x4 inch) framing was selected for a few test walls.

### Structural Sheathing

Structural sheathing for the test walls includes oriented strand board (OSB) and plywood. OSB was used for a majority of the test walls. For test cycle 1 three specific walls were included that will provide direct comparison between OSB and plywood performance. Both a stucco clad and cement clad wall are included with identical features except sheathing. Plywood was also used on the walls with windows and the exterior insulation and finish wall system.

### Insulation

The dominant insulation method for exterior walls in the Pacific Northwest is R-3.6 SI (R-21 IP) fiberglass batts in the cavity of a 4.4x14 cm (nominal 2x6 inch). An acceptable insulation alternative is a 4.4x8.9 cm (nominal 2x4 inch) frame with R-2.2 SI (R-13 IP) batts and R 0.85 SI (R-5 IP) exterior foam sheathing. This alternative has the potential to significantly change the heat and moisture transport characteristics of the wall system.

**Figure 16** provides photographs of a wall with foam on the exterior.

**Figure 16**      **Foam sheathing prior to the application of stucco**



Wall systems constructed prior to modern energy codes are represented by a wall that incorporates a 4.4x8.9 cm (nominal 2x4 inch) insulated cavity with an R-1.8 SI (R-11 IP) batt only.

#### *Drywall, Interior Paint and Vapor Retarder*

All of the test walls include 13 mm ( $\frac{1}{2}$  inch) drywall painted with a coat of **PVA** primer and a coat of latex paint.

For a single coat of paint that might be used on interior drywall the *ASHRAE Handbook of Fundamentals* lists permeance ranges from 360 to 491 ng/(s m<sup>2</sup> pa) (6.28 to 8.62 perms). The paint selected for the test walls included a PVA primer and a single coat of acrylic latex paint. This is typical of new construction in the Pacific Northwest. ORNL material property testing reported much higher than expected permeance for this coating. As reported to WSU by ORNL, the standard dry cup rating for the drywall and two coats paint is as high as 1146 ng/(s m<sup>2</sup> pa) (30 perms). Test walls w7/S7 and N7 will have very high vapor transmission rates. Detailed test results of the materials property testing can be found in separate reporting completed by ORNL.

Many of the walls include polyethylene sheeting vapor retarder installed just behind the drywall. The vapor control expected from polyethylene sheeting is documented in the

*ASHRAE Handbook of Fundamentals*. For 0.1 mm (4 mil) polyethylene sheeting the value listed is 3.4 ng/(s m<sup>2</sup> pa) (0.08 perms).

A smart vapor retarder, MemBrain™, has been included on a number of test walls. As reported by the manufacturer, MemBrain™ tests at 57 ng/(s m<sup>2</sup> pa) (1 perm) or less when tested in accordance with the ASTM E 96 standard dry cup method. MemBrain has a permeance of 570 ng/(s m<sup>2</sup> pa) (10 perm) or greater when tested in accordance with, ASTM E 96 standard water or wet cup method, and increases to 2060 ng/(s m<sup>2</sup> pa) (36 perms) or more at an average relative humidity of 95%. This variable resistance is expected to provide good vapor resistance during the heating season while allowing the wall to dry to the interior during spring and summer.

### *Weather Resistive Barrier*

For the first test cycle, the research team selected a single weather resistive barrier system. Two layers of 60-minute building paper were selected for all of the test walls. Previous research by ORNL suggests that a two layer system provides an effective barrier to rainwater penetration (Karagiozis, 2002).

At the beginning of test cycle 2, one wall was constructed with a single layer of building paper. This provided an opportunity for comparison with similar walls with two layers.

The exterior insulation and finish system added for test cycle 2 has a liquid applied barrier to provide drainage.

One additional variation in weather resistive barriers includes the addition of a drainage mat under one of the foam clad wall system. A grid of loosely woven nylon mesh creates an air space that is approximately 1 cm (3/8 inch) deep. This was used in addition to two layers of building paper.

### *Cladding*

For test cycle 1, the research team selected stucco to represent a storage cladding system. Lap siding was chosen to represent cladding with no moisture. In test cycle 2 vinyl siding and a wall with a proprietary exterior insulation and finish system were added to the matrix. Within these systems, specific materials and finishes were selected.

All of the stucco cladding was a 22 mm (7/8 inch) trowel applied cement stucco with a natural cement finish coat. This system was chosen specifically to meet the needs of the ORNL modeling experiments. A natural cement finish was selected because it will have the most dynamic wetting and drying characteristics and better represent a true storage cladding system.

Lap siding was selected as a representative material for a low mass cladding system. Lap siding is designed to shed most of the water. However, standard assembly methods may allow small amounts of water intrusion during significant weather events. The lap assembly also creates a small cavity behind the siding that may change the drying characteristics of the wall. Cement lap siding was selected because of its growing market share in the Pacific Northwest. The lap siding test walls were painted with one coat of exterior latex paint over the factory applied primer.

Vinyl siding was added to the test wall matrix at the beginning of test cycle 2. This system was added to demonstrate a low cost system that provides some ventilation behind the cladding. This system was included at the request of US DOE Building America team members.

The exterior insulation and finish system added at the beginning of test cycle 2 demonstrates proprietary finish applied over a 10 cm (4 inch) expanded polystyrene board.

The color of the cladding affects the solar gains for the wall. ORNL provided instruments to measure total solar reflectance. For the rough stucco there was some variation in the reflectance and the range is reported. For the other products a single average value is provided.

#### Clay Colored Stucco

Average Solar Reflectance	0.28
Minimum	0.22
Maximum	0.32

#### Pink Colored Stucco

Average Solar Reflectance	0.46
Minimum	0.38
Maximum	0.56

#### White Vinyl Siding

Average Solar Reflectance	0.82
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#### Grey Cement Lap Siding

Average Solar Reflectance	0.14
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### Ventilation of Cladding

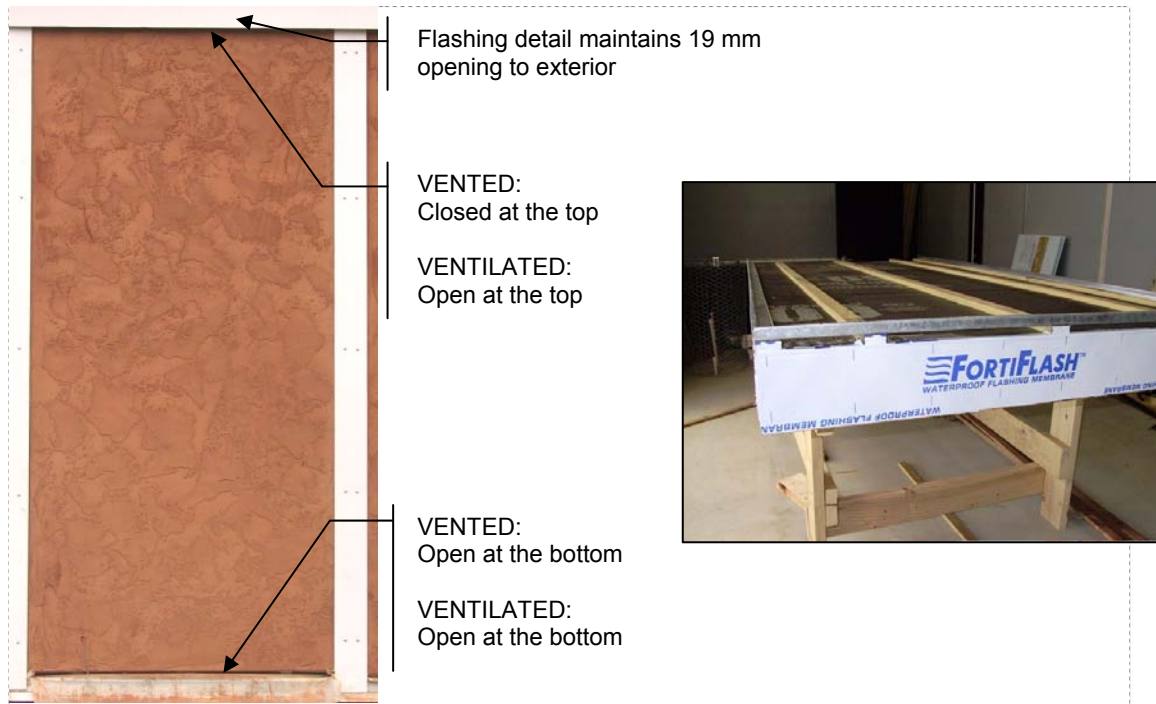
A number of test walls incorporated a 19 mm ( $\frac{3}{4}$  inch) space between the exterior cladding and the weather resistive barrier. This space is passively ventilated with outdoor air. Two systems were utilized. One system includes an opening to the exterior at the bottom and is closed at the top of the test wall and is called a vented system. Walls constructed with openings to the exterior at the bottom and top of the wall are noted in this report as ventilated. The vinyl sided wall installed for test cycles 2 and 3 also provides a degree of venting behind the cladding.

The computer modeling summarized in Karagiozis (2002) concludes that ventilation strategies are very promising methods for reducing wall moisture content. This method was also evaluated by Straube and Burnett (1998), with a more recent study by Van Straaten (2003). This construction method has been adopted widely in western Canada.

The stucco walls are constructed by placing 19mm ( $\frac{3}{4}$  inch) pressure treated wood strapping over the weather resistive barrier. Then, a layer of fiberglass reinforced building paper is applied, then lath and stucco.

For vented and ventilated walls using lap siding, walls are constructed by placing 19mm ( $\frac{3}{4}$  inch) pressure treated wood strapping over the weather resistive barrier, then the lap siding. **Figure 17** provide an illustration differentiating the vented from the ventilated cladding.

**Figure 17** Vented and ventilated stucco cladding defined



### Windows and Flashing

Test cycle 2 and 3 include two test walls with windows. Test walls with windows have been included to demonstrate flashing details. Because of the window details, the frame cavities under and over the windows create smaller test areas, which may be more susceptible to moisture issues.

Windows were installed to a specific test standard. ASTM E 2112 *Standard Practice for Installation of Exterior Windows, Doors, and Skylights*, published in 2001. Two methods for flashing are demonstrated. A method for self adhered flashing material and a method for mechanically attached flashing materials. **Figure 18** shows the details of the flashing on the test walls prior to the installation of weather resistive barriers, lath and stucco.

**Figure 18** Window flashing detail prior to the addition of building paper



## Materials Property Testing

To support ORNL materials property testing work and subsequent computer modeling work, WSU provided a set of materials from the NET test walls to ORNL. In most cases this simply required WSU to cut and ship samples of the materials. For stucco, WSU built 3 additional test walls that were cured and then cut up and shipped to ORNL for testing. This will help determine if there are differences in the stucco performance. Materials shipped to ORNL for testing include:

### Exterior Cement Stucco

- Applied over building paper and plywood
- Applied over building paper and OSB
- Applied over fiberglass reinforced

### Cement Lap Siding

- With factory applied primer
- With factory applied primer and latex finish coat

### Exterior Asphalt Impregnated 60 min Building Papers

### Gypsum Board

- Painted with two coats of oil based paint
- Painted with one coat of PVA primer and one coat of latex paint.

### Hem-fir wood studs

### Plywood (5 ply Douglas fir)

### OSB (aspen)

## **RESULTS AND DISCUSSION**

### **Introduction and General Observations**

Under normal operation most of the test walls demonstrated acceptable performance over a range of interior and exterior environmental loads. Most of the observations detailed in the findings express the difference between acceptable performance and superior performance under normal operating conditions.

Under normal operating conditions, the walls were subjected to the exterior environmental loads created by the weather conditions of the time, and selected interior environmental conditions. This included weather conditions during test cycle 1 and 2 with below normal rainfall and above normal temperatures during the winter months as well as test cycle 3 where exterior loads were more consistent with historical averages for the site. Interior moisture levels were maintained at a level consistent with high occupancy apartments, but were somewhat elevated compared to large new homes.

For all walls, there is no indication that there were leaks in the exterior cladding. All cladding types provided good resistance to water penetration. There are no indications that bulk moisture reached the structural sheathing during rain events.

The transport of moisture from the interior environment to the insulated wall cavities does not occur during the three test cycles documented in this report. Gaskets were installed between the drywall and frame to exclude air movement from the testing.

Vapor transport both from the exterior and the interior are thought to be the primary source of moisture during normal operating conditions. Because other loads were controlled, this function likely dominates the variations in wall performance. We are cautions to note that increasing the loads from air leakage and exterior moisture sources may lead to different results than those discussed in this report. If the magnitude of the load was increased significantly, for example, because of a leak in the cladding, the results of the tests are of limited predictive value.

During normal operating conditions many of the walls show increased humidity in the insulated stud cavity and some increase in wood moisture content during the fall and winter months. When the outdoor temperatures begin to warm, walls with high interior vapor resistance show a redistribution of moisture to the top of the insulated wall cavity. Late in spring and summer all of the walls become very dry.

During the winter months, any moisture present in the insulated wall cavity will be redistributed toward the exterior side of the wall cavity. This occurs because of the indoor to outdoor temperature gradient and resulting vapor drive toward the exterior. A key indicator of the moisture performance of the wall is the relative humidity between the wall cavity insulation and the exterior sheathing.

The walls with superior performance had lower relative humidity in the insulated cavity at the exterior sheathing layer. The mean weekly relative humidity for walls with superior performance is below 75 percent in the winter. This is compared to test walls where the humidity at this location ranges from 85 to 100 percent. Above 85 percent, some moisture accumulation is expected, and does occur in the exterior sheathing.

One wall type did not provide acceptable performance under normal operation. The stucco clad walls with limited vapor control experienced elevated moisture accumulation on the interior surface of the structural sheathing board. This resulted in mold growth on the exterior sheathing. These findings will be discussed in detail in the section about interior vapor control.

Exaggerated moisture loads were introduced during the spring of test cycle 2. By injecting moisture into the wall cavities additional performance comparisons between different wall types can be observed. For the most part the wall comparisons are consistent with testing under normal operating conditions. But there are some exceptions that will be discussed under the specific performance findings that follow.

## **Cladding Type**

All of the cladding types functioned well. Small differences in moisture performance can be noted when examined closely. Three south facing walls provide a detail of the differences between conventional cement stucco cladding (wall 1, S1), cement lap siding (wall 12, S12, and vinyl siding (wall S8, test cycle 2 and 3 only). These walls are of identical construction, except for the cladding.

Stucco cladding applied directly over the building paper had slightly higher moisture levels than an identical wall with conventional application of cement lap siding. The stucco wall has a slightly higher relative humidity in the insulated wall cavity, but this does not result in notably higher wood moisture content.

The test wall with vinyl lap siding has lower humidity in the test cavity, and the resulting wood moisture content is lower than the two other cladding types. This is likely the result of ventilation between the vinyl siding and building paper.

## **Cladding Ventilation**

This project tested a variety of cladding ventilation designs. This included vented and ventilated stucco, as well as vented and ventilated lap siding. Ventilated stucco and cement lap siding has been on two orientations, north and south.

### **Ventilation of Stucco Cladding**

A distinction between two stucco cladding ventilation strategies can be compared to a conventional cement stucco application during all three test cycles. Under normal conditions, the fully ventilated stucco wall (wall 4, S4), performed much better than the conventional stucco wall (wall 1, S1) or the vented stucco wall (wall 3, S3). During the winter months, the relative humidity in the insulated stud cavity next to the exterior sheathing of the ventilated stucco wall was approximately 20 percent lower than the other two wall designs. The wood moisture content of the ventilated case remained at the bottom of the measurable scale.

When the vented wall and the conventional stucco wall are compared, there is little difference in performance. The stud cavity humidity is almost identical, as is the resulting wood moisture content.

Test cycle 2 and 3 also include a ventilated stucco wall installed on the north side of the building (wall N4). The wall cladding is cooler because it receives little direct solar radiation. The best examples for comparison occur during test cycle 3. The north facing wall performs very well, but has higher humidity in the wall cavity and some increase in moisture content when compared directly to the ventilated stucco wall facing south.

When additional moisture loads are added to the wall cavities during the wetting test conducted during test cycle 2, increases in moisture accumulation were noted in all cases. The south facing ventilated stucco wall outperformed most of the designs. But some moisture accumulation did occur during the wetting test, demonstrating the limits of the system. The ventilated test wall facing north showed even greater moisture accumulation during this test. Improved moisture loading methods are needed to confirm these results.

To provide further performance distinctions between the vented and ventilated stucco clad walls, a set of manometers were installed to measure the static air pressure in the cladding ventilation pathway. For most of March 2006, air pressure difference, relative to the interior space, was measured high and low in the cladding ventilation pathway. For the vented case, there was virtually no difference in the air pressure high and low in the ventilation space. This indicated little or no air movement. For the ventilated case, an average pressure difference between the lower and upper area in the ventilation space of approximately 0.50 Pascals was recorded. This pressure difference indicates airflow entering low on the wall and exiting at the top. Further analysis revealed that the pressure difference is greatest mid day when the wall is warm, and is almost nonexistent during the nighttime hours. A temperature difference is required to create the pressure difference and move the air. **Figure 19** provides the pressure difference in the wall with vented cladding. **Figure 20** provides the pressure difference in the wall with ventilated cladding.

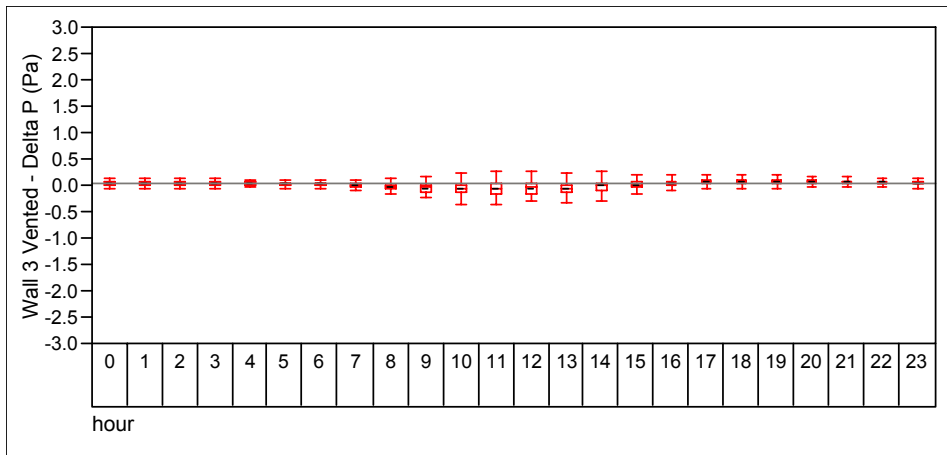
To achieve the full benefits of a cladding ventilation strategy, stucco cladding requires a complete air pathway that accommodates air movement, not just a static space between the cladding and weather resistive barrier.

It should be noted, that this test does not include the drainage benefits an air space might provide. The test walls were not subjected to rain loads between the cladding and weather resistive barrier that might occur if the cladding leaked. Both the vented and ventilated wall will likely outperform the direct applied stucco wall when a cladding leak occurs.

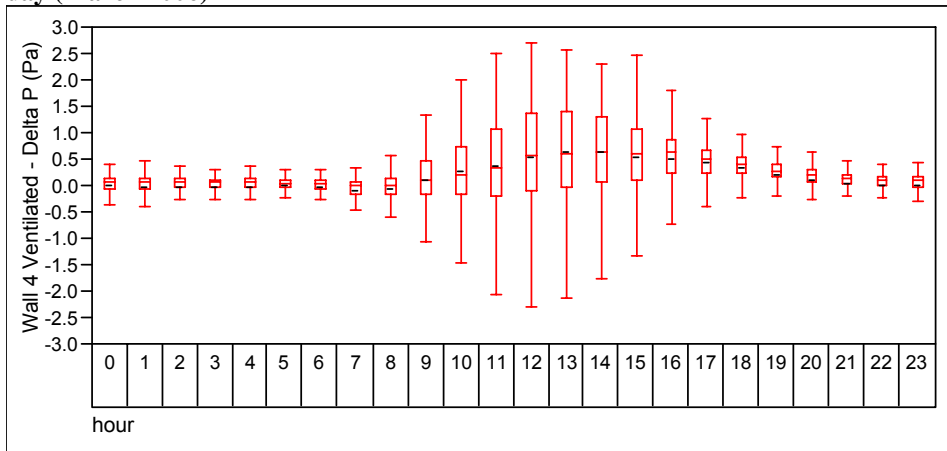
### Ventilation of Cement Lap Siding

During test cycle 1, three cement lap sided wall designs were tested. This included standard lap siding installation (wall 12) and walls with vented (wall 10) and ventilated (wall 11) designs. During test cycle 1, all of the walls remained very dry. But a small difference in moisture performance between the standard lap wall and the other two can be noted. The ventilated and vented lap walls had the same moisture performance. This result is different from that of the stucco experiments that noted different performance between the vented and ventilated cases.

**Figure 19 Vented stucco cladding: pressure difference in the ventilation cavity, by hour of the day (March 2006)**



**Figure 20 Ventilated stucco cladding: pressure difference in the ventilation cavity by hour of the day (March 2006)**



## Interior Vapor Control

Three different vapor control strategies have been tested. This includes designs with interior paint only, designs with interior paint and polyethylene sheeting, and a design with interior paint and the vapor retarder material MemBrain™. The test wall assemblies have been tested for all three test cycles, allowing performance comparisons under different environmental loads.

The test walls that provide the most direct comparison of vapor control include w1/S1, which includes poly sheeting, (wall 2, S2) which includes MemBrain™, (wall 7, S7) and (wall N7) that only include one coat of PVA primer and one coat of latex paint. All of these walls are identical except the interior vapor control materials.

Vapor control strategies retard both the moisture transport from the interior environment to the insulated wall cavity during the heating season, and the vapor transport from the wall cavity to the interior environment when solar gains drive vapor toward the interior.

More robust vapor control strategies demonstrated by walls with polyethylene sheeting provide excellent vapor control during the heating season, but retard the walls from drying to the interior during the warmer months. Less vapor control can result in more winter moisture accumulation in the wall, but increased drying potential in the spring and summer months.

### Limited Interior Vapor Control

The south facing stucco wall that only utilized paint as a vapor retarder did not perform well in test cycle 1. During the winter months, the relative humidity in the insulated cavity next to the exterior sheathing was sustained at 100 percent. This resulted in moisture accumulation in the exterior sheathing board and framing members. The moisture content of the wood sheathing and framing exceeded 25 percent for a number of months. When the wall was opened for inspection, mold was present on the exterior sheathing board.

The interior environmental conditions were adjusted somewhat during test cycle 2 and 3. The interior moisture levels were reduced and the resulting vapor pressure difference from indoors to outdoors was reduced. Under this scenario, walls with limited vapor control performed better, but not to an acceptable standard. On the south facing wall, moisture accumulation was less than during test cycle 1. But an identical wall facing north did not perform well. During the winter months, the relative humidity in the insulated cavity next to the exterior sheathing was sustained at 100 percent. This resulted in moisture accumulation in the exterior sheathing board and framing members or the north facing wall.

During the drying periods that occur early in the spring, the walls with limited vapor control dried very quickly. This is especially evident during the wall wetting experiment conducted in the spring of test cycle 2. While the experimental design would tend not to favor this assembly, limited vapor control does have advantages. But it is only viable if winter moisture accumulation can be limited.

Also worth noting is the range of vapor transmission rates for different interior coatings. We were surprised to find that the PVA primer plus latex paint used in the experimental walls had such a high vapor transmission rate. When compared to the vapor transmission rates listed in the *ASHRAE Handbook of Fundamentals*, the tested values are very high. The use of untested coatings as a vapor retarder should be examined more closely.

### Smart Vapor Retarder

The MemBrain™ vapor retarder provided adequate vapor control during the winter months. When compared to an identical wall design with a polyethylene vapor retarder, the wall with MemBrain™ only showed moisture performance differences.

As designed, the variable vapor transmission characteristics of the MemBrain™ did provide benefit in the spring when vapor drive was from the exterior to the interior. When compared to an identical wall design with a polyethylene vapor retarder, the wall with MemBrain™ had lower humidity at the vapor retarder location, especially during the warmest hours of the day. This indicated that MemBrain™ was allowing the moisture to pass through the material. **Figure 21** provides a detailed graph noting a 24 hour cycle at

the exterior sheathing layer in the insulated wall cavity. During the wetting experiments conducted during test cycle 2, the wall with MemBrain™ had lower wood moisture content than the comparable wall with a polyethylene vapor retarder.

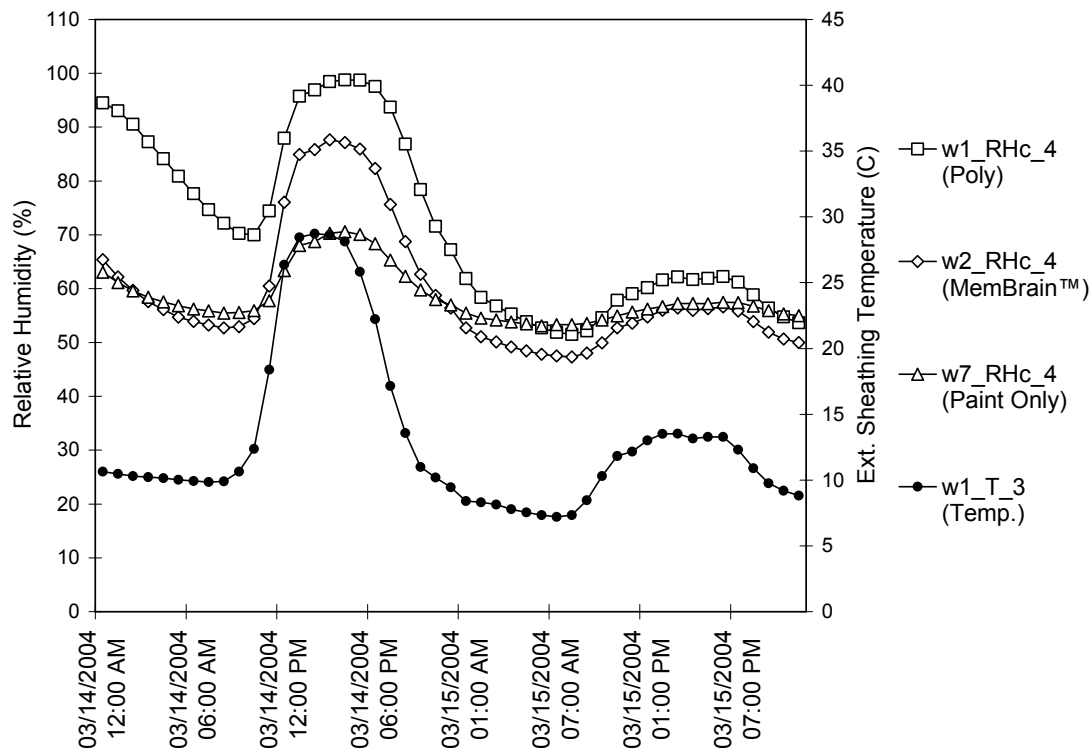
### Polyethylene Vapor Retarder

For the most part, test walls with polyethylene vapor retarder performed well during all of the test cycles. There are some exceptions worth noting.

In the spring, south facing walls with polyethylene vapor retarders experience a redistribution of moisture in the insulated wall cavity. The moisture accumulates at the top plate. The moisture measurements indicate unusually high moisture levels. This only lasts for a few weeks and inspections did not identify any resulting damage from this occurrence.

Also, during the wall wetting experiment, walls with a polyethylene vapor retarder showed greater moisture accumulation than walls with other vapor control strategies. During the period following the introduction of moisture, the walls with polyethylene vapor retarders did dry at a reasonable rate.

**Figure 21** Relative humidity at the vapor retarder layer and exterior sheathing temperature for three different south facing stucco walls



## **Exterior Foam Sheathing**

The moisture performance of test walls with exterior foam sheathing is better than most other walls in our test. Foam sheathing provides a good resistance to exterior moisture loads, both bulk moisture and moisture in a vapor state. The foam sheathing keeps the interior wall cavity warm, preventing moisture accumulation caused by condensation of moisture on cold surfaces of the assembly.

During test cycle 1, a 2x4 frame wall with R-13 batt insulation and R-5 exterior foam was tested, (wall 8). This wall was located on the south side of the NET during this test cycle. Throughout test cycle 1, there was no measurable change in the wood moisture content. The relative humidity measure in the insulated stud cavity was lower than walls with R-21 cavity insulation alone.

During test cycle 2 and 3, three test walls utilizing exterior foam sheathing were installed on the north side of the NET. During normal operation, these test walls performed exceptionally well. This included test walls (N5, N6 ) with cavity insulation and exterior foam sheathing, and test wall N8 with 96 CM (4 inch) exterior foam sheathing and no cavity insulation. Foam clad walls wall (N5, N6) utilize MemBrain™ as a vapor retarder. The wall with 96 CM (4 inch) polystyrene insulation only (N8) uses just paint. There is no notable change in the wood moisture content of these walls during normal operating conditions.

During the wetting experiments conducted during the spring of test cycle 2, a change in wood moisture content can be noted on test walls N5 and N6. During the time period when moisture introduction occurs, the moisture level of the wood sheathing increases. The change in wood moisture content is similar to other designs with R-21 cavity insulation alone. During the drying period that follows, the walls N5 and N6 dry at a reasonable rate.

Test wall N8 demonstrated the best performance overall during the wall wetting experiments. There was no notable change in the wood moisture content during the experiment. It is probable that this wall simply dried to the interior.

It should be noted that the wall wetting experiment introduces water to the insulated cavity of the wall. If the water were introduced between the exterior sheathing board and the foam sheathing, the results may have been different.

## **Water Resistive Barriers**

All of the test walls include two layers of 60 minute building paper, with two exceptions. During test cycle 2 and 3, these walls were added. Wall S11 is a stucco clad wall with only a single layer of building paper. This wall is best compared to wall S1, but differences in wall color and resulting solar absorption make it difficult to provide direct comparisons. Wall N8 includes a liquid applied water resistive barrier. There isn't a comparable wall with building paper available for direct comparison.

The tests did not provide notable performance differences between one layer and two layers of building paper.

The wall with a liquid applied water resistive barrier performed very well, but this is likely because of other design features.

### **Walls that Include Windows**

During test cycles 2 and 3, two walls with windows were installed on the south side of the NET, S9 and S10. These walls were well flashed. Because these walls have plywood sheathing, they are best compared to the whole wall with plywood sheathing, S6. The walls with windows have moisture performance in-line with a wall without windows.

### **Comments on the Bulk Moisture Experiments**

To introduce moisture into the walls using a controlled method, WSU installed irrigation tubing and a medium that would hold the moisture into each primary test wall cavity. The medium is located in the wall cavity between the drywall or vapor retarder and the insulation. In theory the moisture enters the medium and distributes the moisture to the wall through evaporation. There were cases where the medium did not hold all of the water introduced. There times the water left the medium in a liquid state rather than vapor, and it was distributed in large concentrations to the bottom plate.

This test was conducted first in March and then again in June. This is not the ideal time frame for these tests. This test requires that a temperature difference between the interior and exterior drive the moisture to the exterior. This worked fairly well in March. Most walls noted an increase in moisture content in the wood material. In June, this was only somewhat effective on the north facing walls. This test should be conducted early in the winter to be effective.

As noted in many of the test results listed above, most walls got wet and then dried fairly quickly during the March testing. These comments are limited to the test that went as planned. That is, when the moisture was distributed to the sheathing board through vapor transport. When the test malfunctioned and moisture simply dumped to the bottom plate sensor, the results are somewhat different, and informative.

When moisture accumulated at the bottom plate, there was an extended drying time. Good examples are vinyl clad wall S8 and a ventilated stucco wall N4. Both walls had moisture distributed on the bottom plate, likely in large quantities. In both cases the bottom plate took almost a year to dry. These walls are thought to have superior drying capabilities. For the most part they do. But neither can provide enough drying to compensate for what would be a large leak into the insulated wall cavity. Many of the test walls are capable of tolerating minor moisture loads, but it is unlikely that any would tolerate large leaks.

### **Wall Orientation**

North facing walls showed significantly less drying potential than south facing walls. Solar gain on north facing walls in the Pacific Northwest is minimal for a majority of the annual cycle; and in particular, during the wettest months of the year.

## Cladding Color and Type

Dark colored wall systems showed higher solar gain/temperatures for longer periods of time leading to slightly improved wall system performance. The majority of the cladding systems tested in this study were terra cotta colored stucco approximately 7/8-inch thick. In one test wall, where the stucco was direct applied to the exterior structural sheathing, the temperature reached 130 degrees F on a clear day with an outside temperature of 20 degrees F. The stucco products provided the greatest solar gain. Conversely, white vinyl siding provided the most effective resistance to heat build-up.

## Structural Sheathing Differences

The data provided some indication of different performance levels between plywood and OSB. However, the data are not conclusive. It is well known that significant differences exist between the myriad products available. This study compared one plywood type and one OSB product.

## CONCLUSIONS

WSU's primary role in the project was constructing the building and the test walls, and collecting the data, with ORNL performing the detailed analysis and incorporating the results in its moisture modeling tools. However, the additional analysis performed on the data by WSU did lead to several conclusions about the performance of wall assemblies in the Pacific Northwest marine climate. They are as follows:

- The amount of cavity insulation does not change the moisture performance of walls significantly. Both R-11 and R-21 walls had similar moisture accumulation for the test years examined.
- Walls constructed with R-13 cavity insulation plus R-5 foam sheathing provides better moisture performance than a wall with R-21 cavity insulation only. Combined with a smart vapor retarder, The R-13+5 construction provides excellent performance.
- Cladding ventilation is effective at lowering the wood moisture content of insulated wall cavities. A fully ventilated cladding that includes openings to the exterior both high and low on the wall is critical. Simply providing an air space behind the cladding without openings to the exterior is not effective.
- Vapor retarders with a dry cup perm rating less than 1 are important in the Pacific Northwest climate. The use of a smart vapor retarder provides additional benefits by allowing additional drying to the interior from the wall cavity in the spring and summer. This is likely true for other marine climates.
- Long term study of wall performance under a variety of environmental conditions is needed to provide a reliable performance evaluation.

## **Further Research Recommendations**

The project provided information on a number of wall assemblies, using the best test equipment and strategies available. However, a number of issues arose that lead to the development of some further research and development recommendations. These include:

- Additional and more accurate instrumentation is needed in all test walls to further assess the movement of moisture in the walls.
- Product specific moisture content correction factors need to be developed.
- Window (opening) cavity effects need additional quantification.
- Additional wetting studies could be done, which would significantly advance modeling capability.
- Further experiments with identical cladding color on all walls should be conducted to control further for the effects of wall exterior color.
- Additional OSB and plywood products should be studied to assess their performance in wall systems.
- Further investigation should be done on the apparent promising effects of variable permeability vapor retarders.
- Further examination of foam clad wall systems should be conducted.

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## **LIST OF ACRONYMS AND ABBREVIATIONS**

ASHRAE	American Society of Heating, Refrigerating and Air-conditioning
Engineers	
HVAC	Heating ventilation and air-conditioning
MCc	Wood moisture content
NET	Natural Exposure Test
ORNL	Oak Ridge National Laboratory
OSB	Oriented strand board
RHc	Relative humidity
SIP	Structural insulated panels
T	Temperature
US DOE	U.S. Department of Energy
WSU	Washington State University

## **APPENDICES**

Appendix A - Test Cycle 1

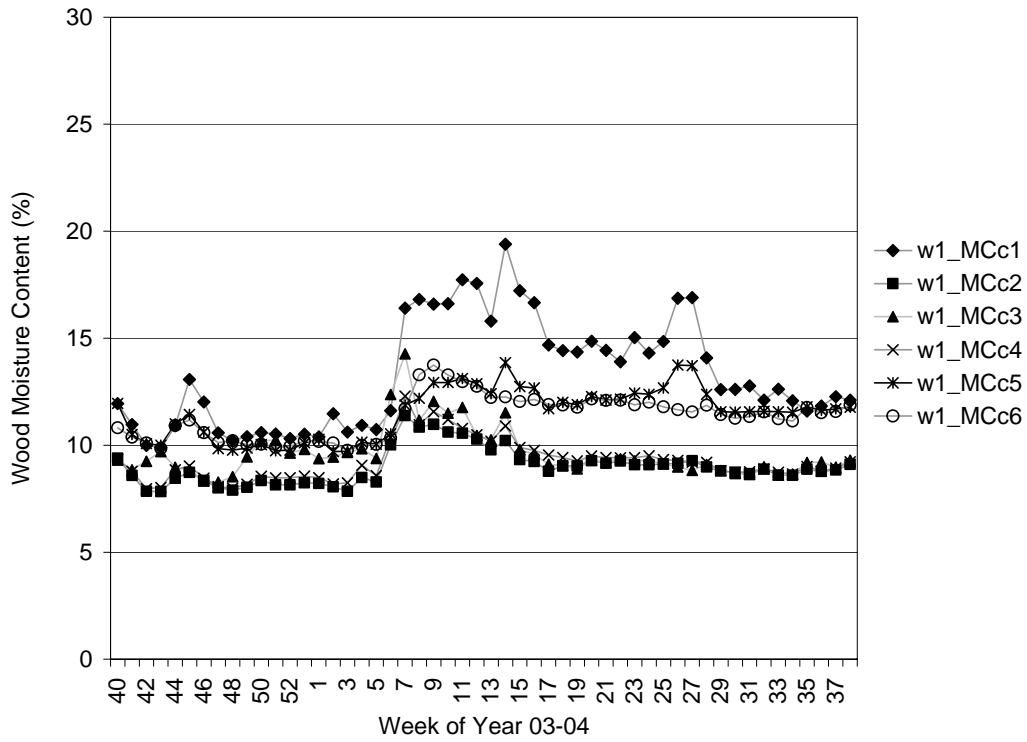
Appendix B - Test Cycle 2

Appendix C - Test Cycle 3

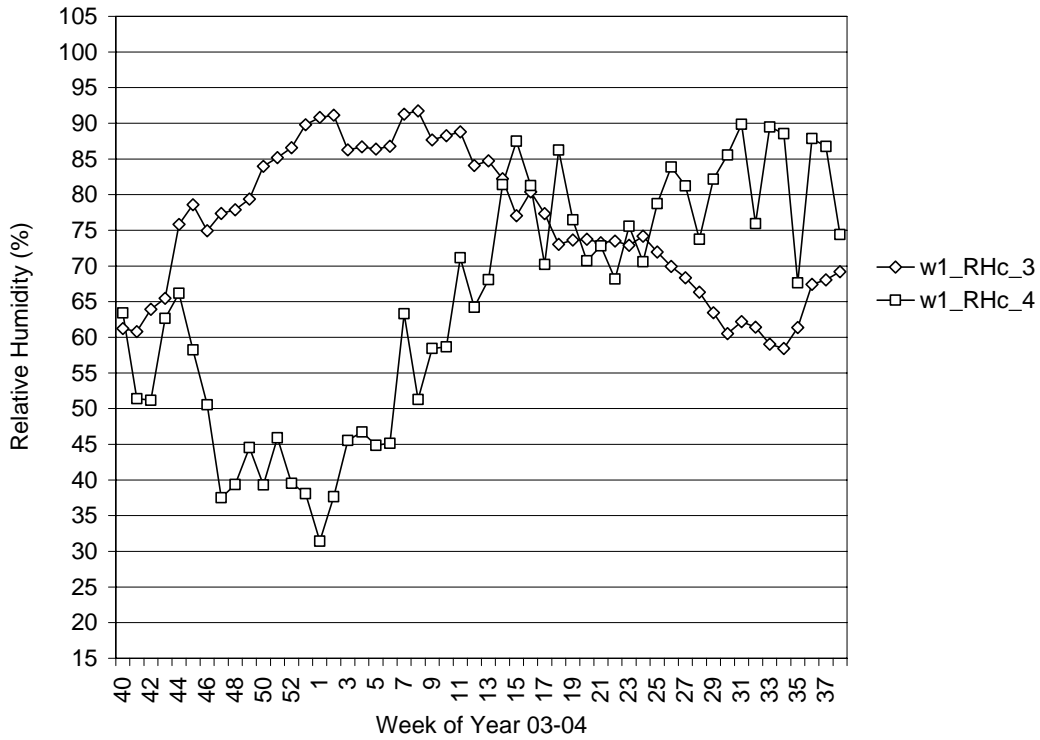
Appendix D - Weather Data

**Appendix A**  
**Test Cycle 1 Figures**  
**October 1, 2003 to September 14, 2004**

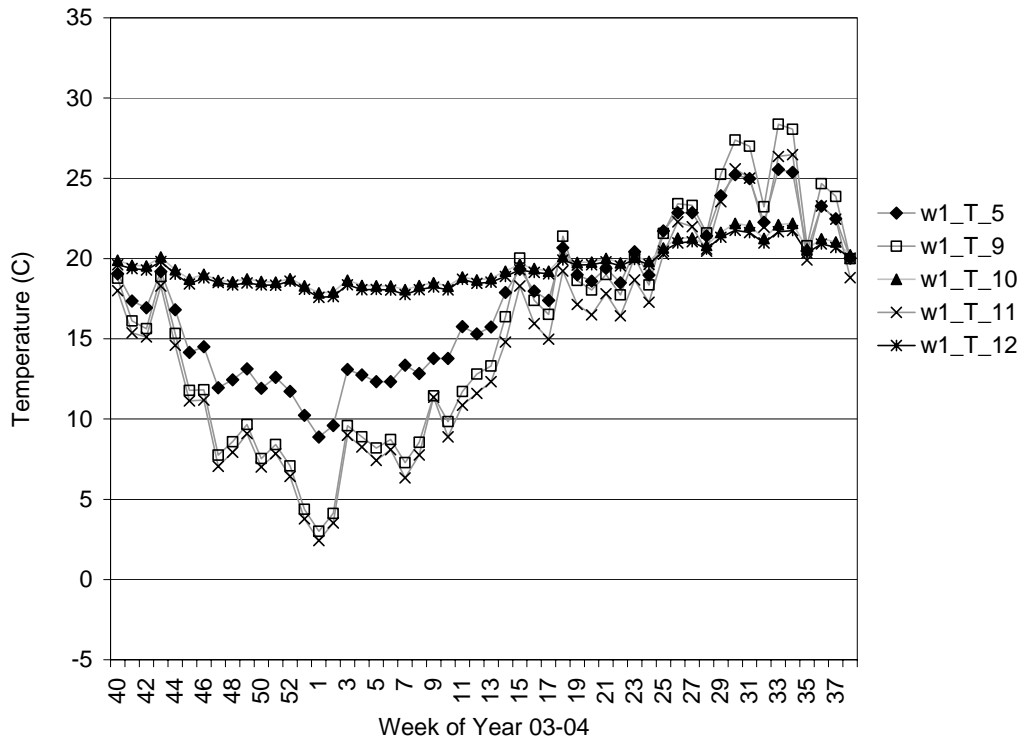
**Figure A 1-1 Wall 1 – Wood Moisture Content**



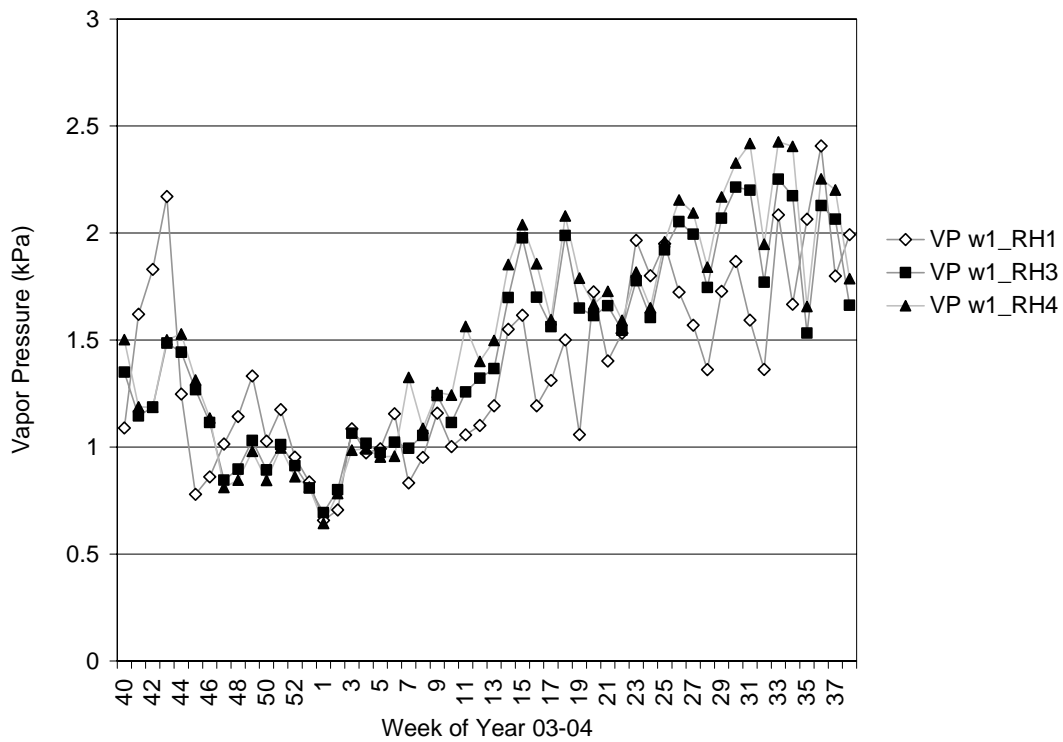
**Figure A 1-2 Wall 1 – Cavity Relative Humidity**



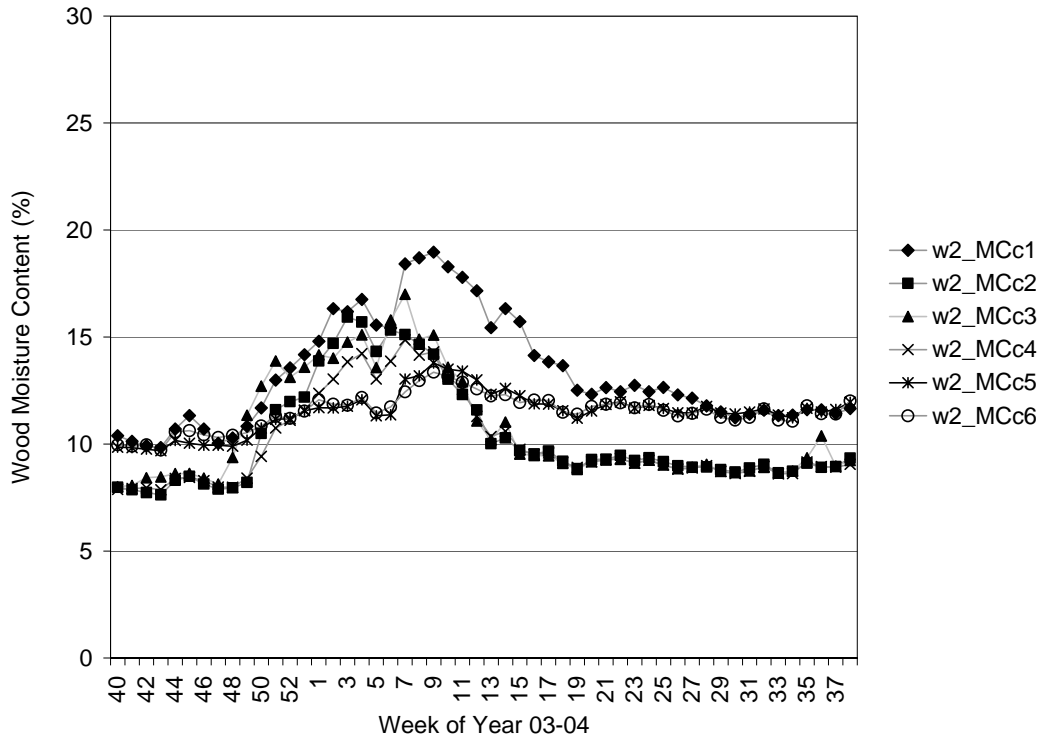
**Figure A 1-3 Wall 1 - Temperature**



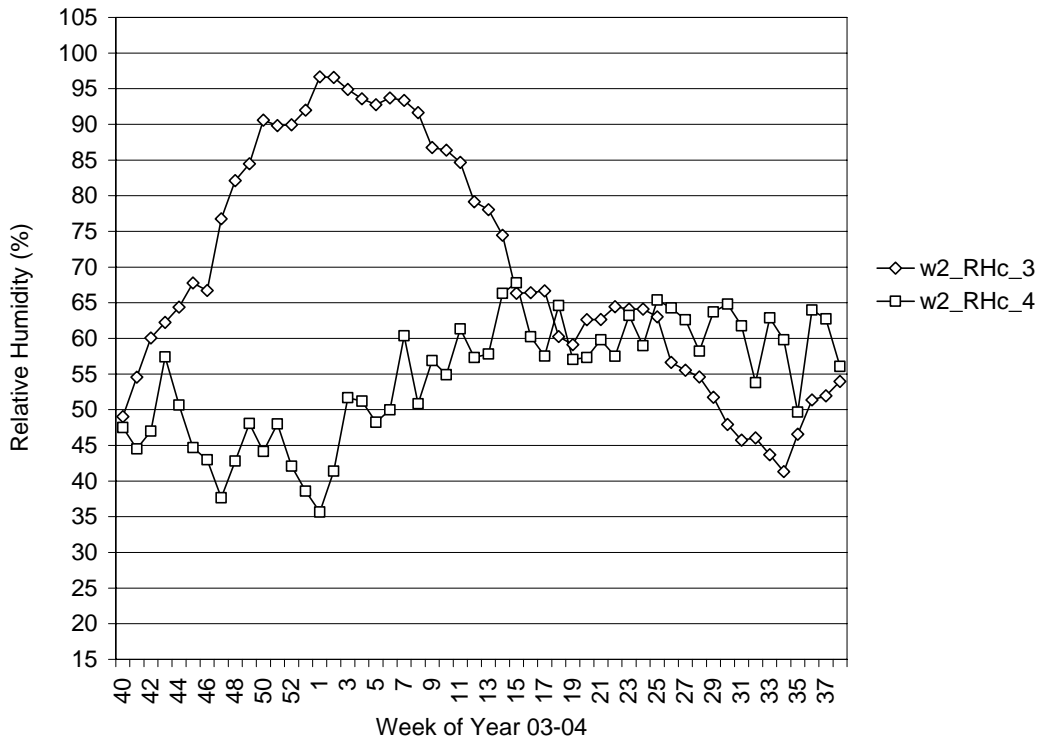
**Figure A 1-4 Wall 1 - Vapor Pressure**



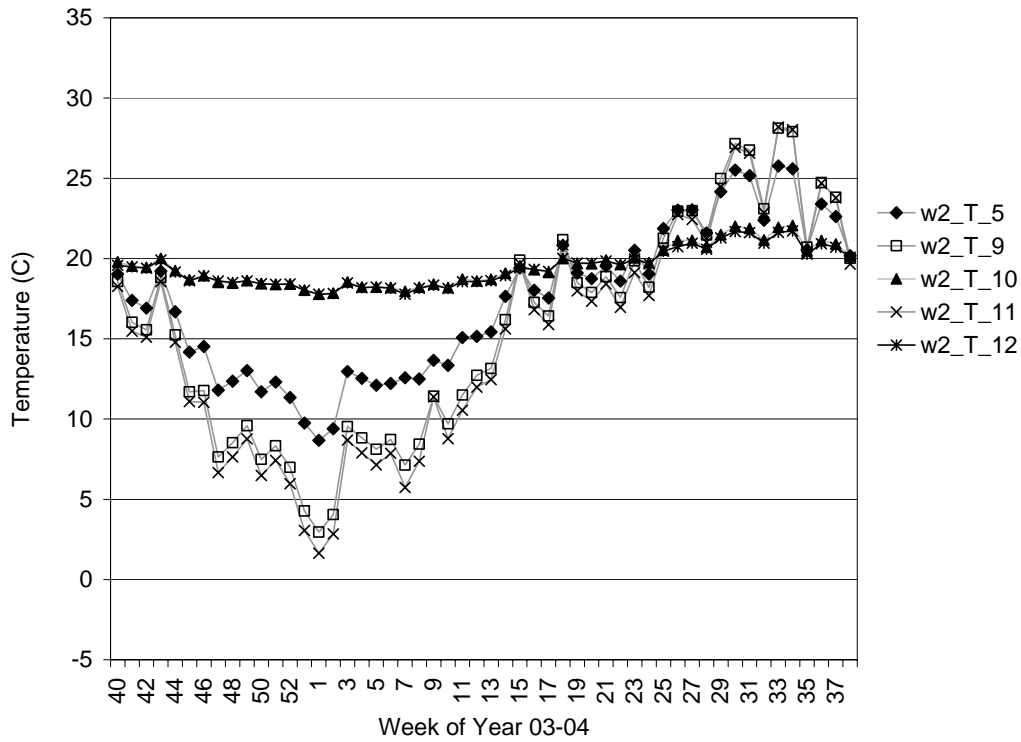
**Figure A 2-1 Wall 2 – Wood Moisture Content**



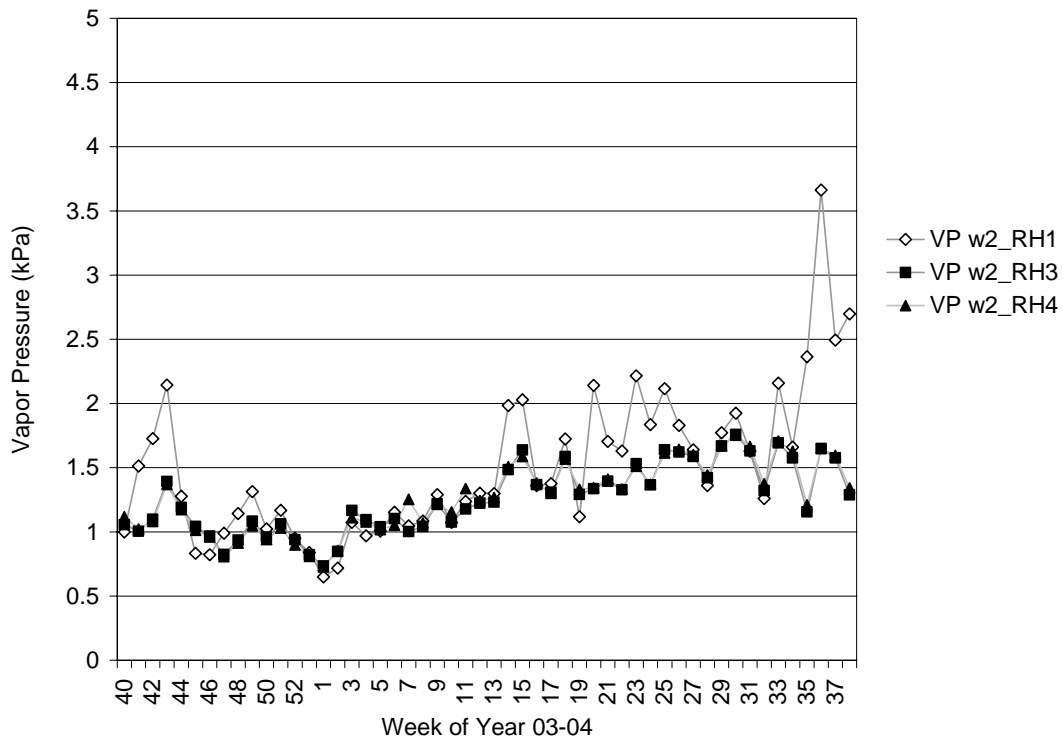
**Figure A 2-2 Wall 2 – Cavity Relative Humidity**



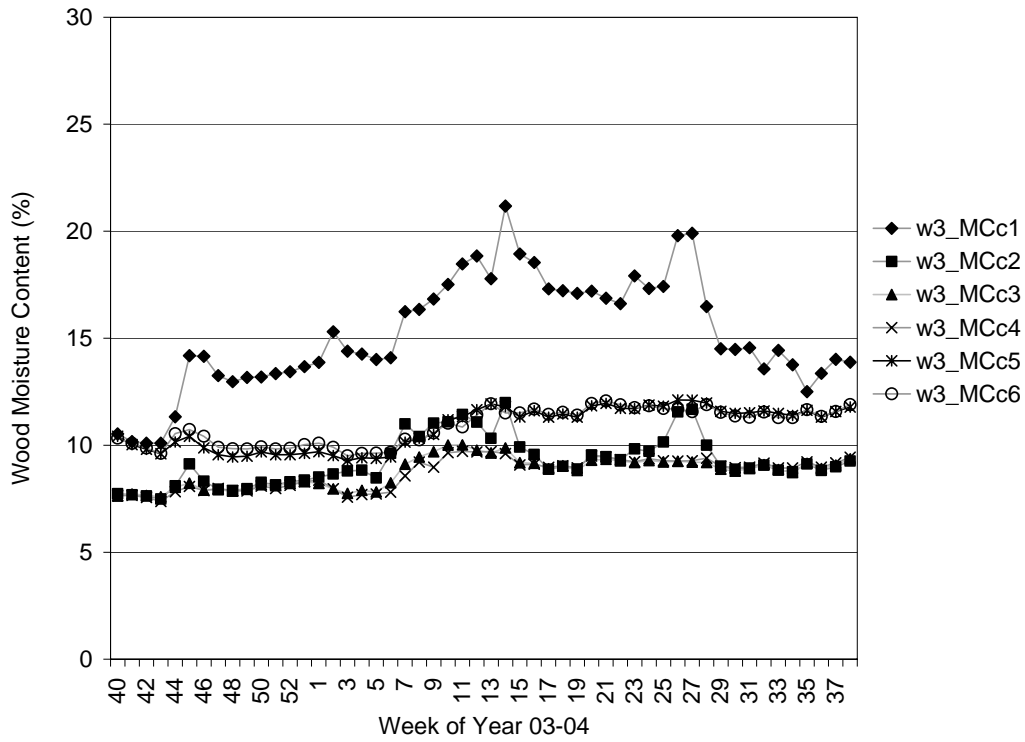
**Figure A 2-3 Wall 2 – Temperature**



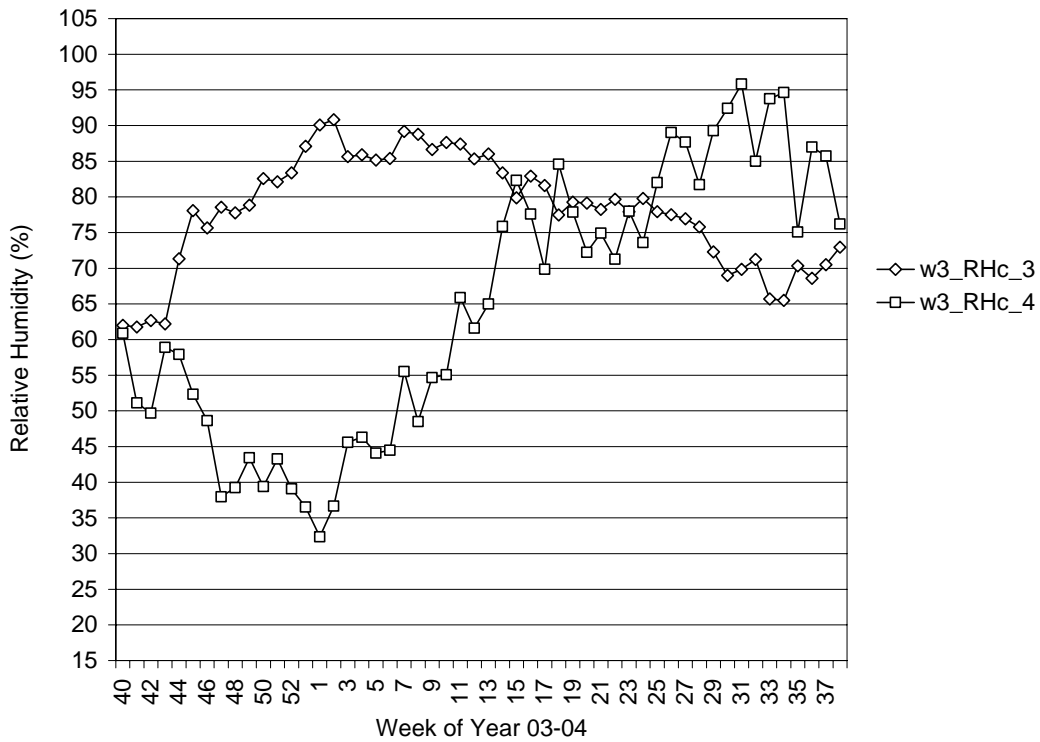
**Figure A 2-4 Wall 2 Vapor Pressure**



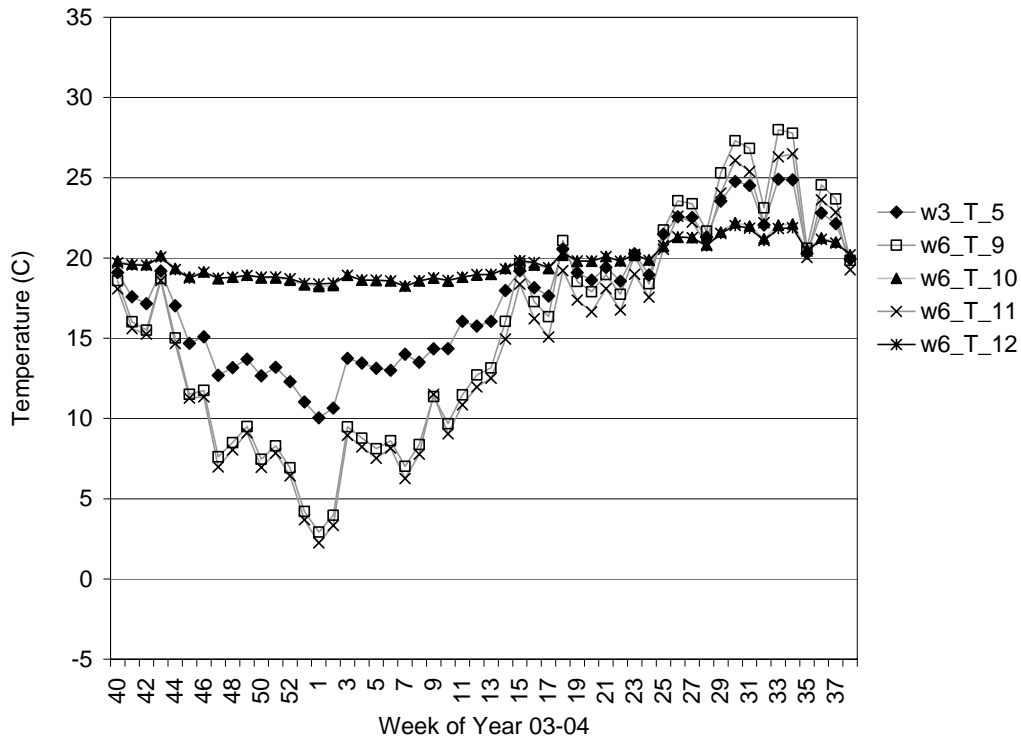
**Figure A 3-1 Wall 3 – Wood Moisture Content**



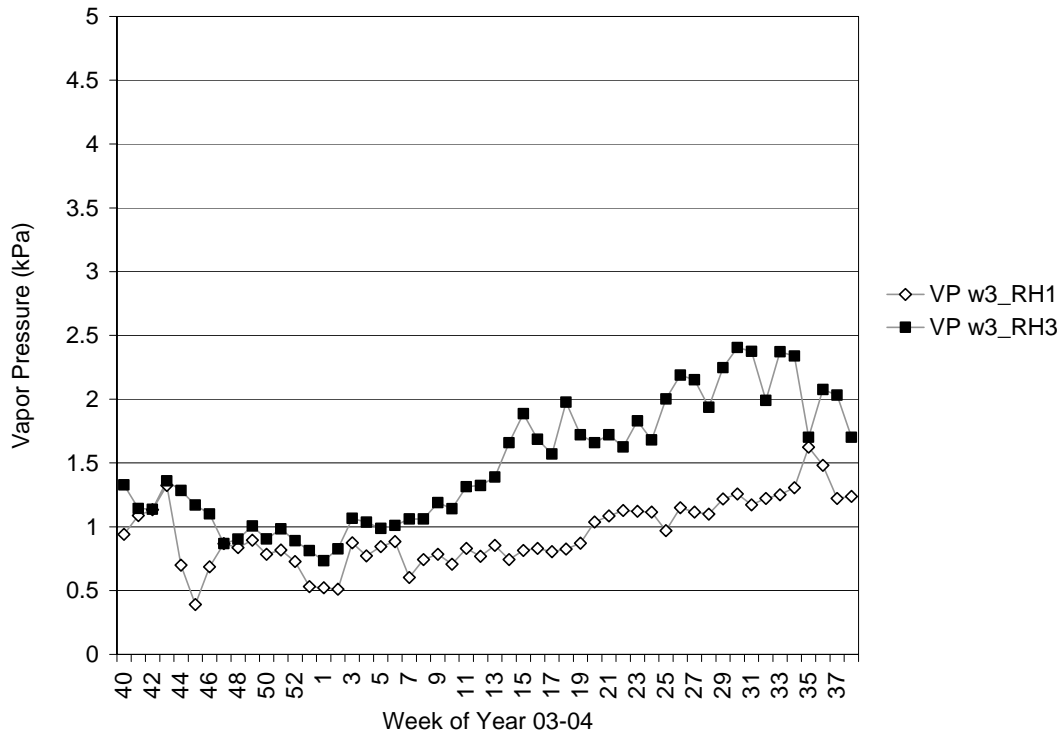
**Figure A 3-2 Wall 3 – Cavity Relative Humidity**



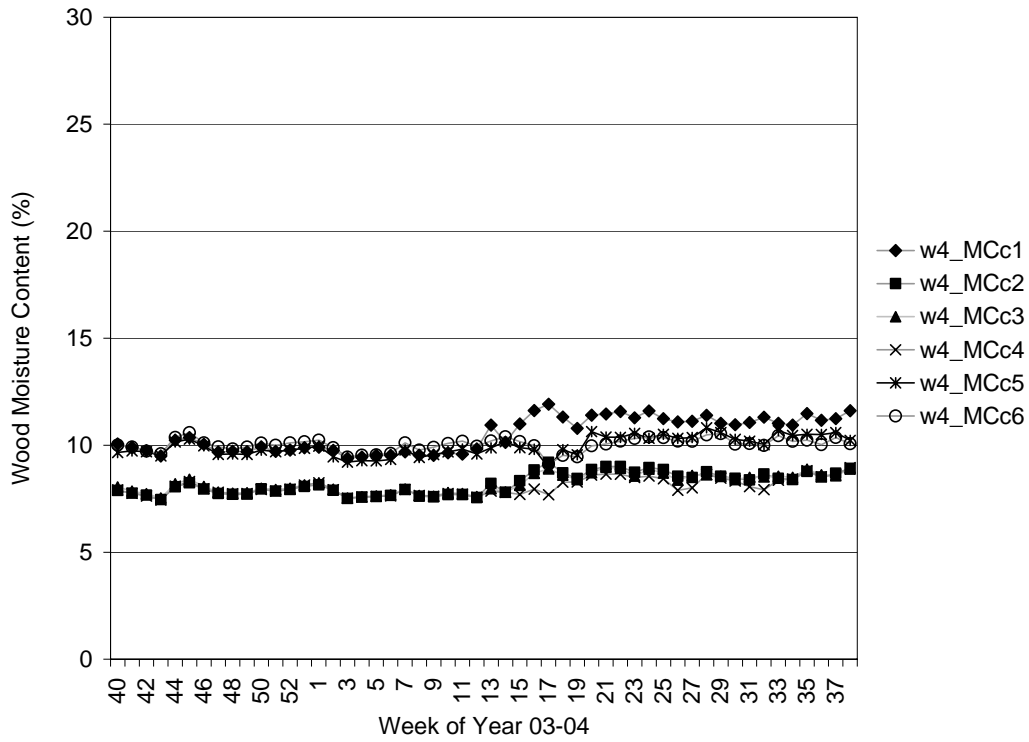
**Figure A 3-3 Wall 3 - Temperature**



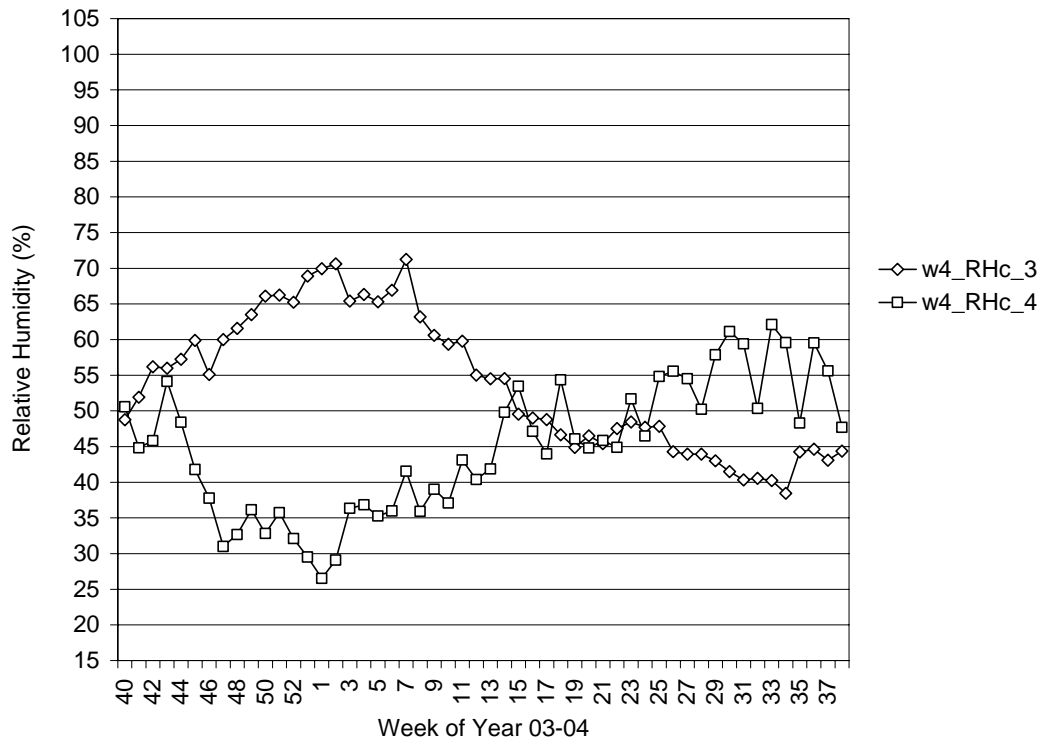
**Figure A 3-3 Wall 3 – Vapor Pressure**



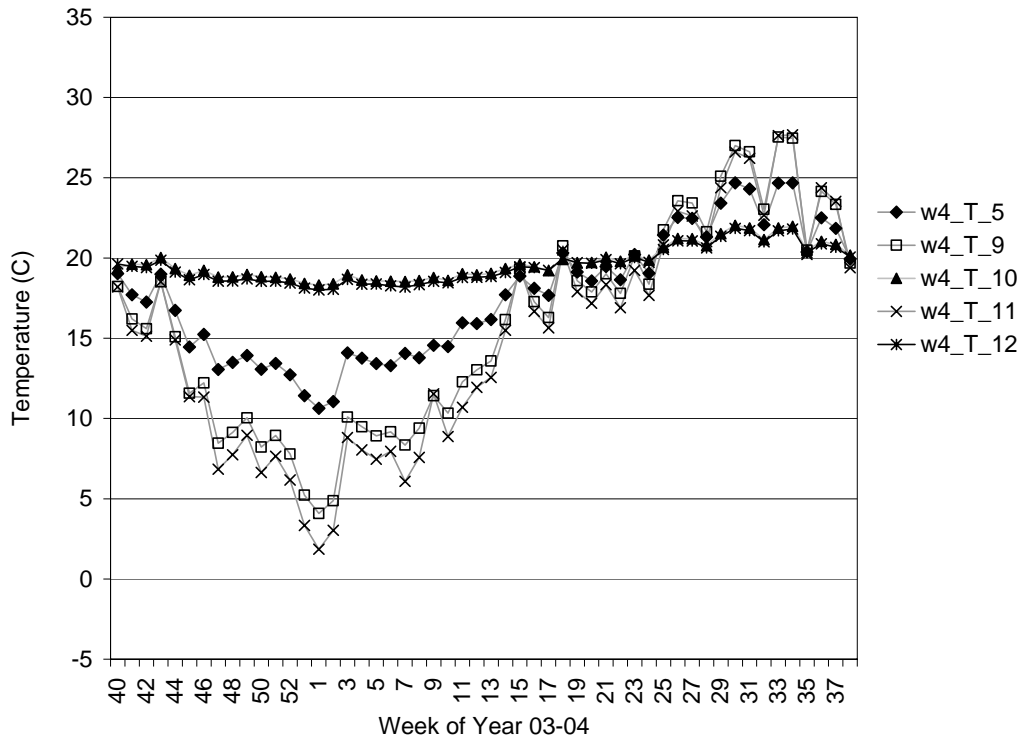
**Figure A 4-1 Wall 4 – Wood Moisture Content**



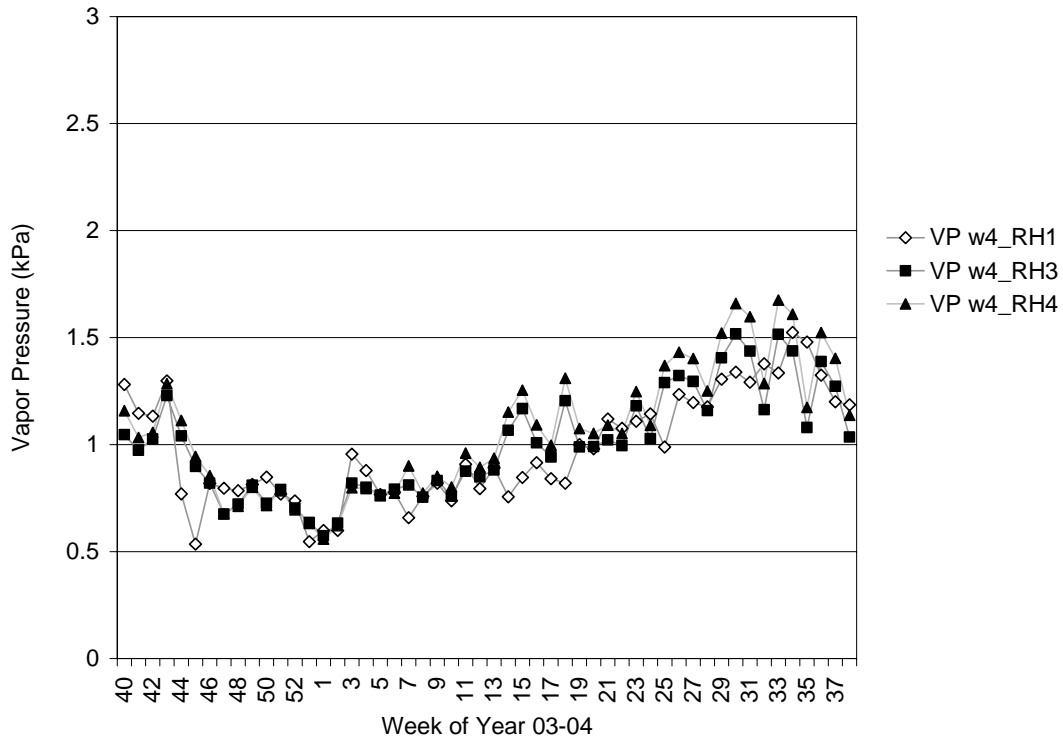
**Figure A 4-2 Wall 4 – Cavity Relative Humidity**



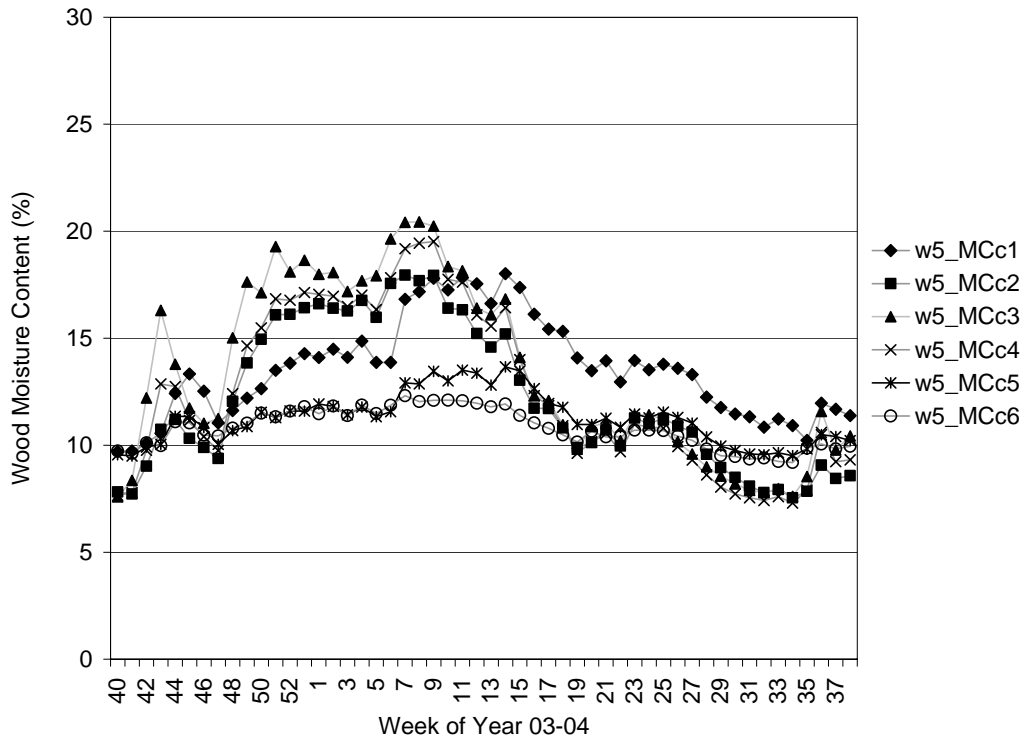
**Figure A 4-3 Wall 4 - Temperature**



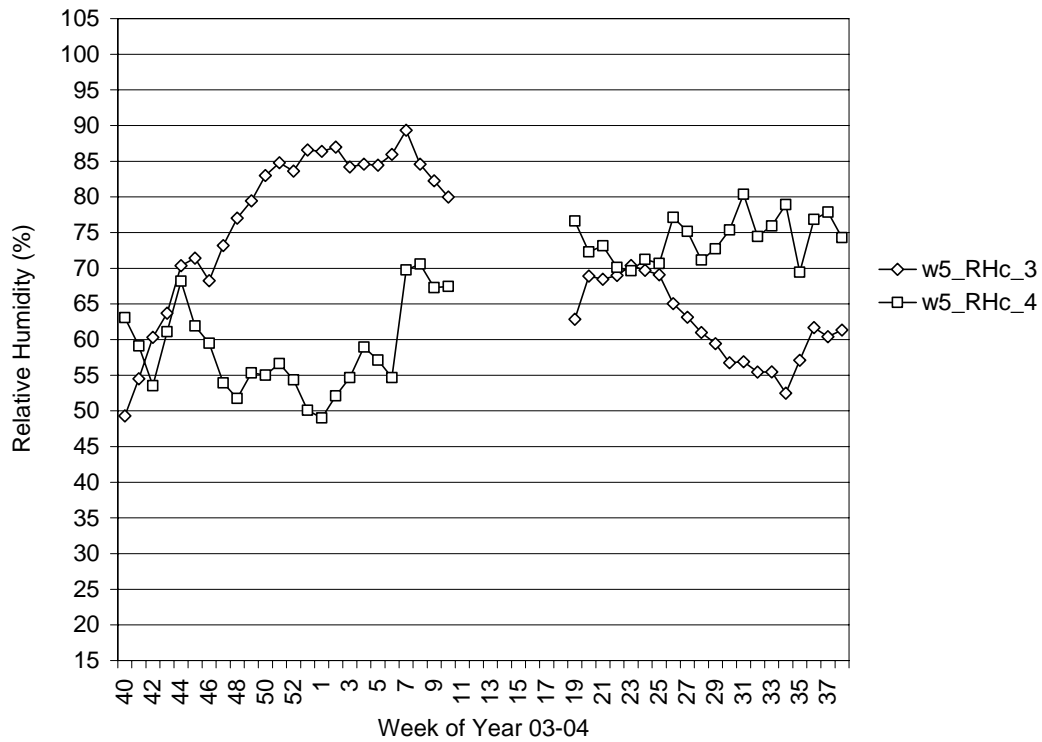
**Figure A 4-4 Wall 4 - Vapor Pressure**



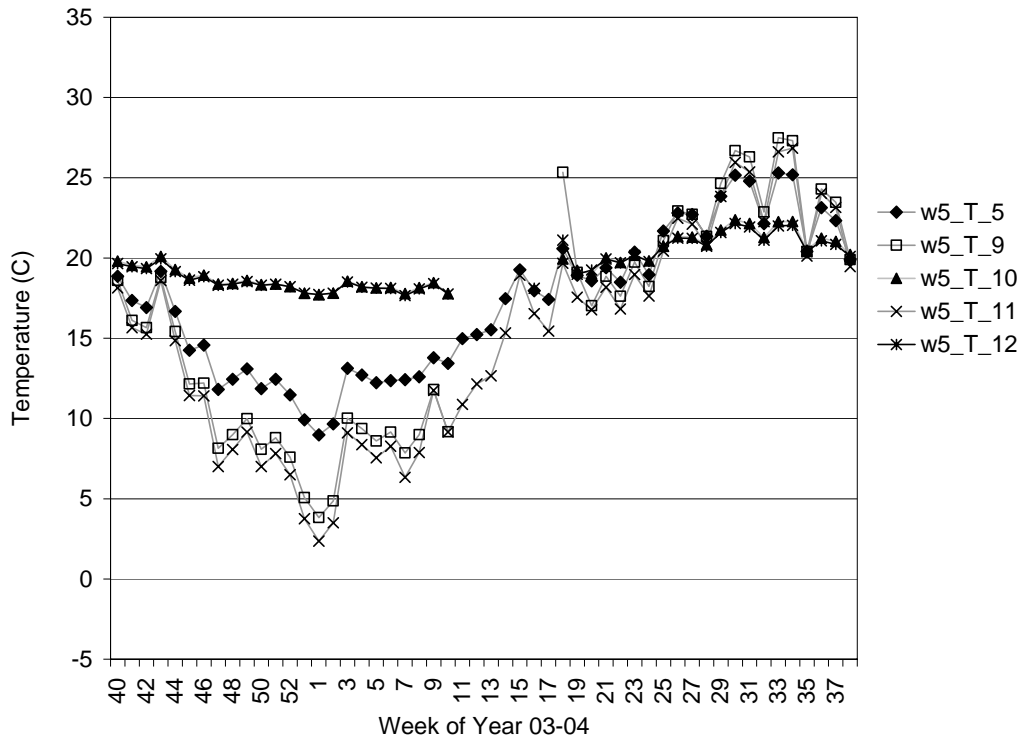
**Figure A 5-1 Wall 5 – Wood Moisture Content**



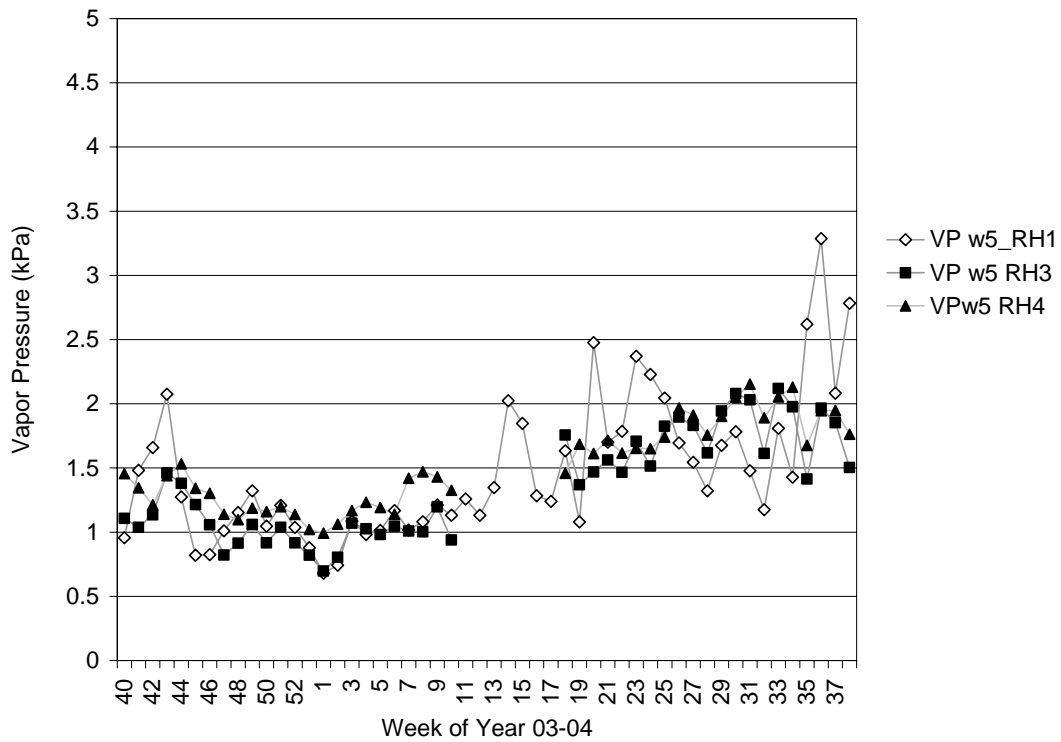
**Figure A 5-2 Wall 5 – Cavity Relative Humidity**



**Figure A 5-3 Wall 5 - Temperature**



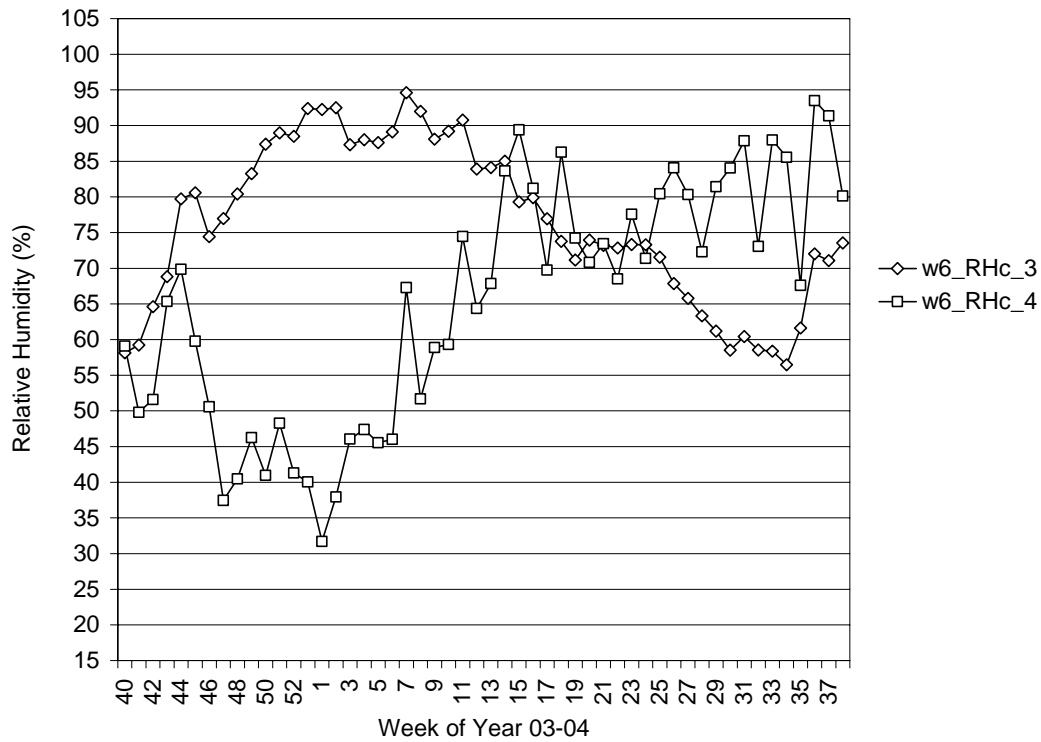
**Figure A 5-4 Wall 5 – Vapor Pressure**



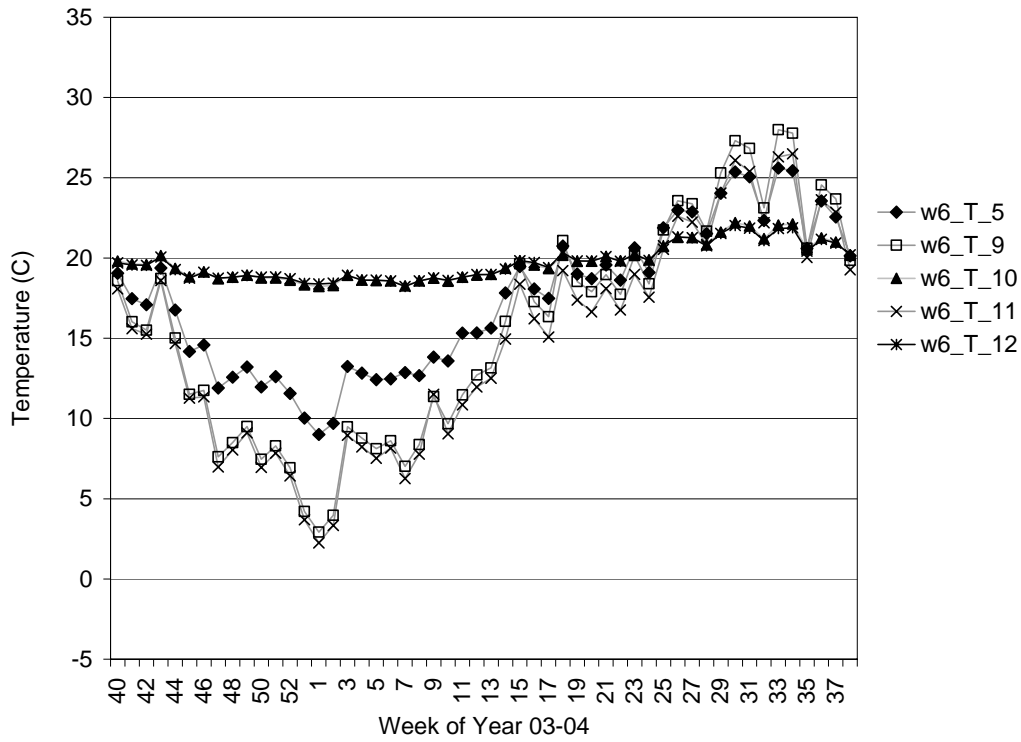
**Figure A 6-1 Wall 6 – Wood Moisture Content**



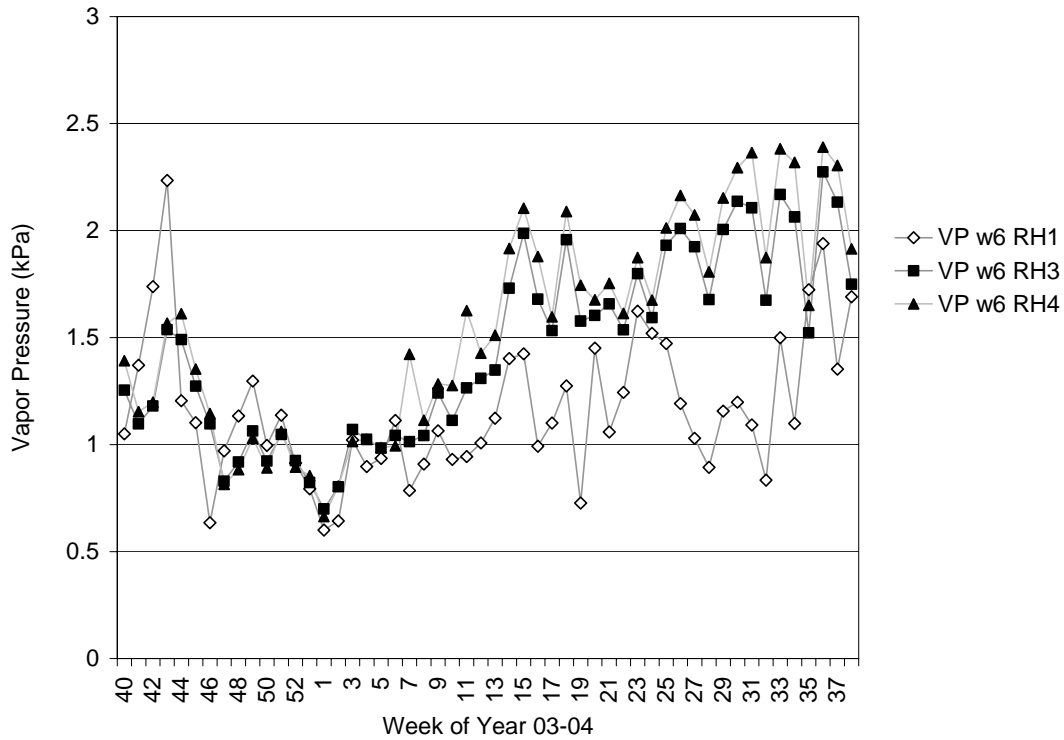
**Figure A 6-2 Wall 6 – Cavity Relative Humidity**



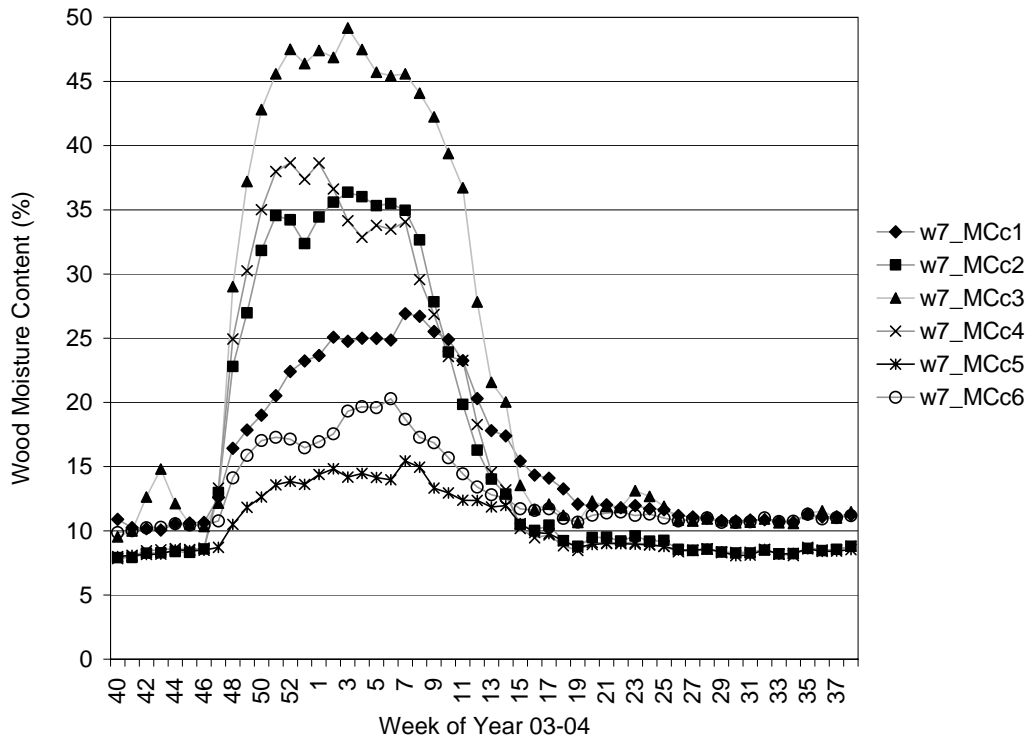
**Figure A 6-3 Wall 6 - Temperature**



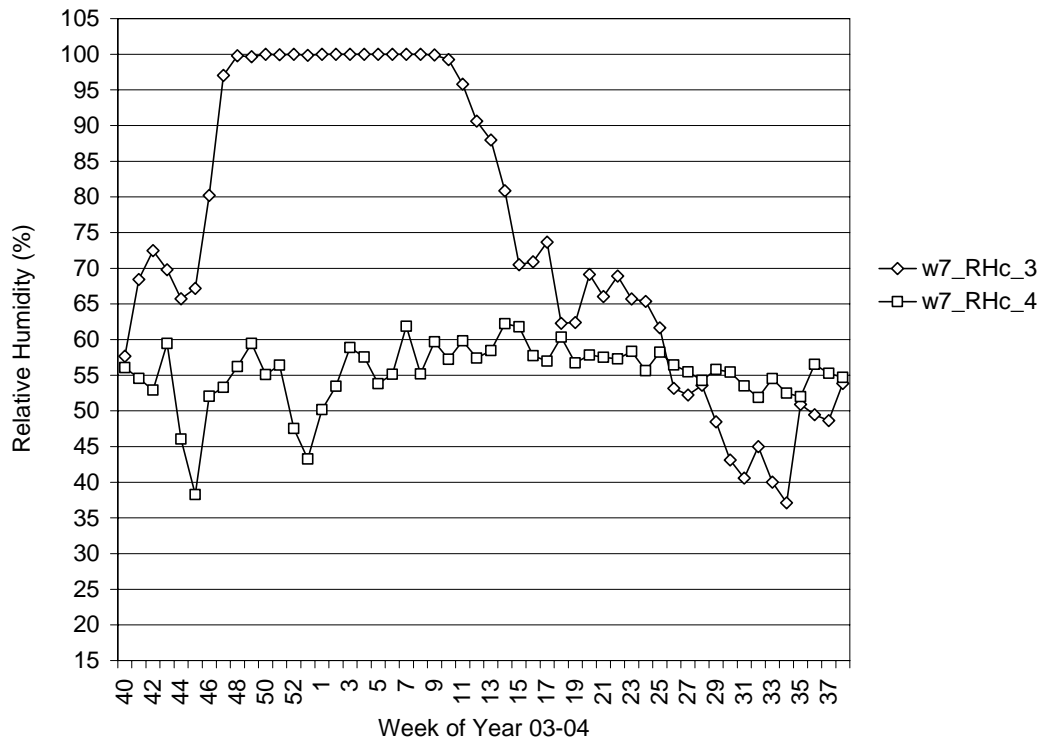
**Figure A 6-4 Wall 6 – Vapor Pressure**



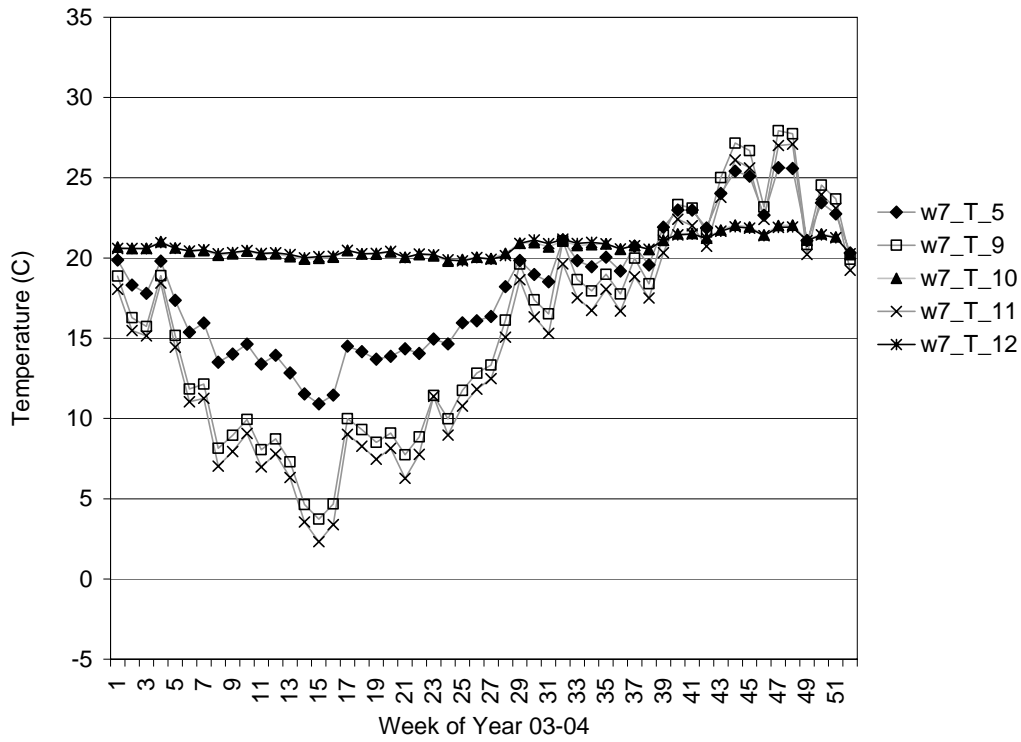
**Figure A 7-1 Wall 7 – Wood Moisture Content**



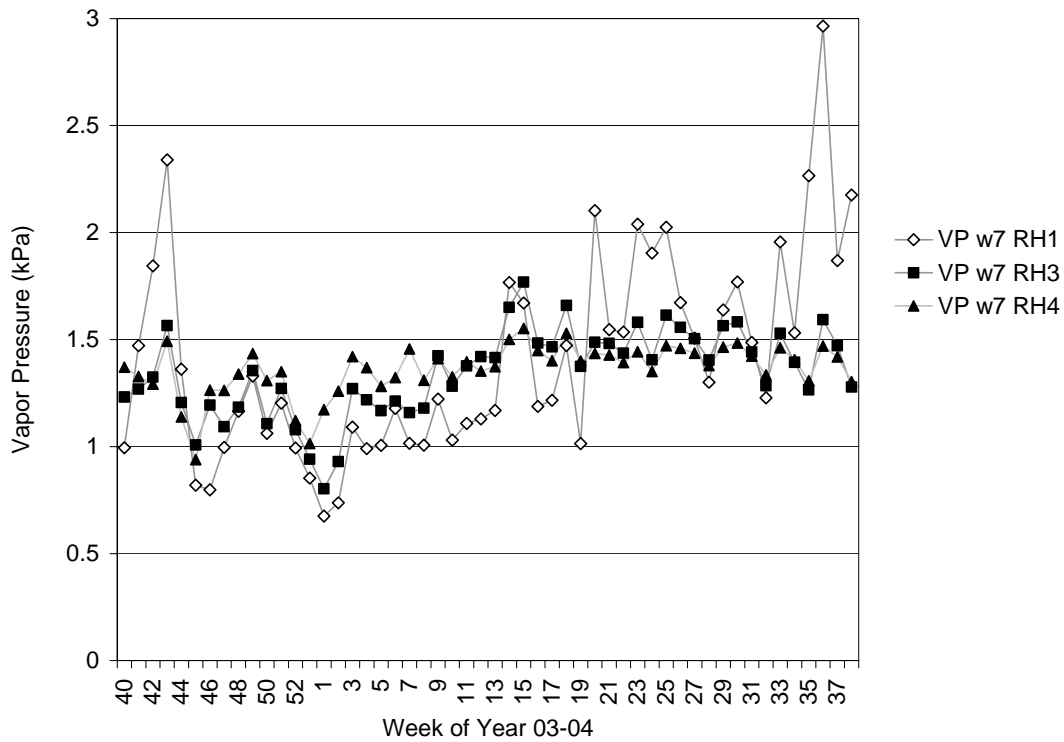
**Figure A 7-2 Wall 7 – Cavity Relative Humidity**



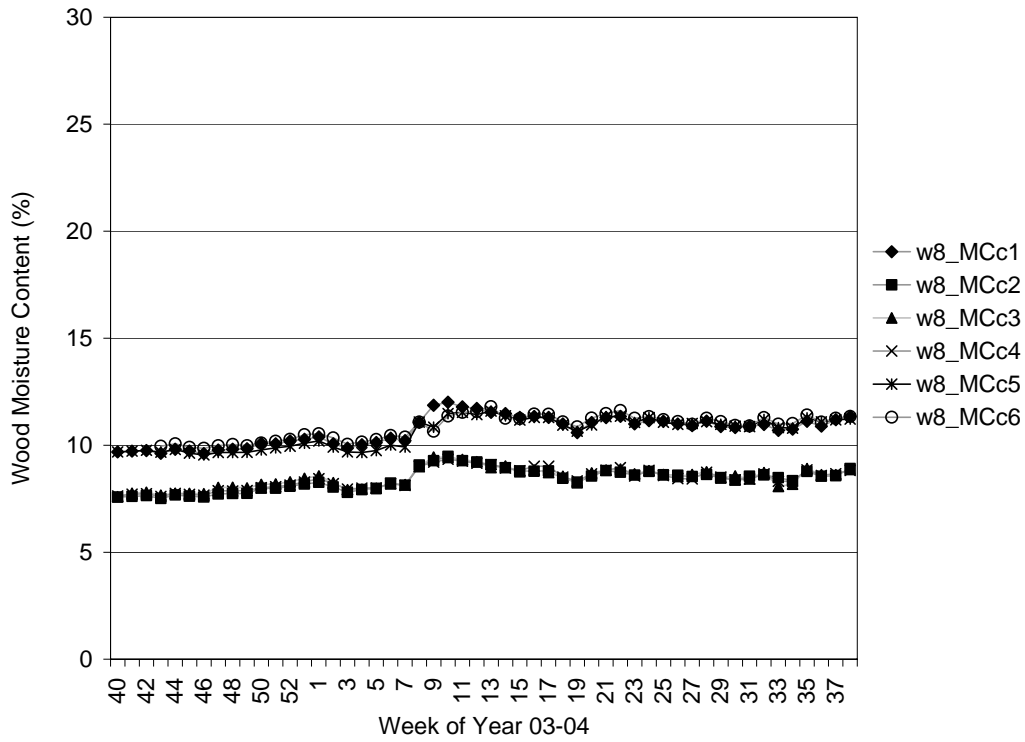
**Figure A 7-3 Wall 7 - Temperature**



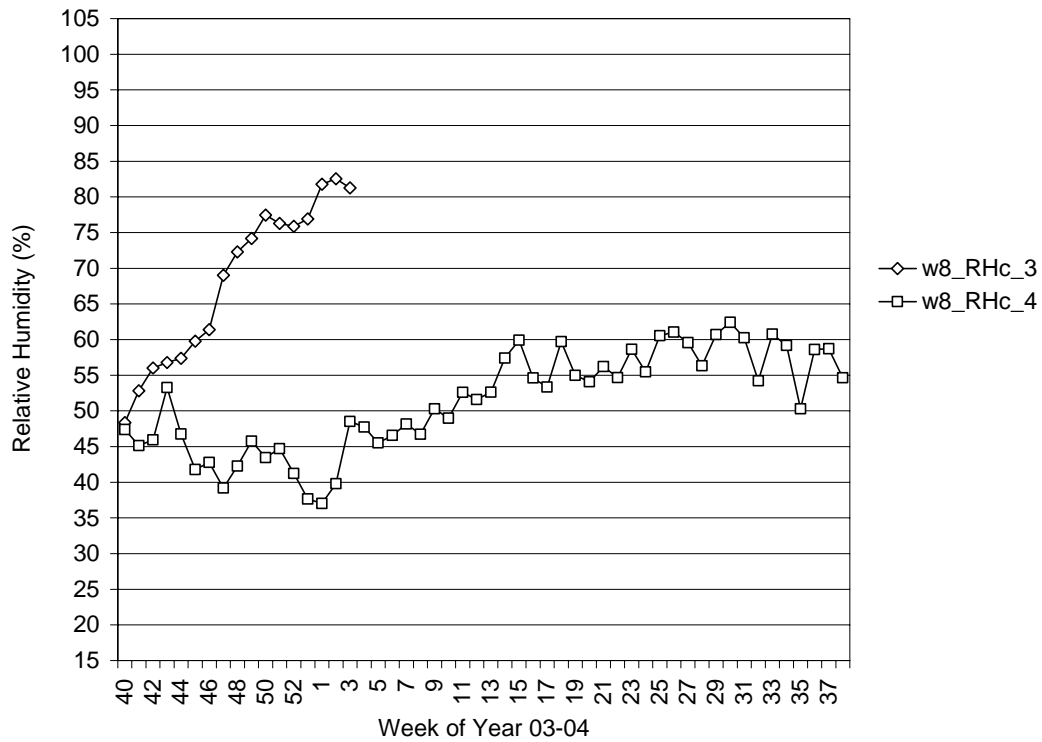
**Figure A 7-4 Wall 7 - Vapor Pressure**



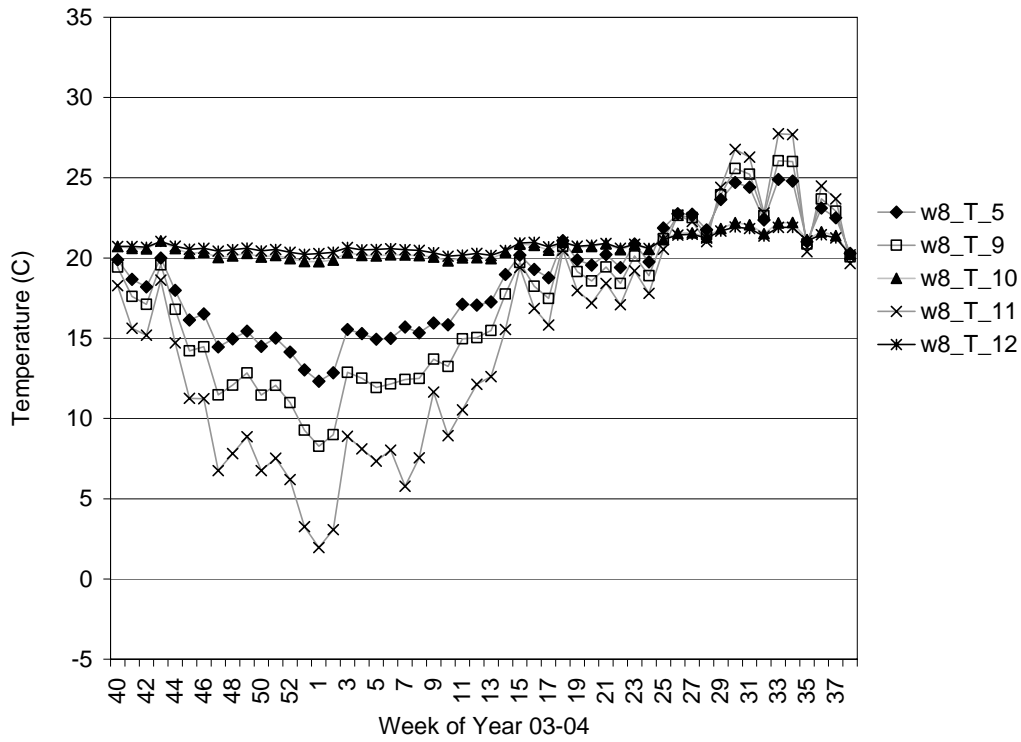
**Figure A 8-1 Wall 8 – Wood Moisture Content**



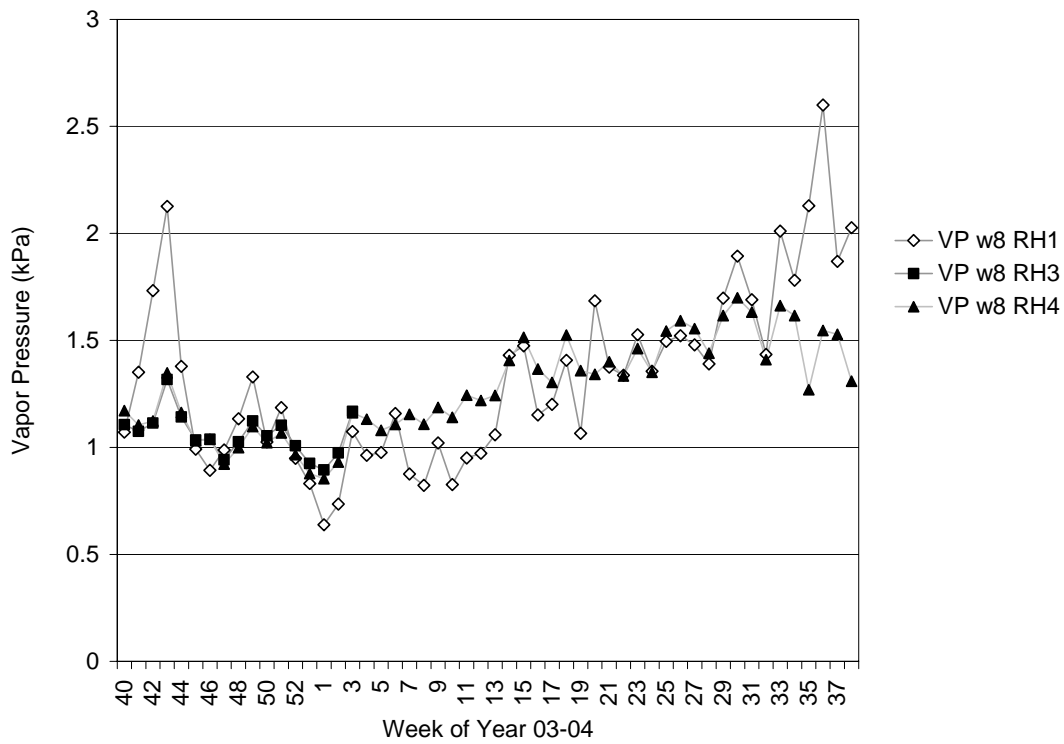
**Figure A 8-2 Wall 8 – Cavity Relative Humidity**



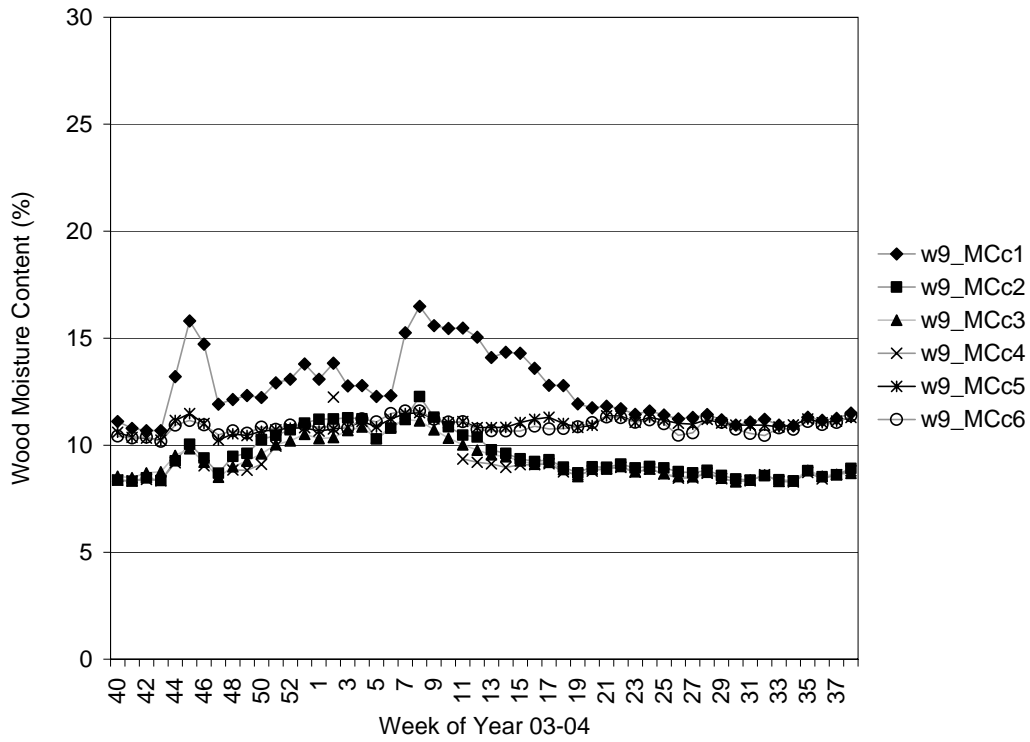
**Figure A 8-3 Wall 8 - Temperature**



**Figure A 8-4 Wall 8 – Vapor Pressure**



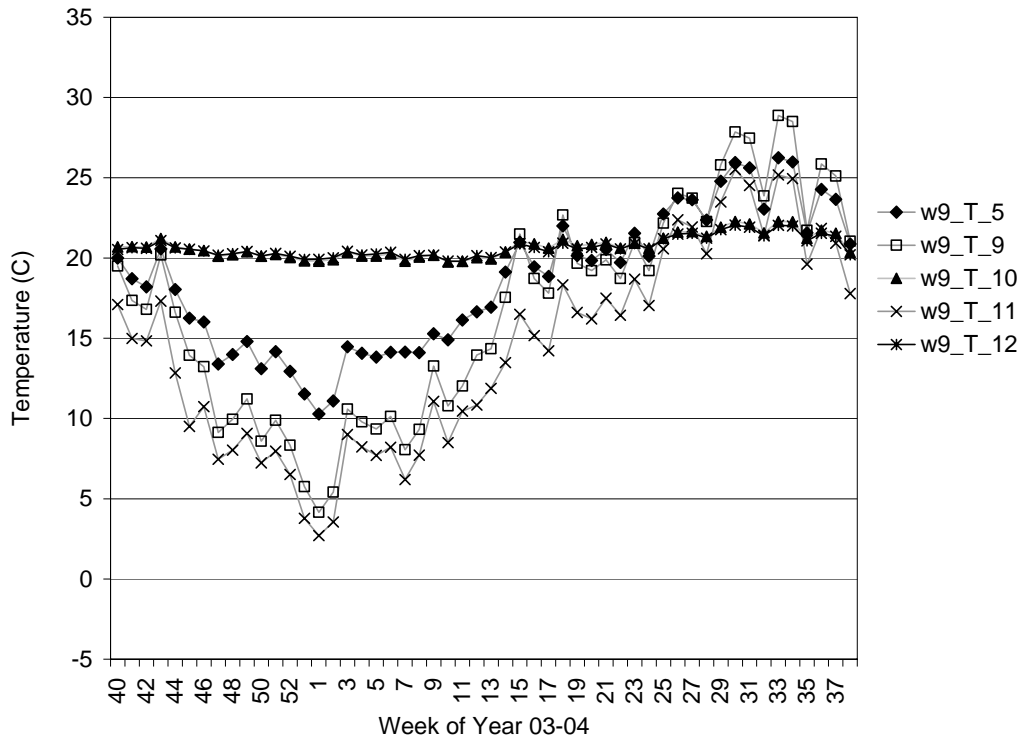
**Figure A 9-1 Wall 9 – Wood Moisture Content**



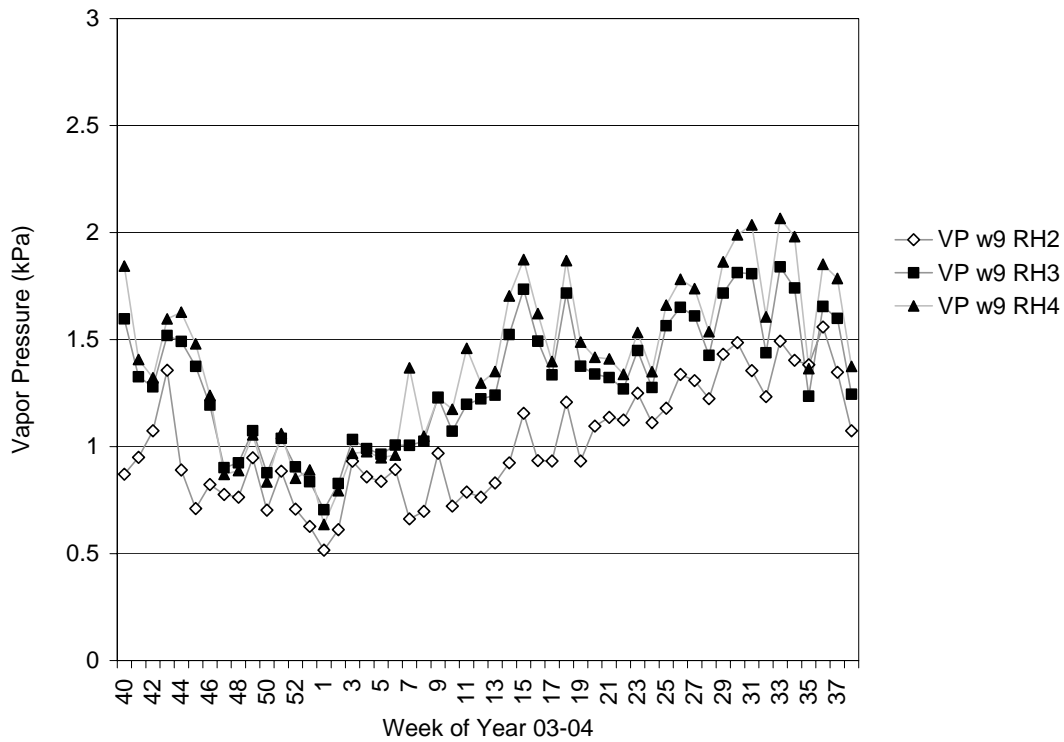
**Figure A 9-2 Wall 9 – Cavity Relative Humidity**



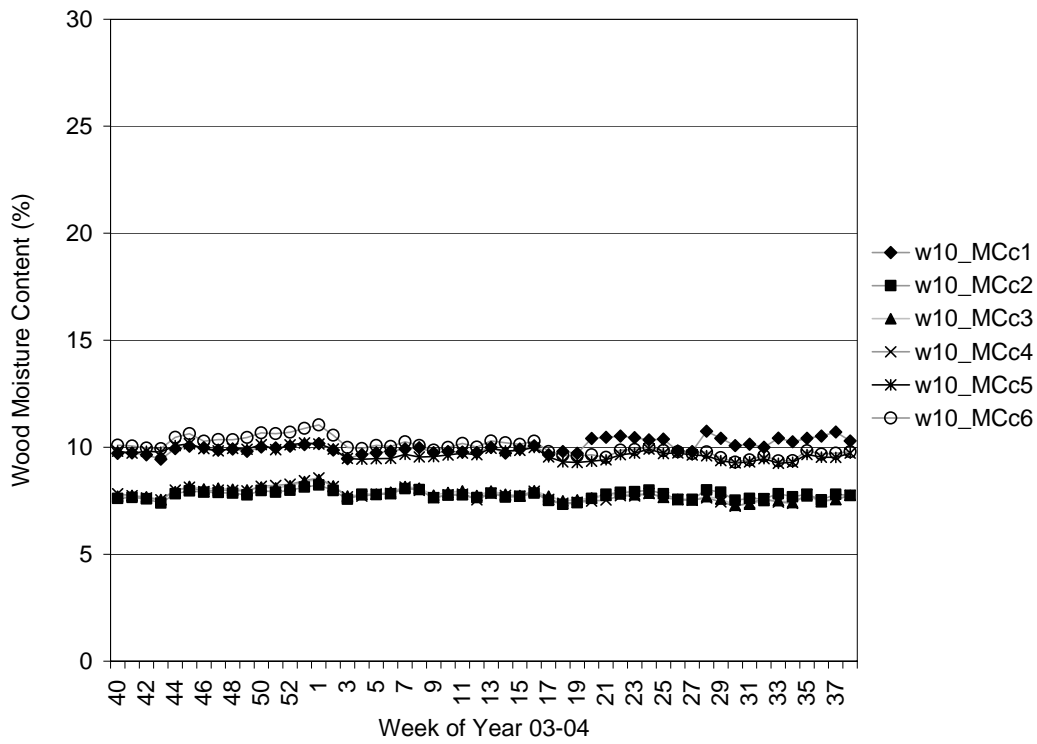
**Figure A 9-3 Wall 9 - Temperature**



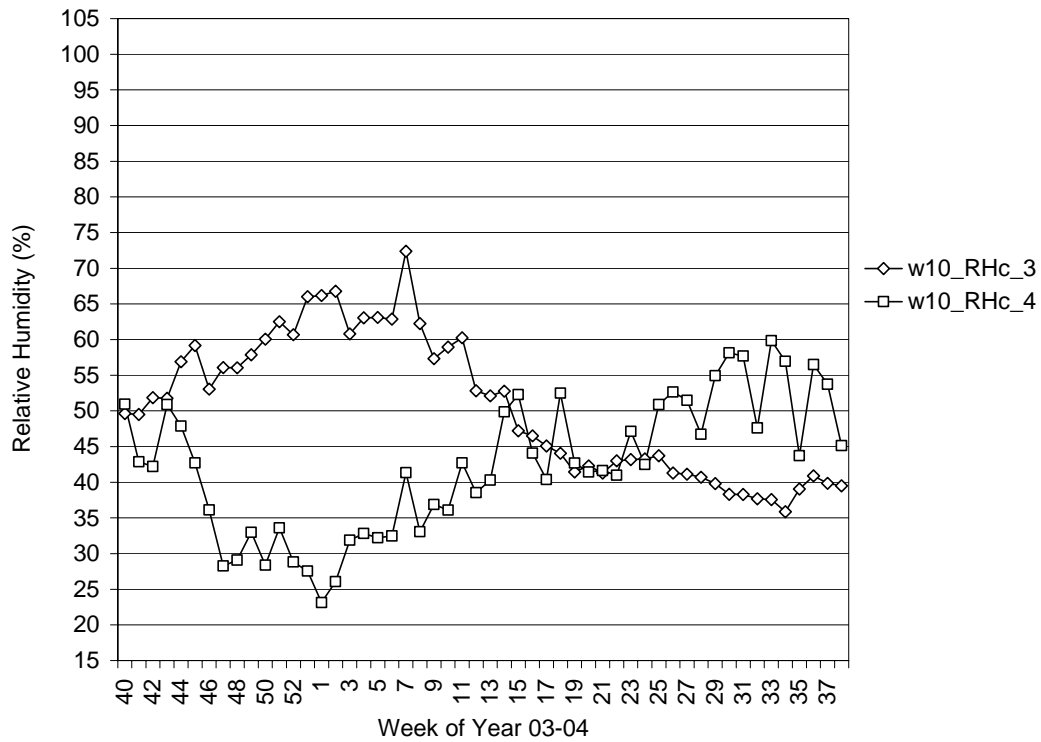
**Figure A 9-4 Wall 9 – Vapor Pressure**



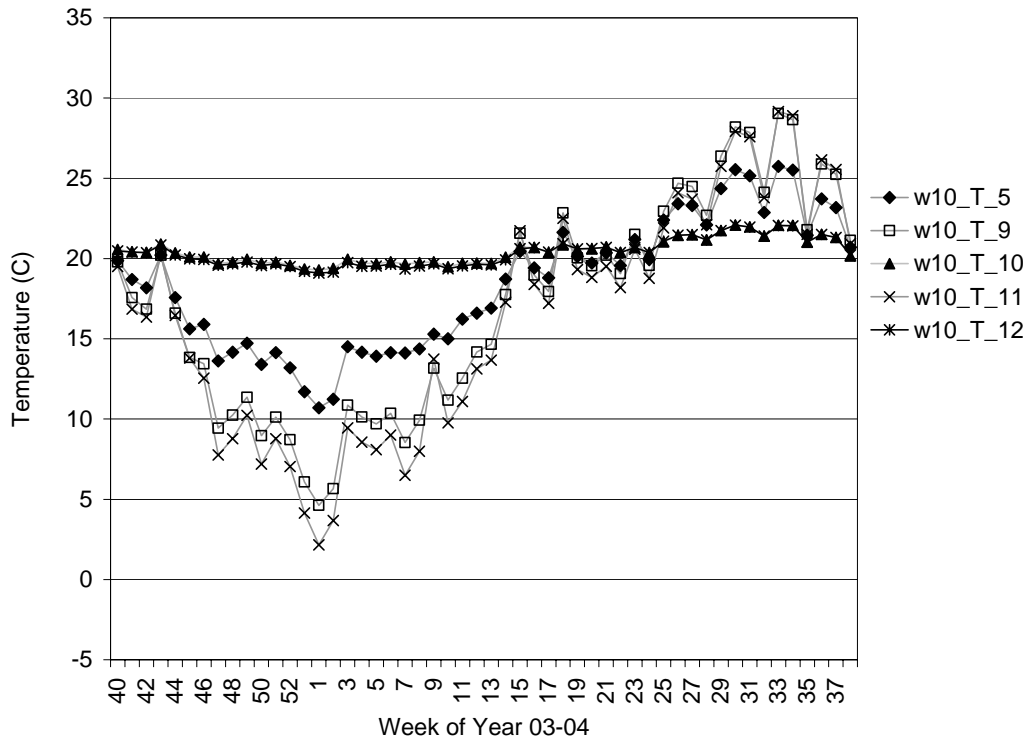
**Figure A 10-1 Wall 10 – Wood Moisture Content**



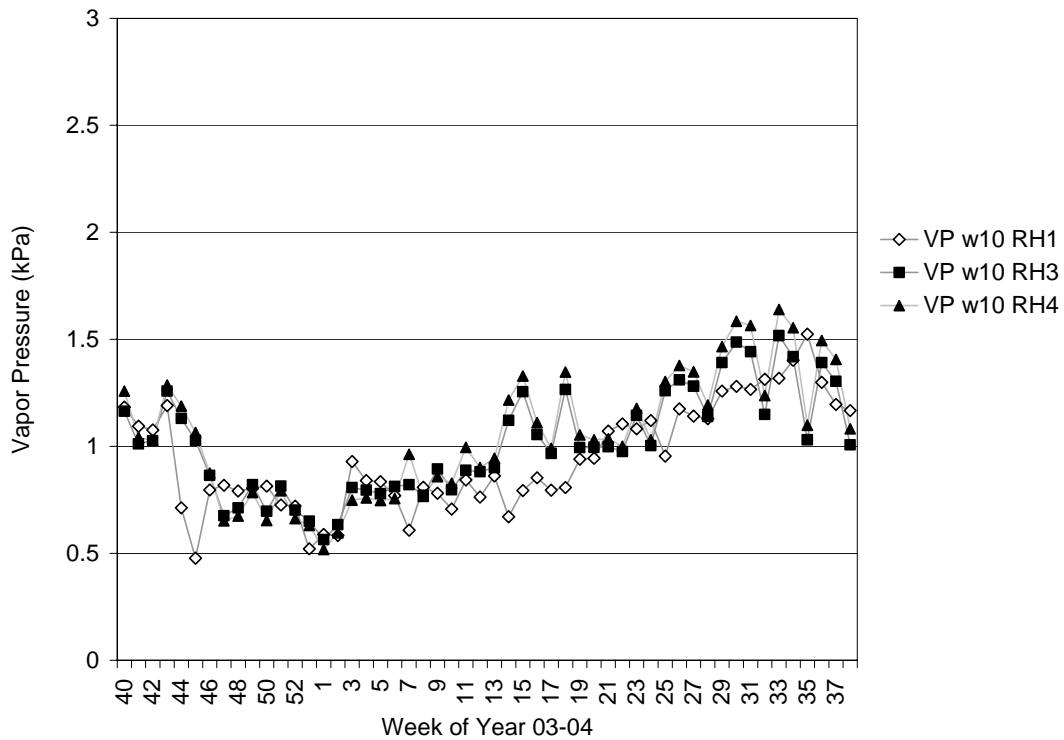
**Figure A 10-2 Wall 10 – Cavity Relative Humidity**



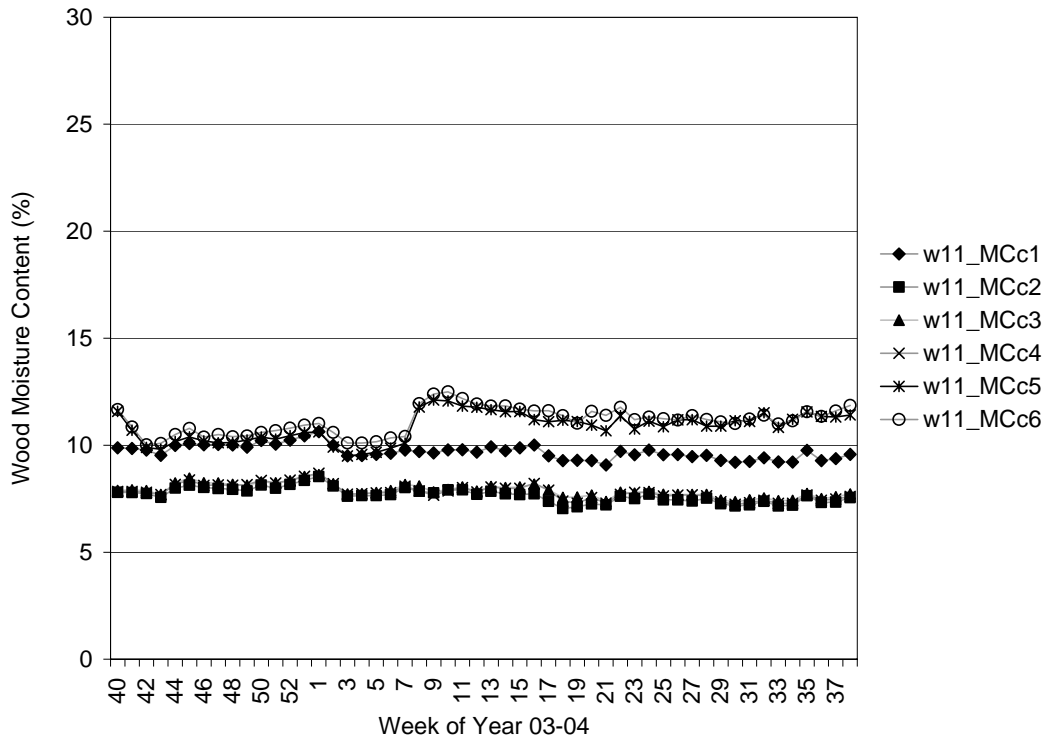
**Figure A 10-3 Wall 10 - Temperature**



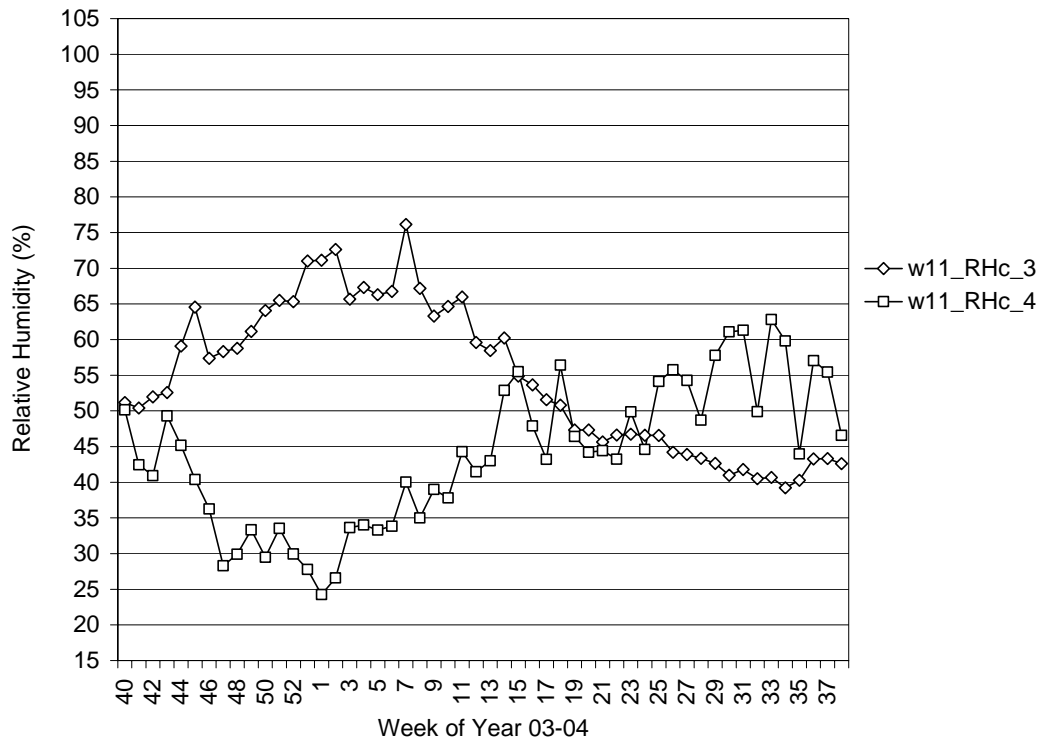
**Figure A 10-4 Wall 10 – Vapor Pressure**



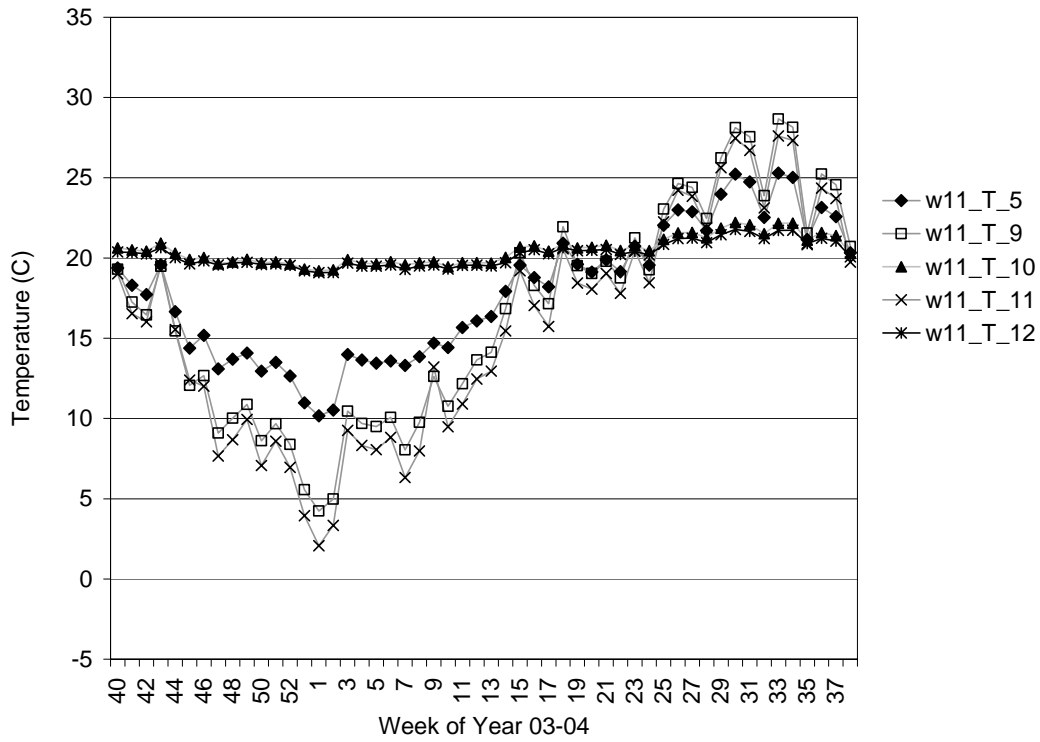
**Figure A 11-1 Wall 11 – Wood Moisture Content**



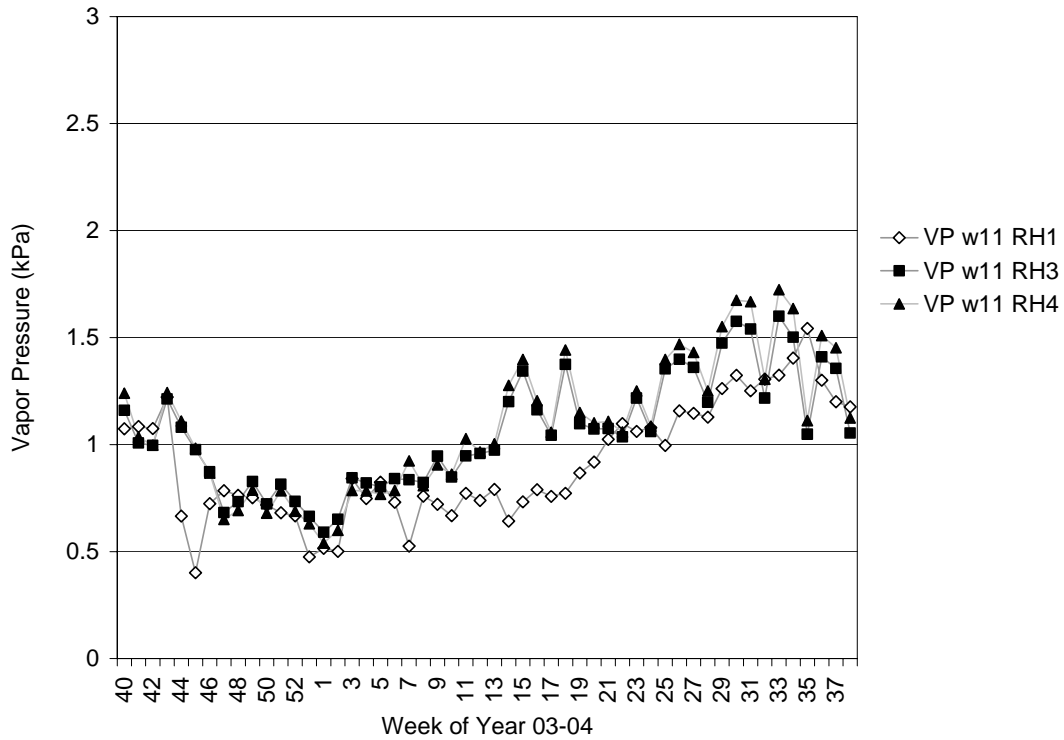
**Figure A 11-2 Wall 11 – Cavity Relative Humidity**



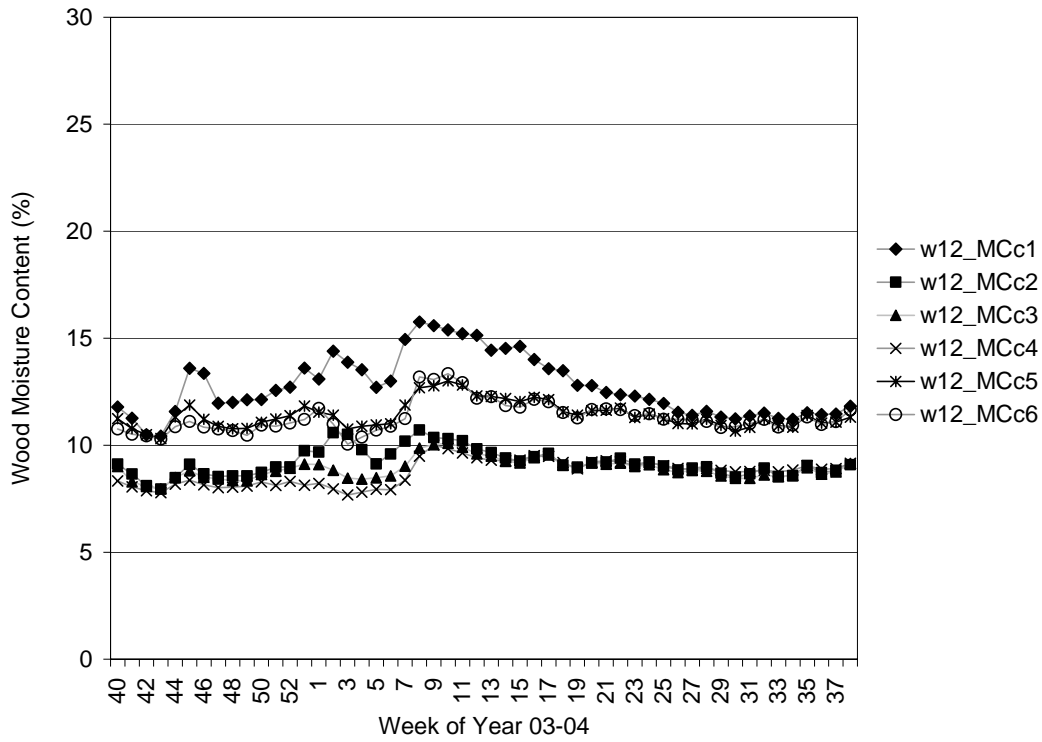
**Figure A 11-3 Wall 11 - Temperature**



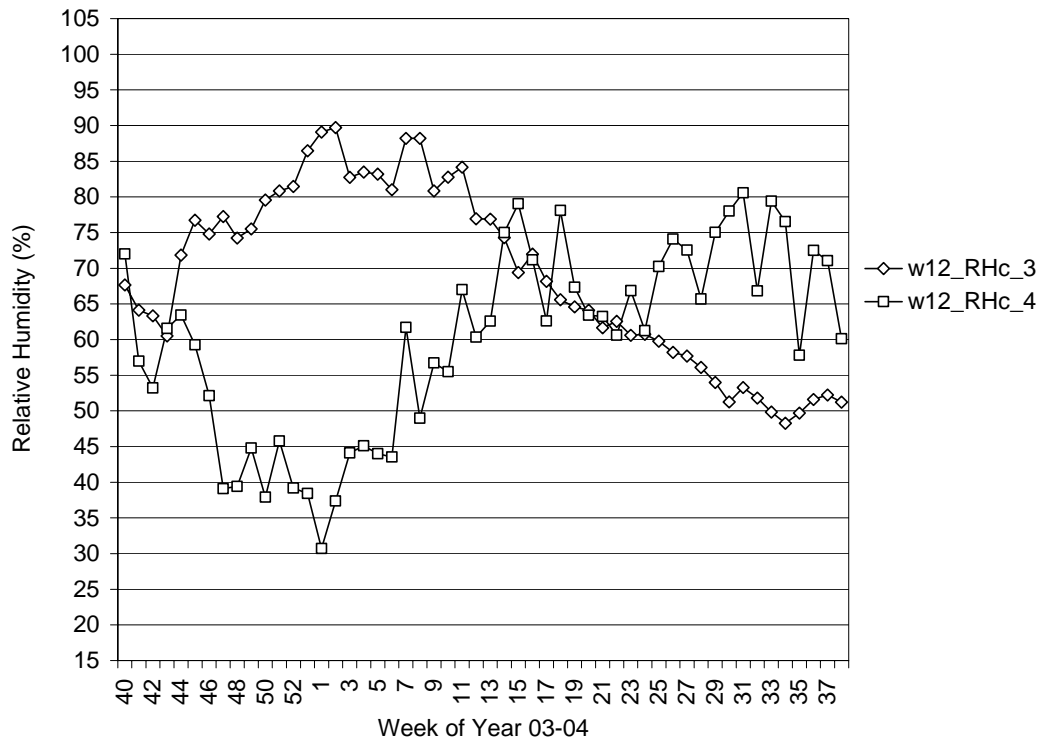
**Figure A 11-4 Wall 11 - Vapor Pressure**



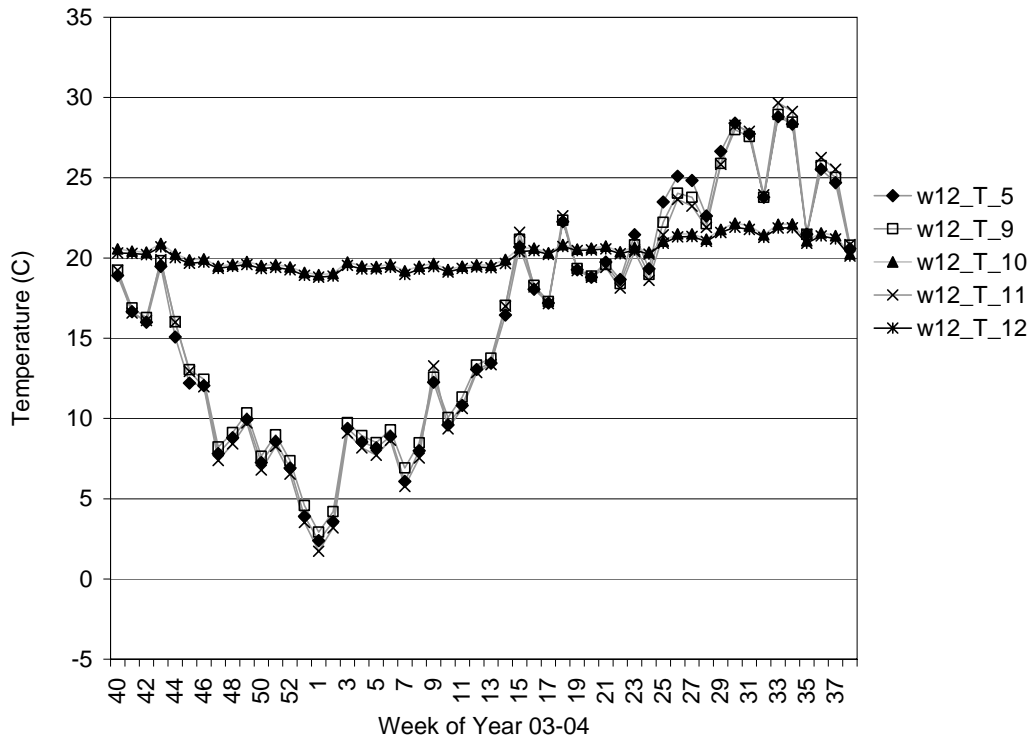
**Figure A 12-1 Wall 12 – Wood Moisture Content**



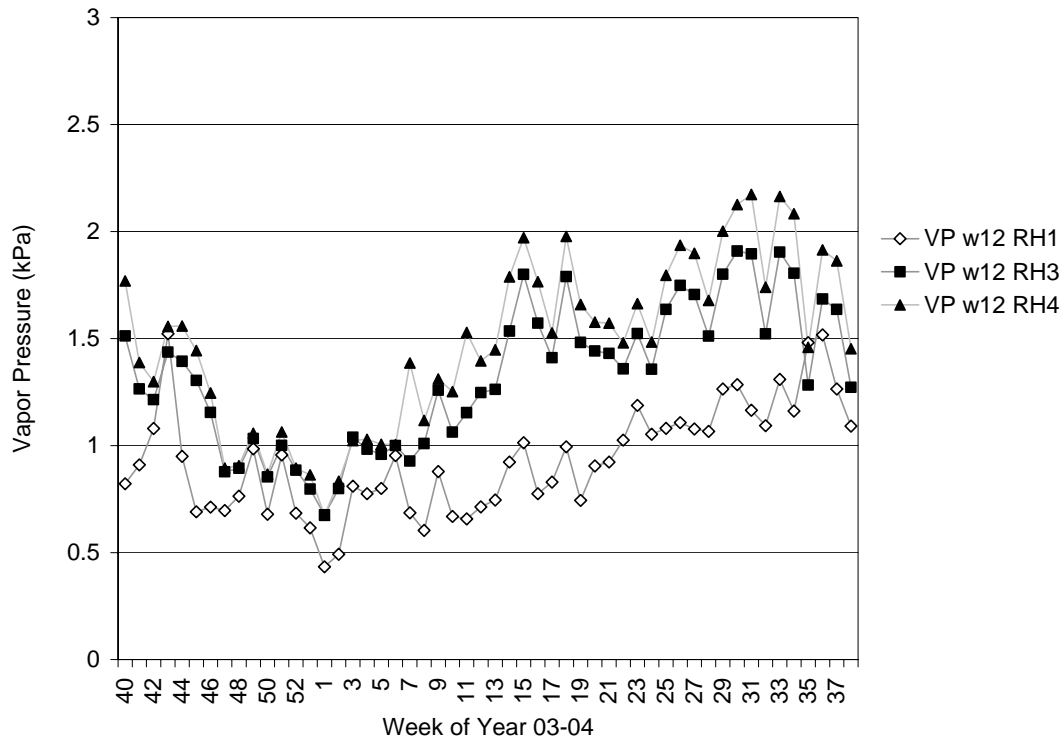
**Figure A 12-2 Wall 12 – Cavity Relative Humidity**



**Figure A 12-3 Wall 12 - Temperature**



**Figure A 12-4 Wall 12 – Vapor Pressure**



**Appendix B**  
**Test Cycle 2 Figures**  
**November 7 2004 to September 20, 2005**



## Experimental Timeline

During test cycle 2, the normal operation of the test was interrupted to implement the wall wetting experiment. For details, read the experimental design section of this report.

The graphic below was created to provide the reader a reference for all of the graphs in Appendix B. The periods of normal operation, wetting, and drying correspond to the week and year listed.

Figure B 5 Test Cycle 2 - Experimental Timeline

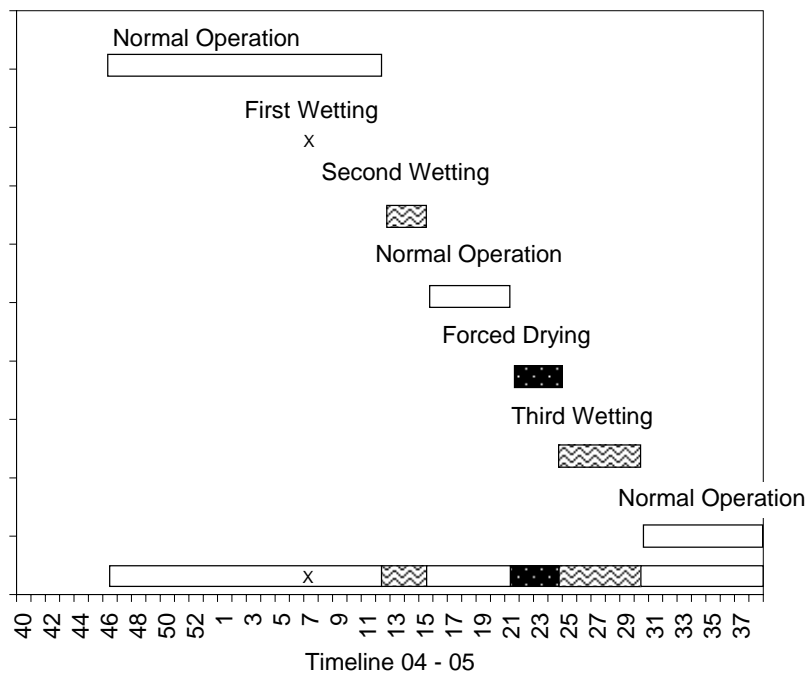


Figure B S1-1

S1 – Wood Moisture Content

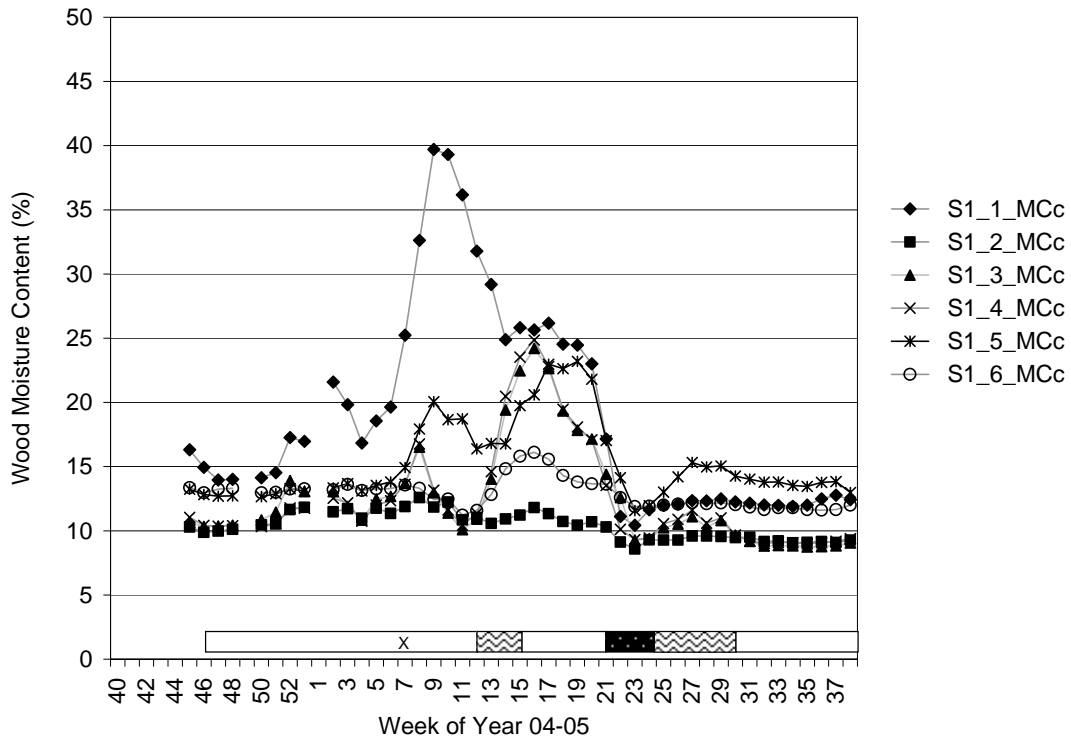
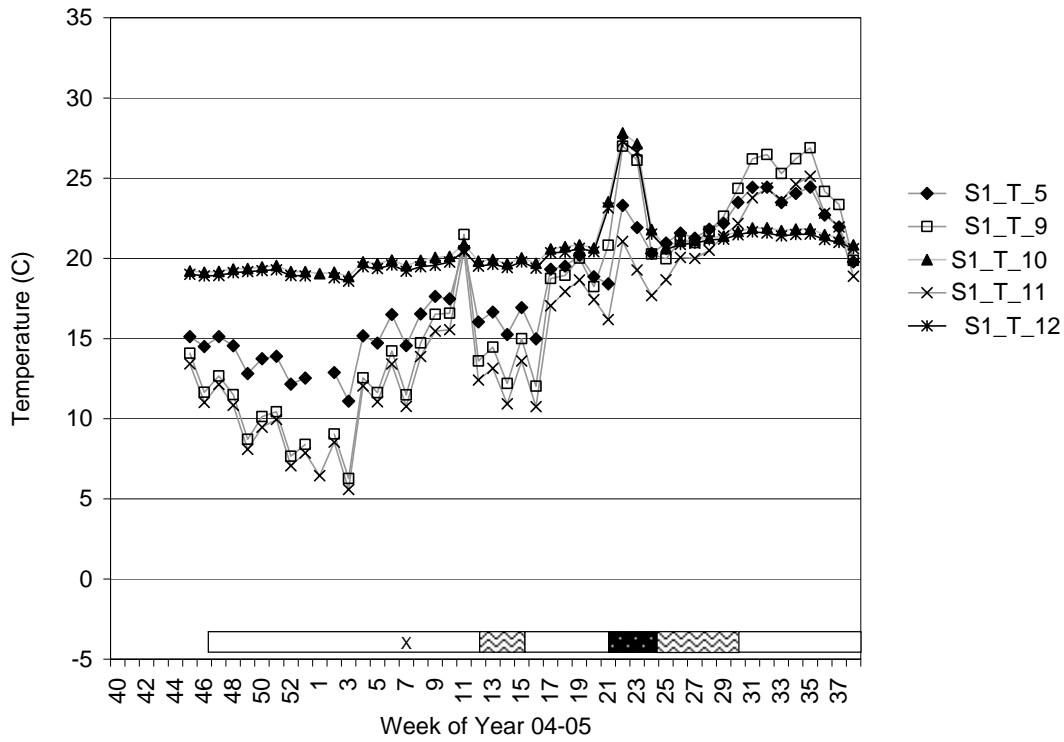


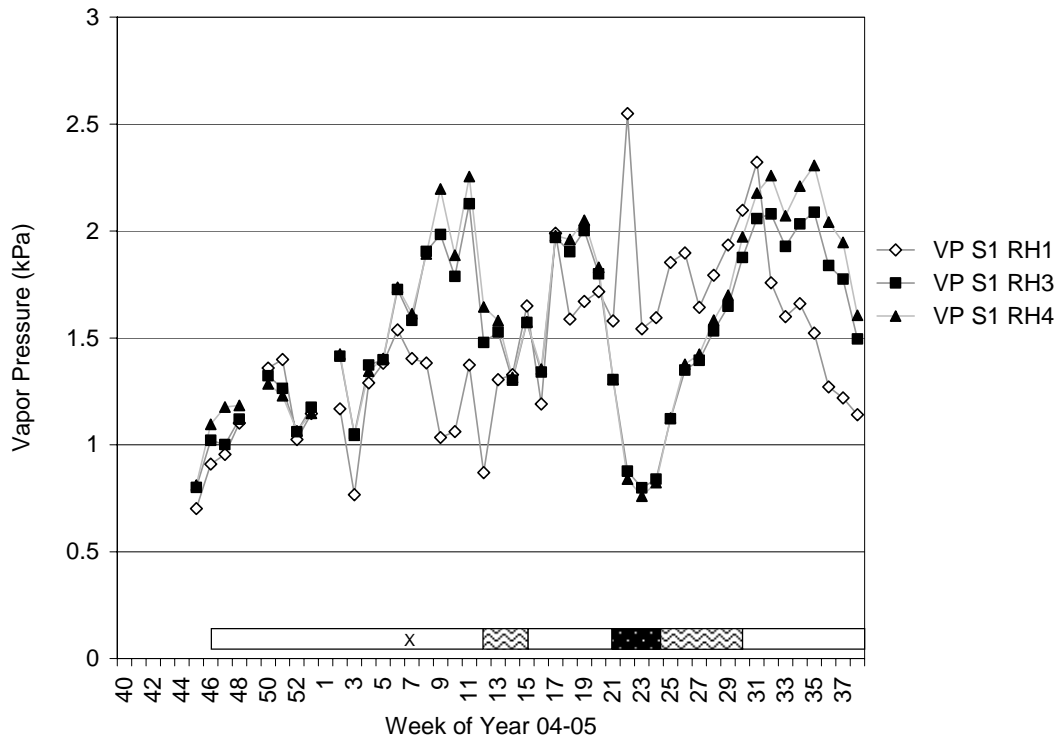
Figure B S1-2 S1 – Cavity Relative Humidity



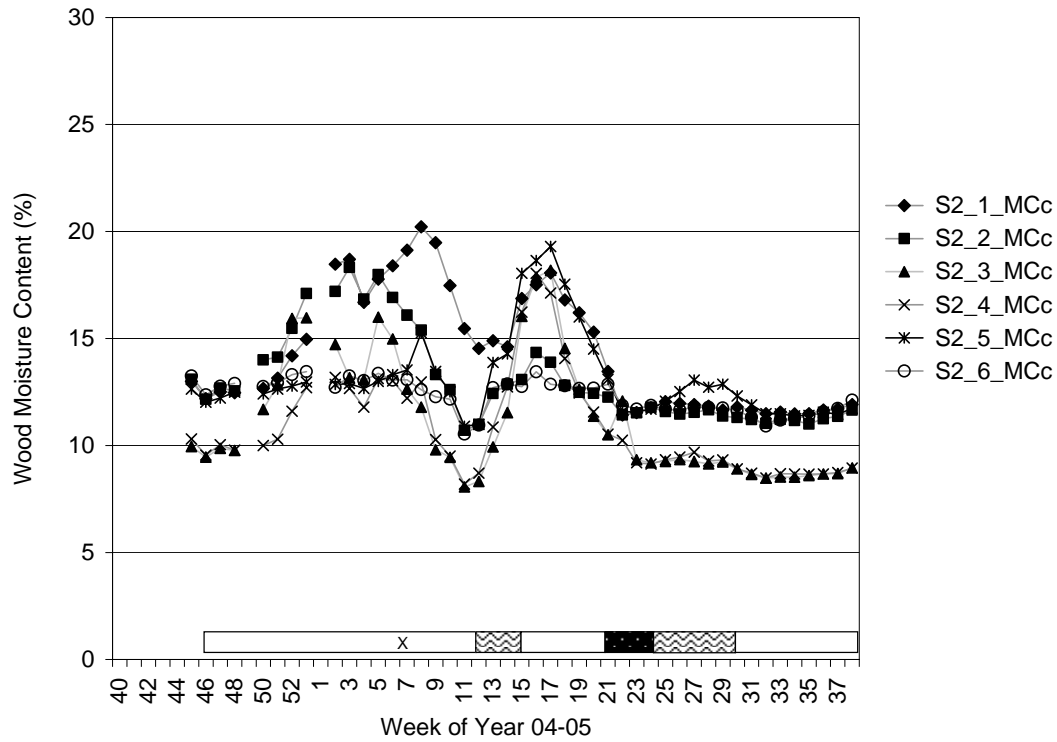
**Figure B S1-3 S1 - Temperature**



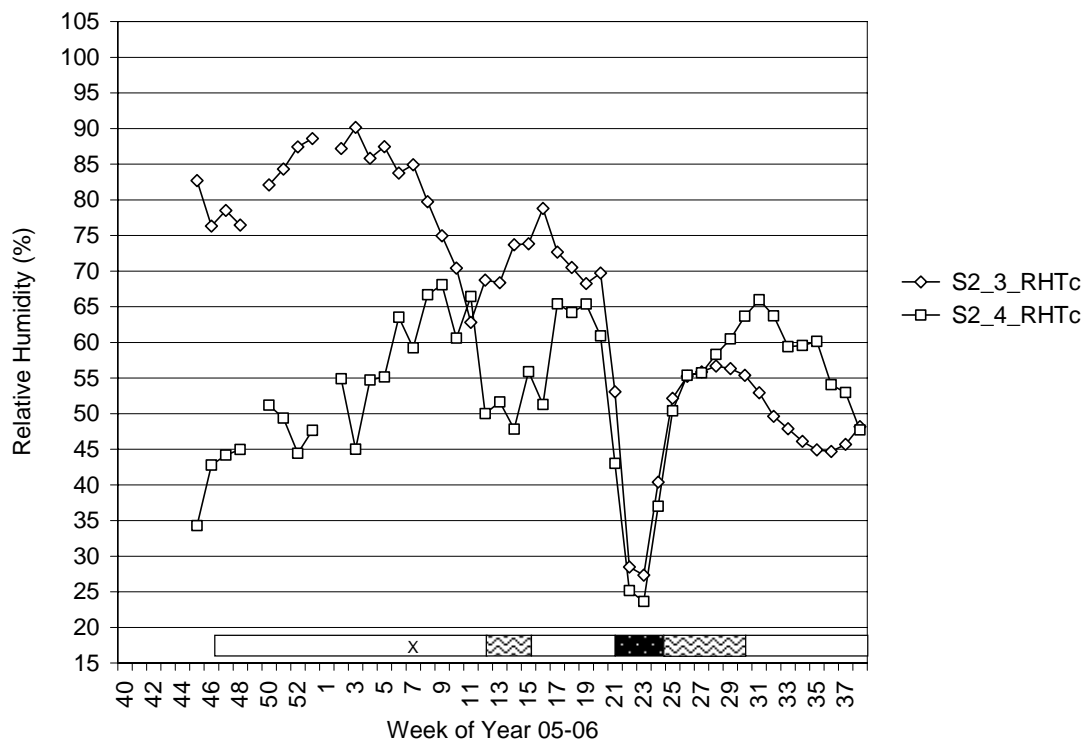
**Figure B S1-4 S1 – Vapor Pressure**



**Figure B S2-1 S2– Wood Moisture Content**



**Figure B S2-2 S2- Cavity Relative Humidity**



**Figure B S2-3 S2- Temperature**

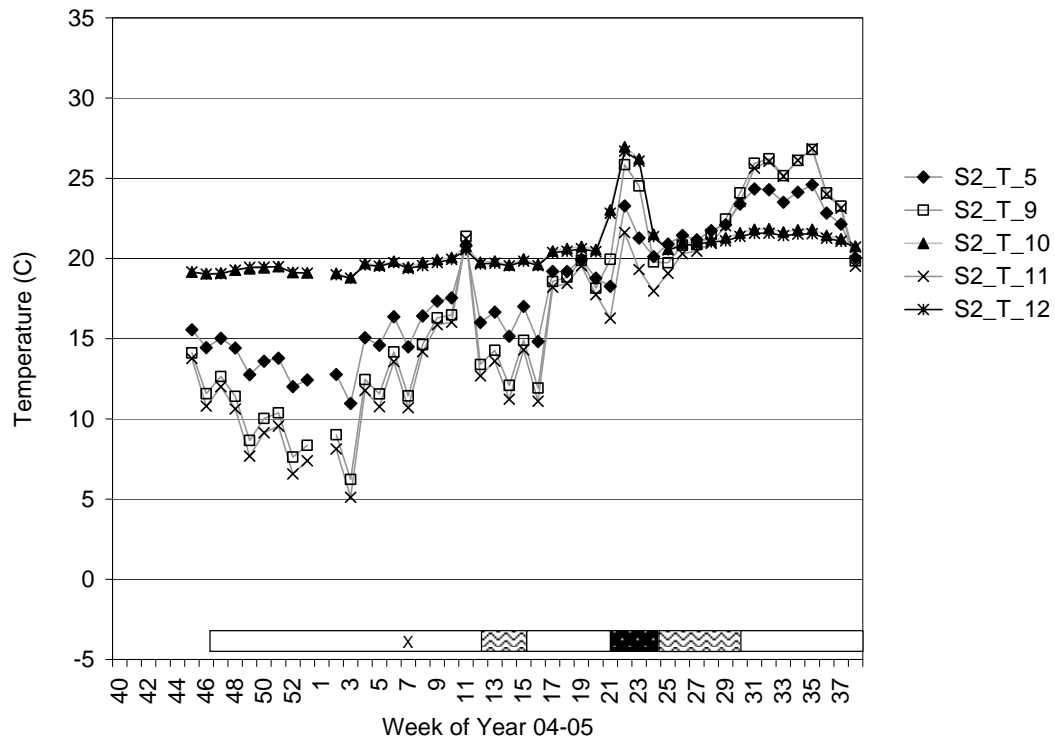


Figure B S2-4 S2 – Vapor Pressure

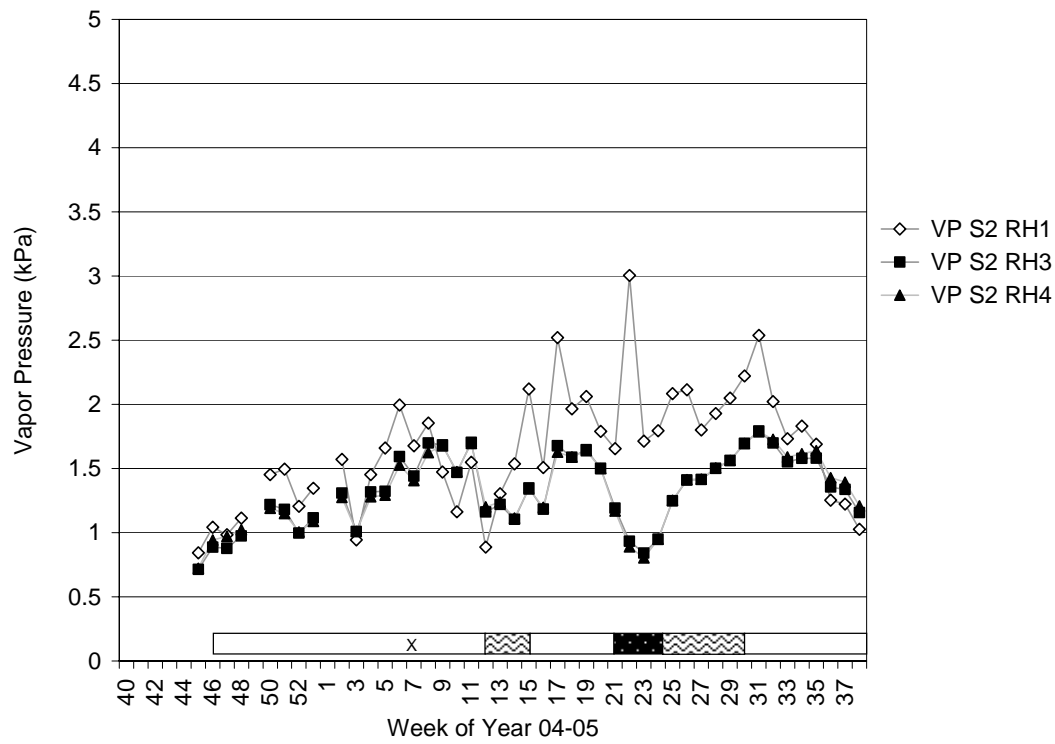


Figure B S3-1 S3 – Wood Moisture Content

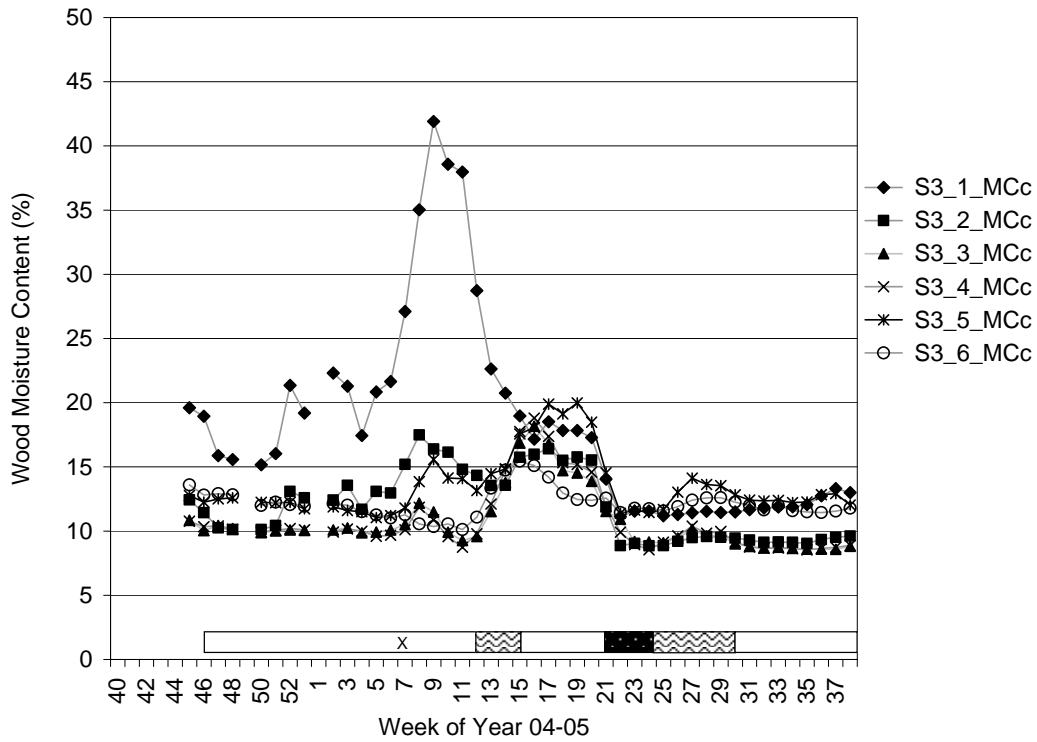


Figure B S3-2 S3 – Cavity Relative Humidity



Figure B S3-3 S3 - Temperature

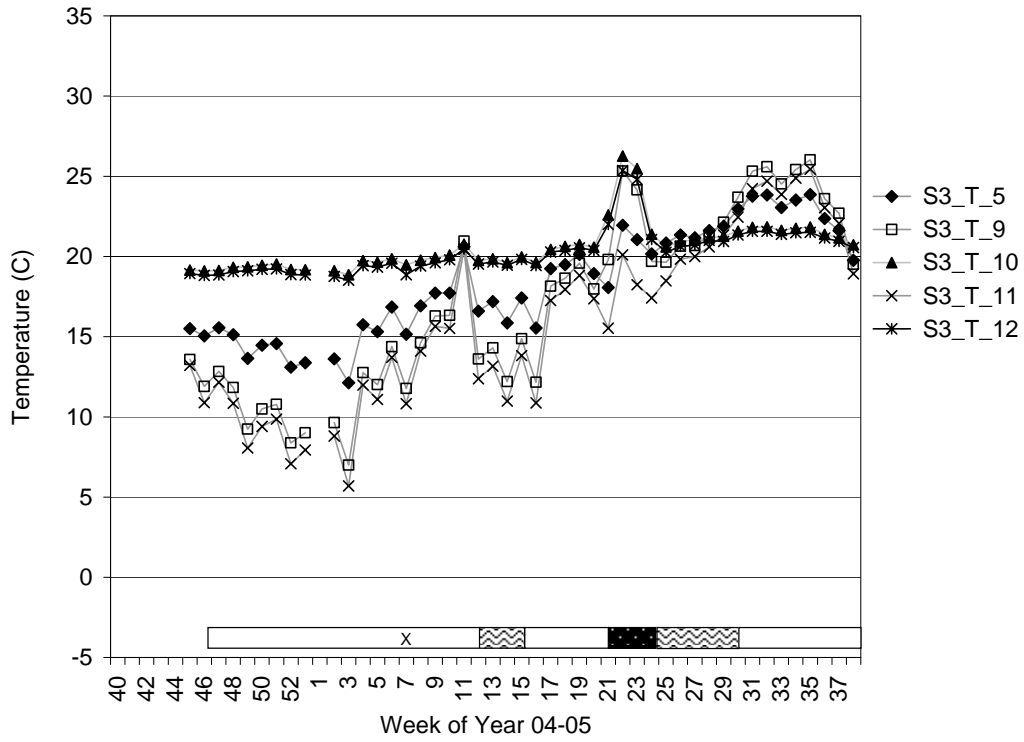
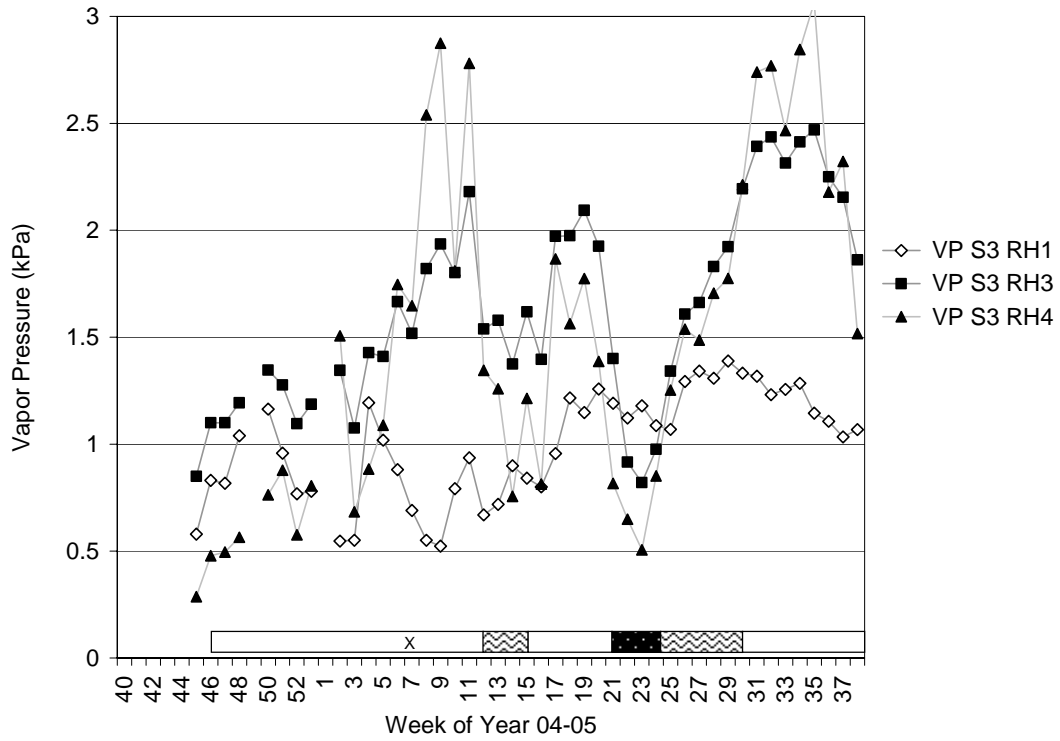
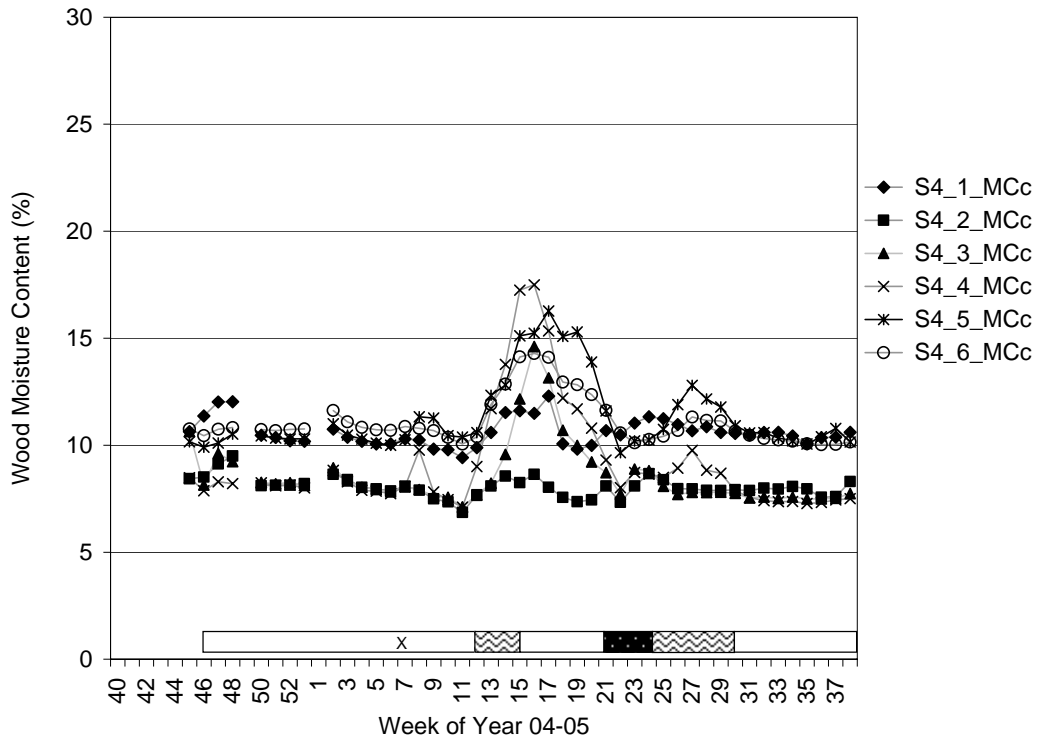


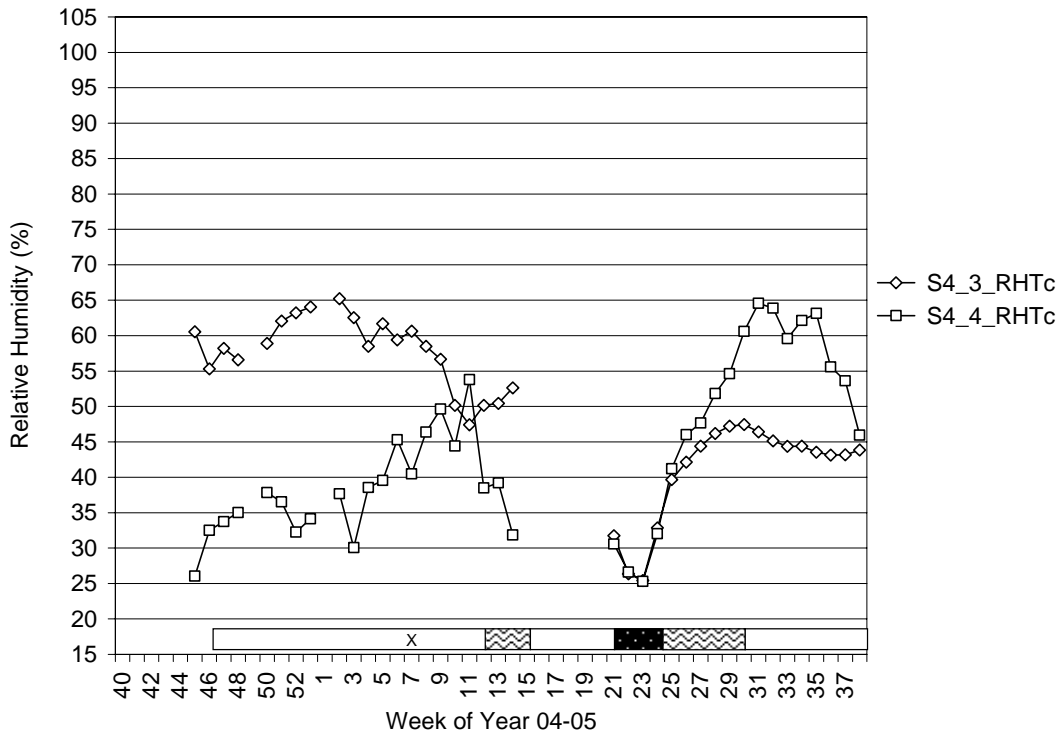
Figure B S3-4 S3 – Vapor Pressure



**Figure B S4-1 S4 – Wood Moisture Content**

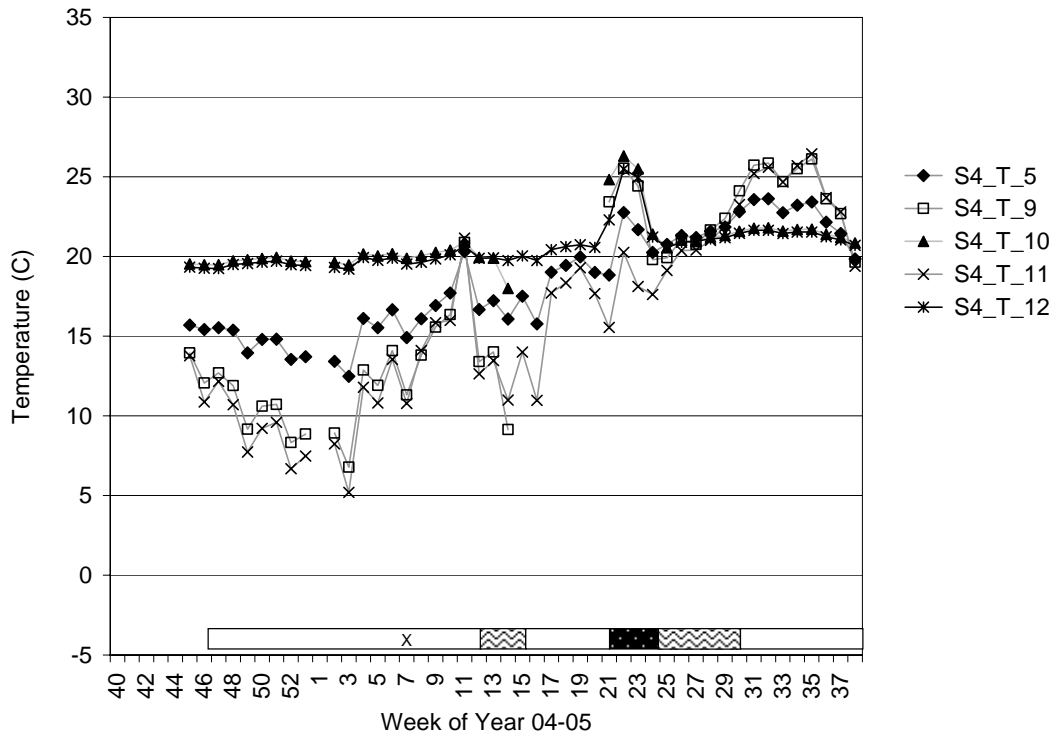


**Figure B S4-2 S4 – Cavity Relative Humidity**

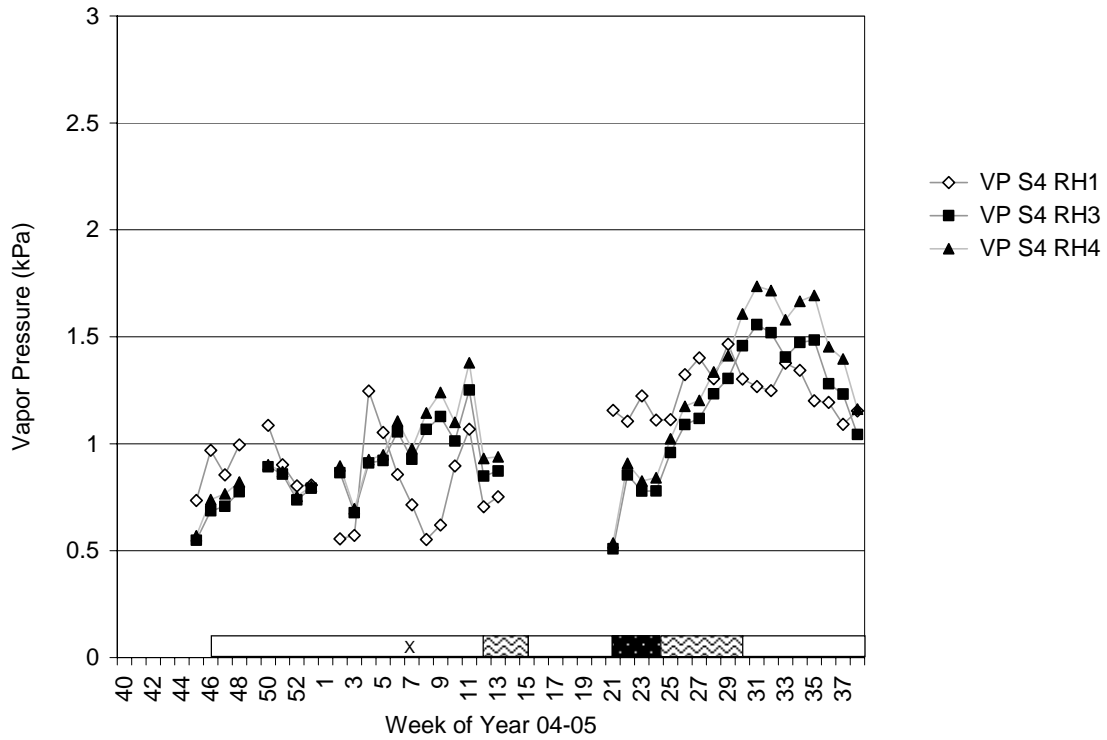


4

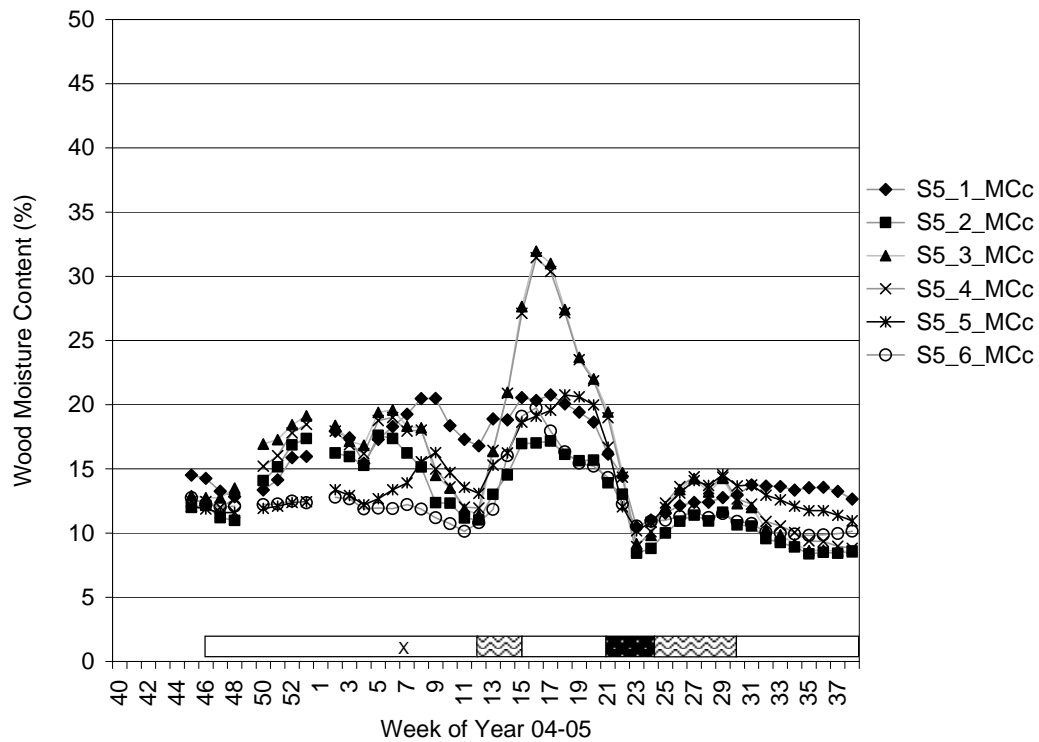
**Figure B S4-3 S4- Temperature**



**Figure B S4-4 S4 - Vapor Pressure**



**Figure B S5-1 S5 – Wood Moisture Content**



**Figure B S5-2 S5 – Cavity Relative Humidity**



**Figure B S5-3 S5 - Temperature**

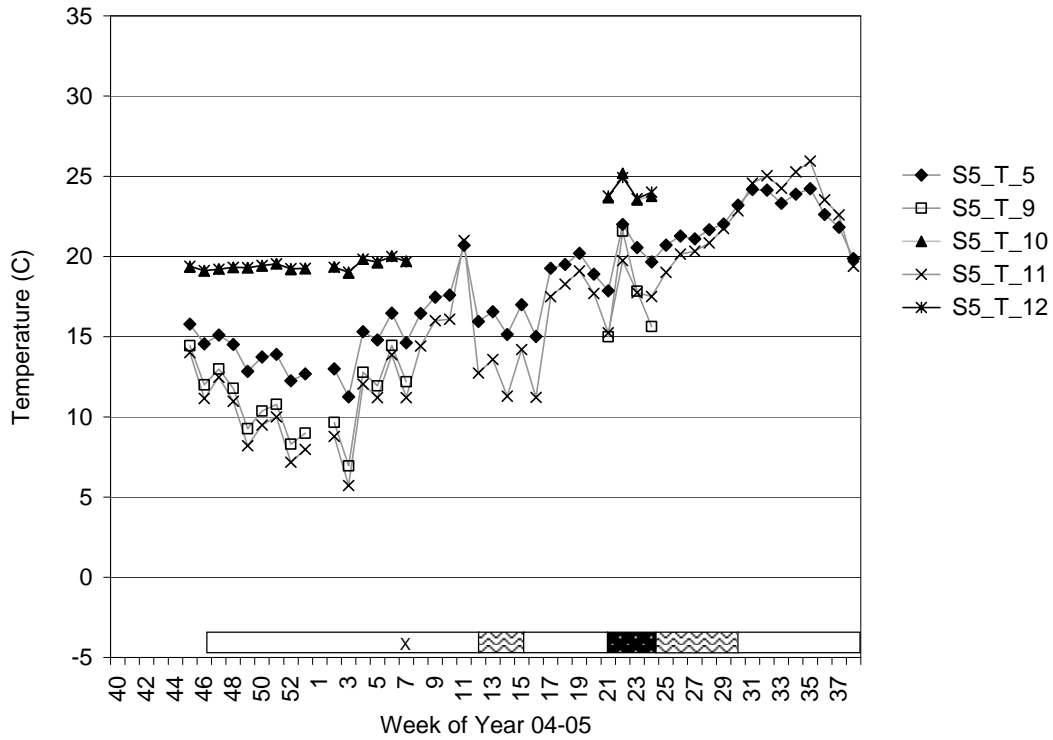


Figure B S5-4 S5 – Vapor Pressure

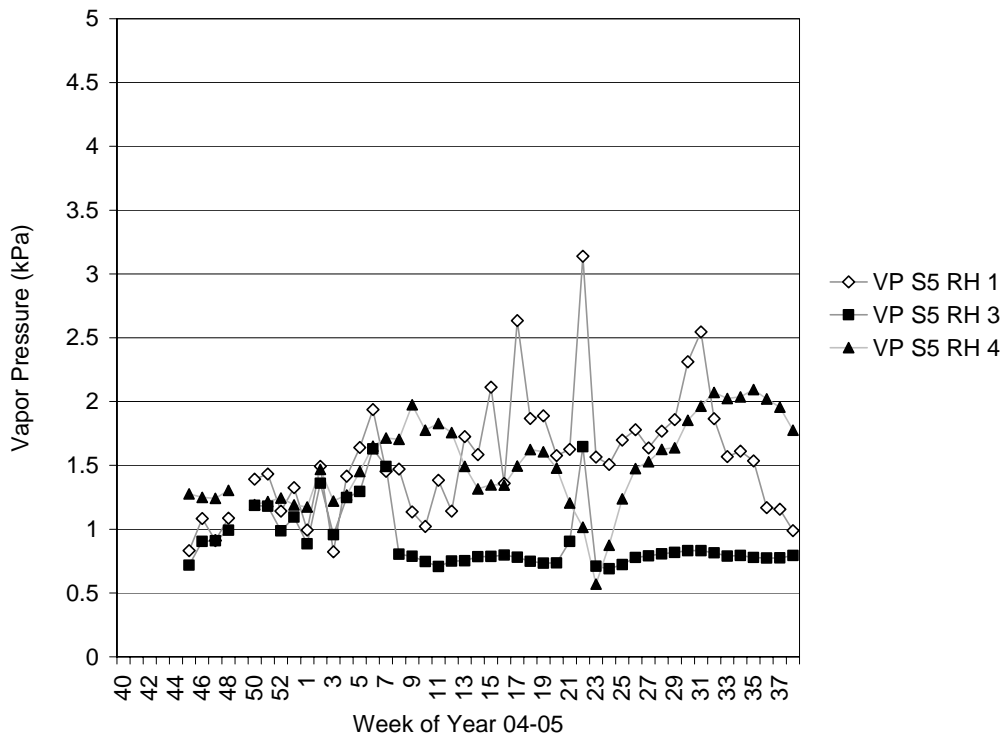
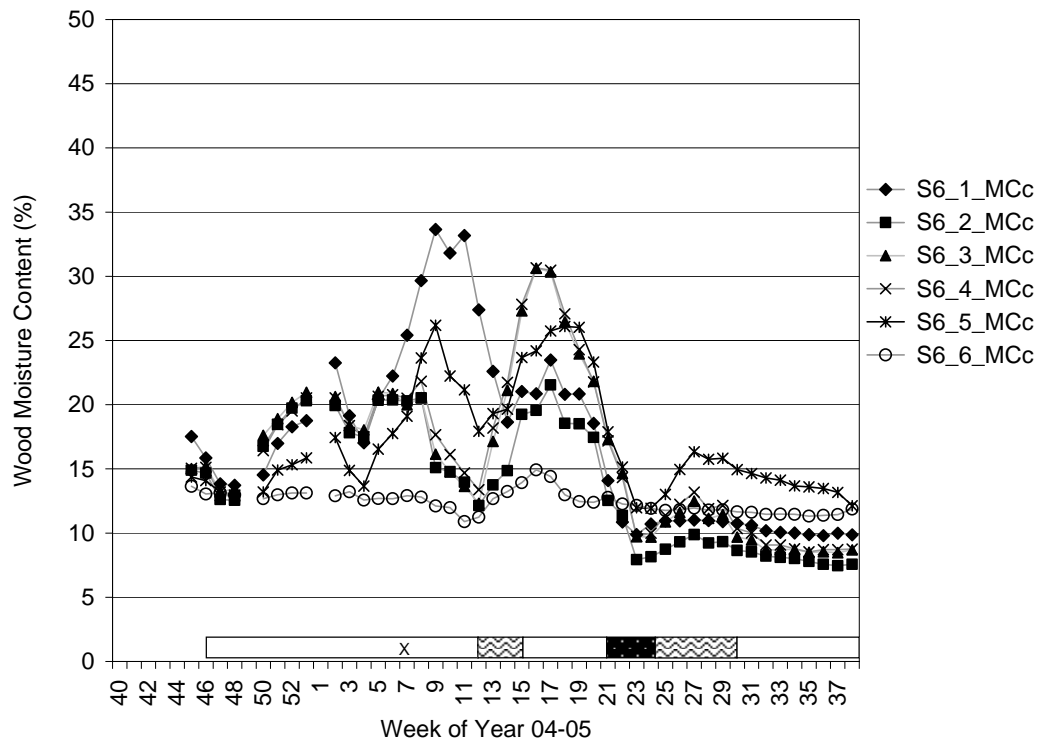
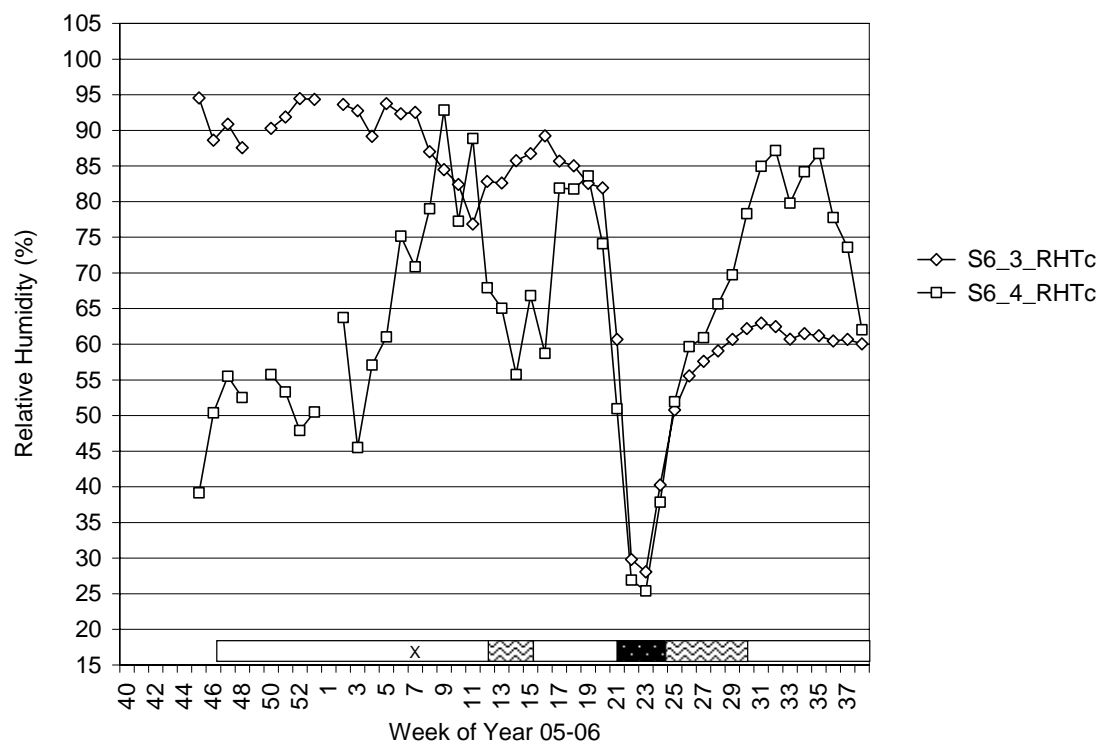


Figure B S6-1 S6 – Wood Moisture Content



**Figure B S6-2 S6 – Cavity Relative Humidity**



**Figure B S6-3 S6 - Temperature**

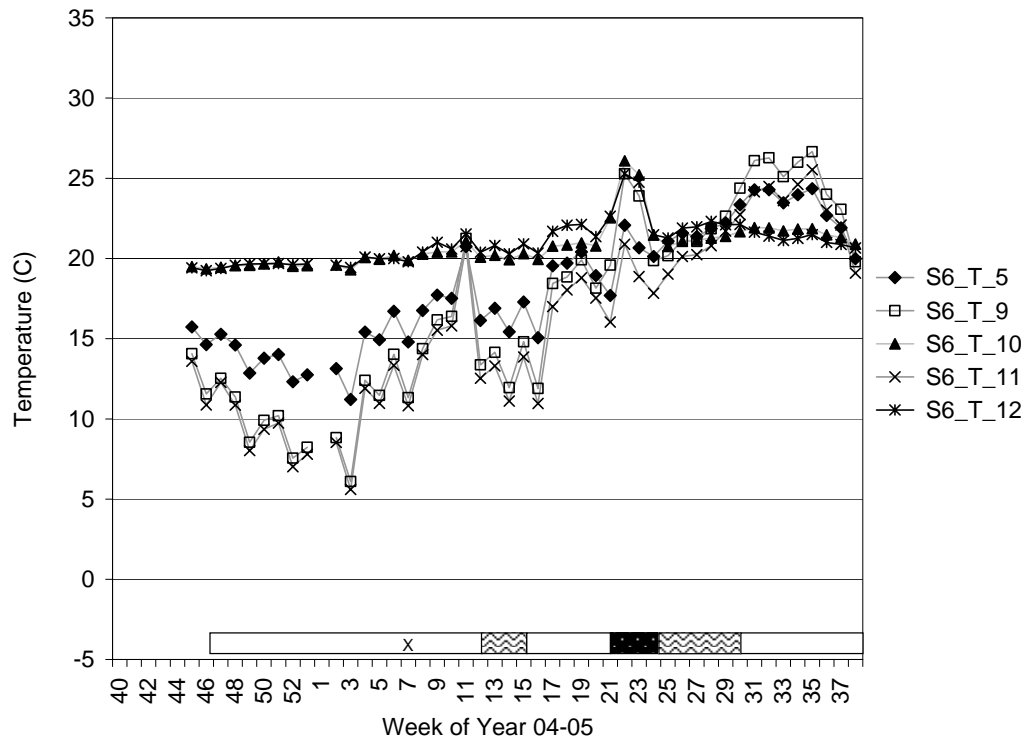


Figure B S6-4 S6 – Vapor Pressure

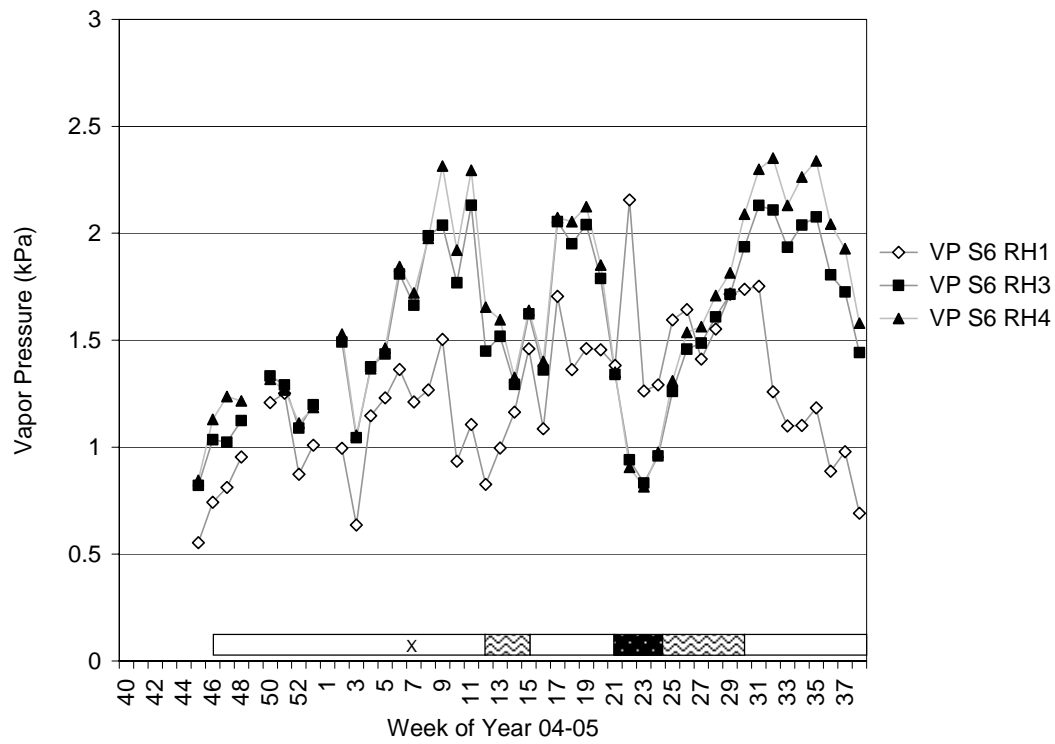


Figure B S7-1 S7 – Wood Moisture Content

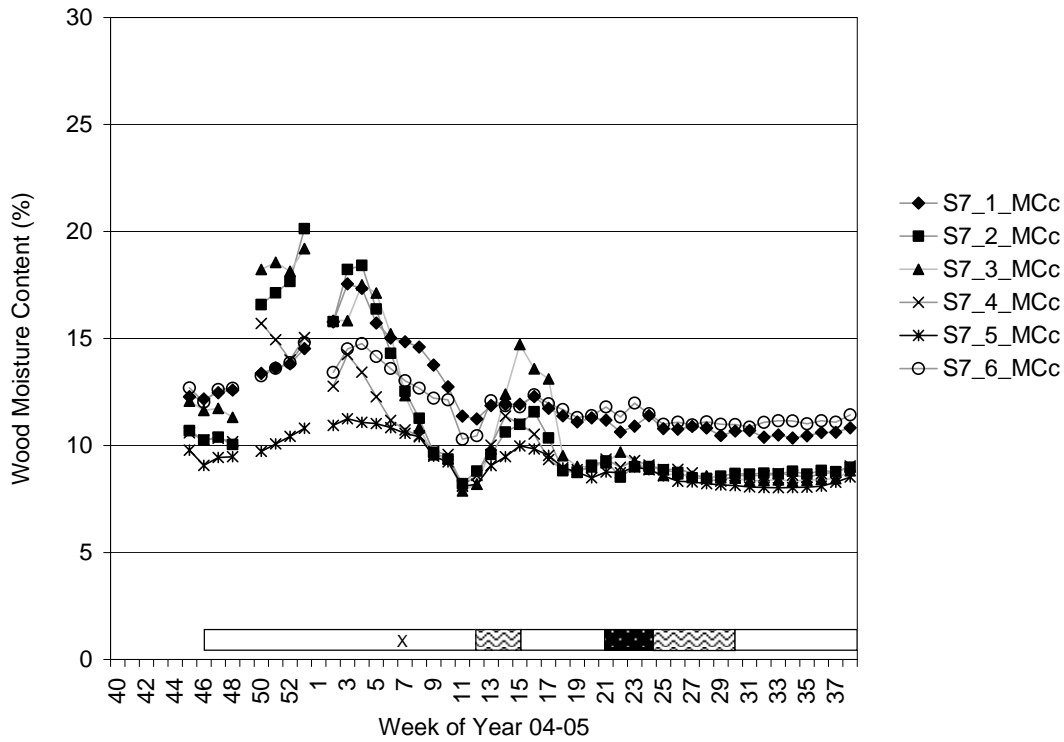


Figure B S7-2 S7 – Cavity Relative Humidity



Figure B S7-3 S7 - Temperature

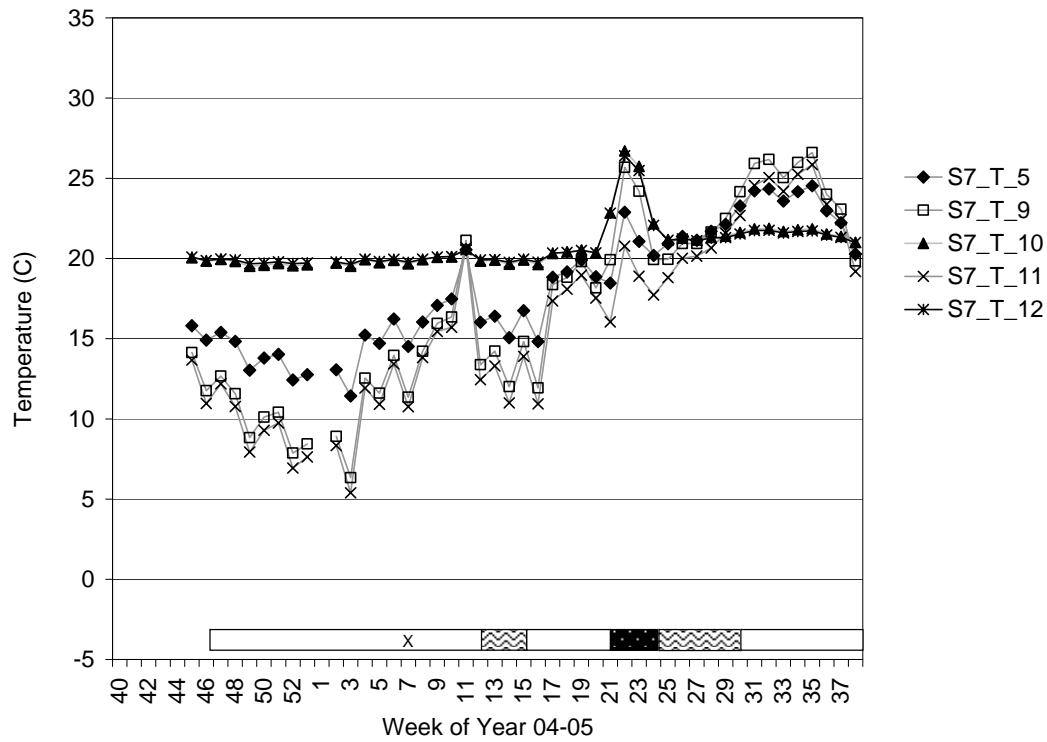


Figure B S7-4 S7 – Vapor Pressure

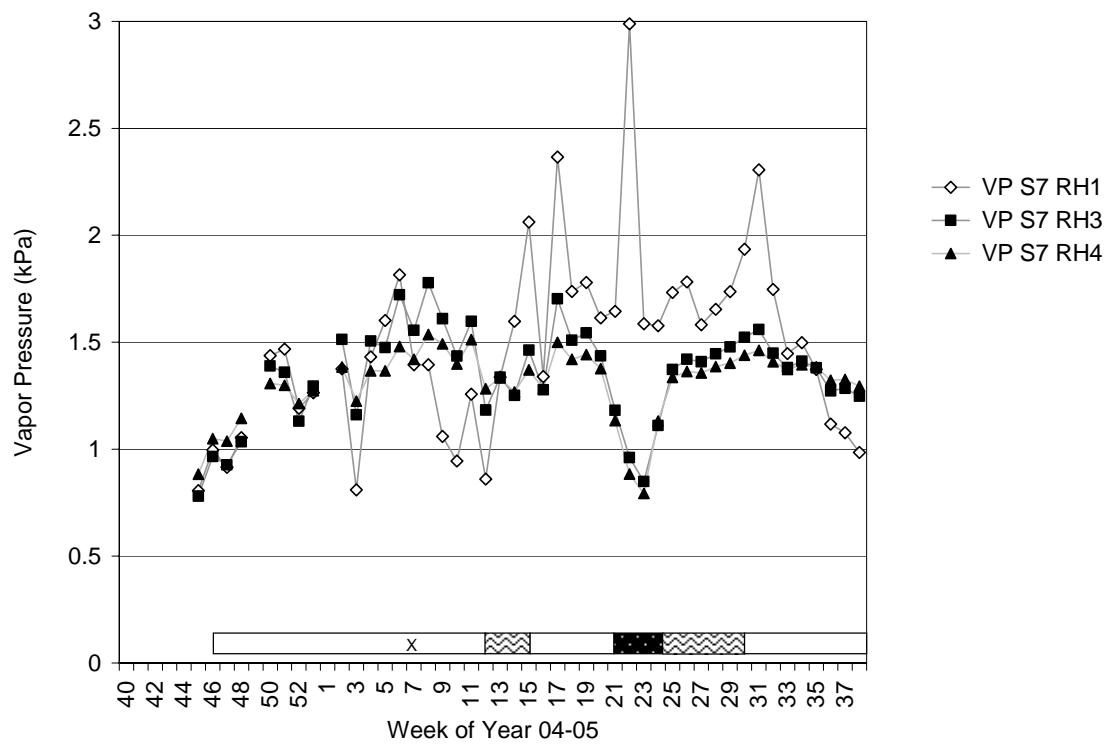


Figure B S8-1 S8 – Wood Moisture Content

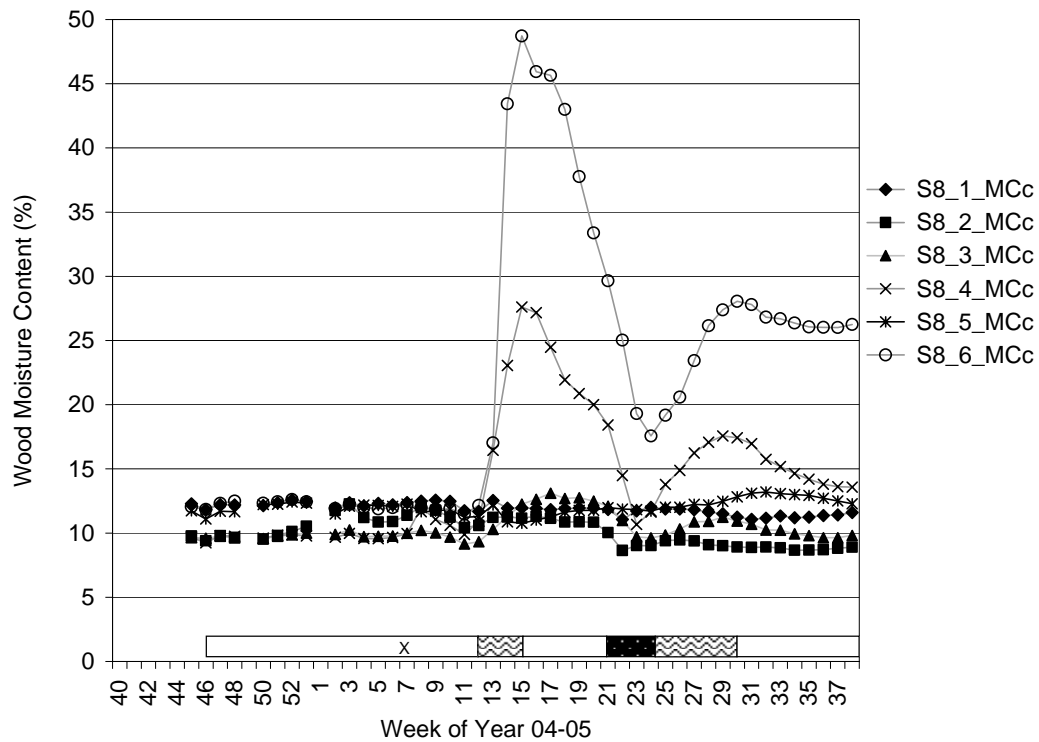


Figure B S8-2 S8 – Cavity Relative Humidity

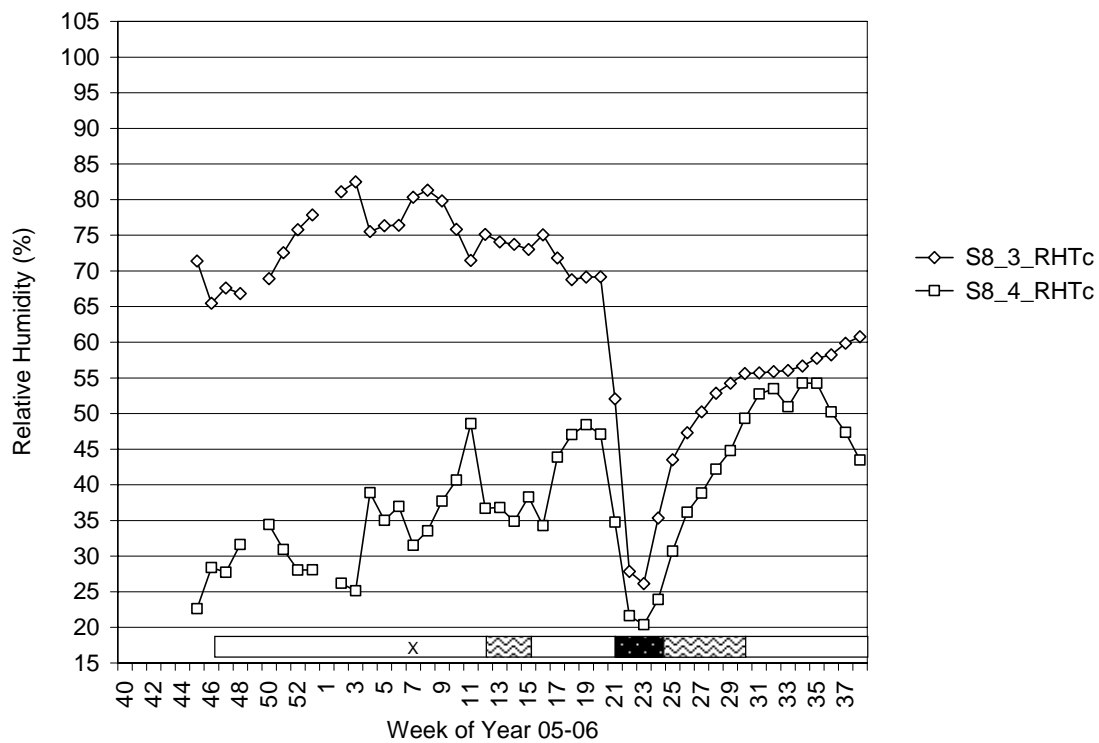


Figure B S8-3 S8 - Temperature

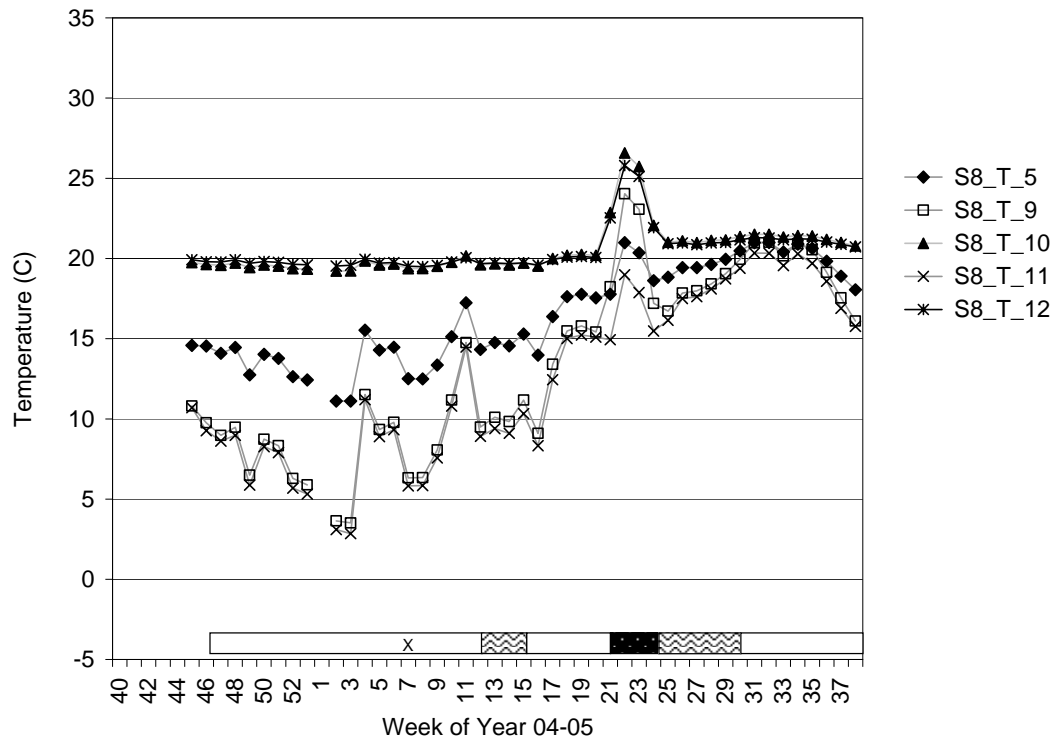


Figure B S8-4 S8 – Vapor Pressure

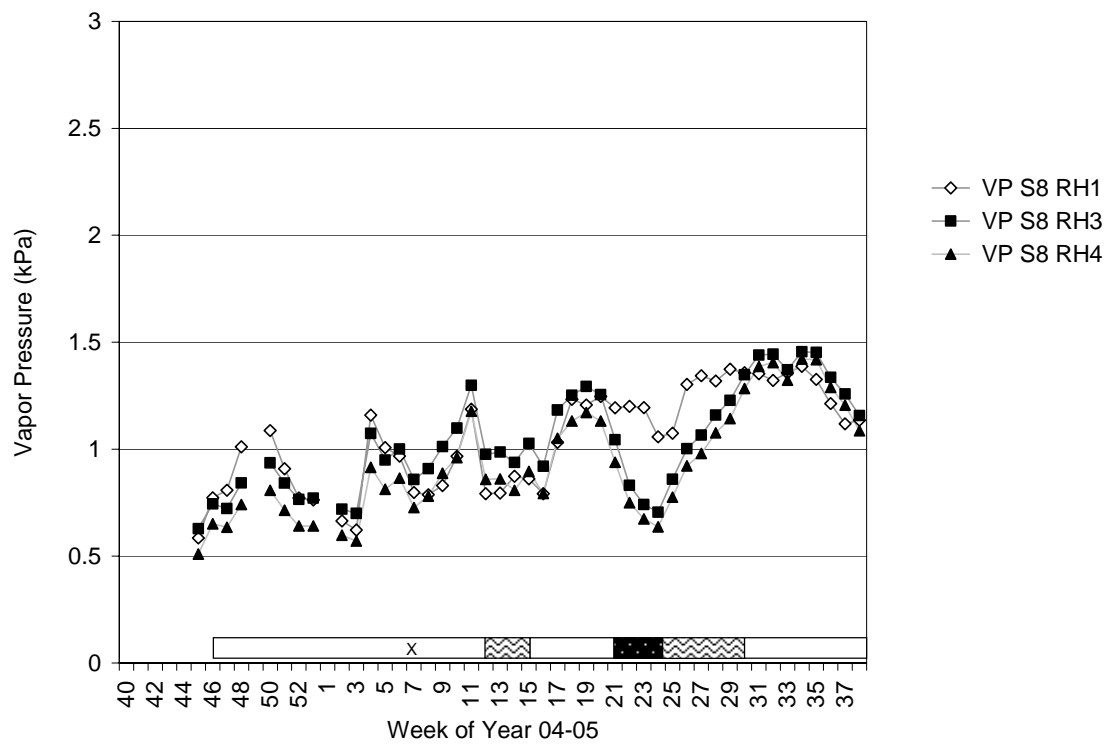


Figure B S8-1 S9 – Wood Moisture Content

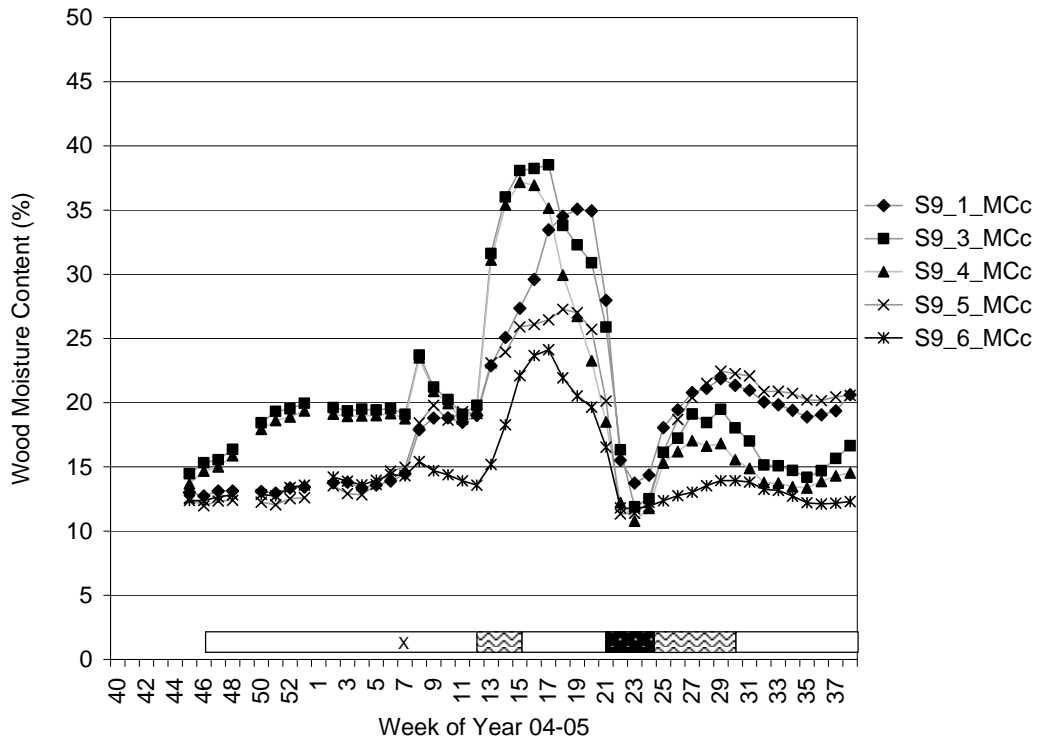


Figure B S9-2 S9 – Cavity Relative Humidity

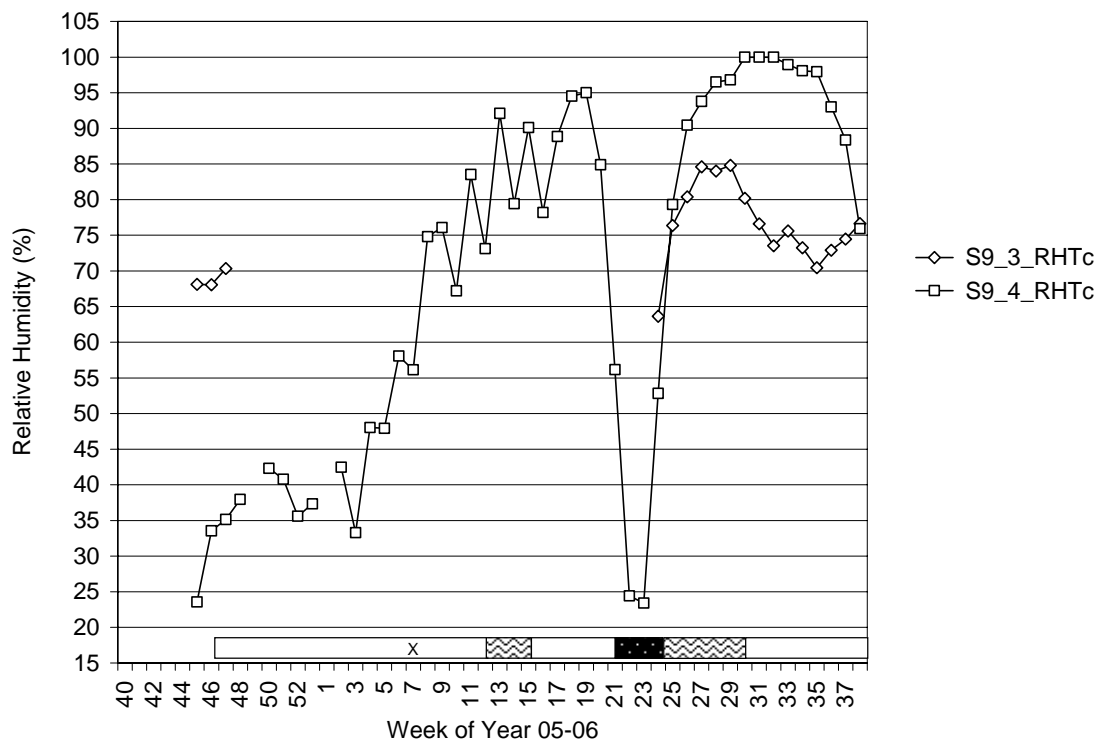


Figure B S9-3 S9 - Temperature

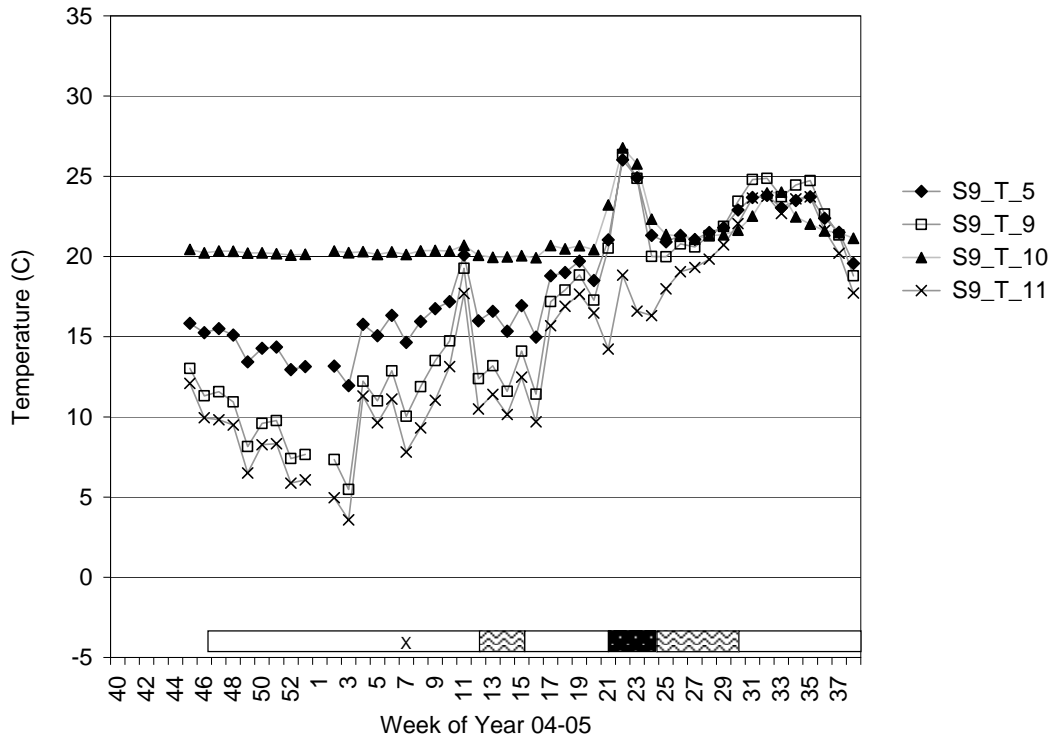


Figure B S9-4 S9 – Vapor Pressure

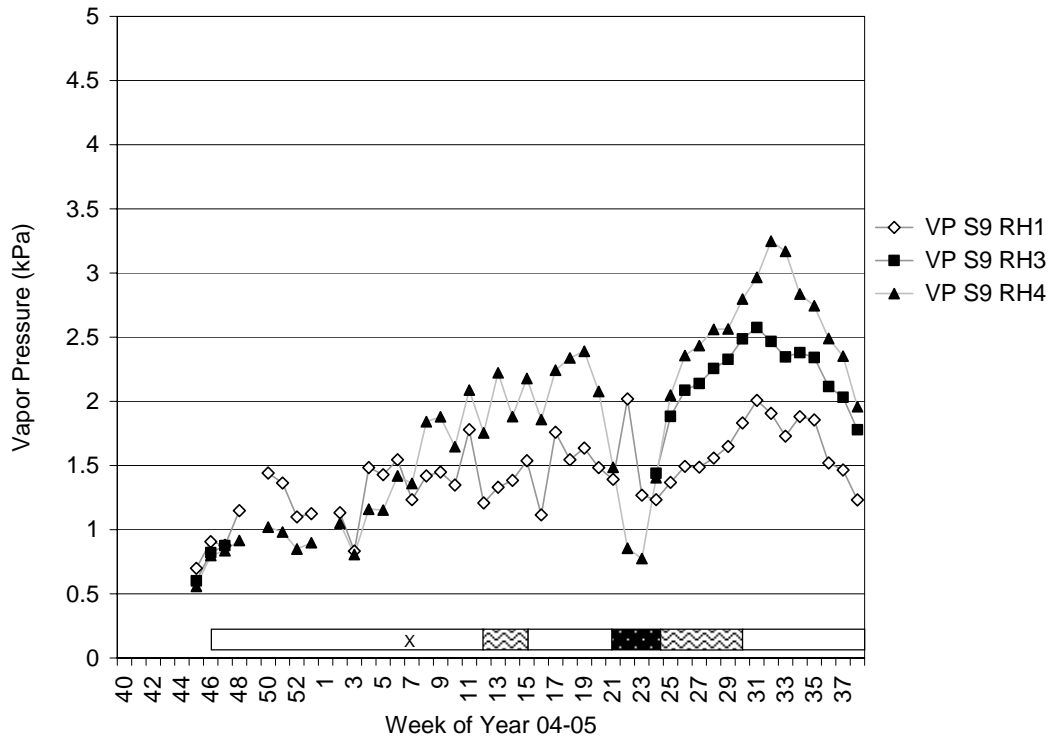


Figure B S9b-1 S9b – Wood Moisture Content

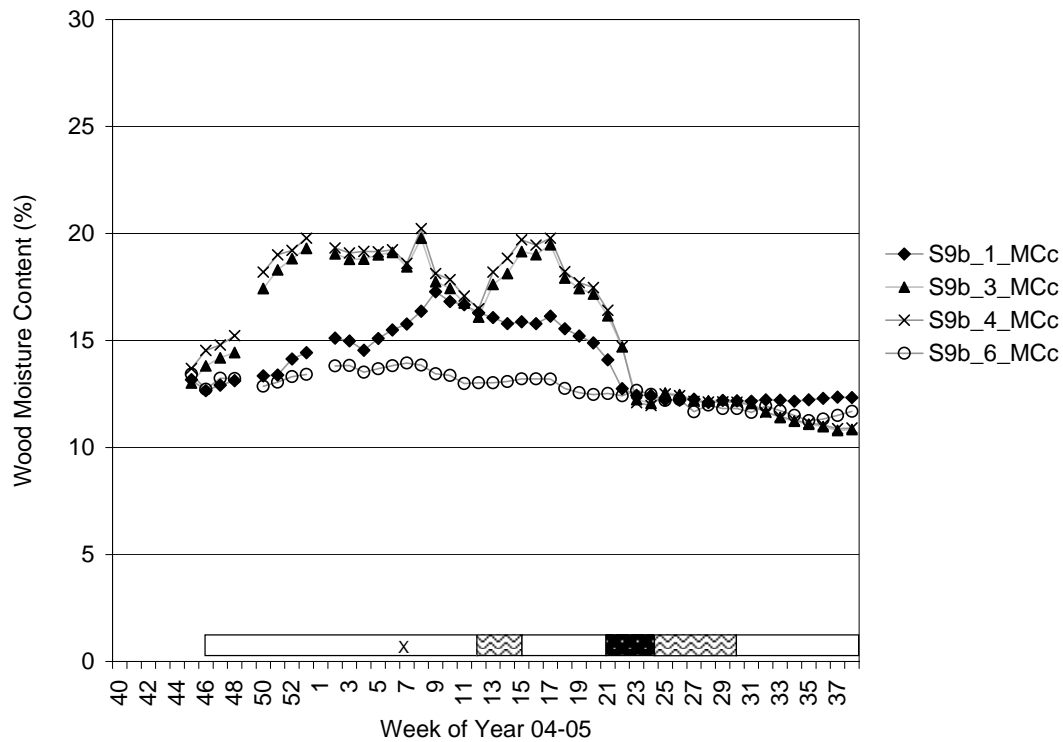


Figure B S9b-2 S9b – Cavity Relative Humidity

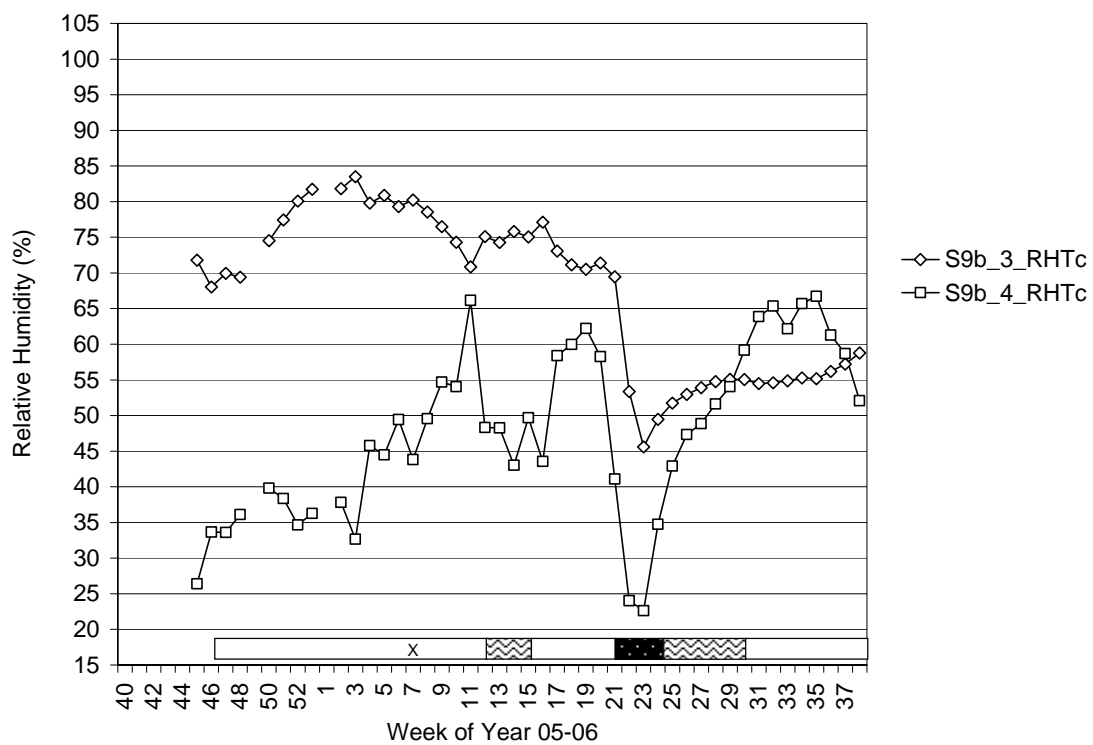


Figure B S9b-3 S9b - Temperature

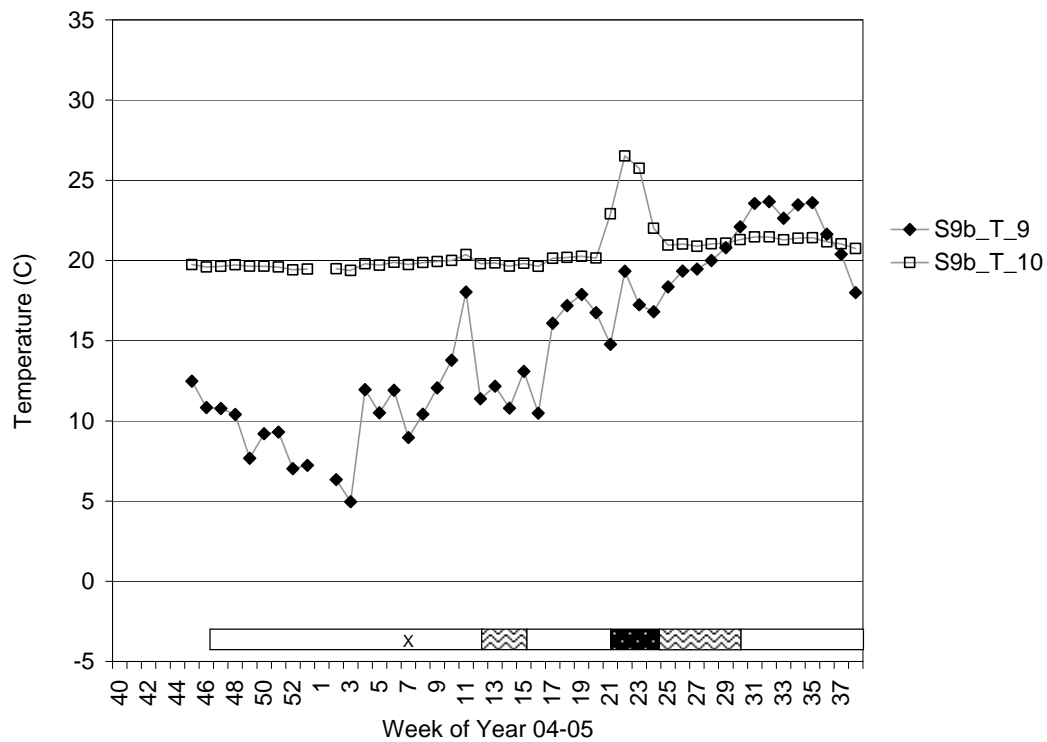
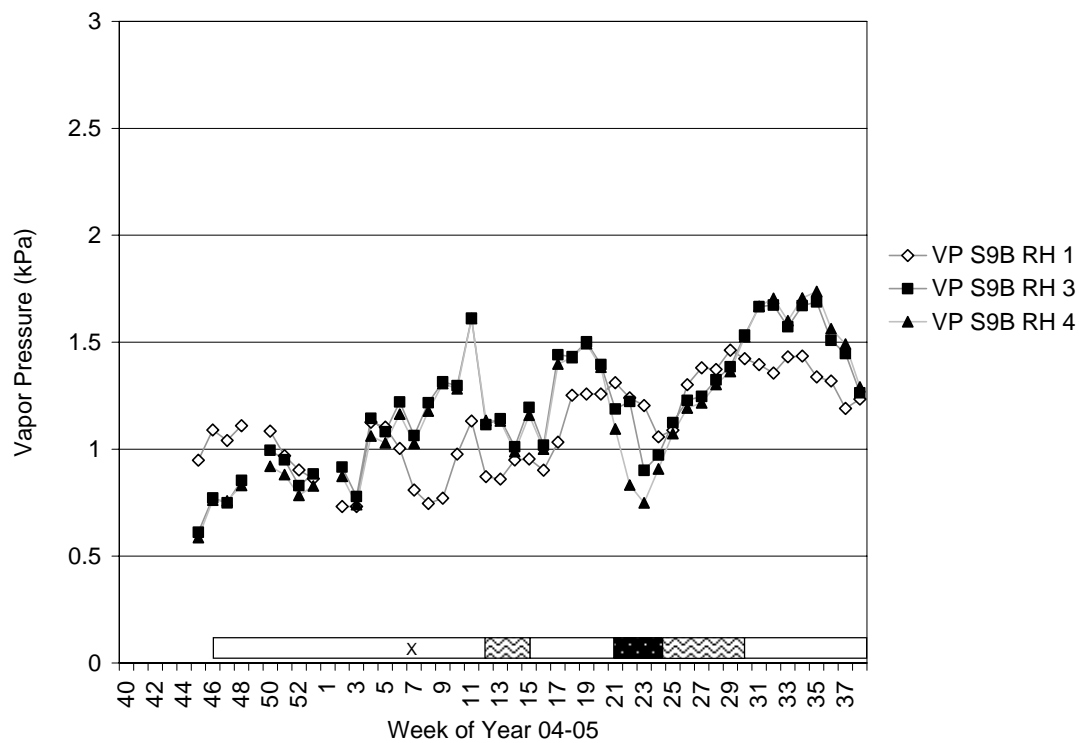
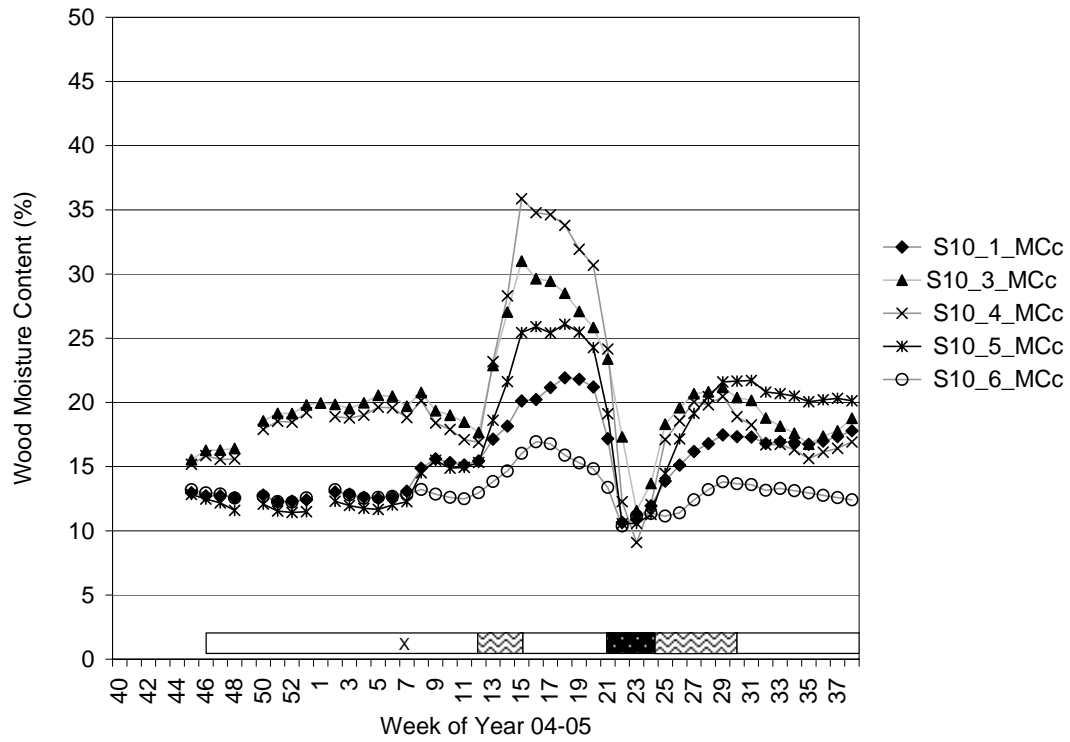


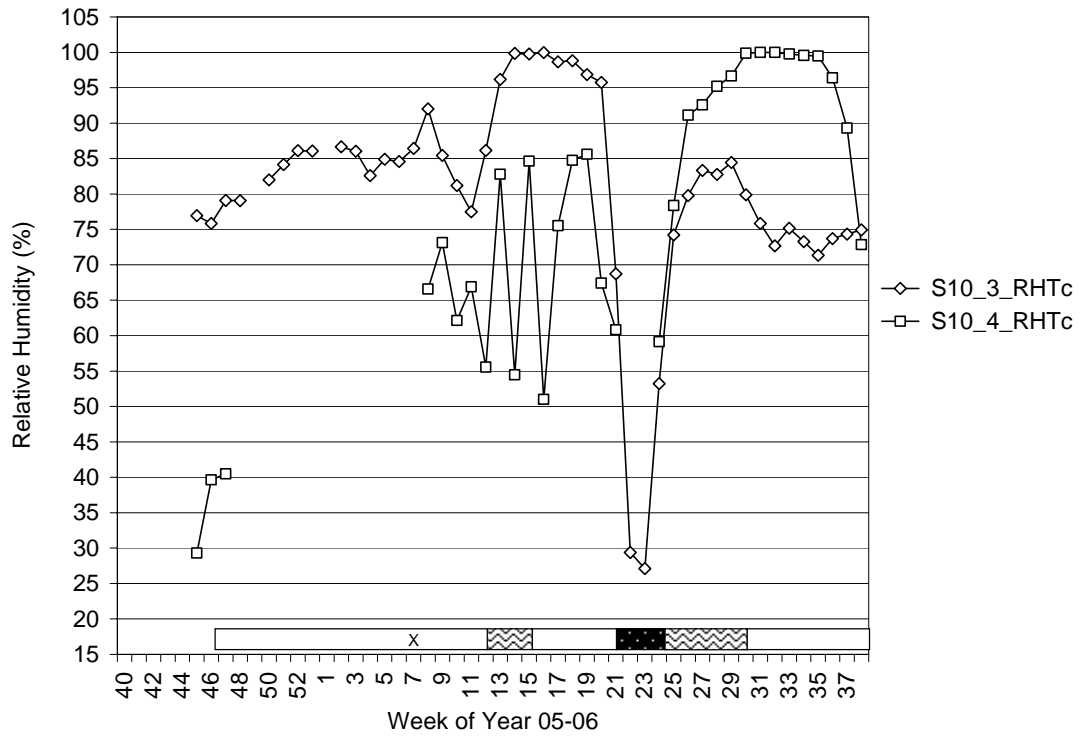
Figure B S9b-4 S9b – Vapor Pressure



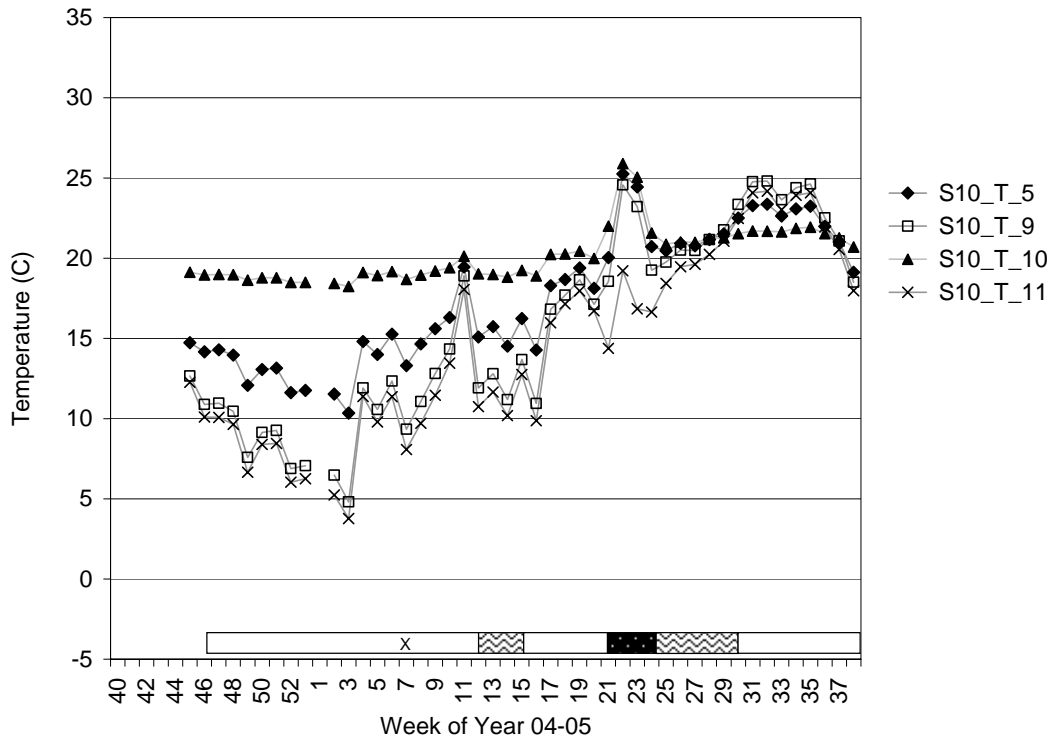
**Figure B S10-1 S10 – Wood Moisture Content**



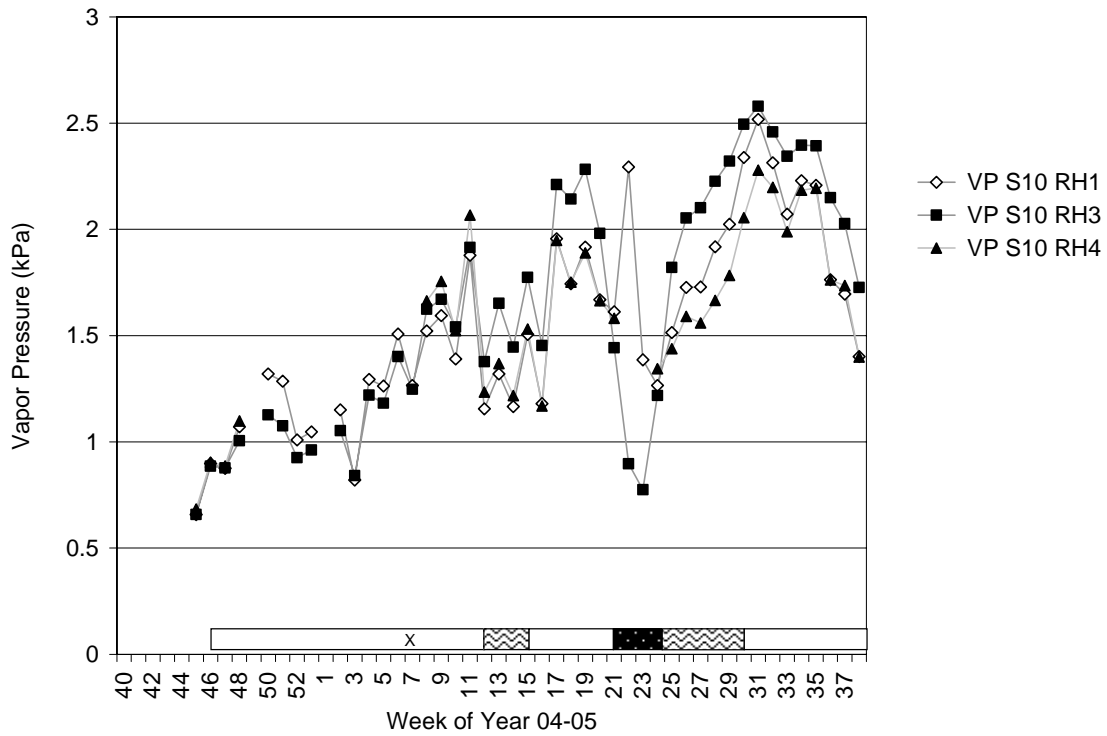
**Figure B S10-2 S10 – Cavity Relative Humidity**



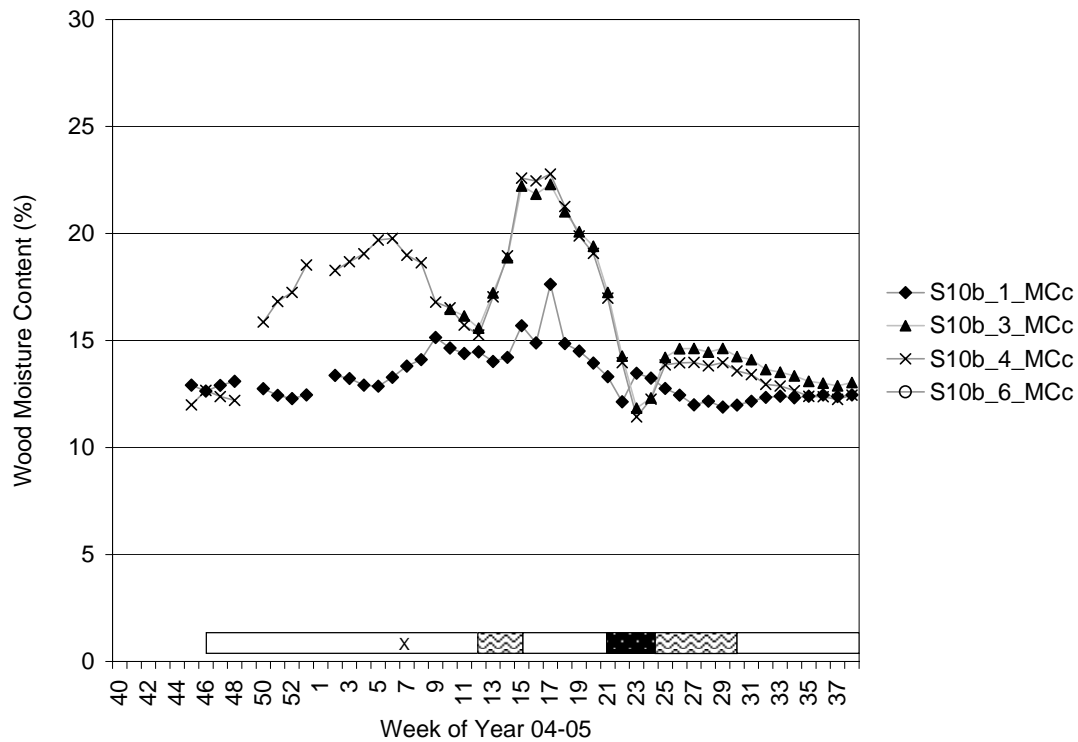
**Figure B S10-3 S10 - Temperature**



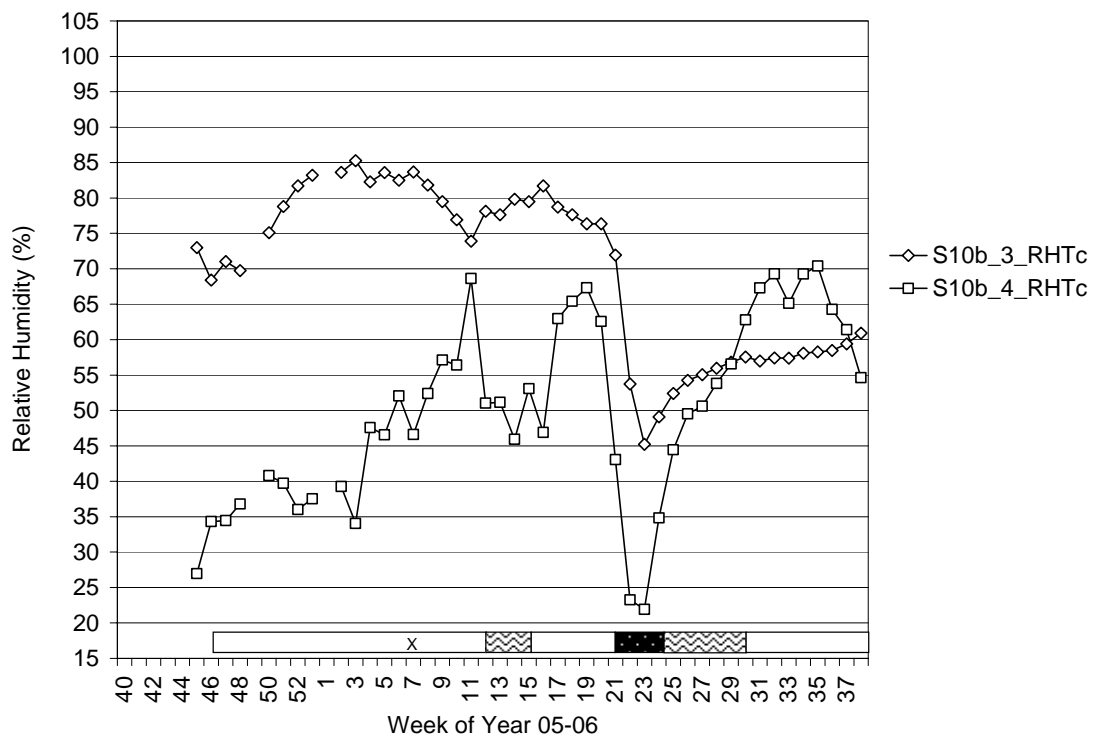
**Figure B S10-4 S10 - Vapor Pressure**



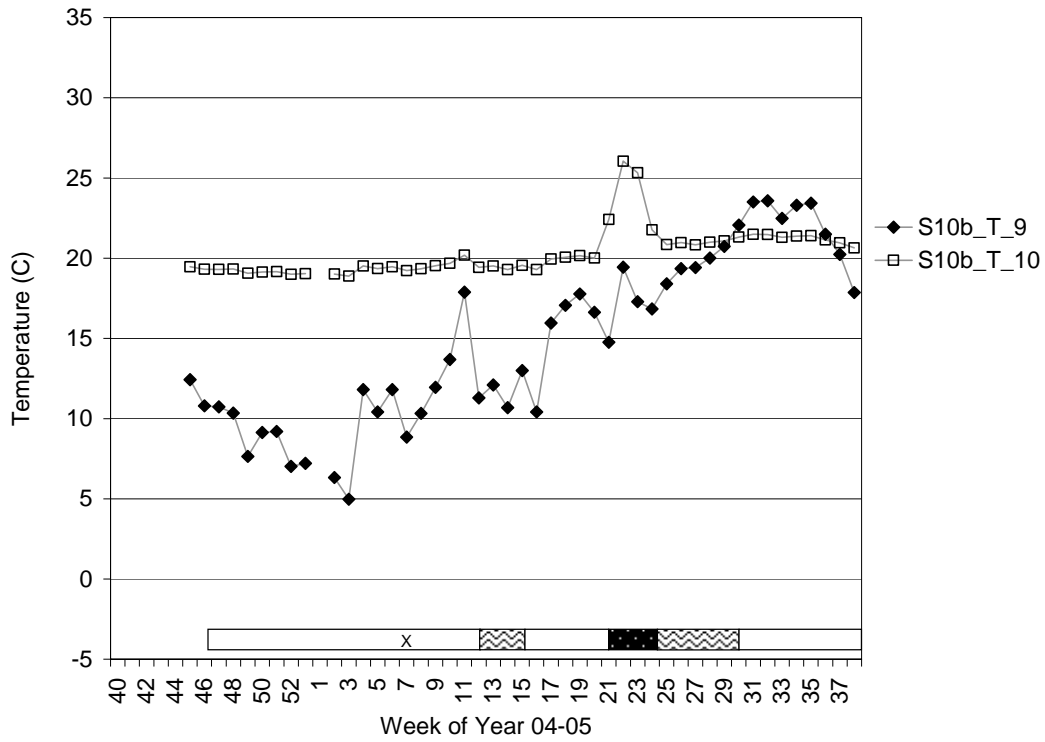
**Figure B S10b-1 S10b – Wood Moisture Content**



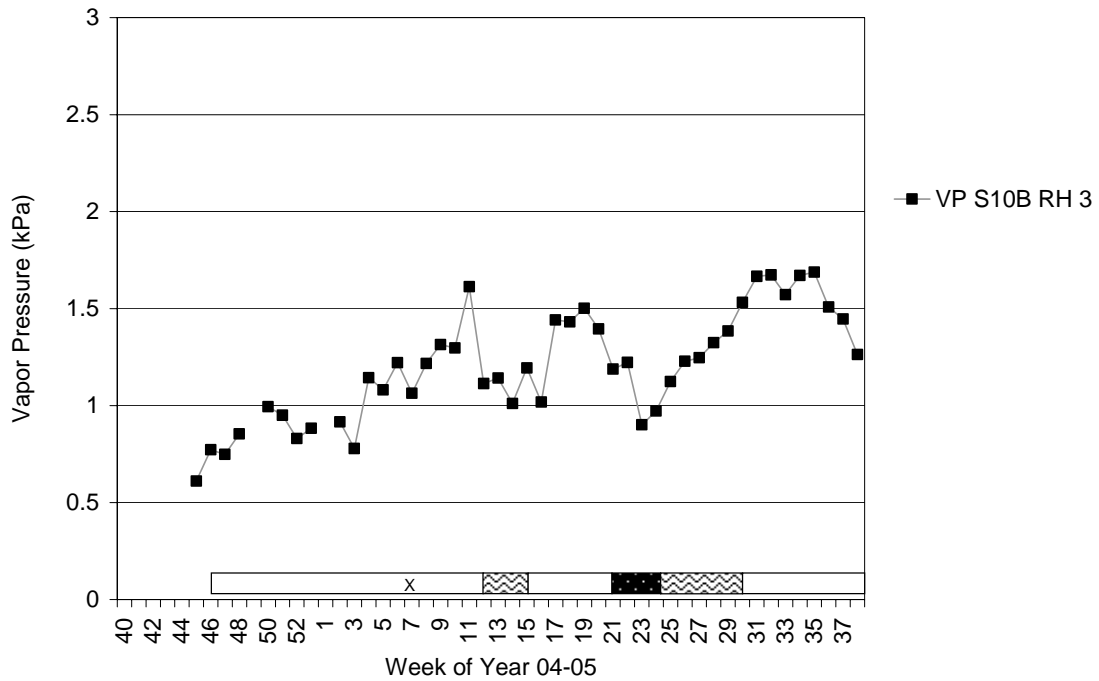
**Figure B S10b-2 S10b – Cavity Relative Humidity**



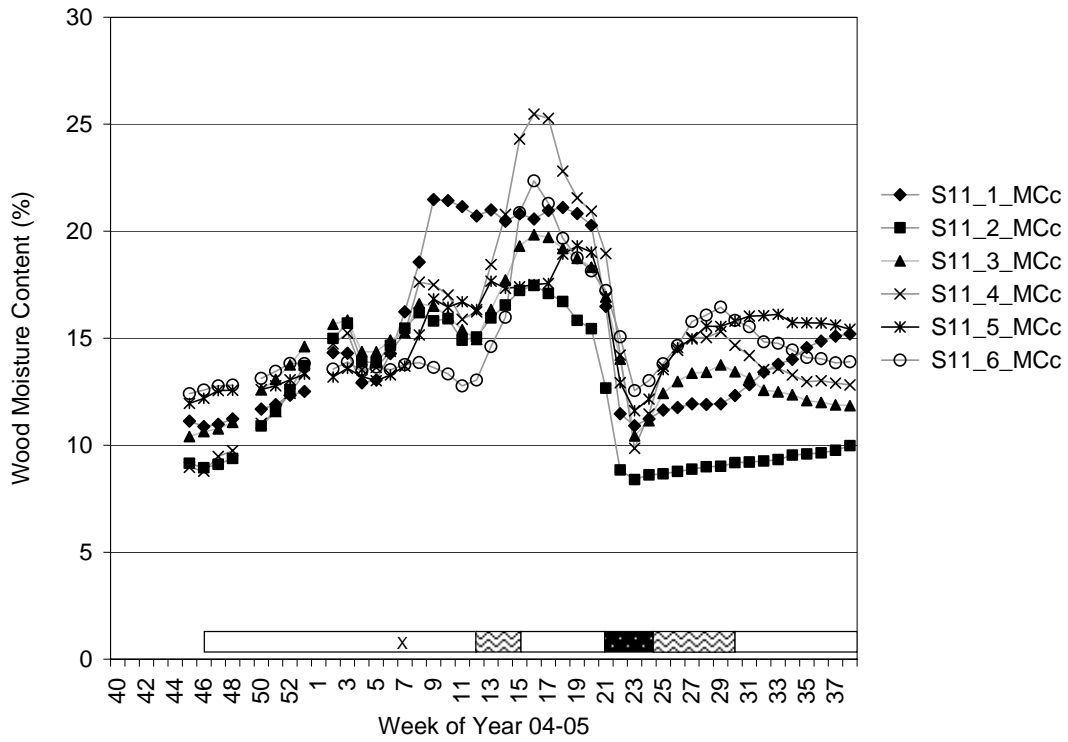
**Figure B S10b-3 S10b - Temperature**



**Figure B S10b-4 S10b – Vapor Pressure**



**Figure B S11-1 S11 – Wood Moisture Content**



**Figure B S11-2 S11 – Cavity Relative Humidity**



Figure B S11-3

S11 - Temperature

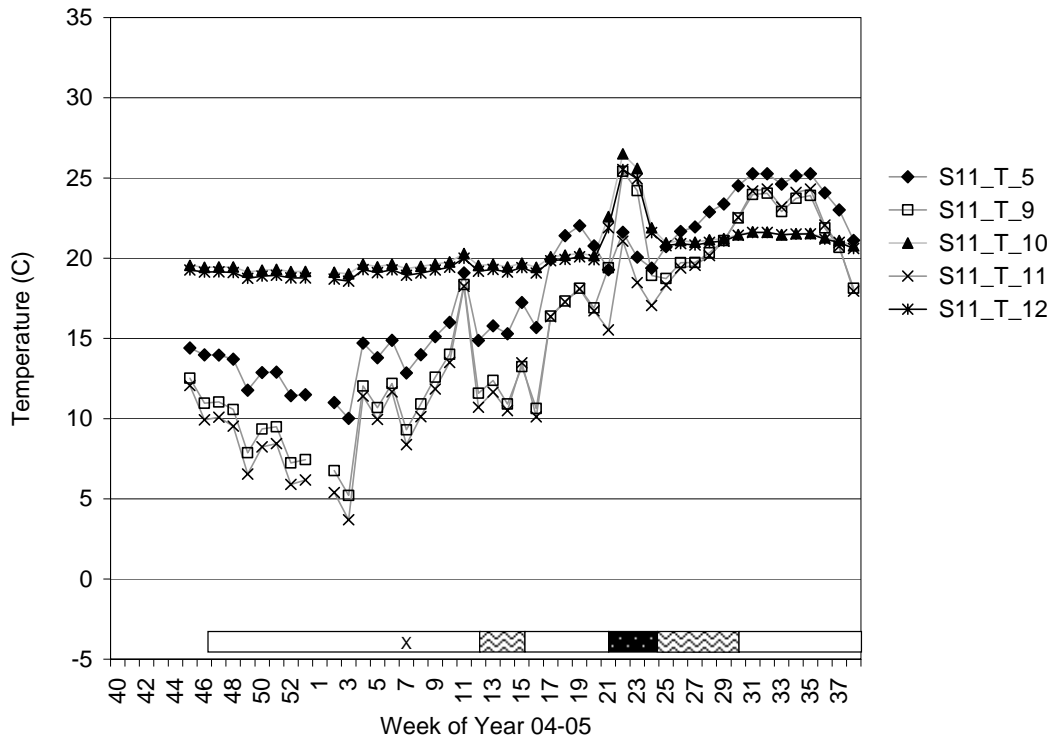


Figure B S11-4

S11 - Vapor Pressure

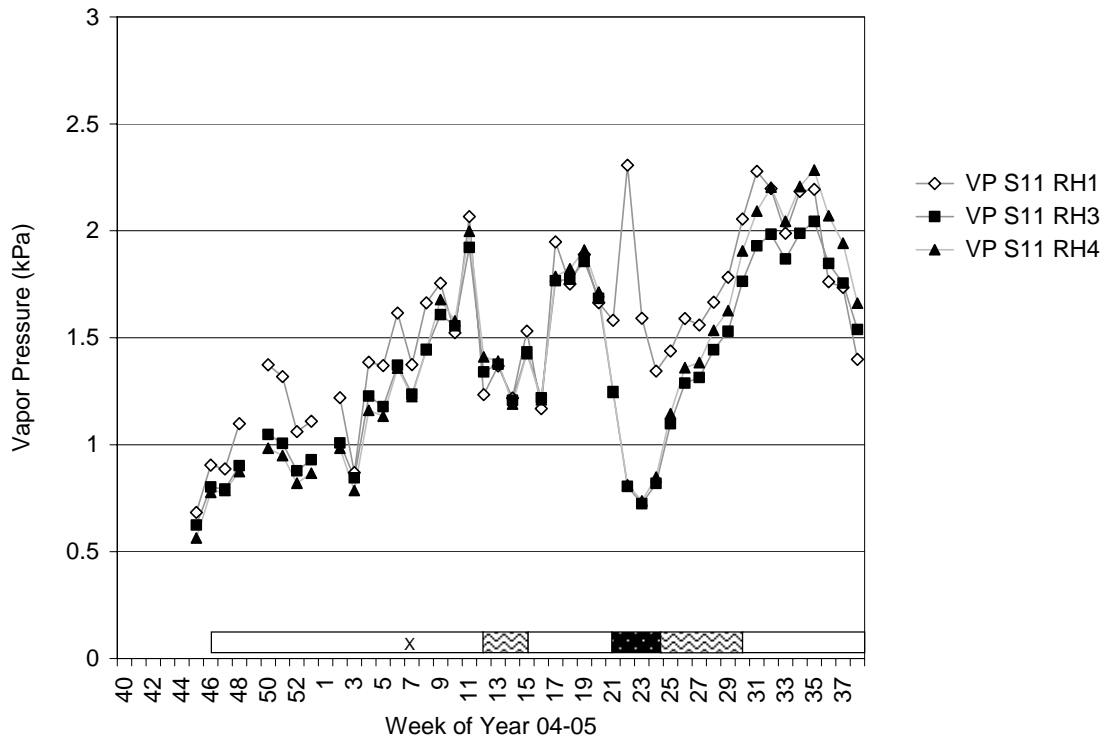


Figure B S12-1

S12 - Wood Moisture Content

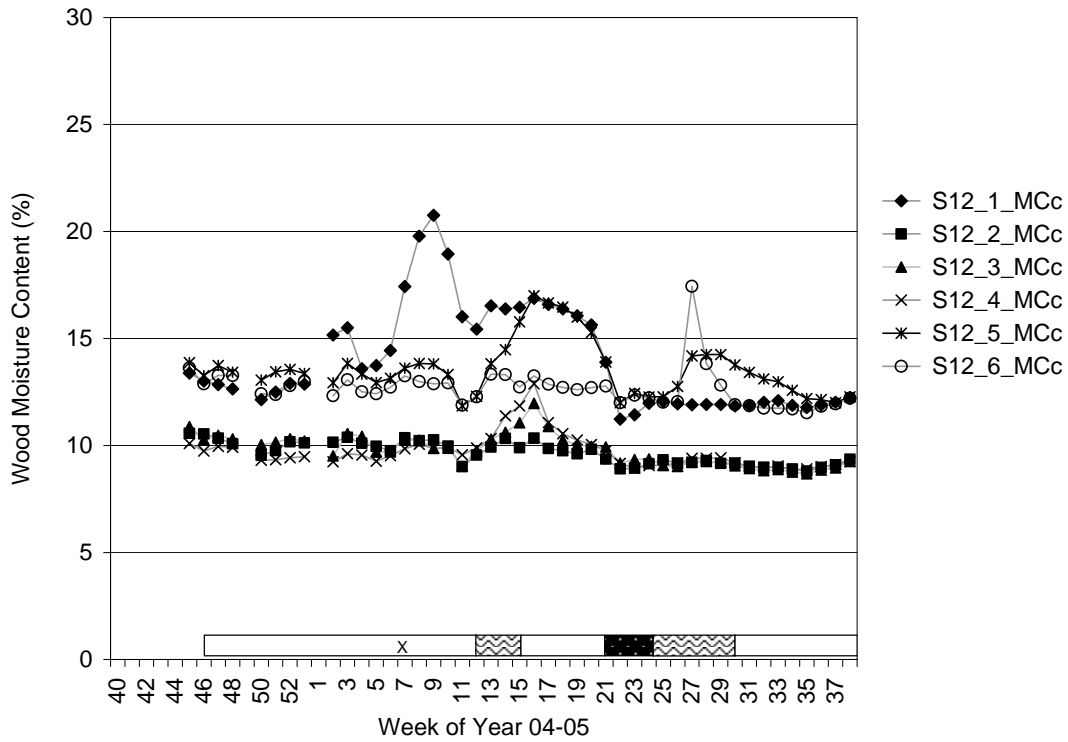


Figure B S12-2 S12 – Cavity Relative Humidity



Figure B S12-3 S12 - Temperature

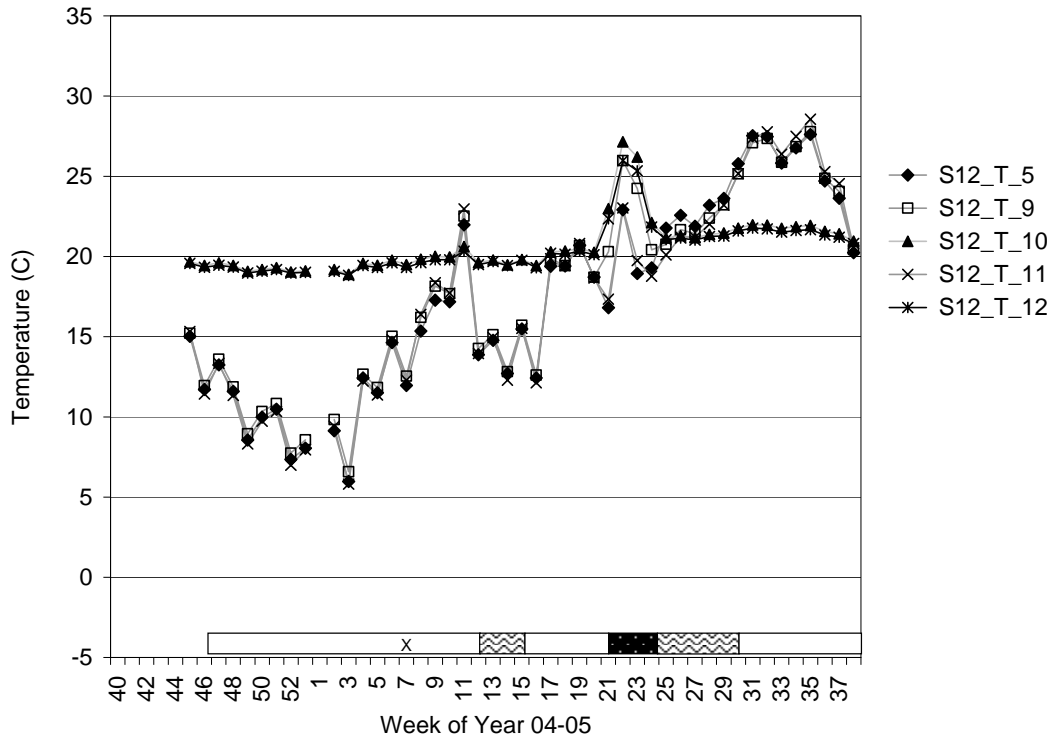


Figure B S12-4 12 – Vapor Pressure

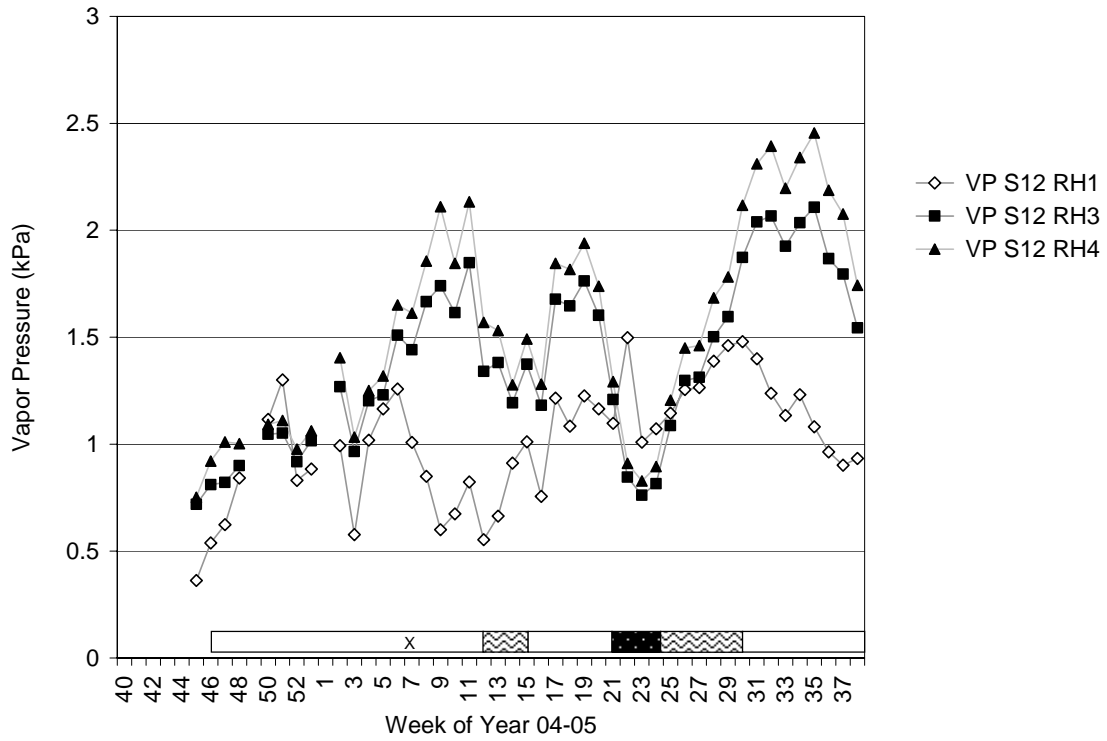


Figure B N3-1 N3 – Wood Moisture Content

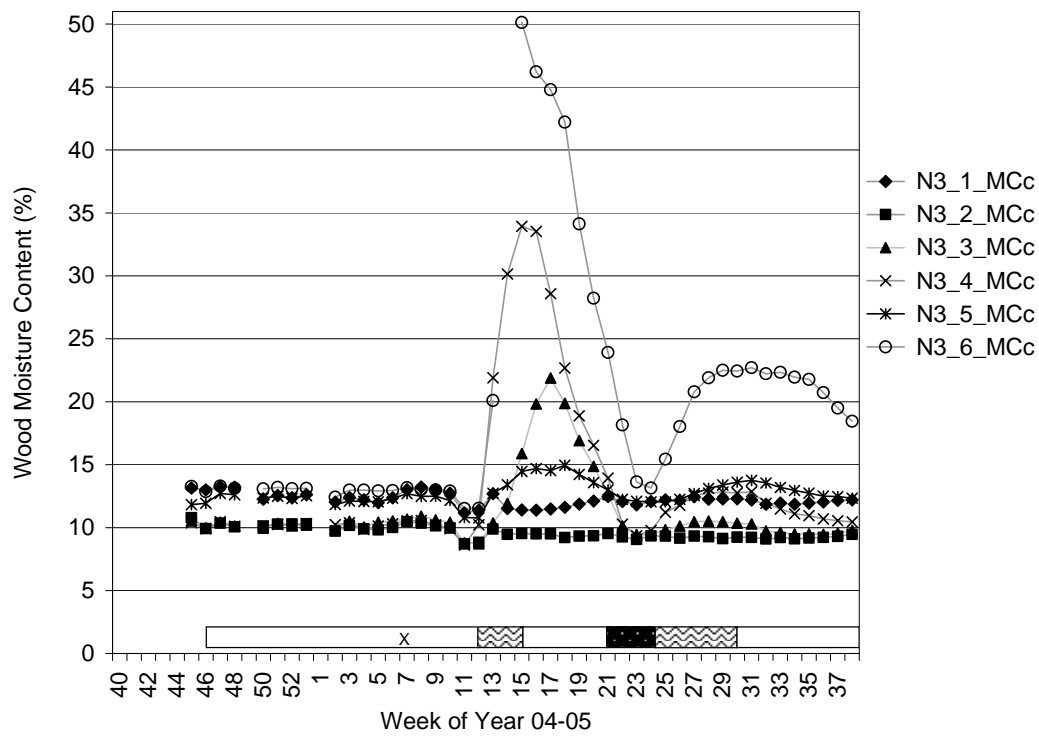


Figure B N3-2 N3 – Cavity Relative Humidity



Figure B N3-3 N3 - Temperature

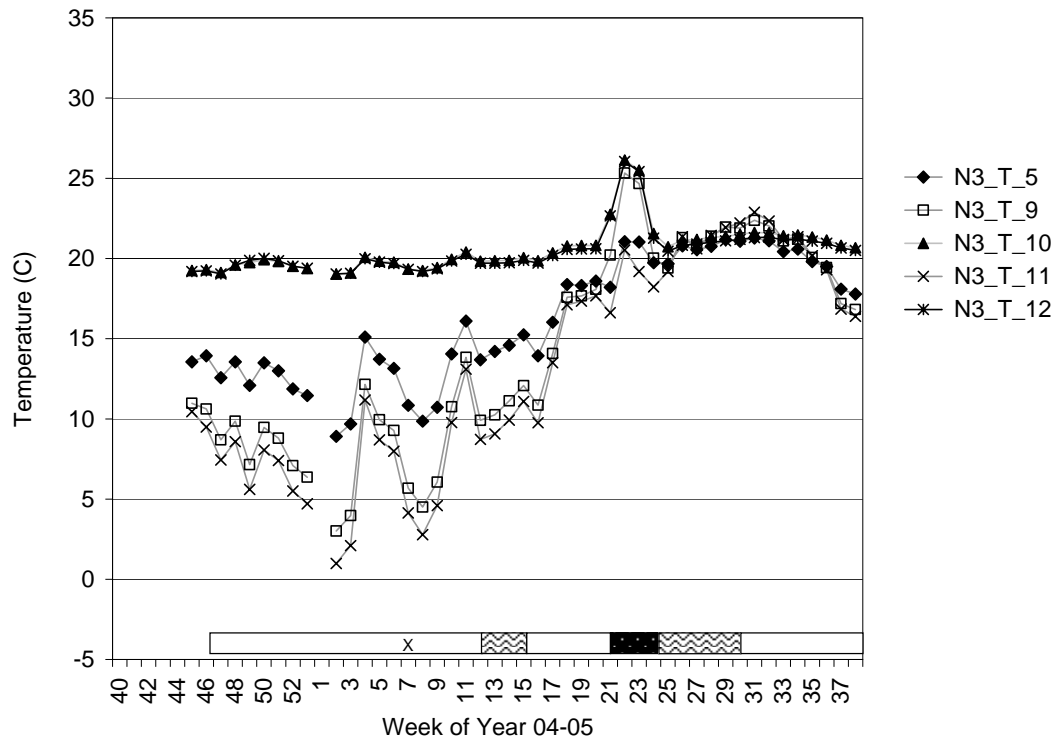


Figure B N3-4 N3 – Vapor Pressure

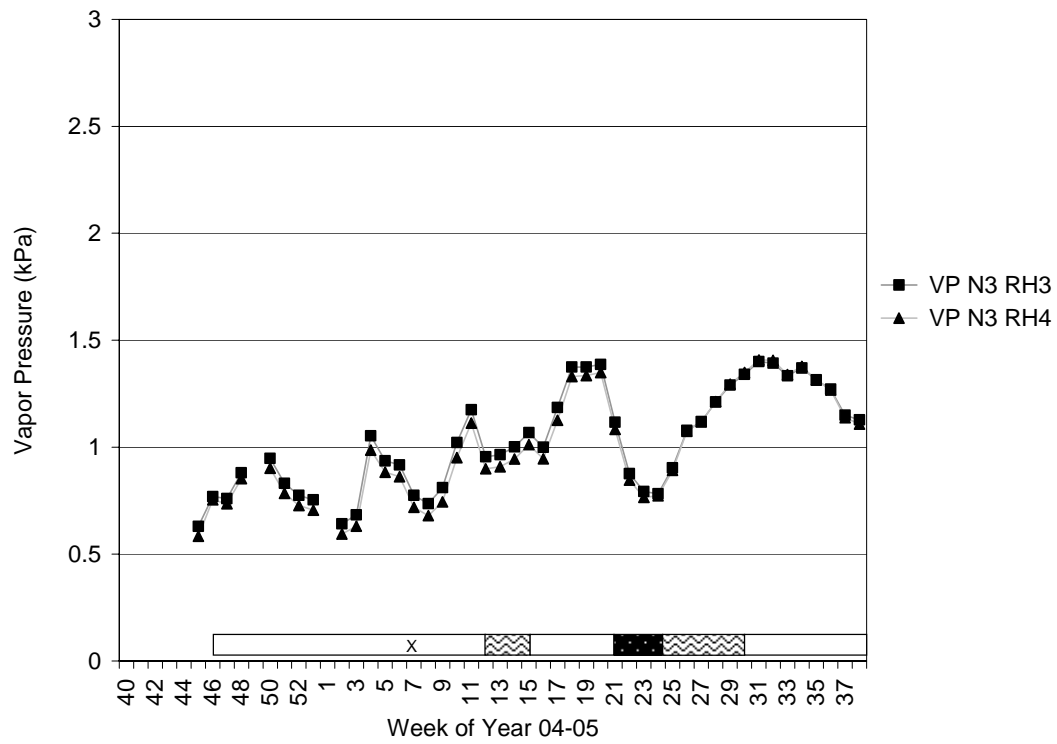


Figure B N4-1 N4 – Wood Moisture Content

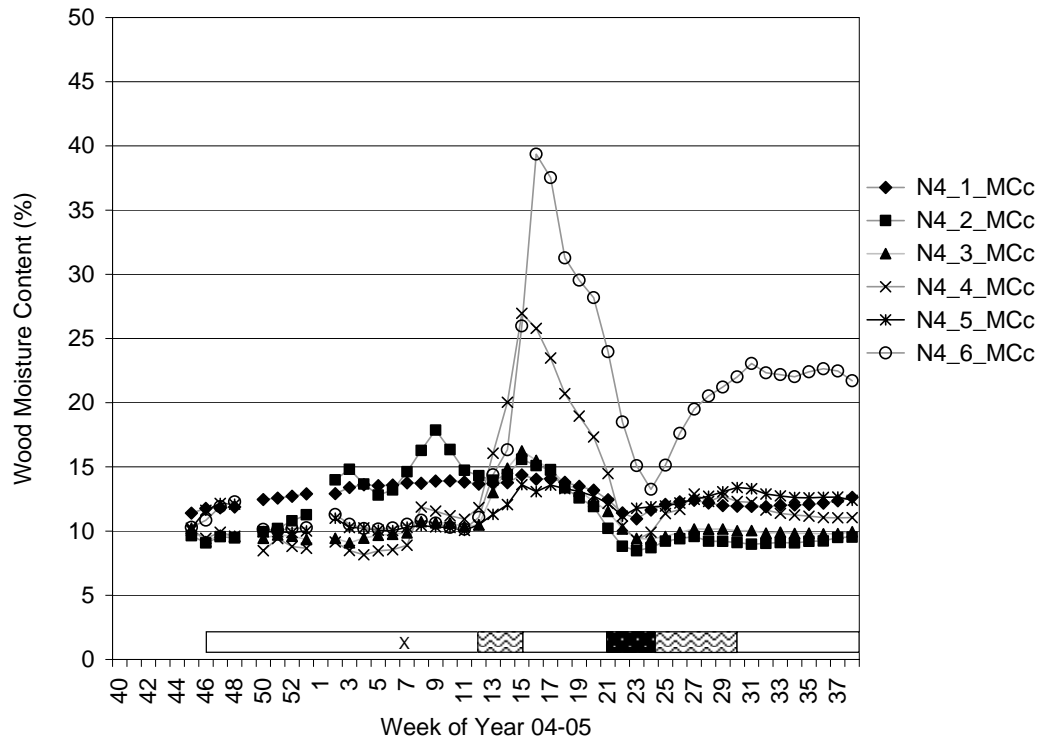


Figure B N4-2 N4 – Cavity Relative Humidity

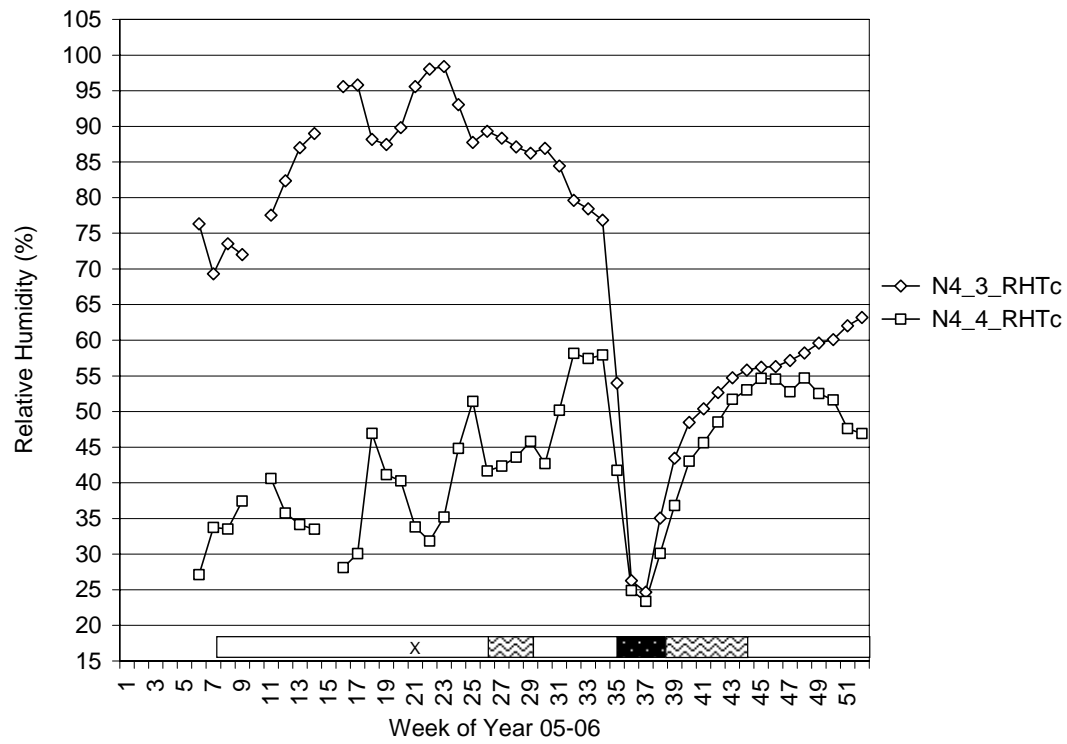


Figure B N4-3 N4 - Temperature

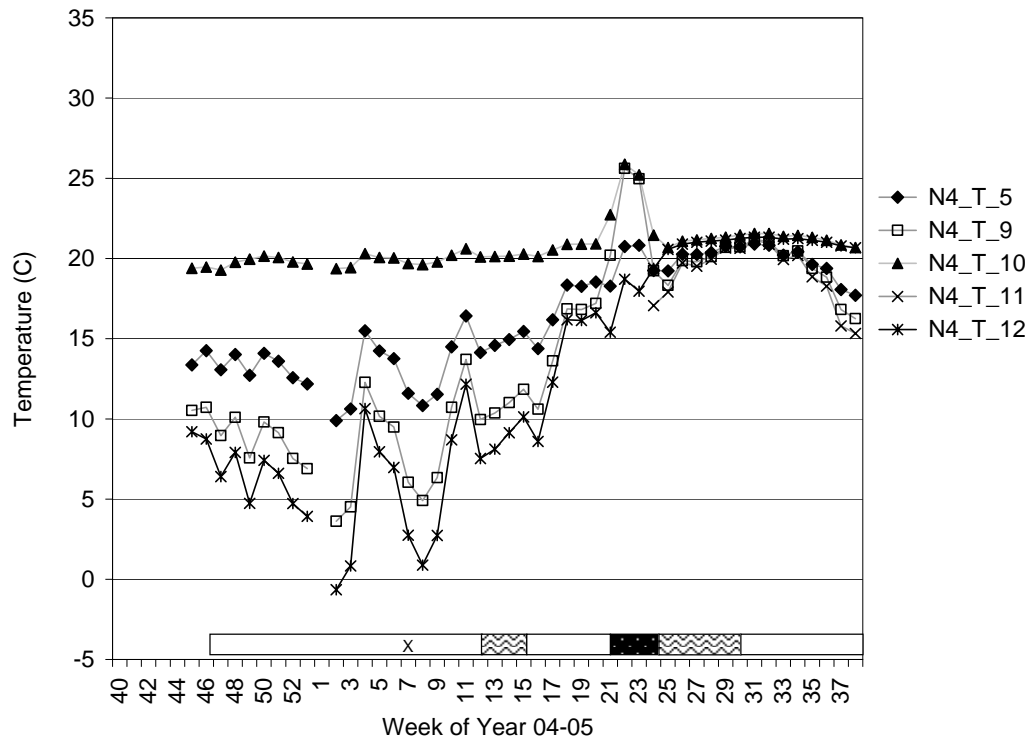


Figure B N4-4 N4 – Vapor Pressure

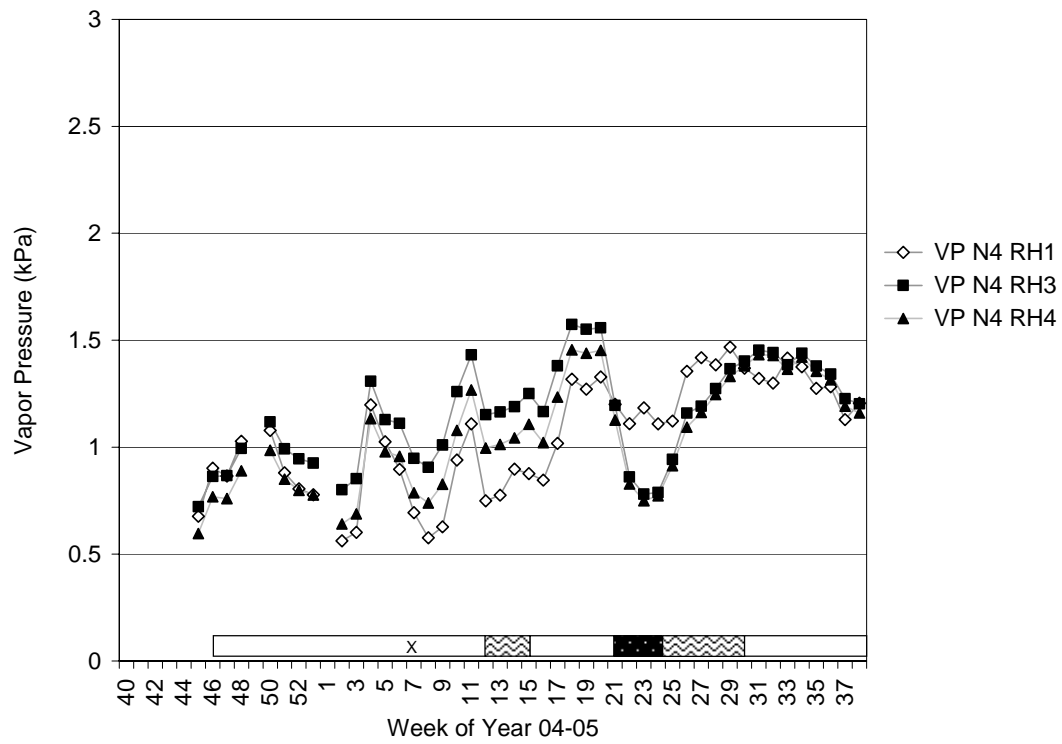


Figure B N5-1 N5 – Wood Moisture Content

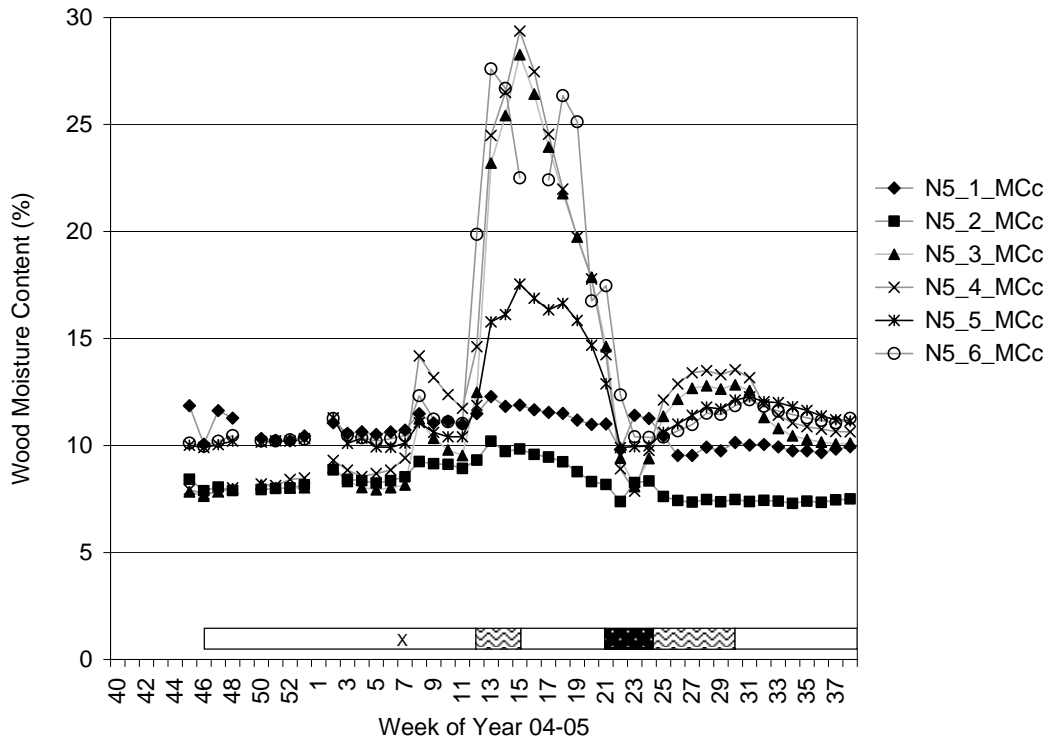


Figure B N5-2 N5 – Cavity Relative Humidity

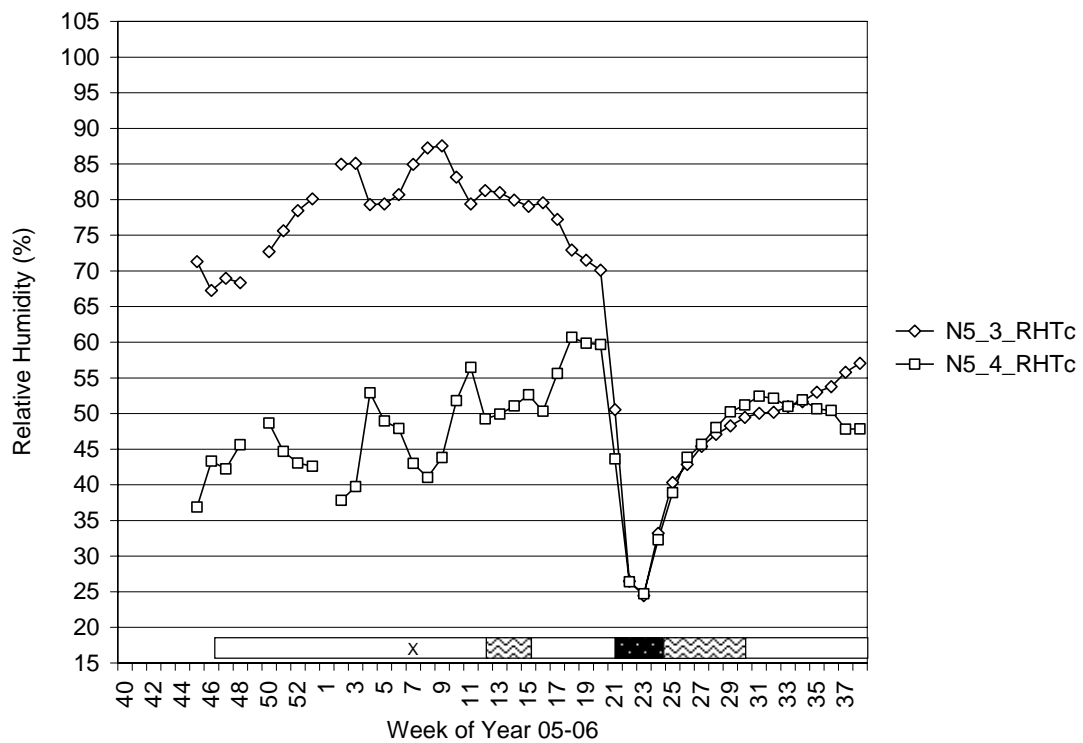


Figure B N5-3 N5 - Temperature

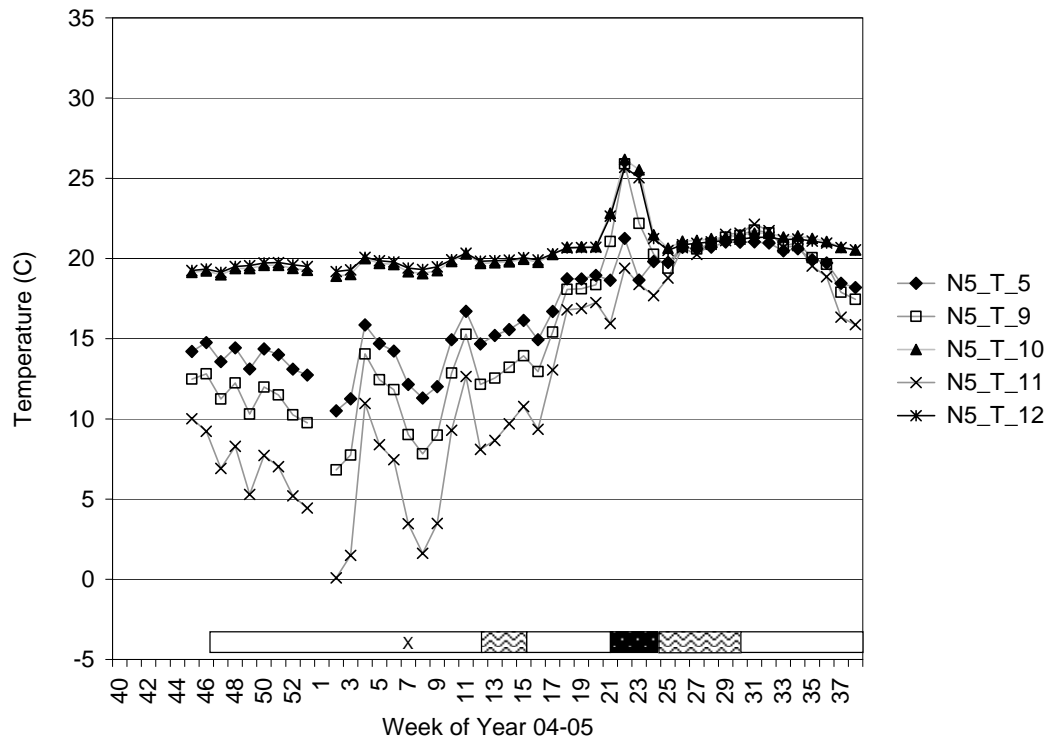


Figure B N5-4 N5 – Vapor Pressure

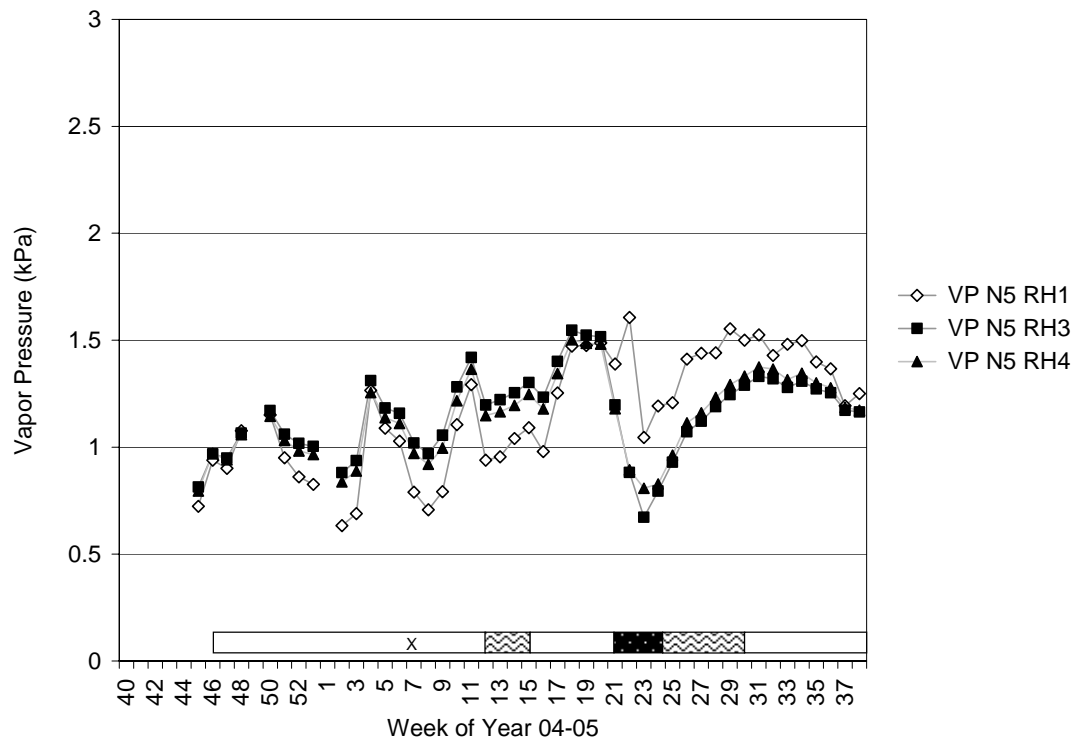


Figure B N6-1 N6 – Wood Moisture Content

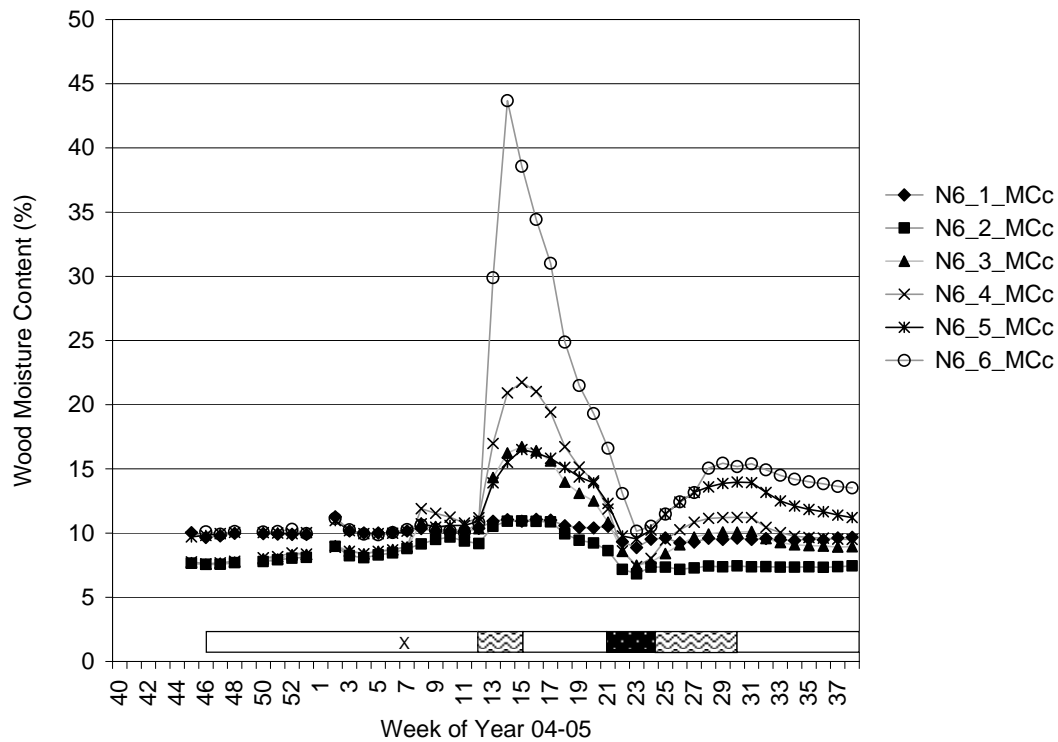


Figure B N6-2 N6 – Cavity Relative Humidity

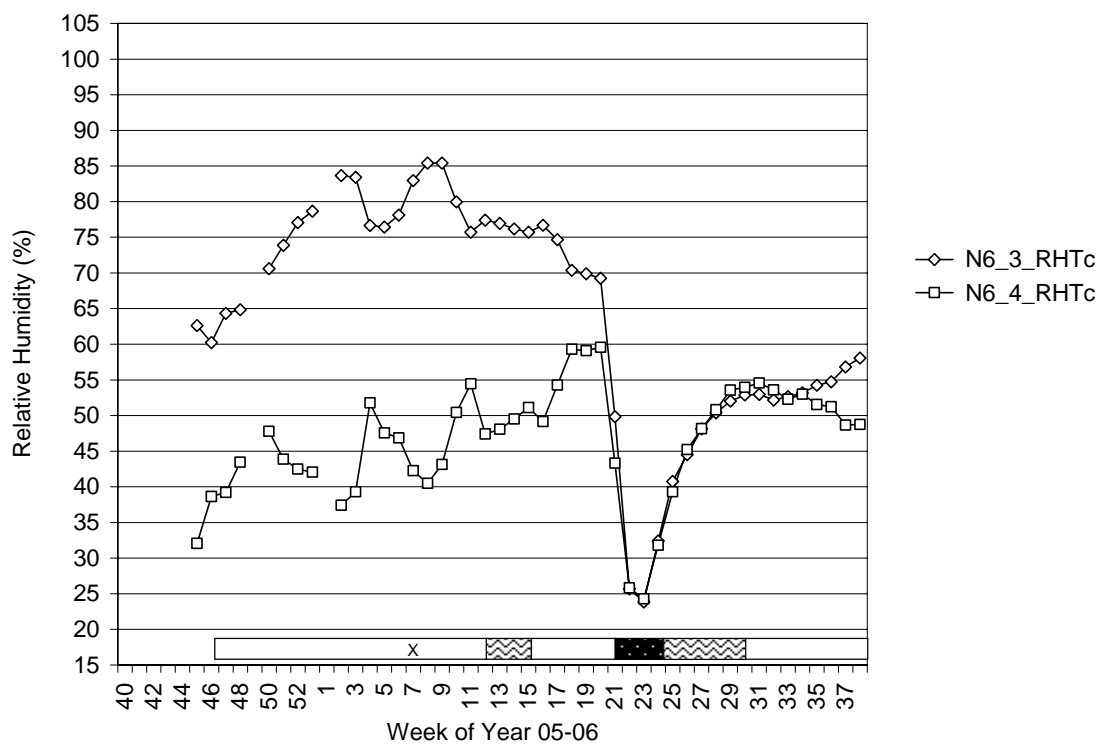


Figure B N6-3 N6 - Temperature

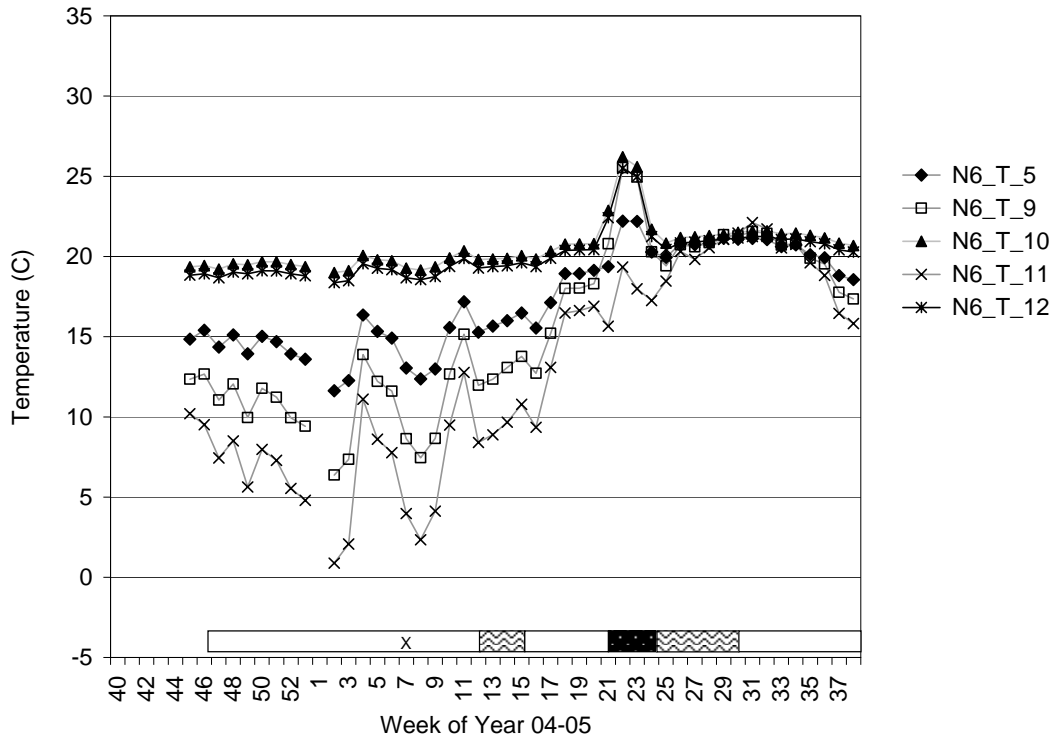


Figure B N6-4 N6 – Vapor Pressure

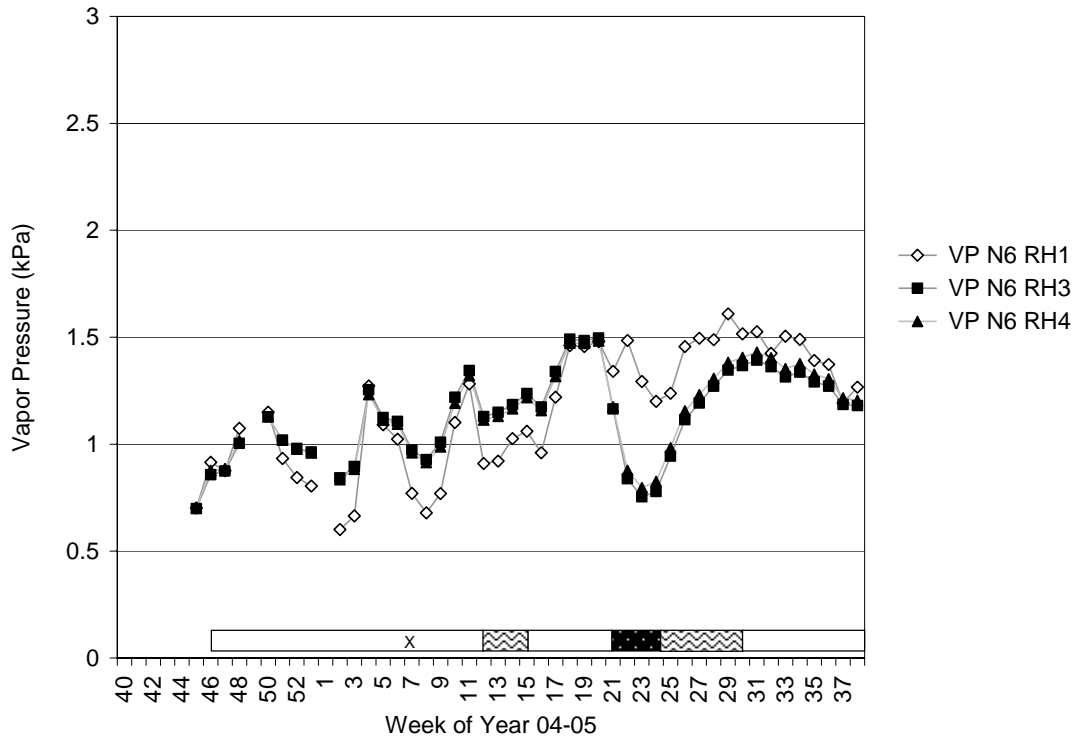


Figure B N7-1 N7 – Wood Moisture Content

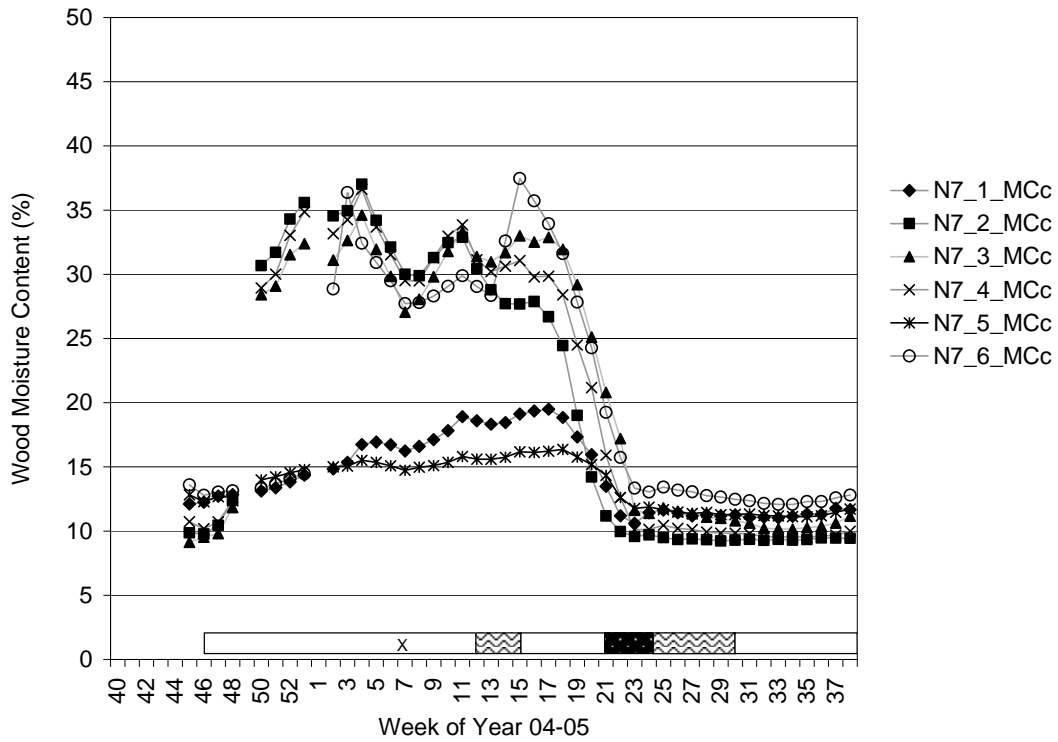


Figure B N7-2 N7 – Cavity Relative Humidity

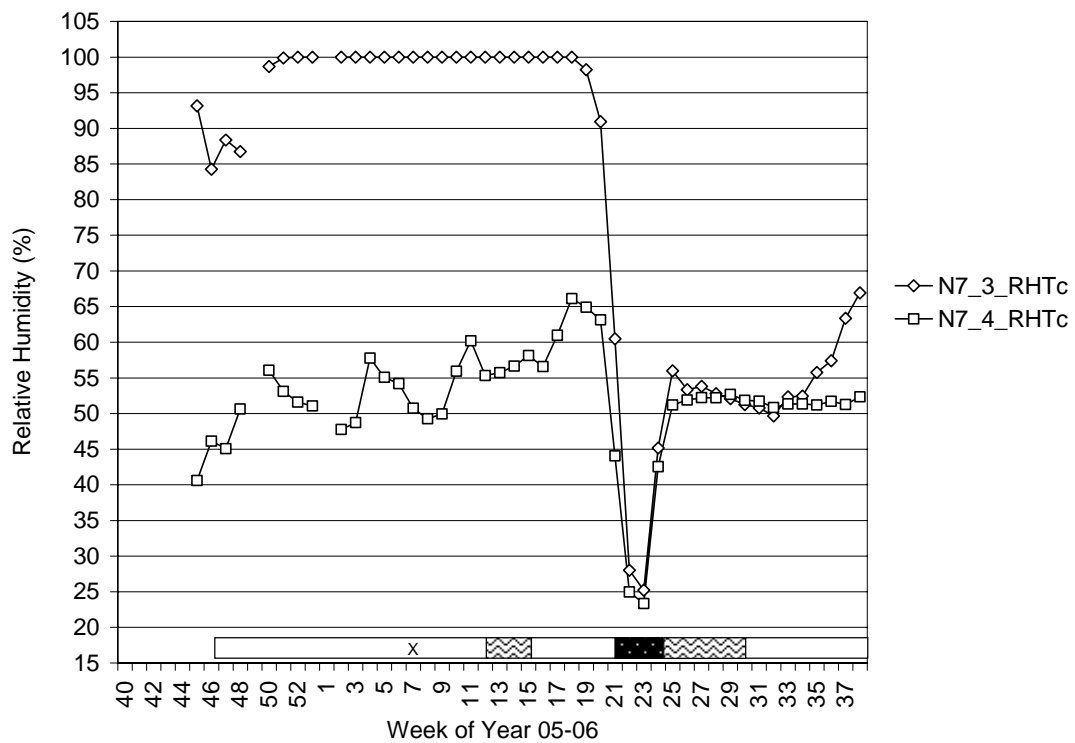


Figure B N7-3 N7 - Temperature

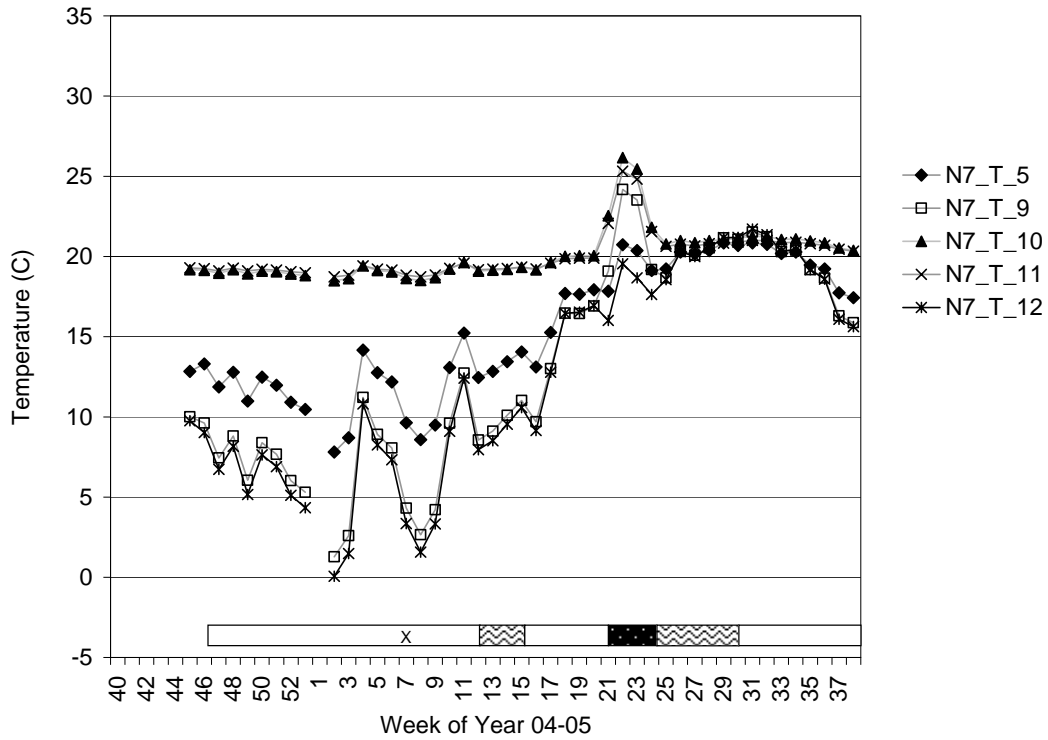


Figure B N7-4 N7 – Vapor Pressure

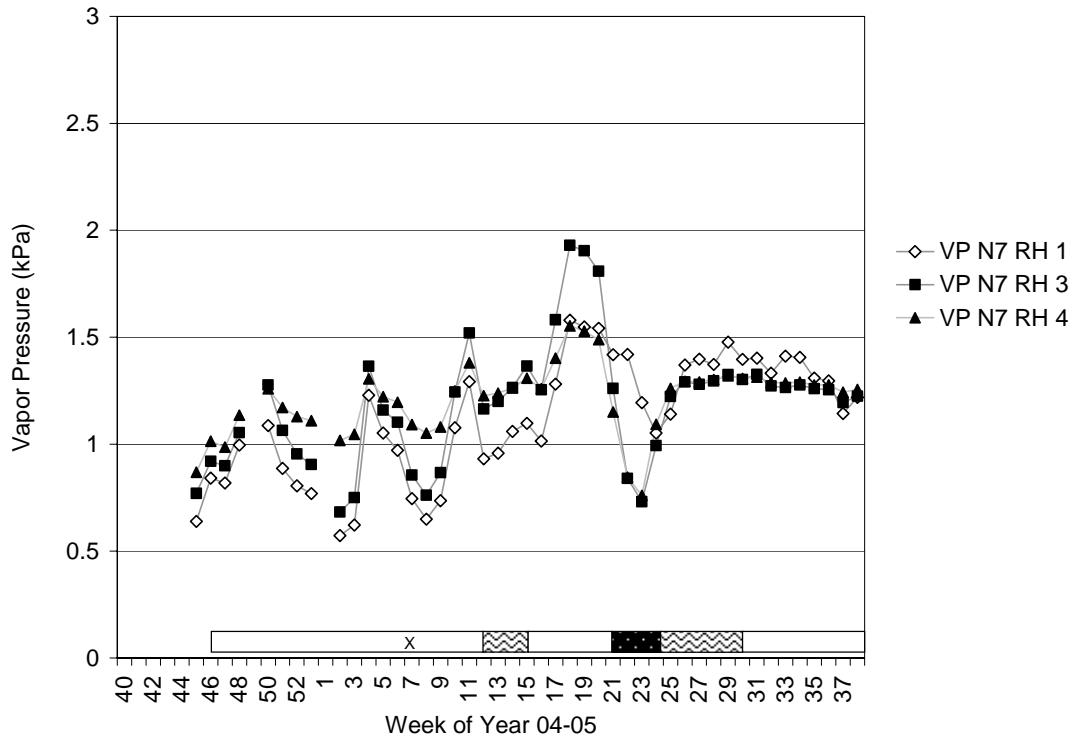


Figure B N8-1 N8 – Wood Moisture Content

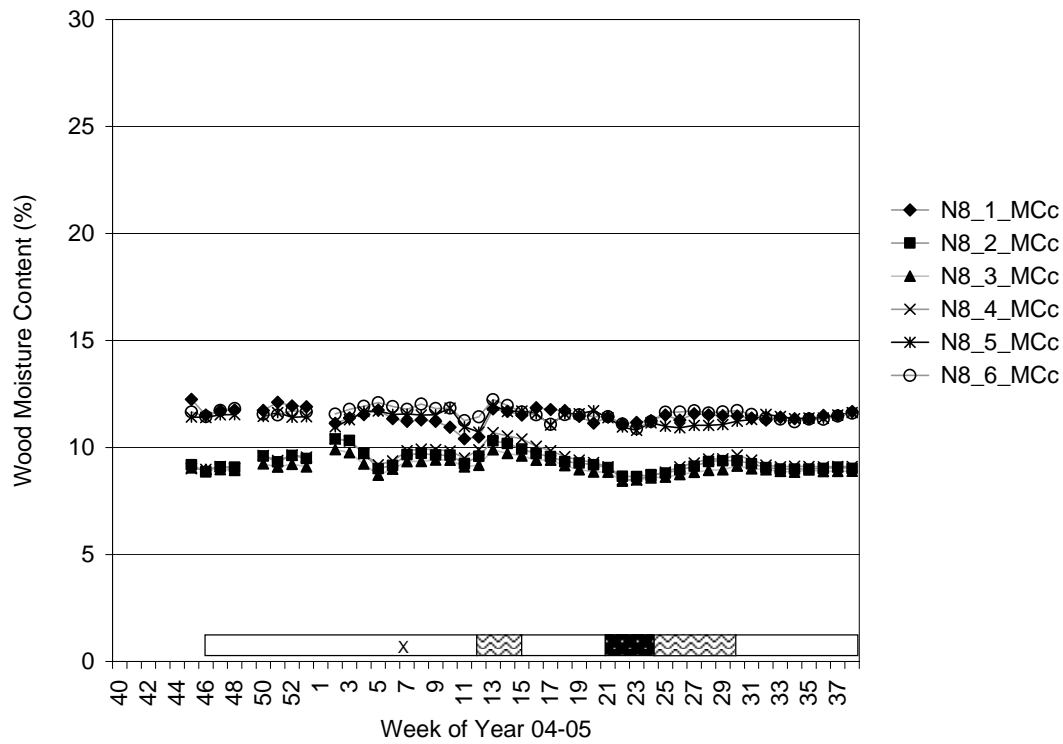


Figure B N8-2 N8 – Cavity Relative Humidity

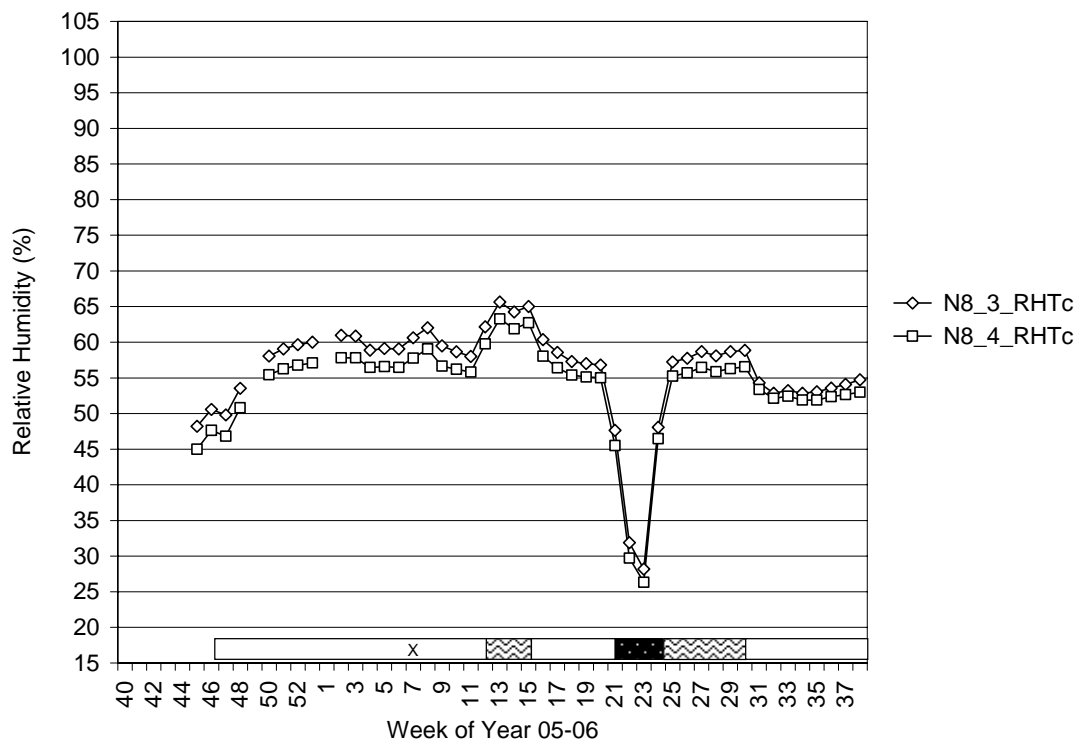


Figure B N8-3 N8 - Temperature

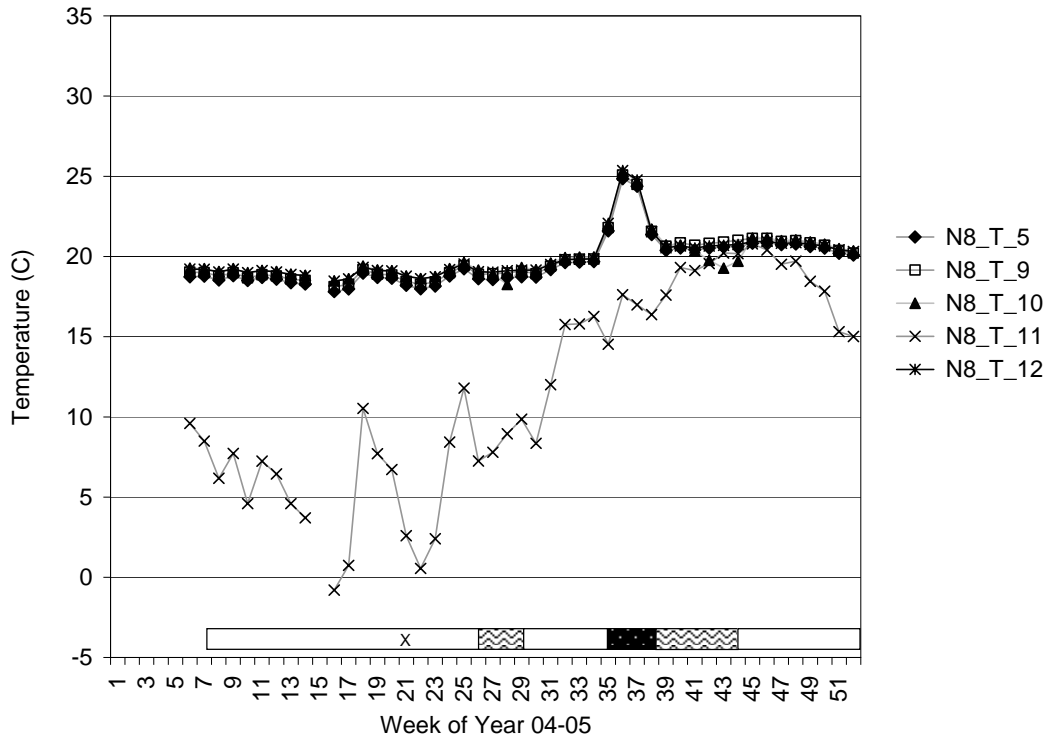
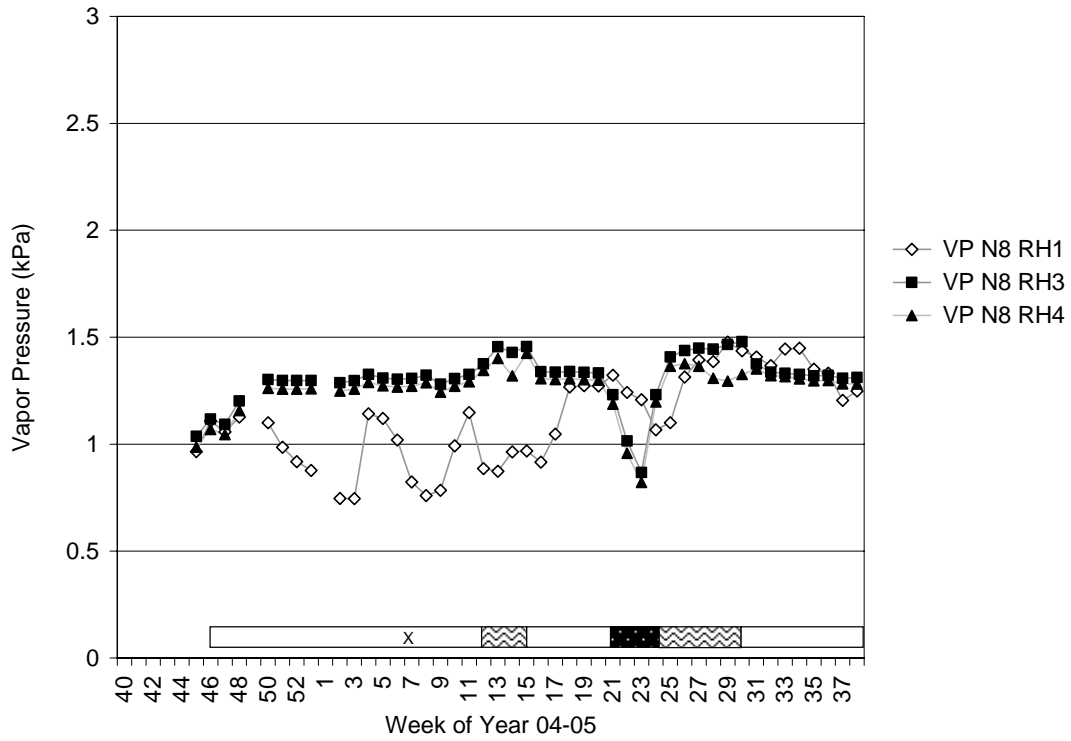


Figure B N8-3 N8 – Vapor Pressure



**Appendix B**  
**Test Cycle 2 Figures**  
**November 7 2004 to September 20, 2005**



## Experimental Timeline

During test cycle 2, the normal operation of the test was interrupted to implement the wall wetting experiment. For details, read the experimental design section of this report.

The graphic below was created to provide the reader a reference for all of the graphs in Appendix B. The periods of normal operation, wetting, and drying correspond to the week and year listed.

Figure B 1 Test Cycle 2 - Experimental Timeline

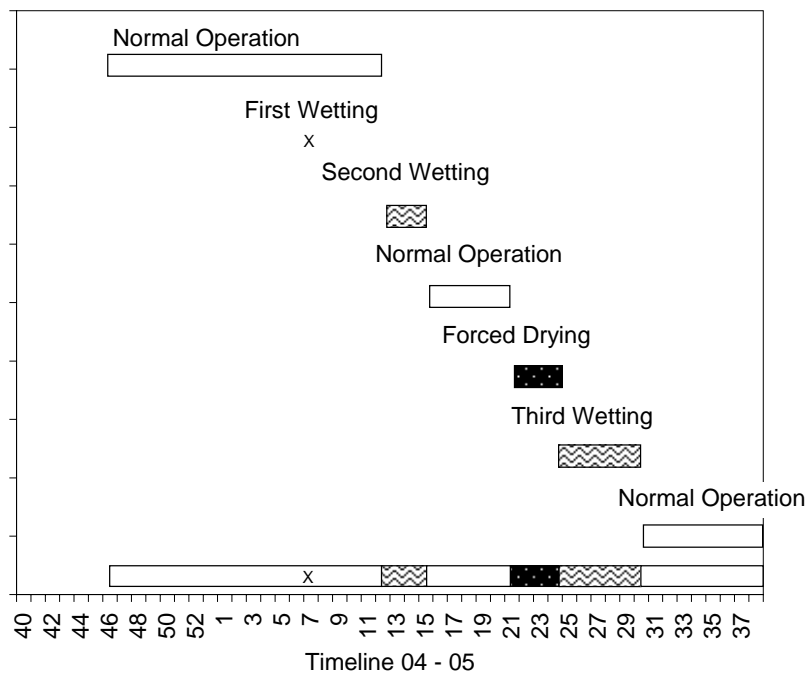


Figure B S1-1

S1 – Wood Moisture Content

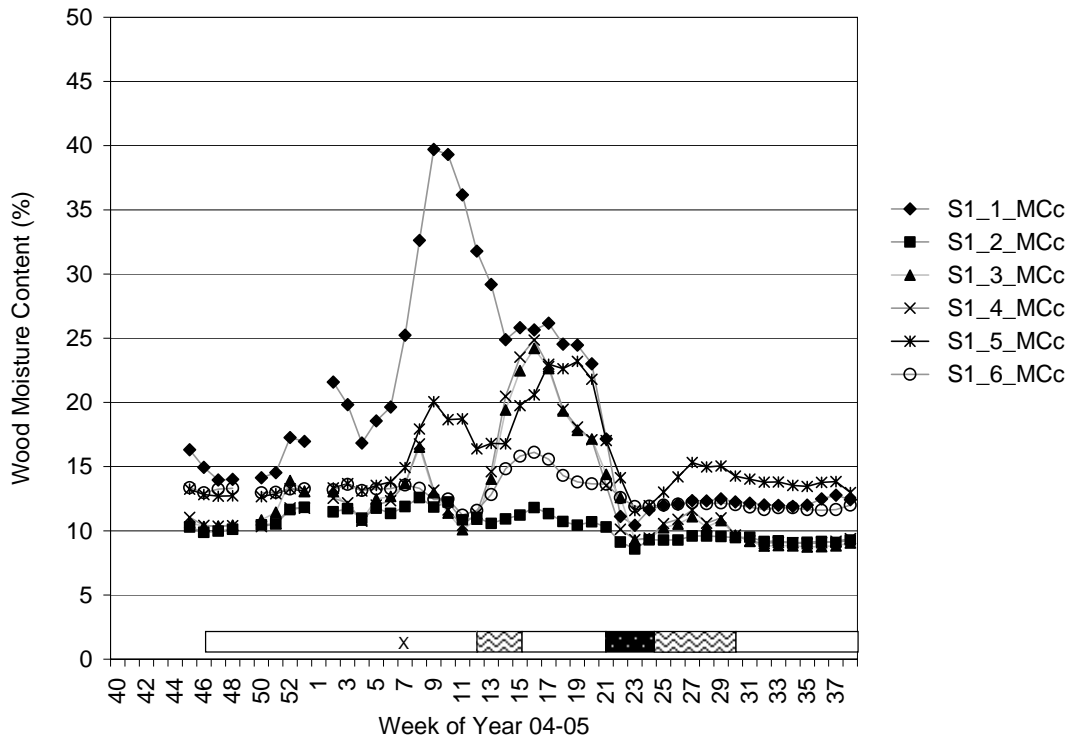
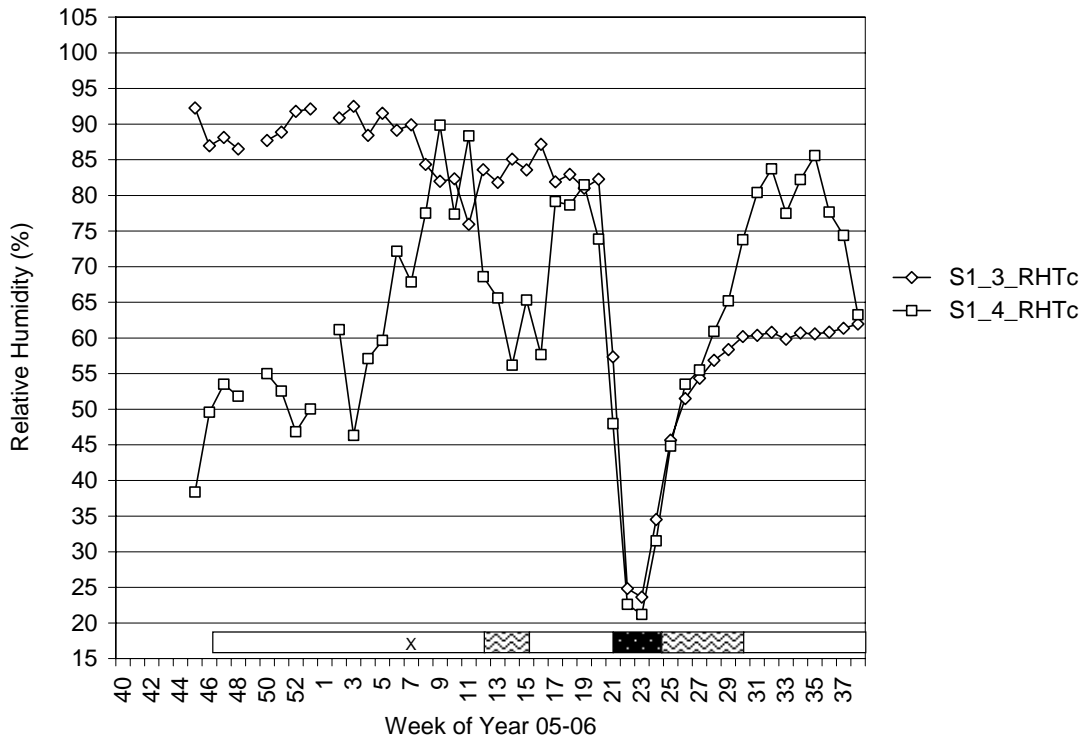
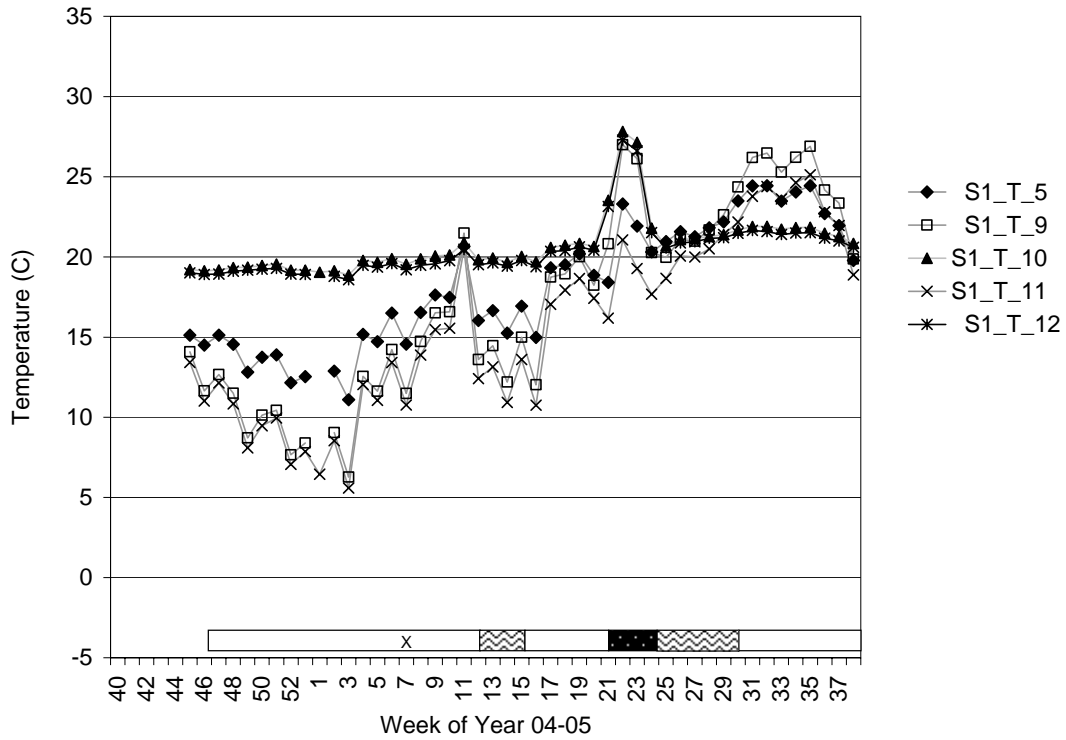


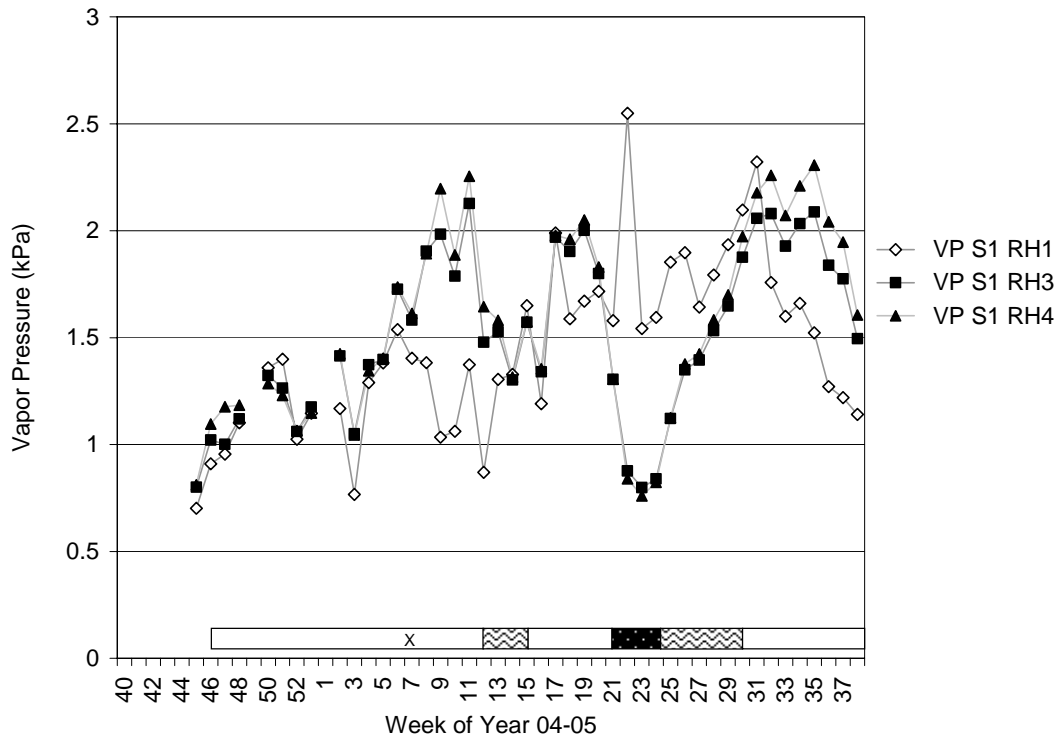
Figure B S1-2 S1 – Cavity Relative Humidity



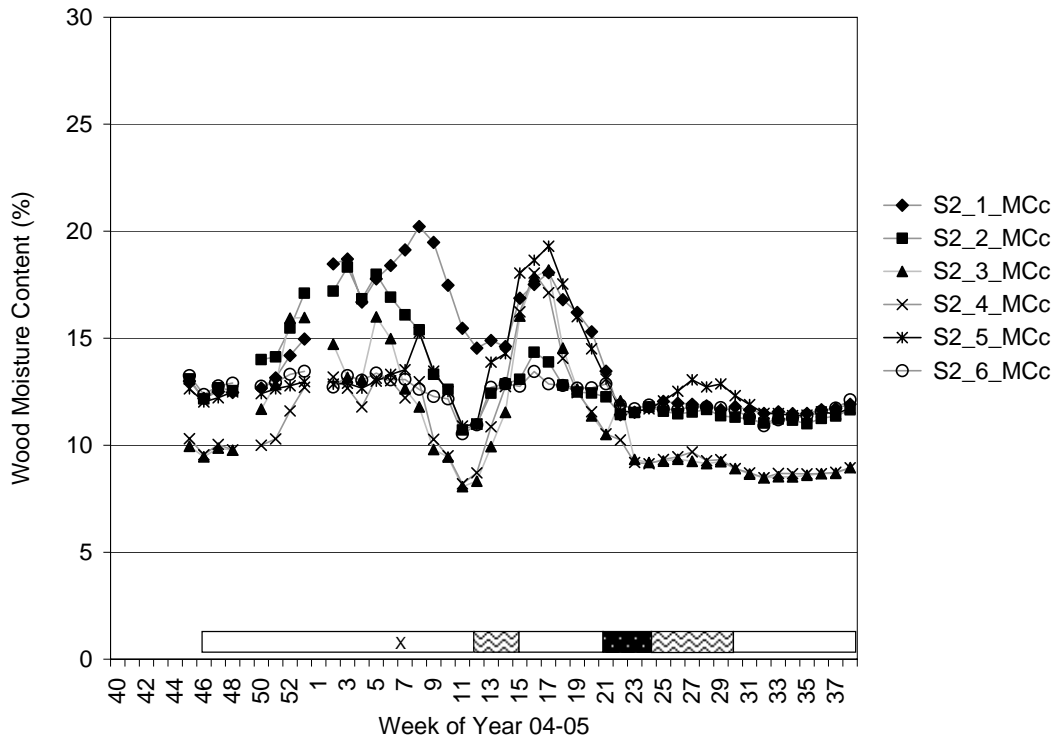
**Figure B S1-3 S1 - Temperature**



**Figure B S1-4 S1 – Vapor Pressure**



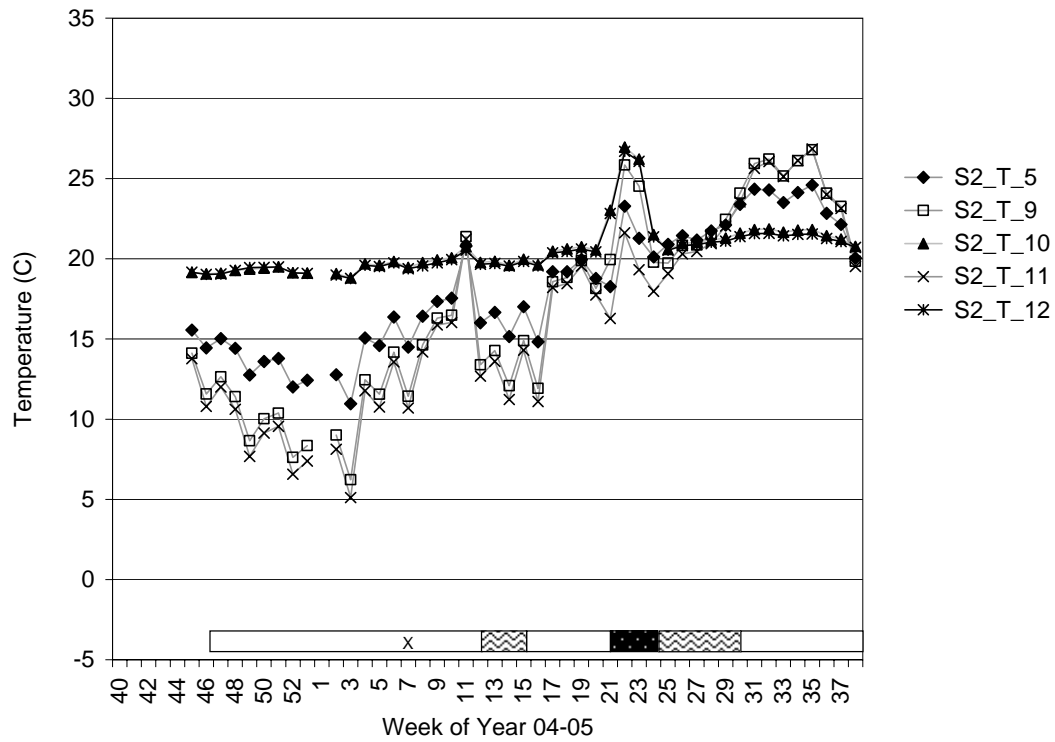
**Figure B S2-1 S2– Wood Moisture Content**



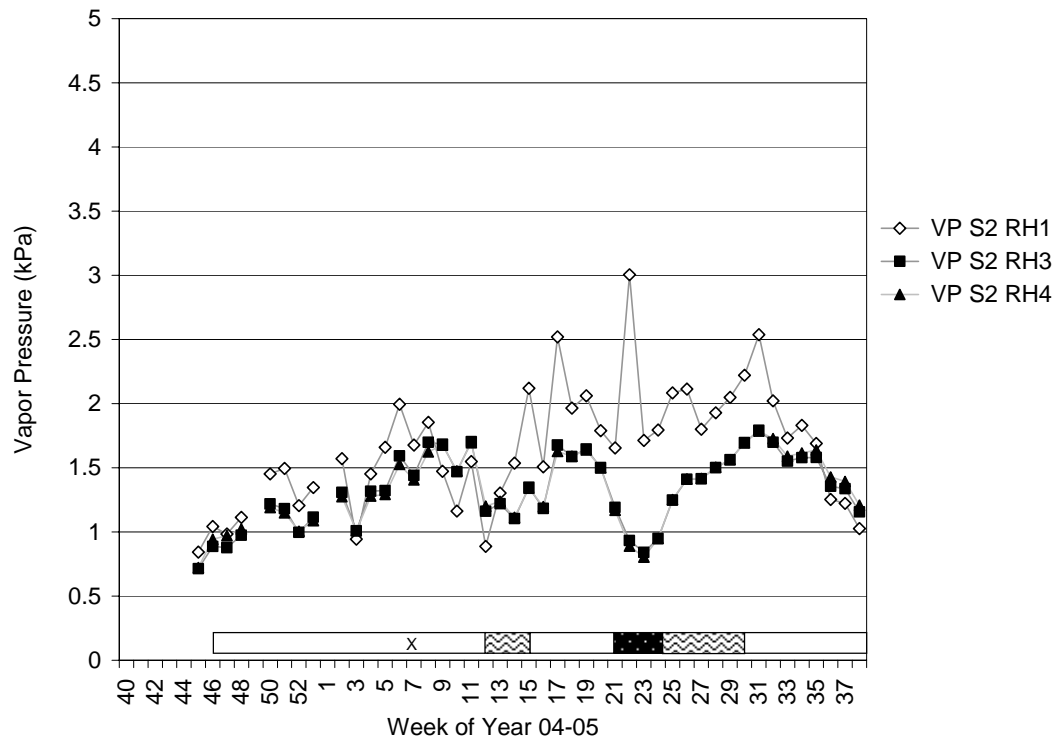
**Figure B S2-2 S2– Cavity Relative Humidity**



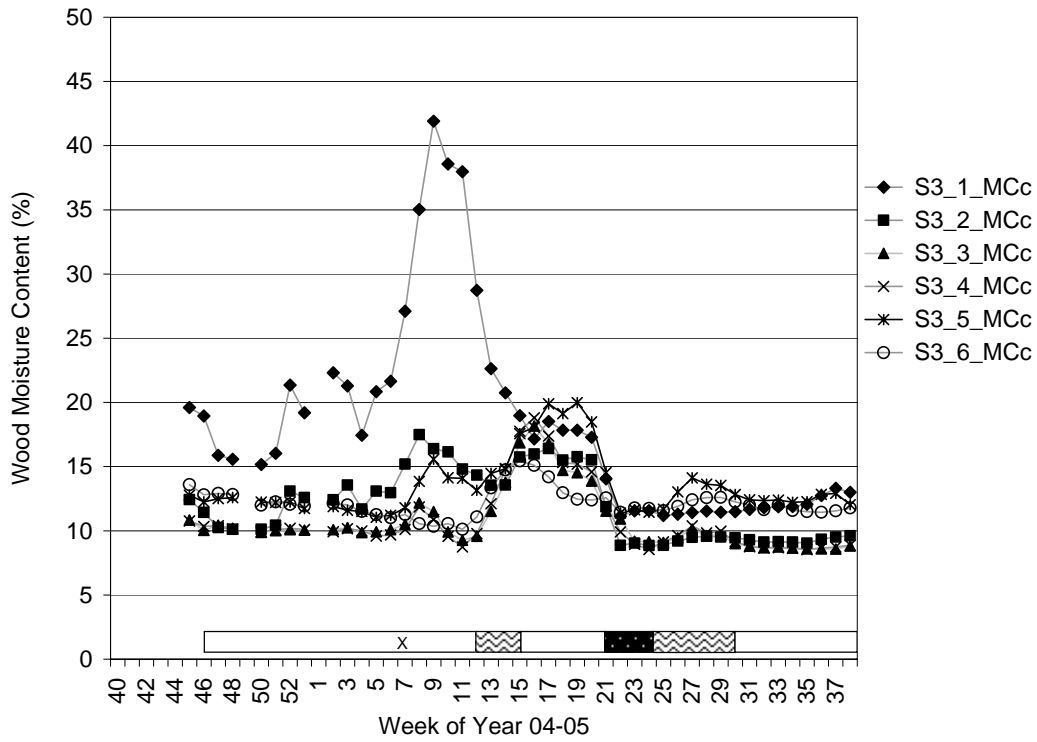
**Figure B S2-3 S2- Temperature**



**Figure B S2-4 S2 – Vapor Pressure**



**Figure B S3-1 S3 – Wood Moisture Content**



**Figure B S3-2 S3 – Cavity Relative Humidity**



Figure B S3-3 S3 - Temperature

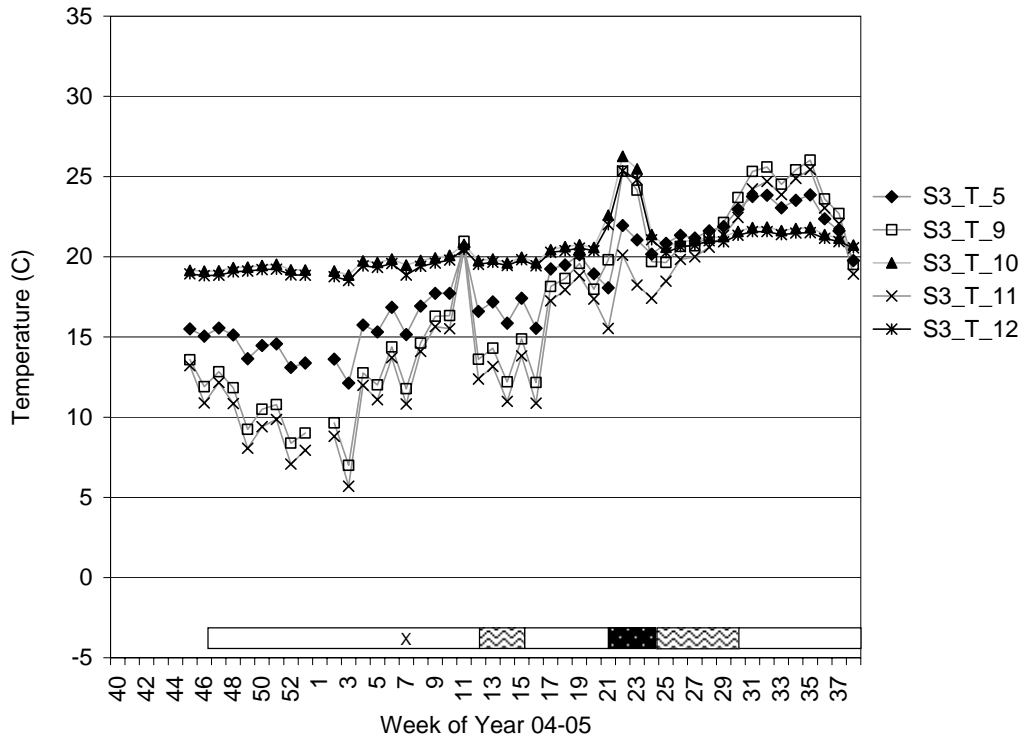
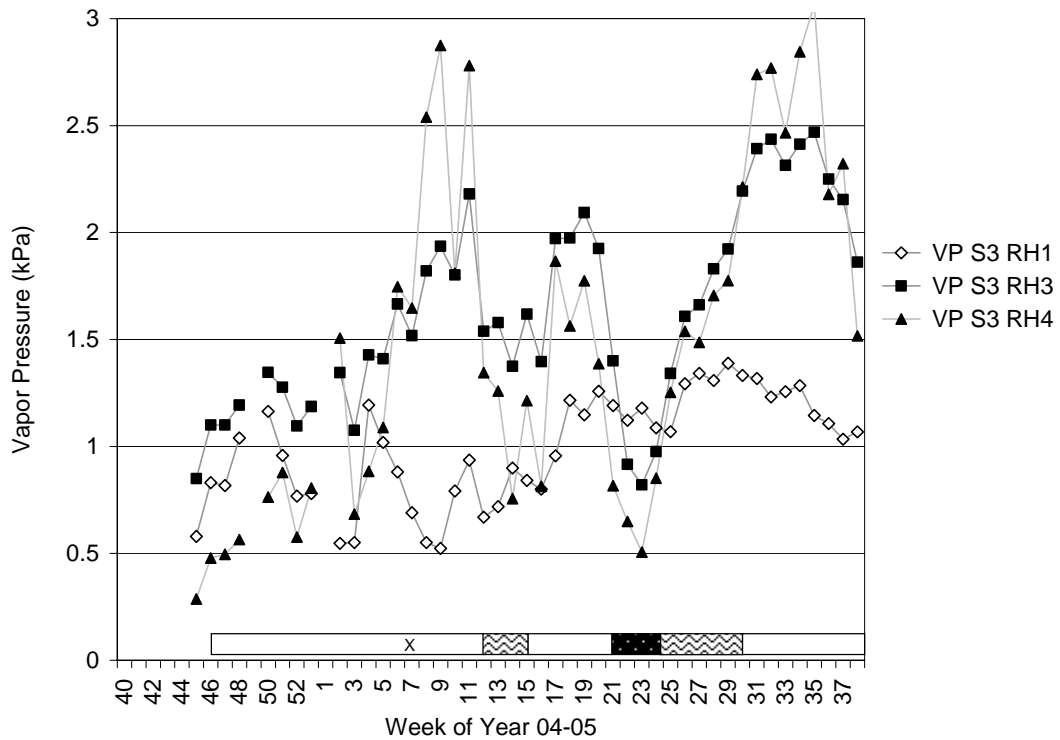
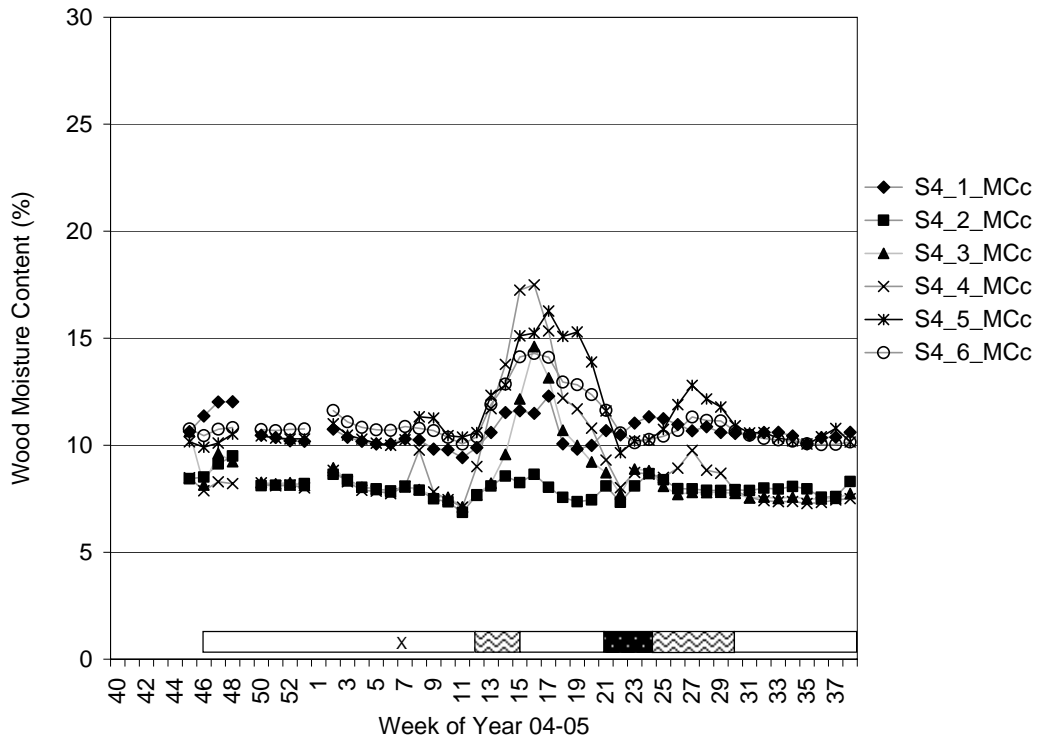


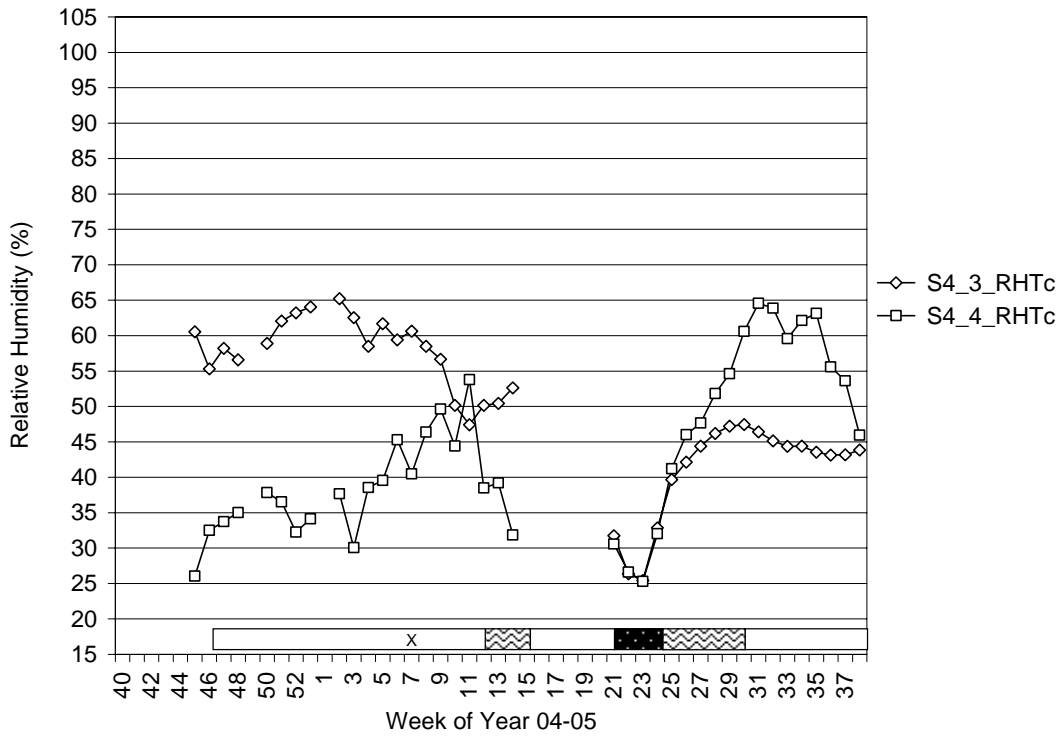
Figure B S3-4 S3 - Vapor Pressure



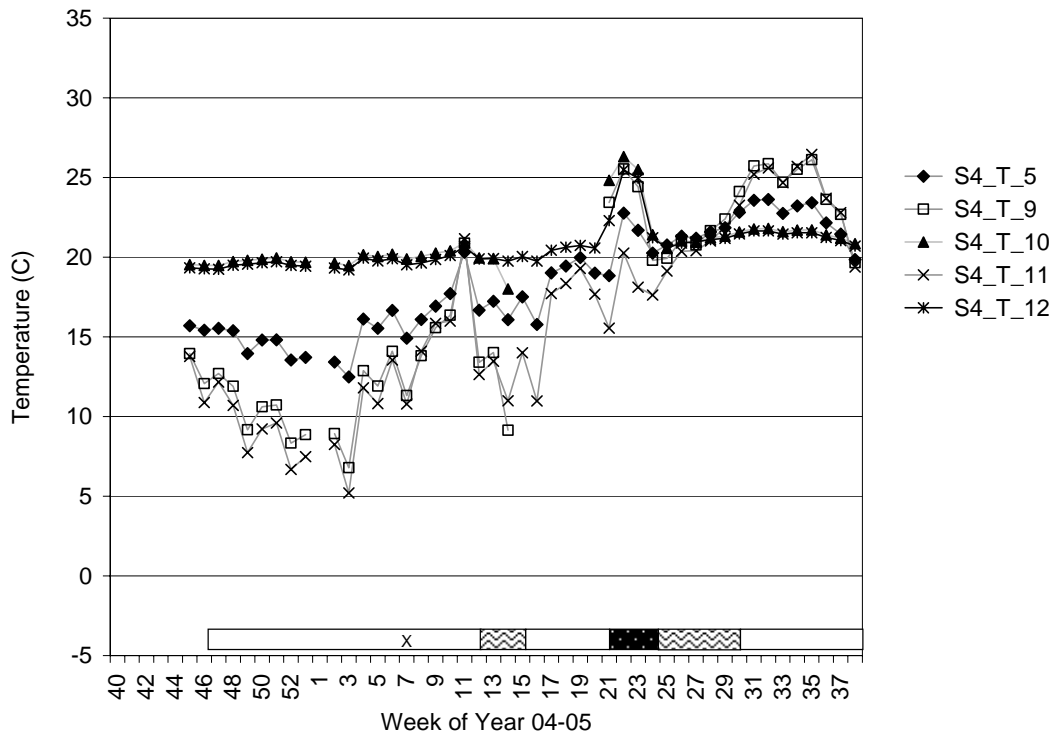
**Figure B S4-1 S4 – Wood Moisture Content**



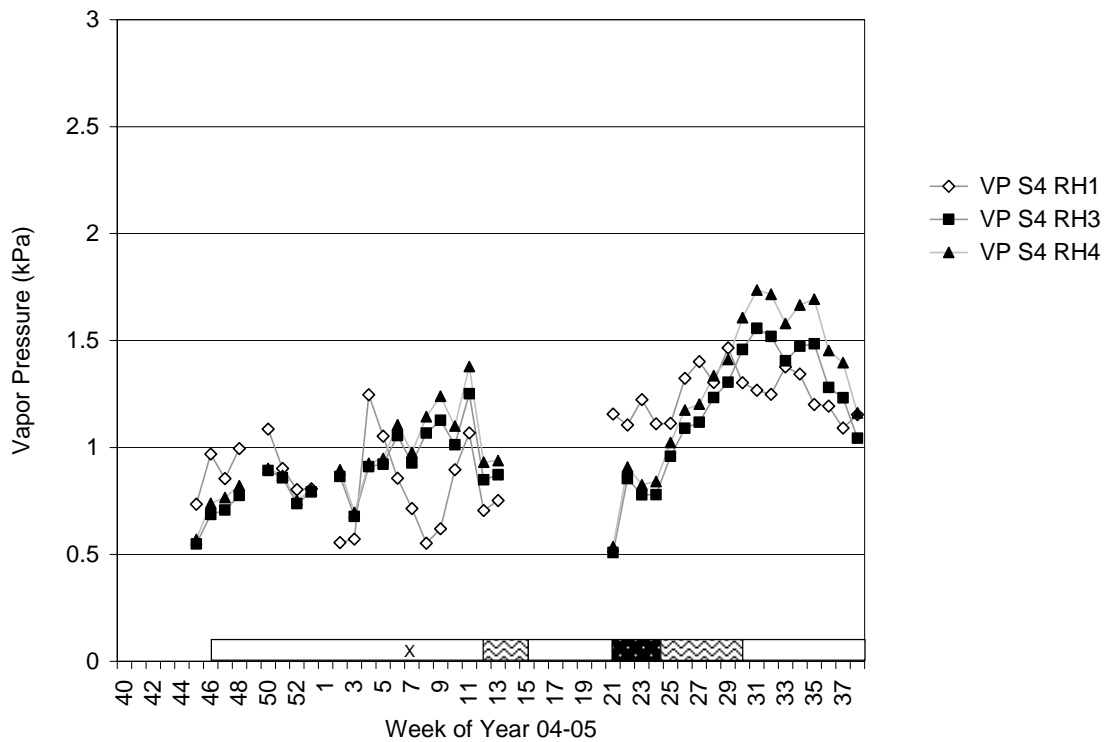
**Figure B S4-2 S4 – Cavity Relative Humidity**



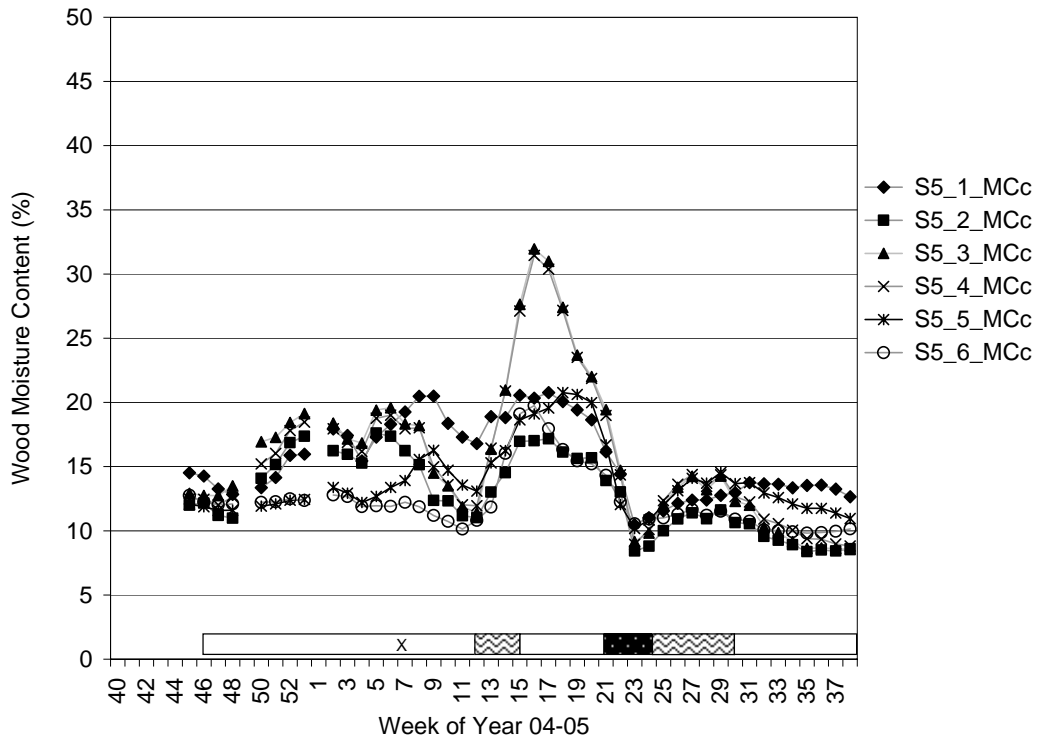
**Figure B S4-3 S4- Temperature**



**Figure B S4-4 S4 - Vapor Pressure**



**Figure B S5-1 S5 – Wood Moisture Content**



**Figure B S5-2 S5 – Cavity Relative Humidity**



Figure B S5-3 S5 - Temperature

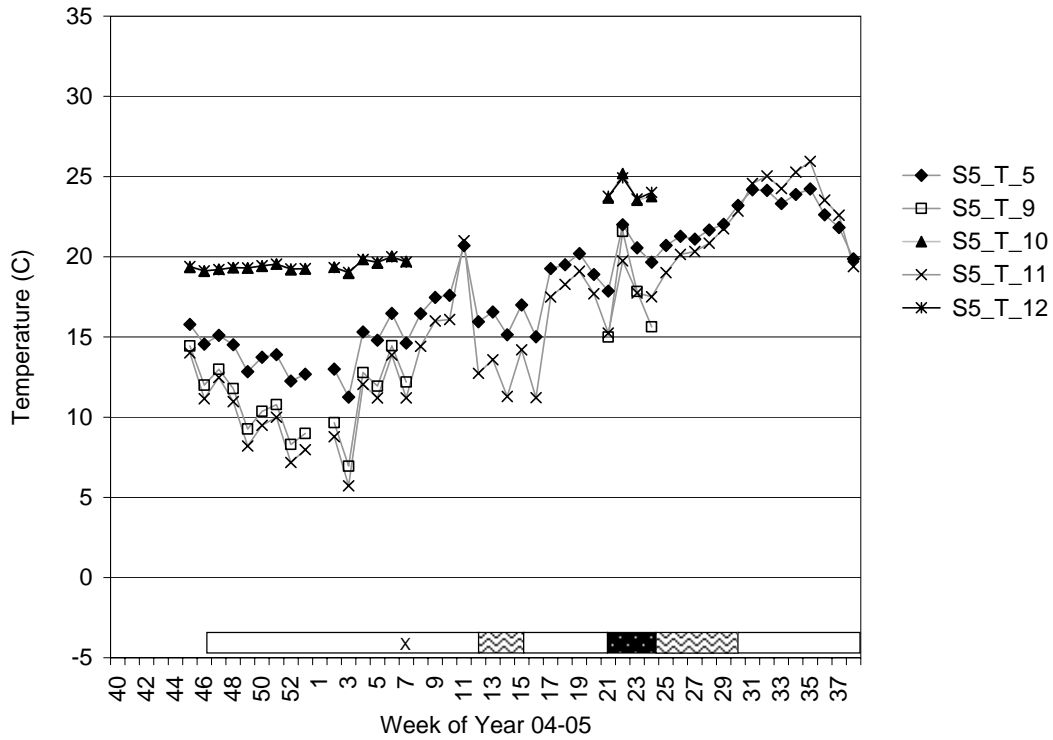
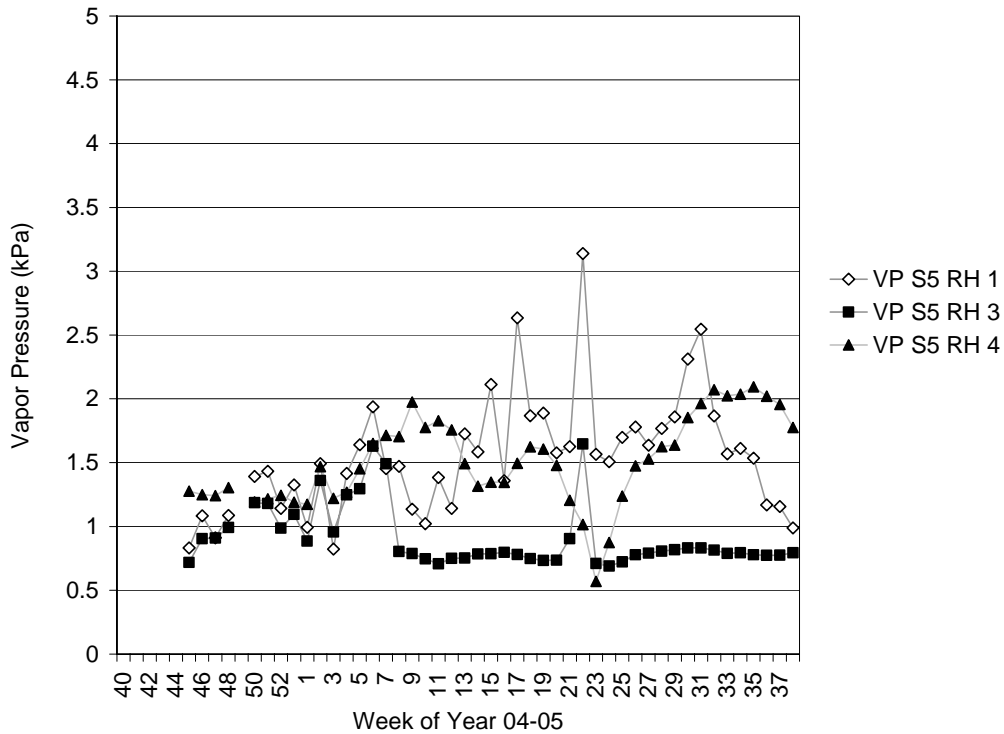
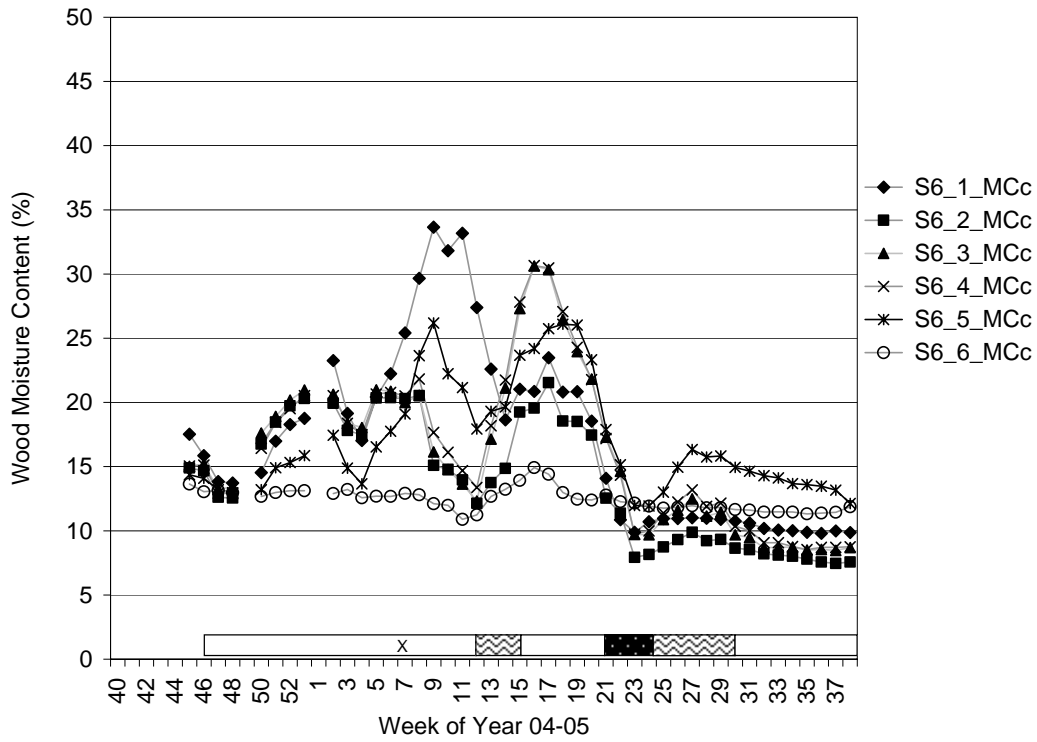


Figure B S5-4 S5 - Vapor Pressure



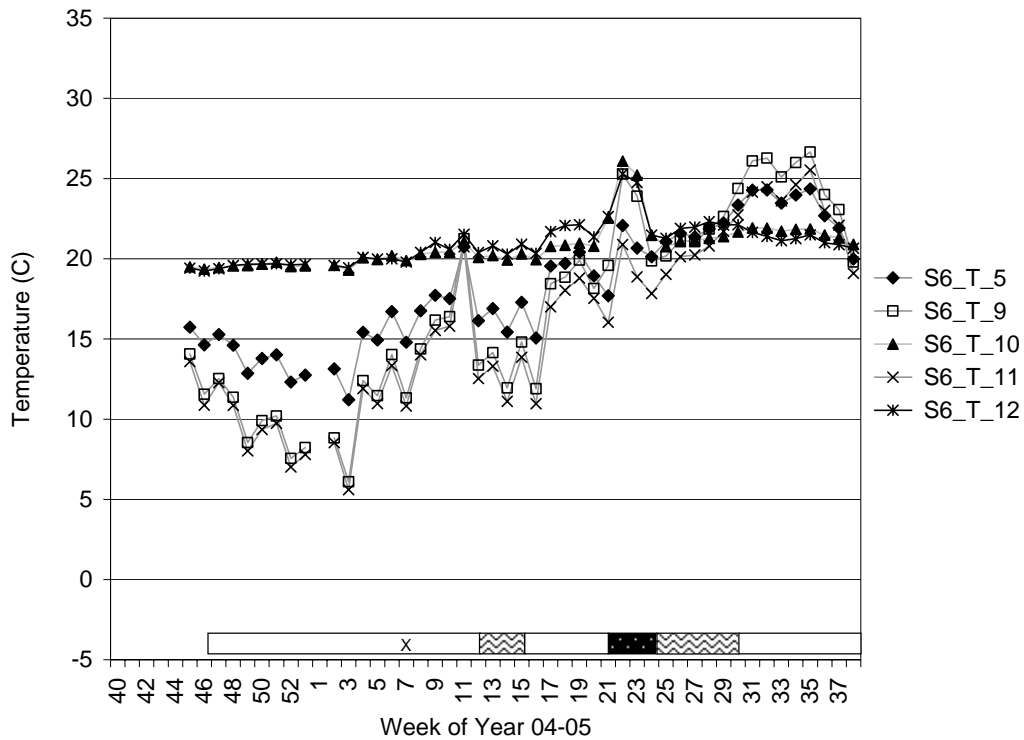
**Figure B S6-1 S6 – Wood Moisture Content**



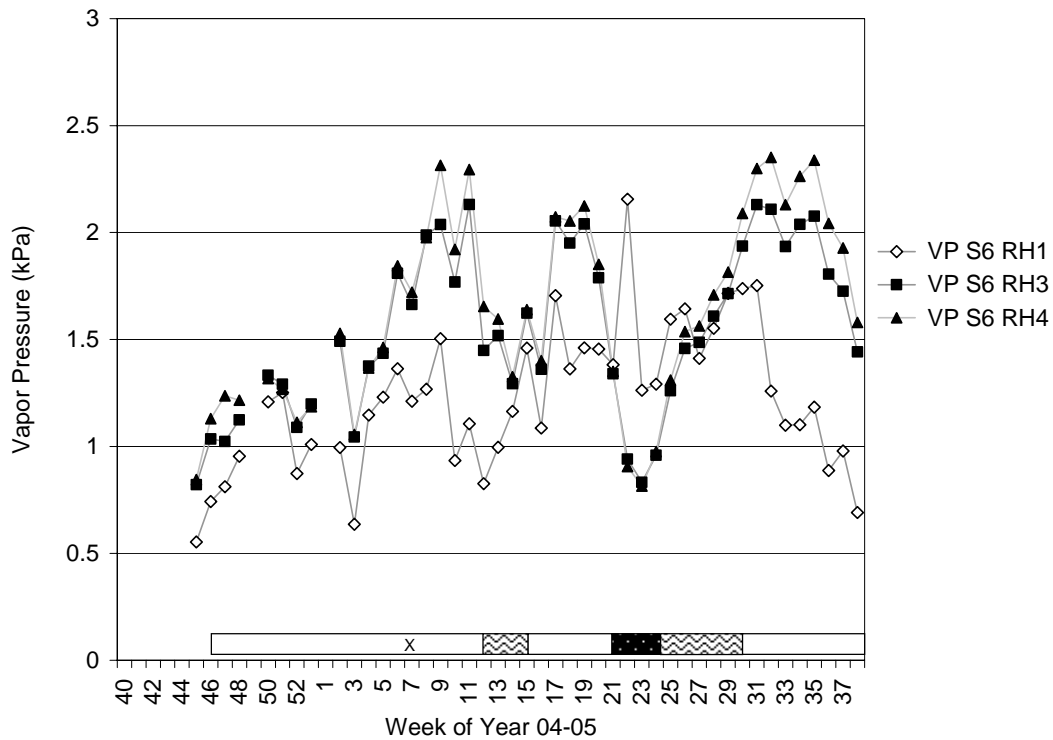
**Figure B S6-2 S6 – Cavity Relative Humidity**



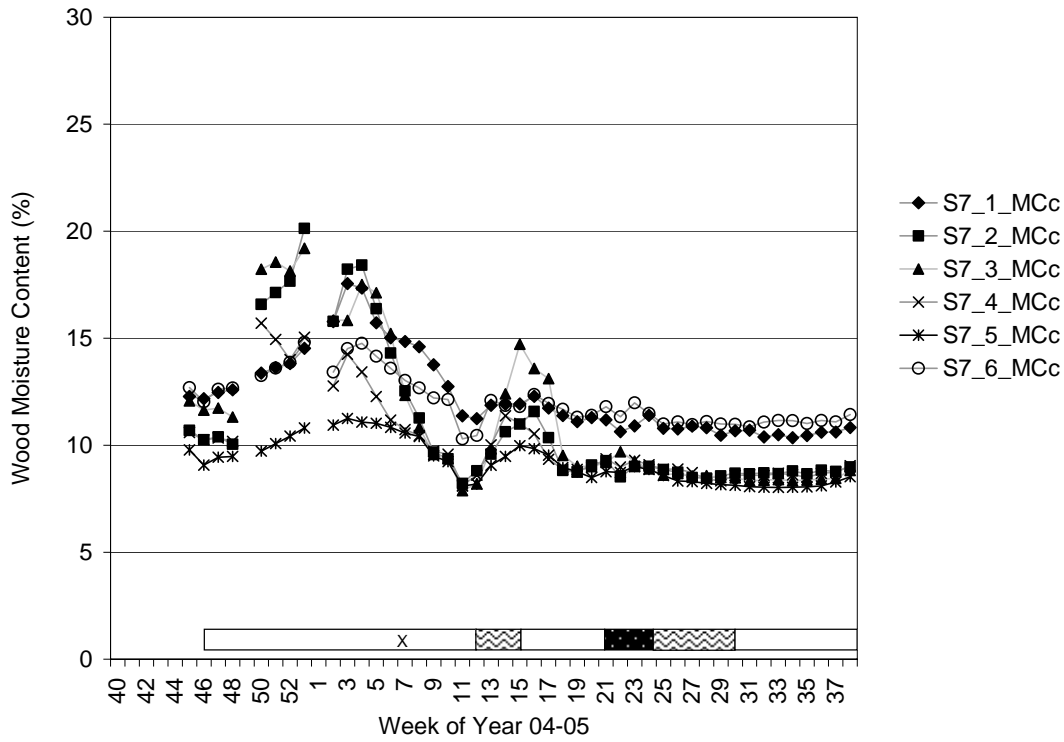
**Figure B S6-3 S6 - Temperature**



**Figure B S6-4 S6 – Vapor Pressure**



**Figure B S7-1 S7 – Wood Moisture Content**



**Figure B S7-2 S7 – Cavity Relative Humidity**



Figure B S7-3 S7 - Temperature

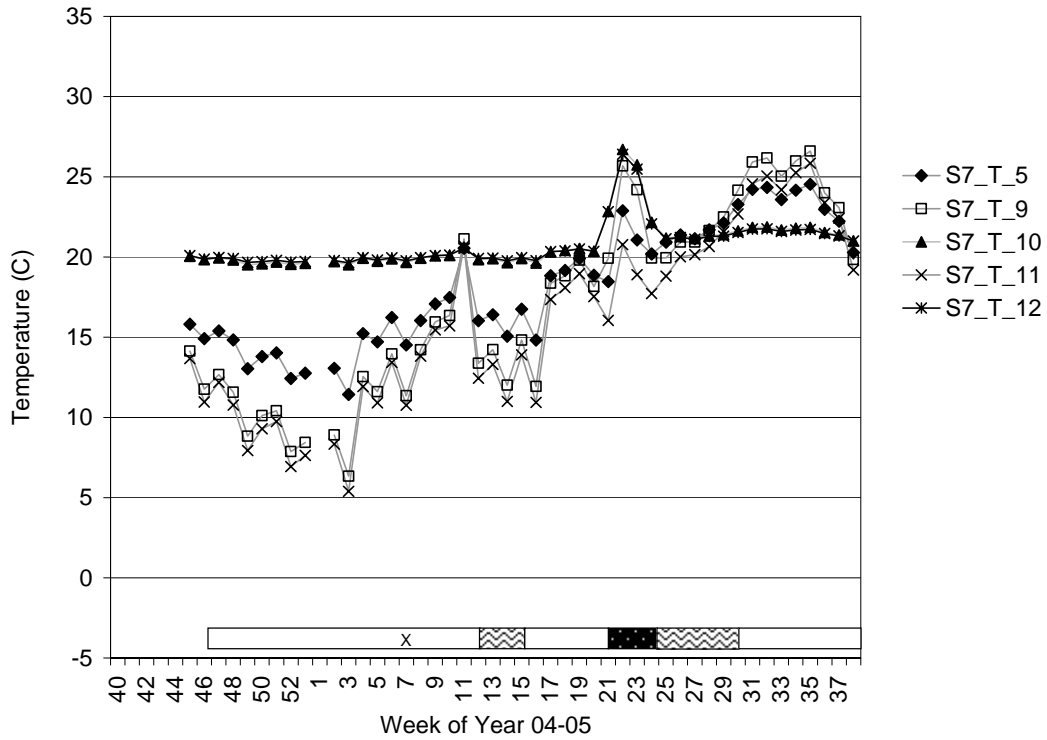
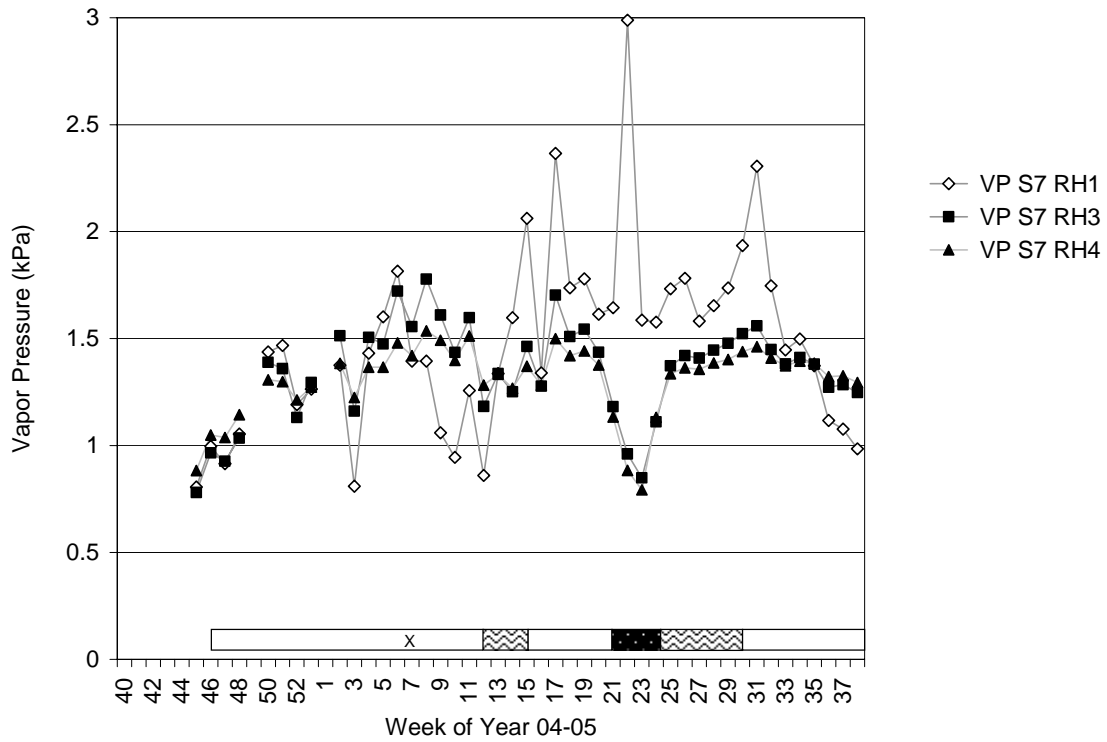
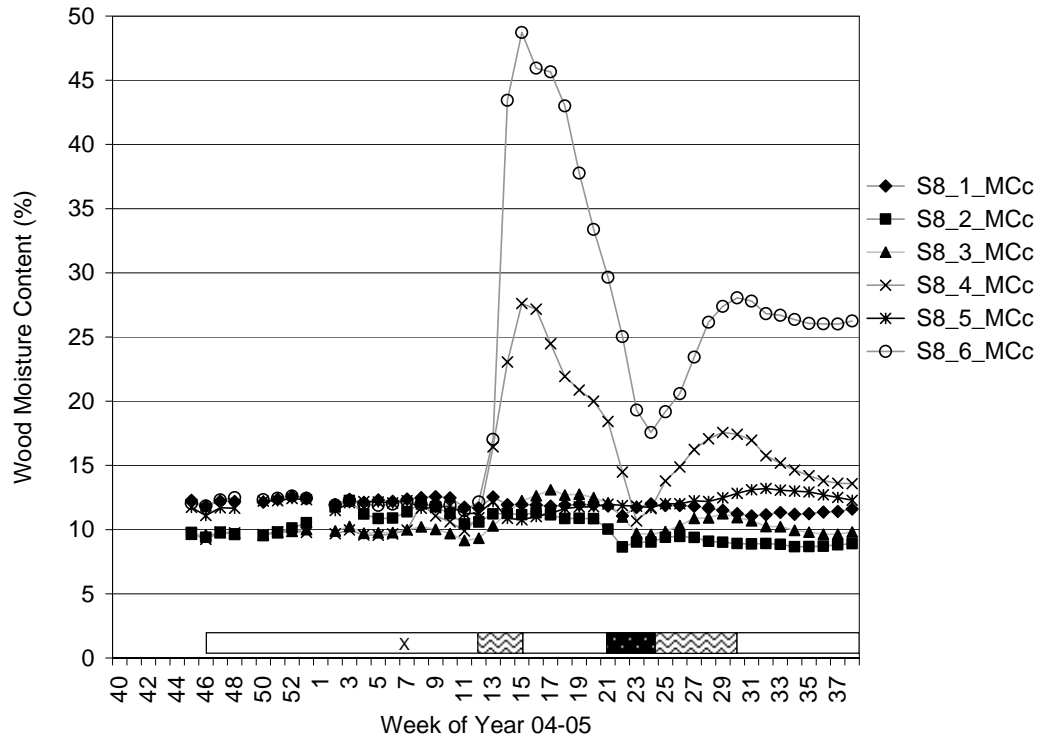


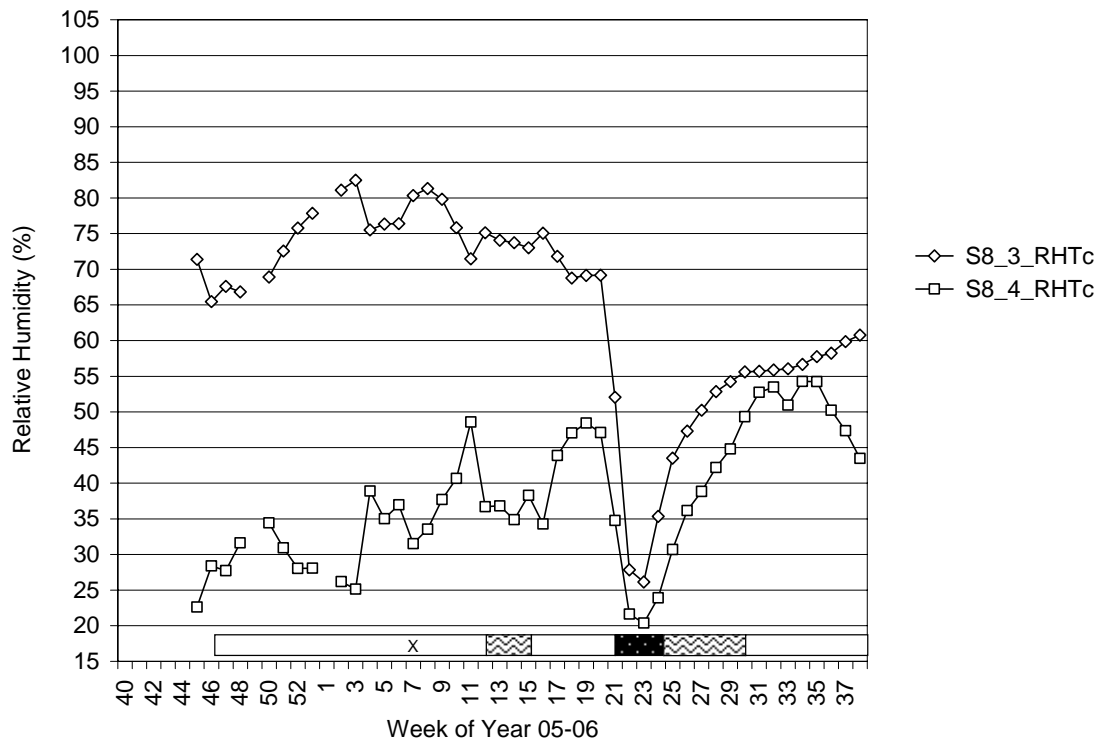
Figure B S7-4 S7 – Vapor Pressure



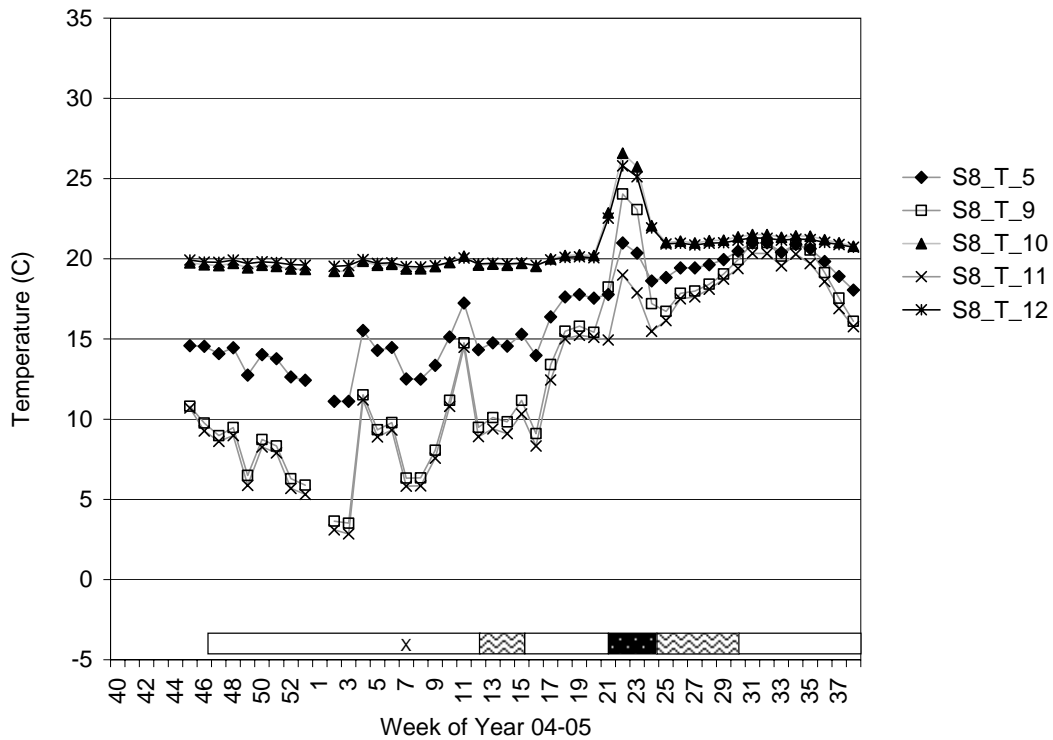
**Figure B S8-1 S8 – Wood Moisture Content**



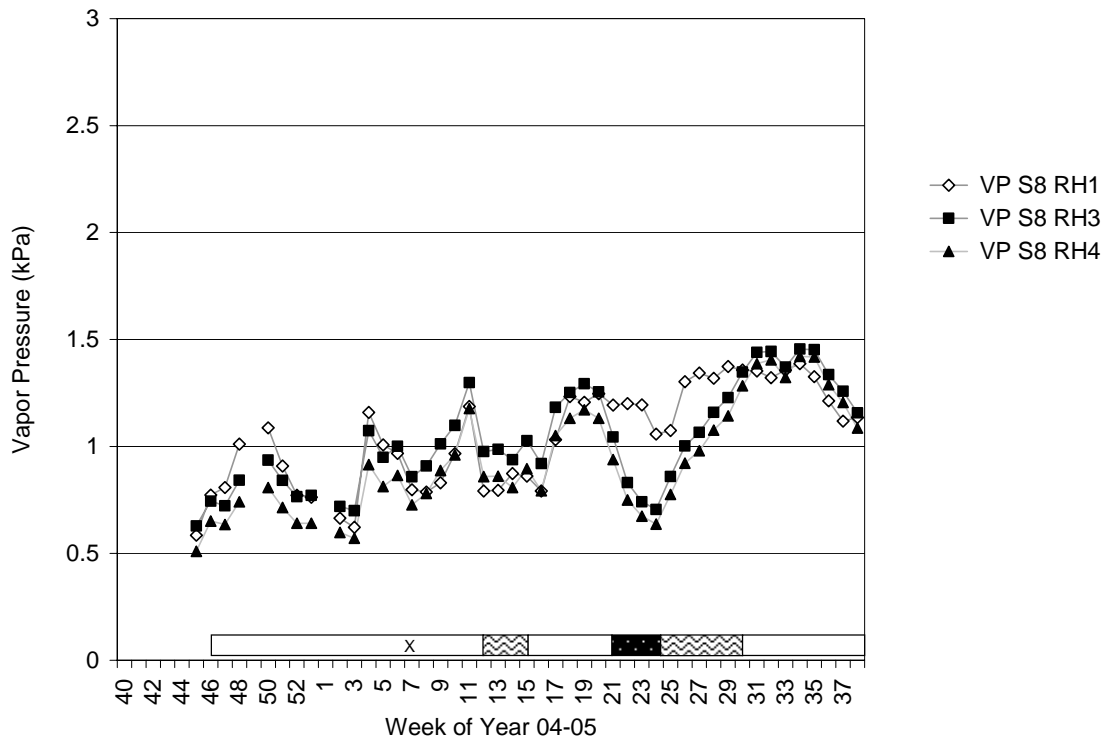
**Figure B S8-2 S8 – Cavity Relative Humidity**



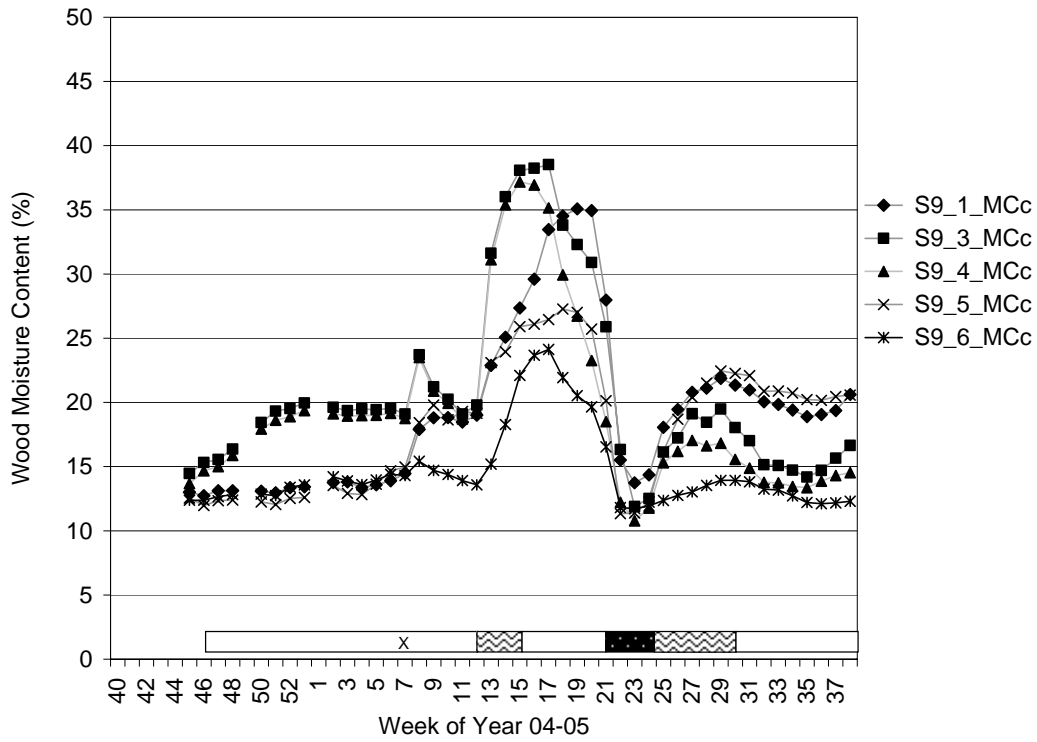
**Figure B S8-3 S8 - Temperature**



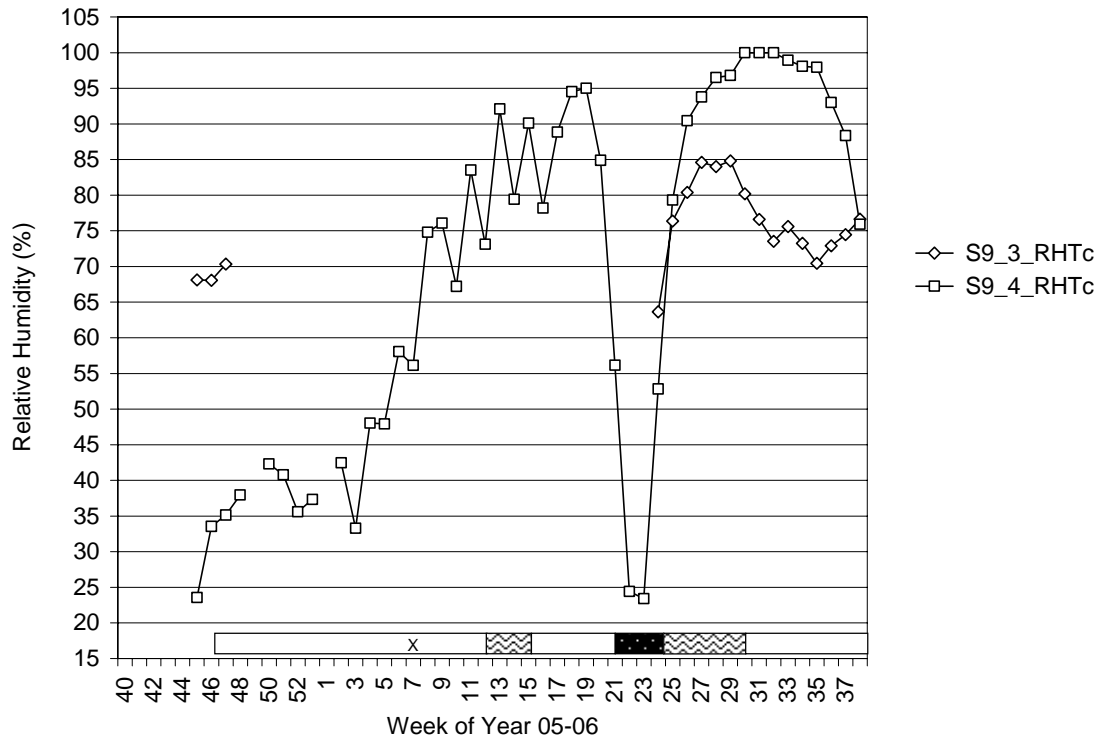
**Figure B S8-4 S8 - Vapor Pressure**



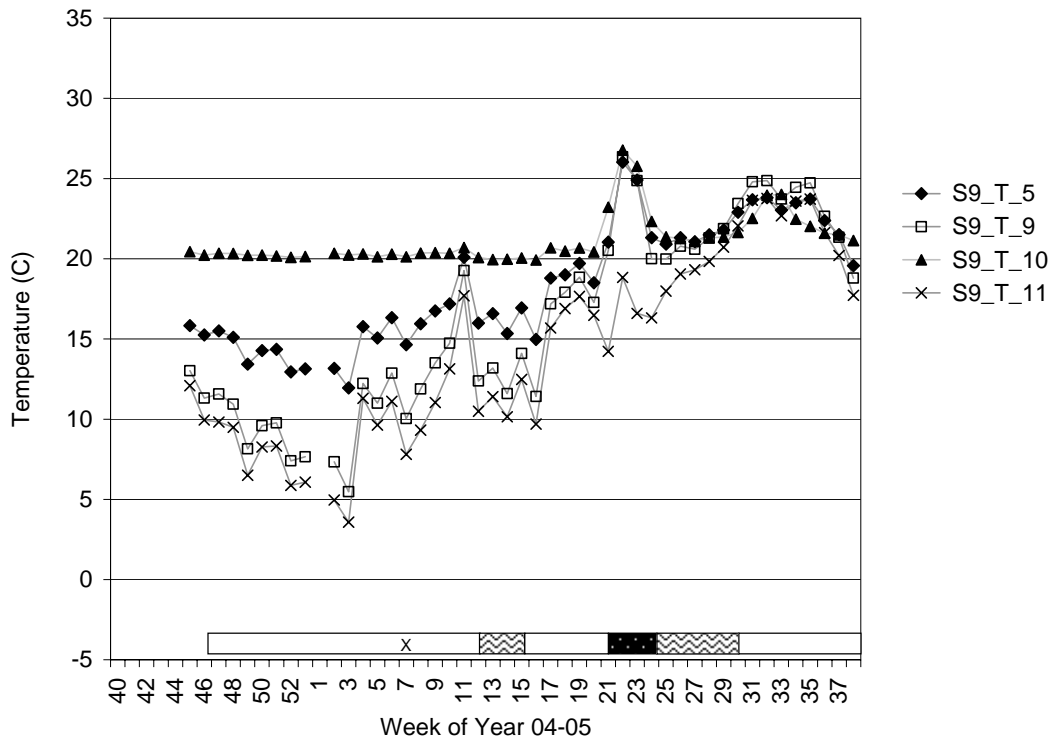
**Figure B S8-1 S9 – Wood Moisture Content**



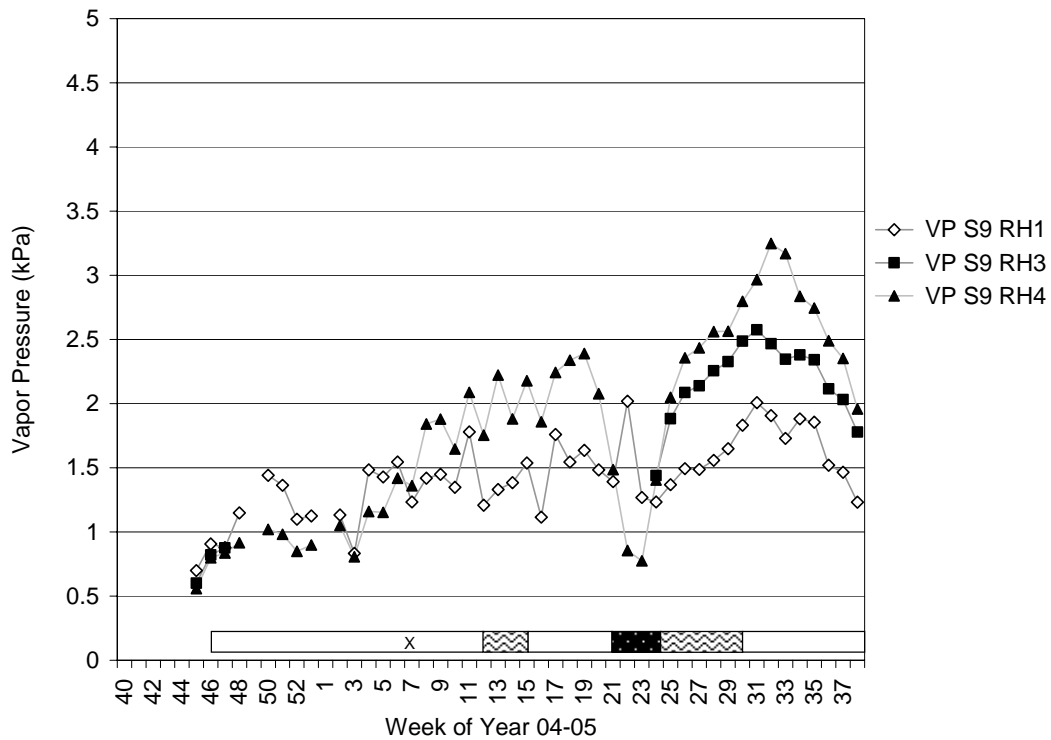
**Figure B S9-2 S9 – Cavity Relative Humidity**



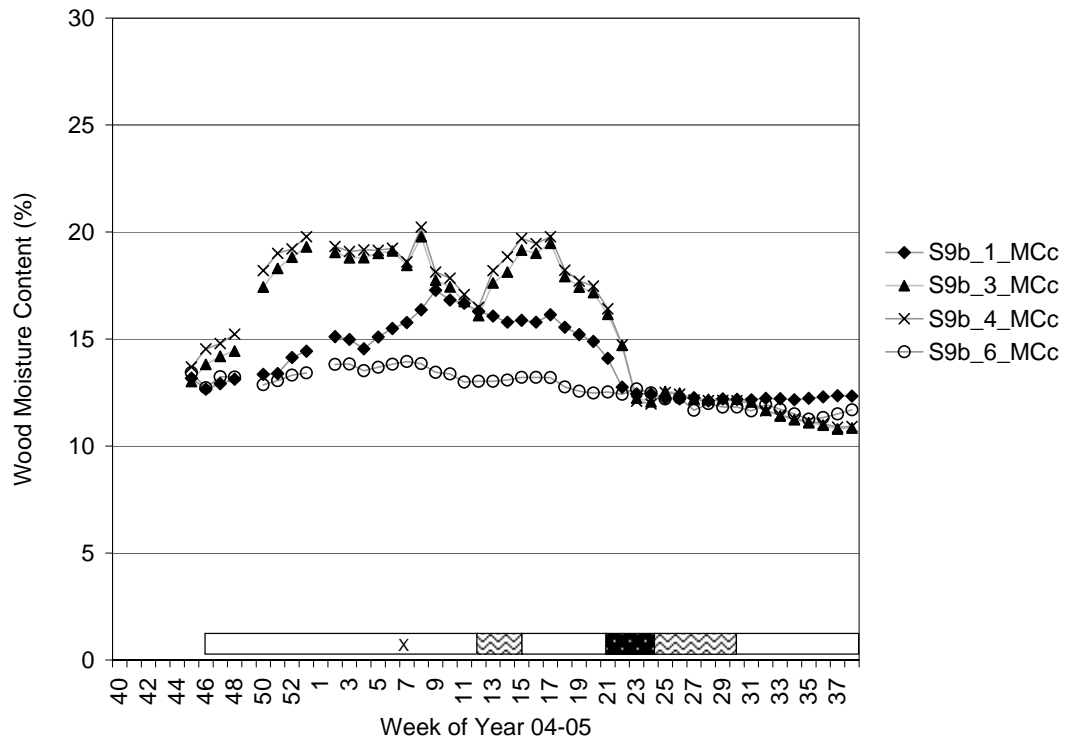
**Figure B S9-3 S9 - Temperature**



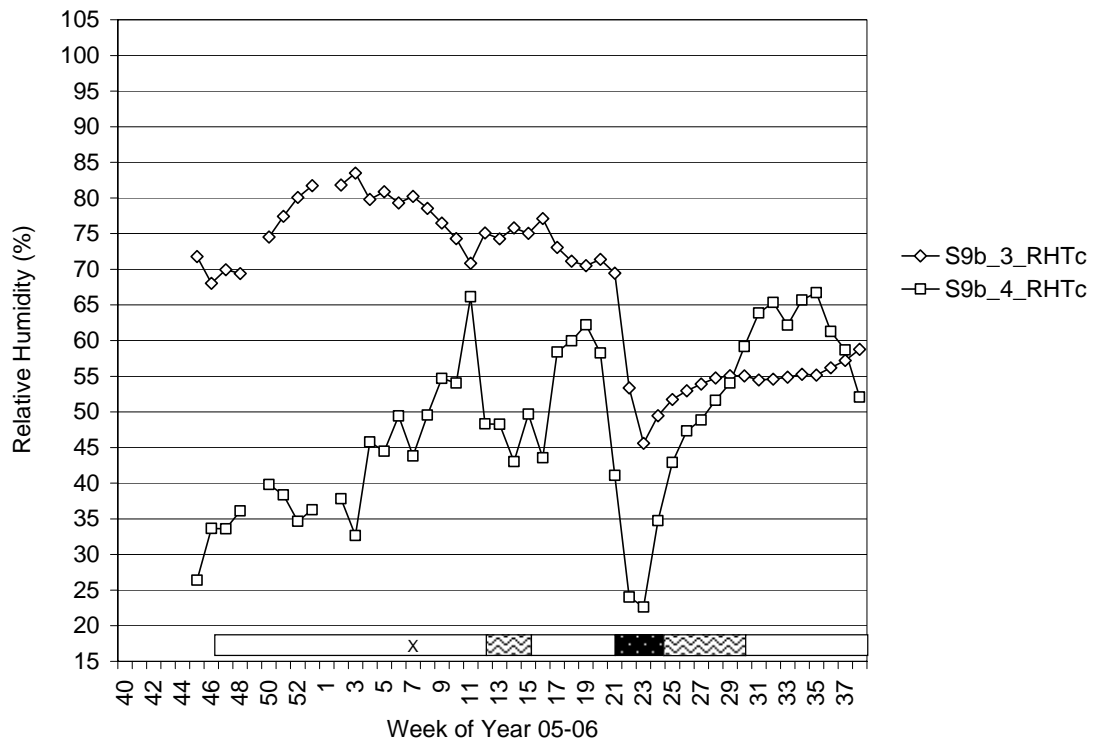
**Figure B S9-4 S9 - Vapor Pressure**



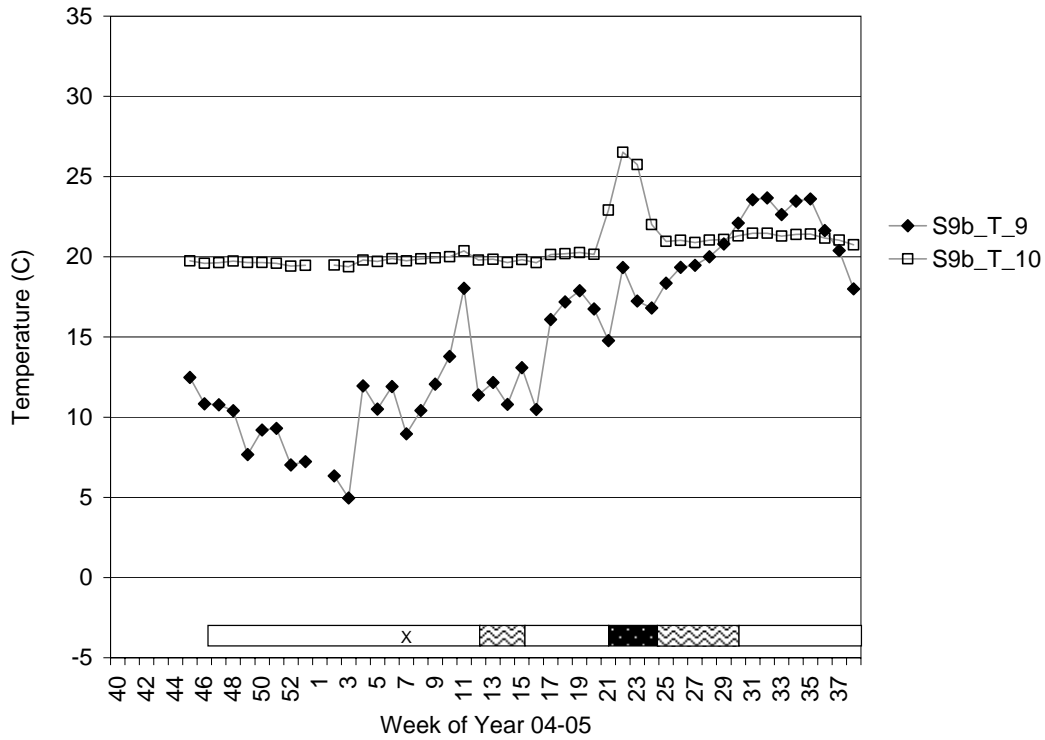
**Figure B S9b-1 S9b – Wood Moisture Content**



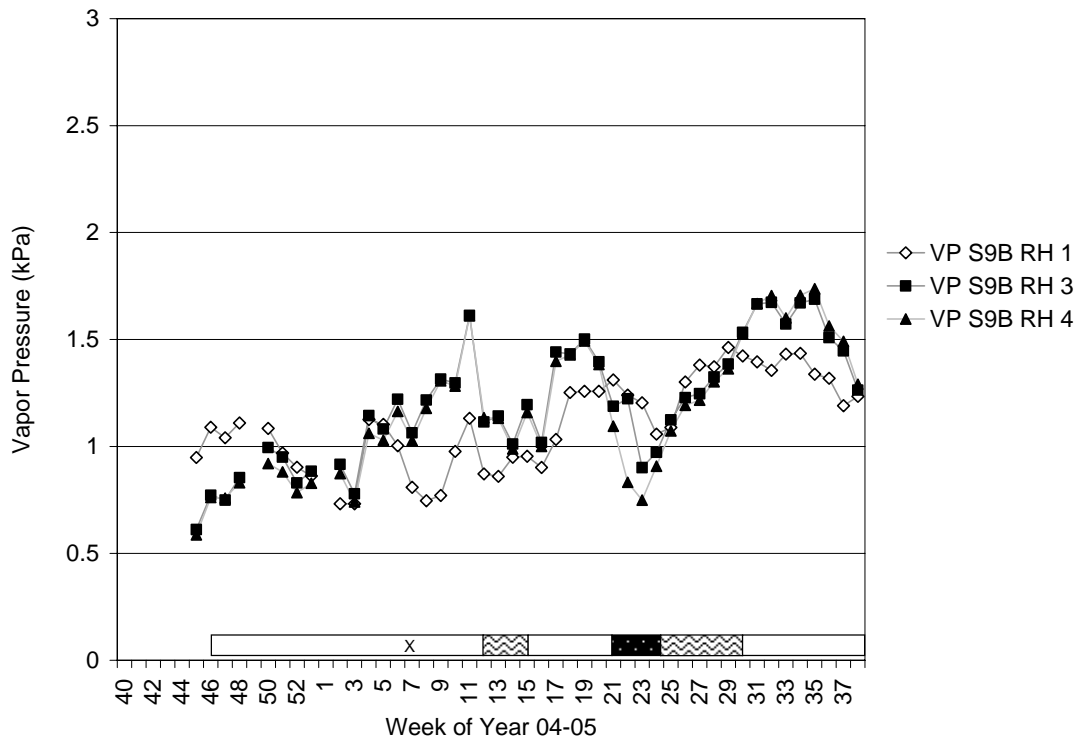
**Figure B S9b-2 S9b – Cavity Relative Humidity**



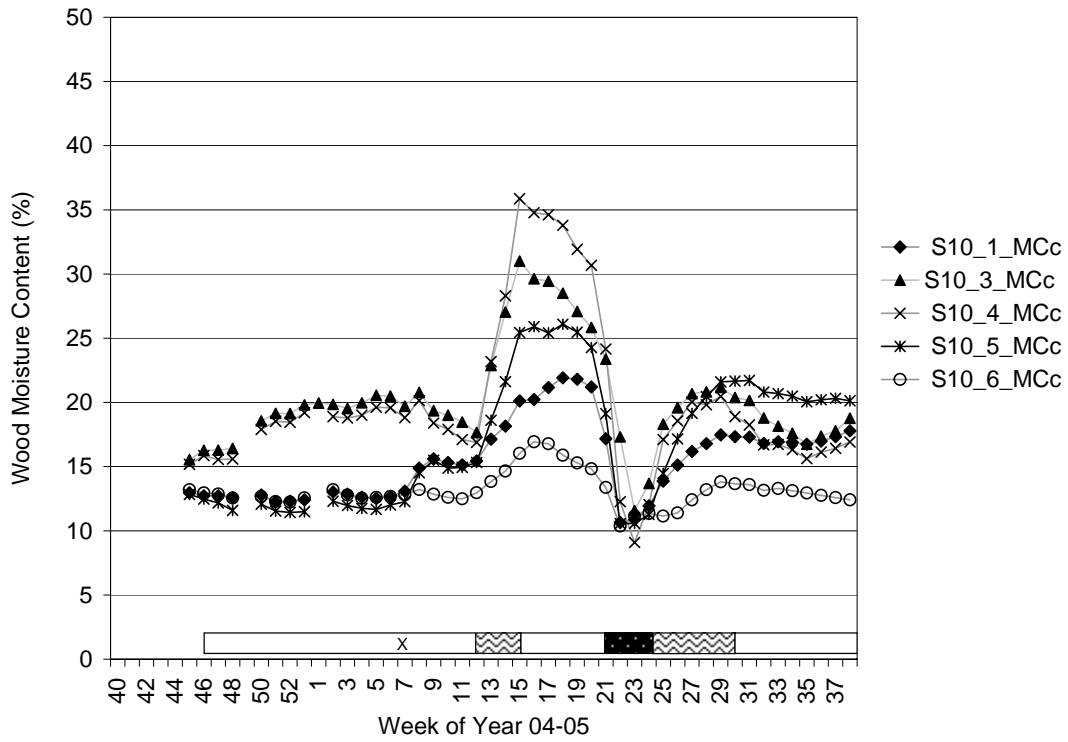
**Figure B S9b-3 S9b - Temperature**



**Figure B S9b-4 S9b – Vapor Pressure**



**Figure B S10-1 S10 – Wood Moisture Content**



**Figure B S10-2 S10 – Cavity Relative Humidity**

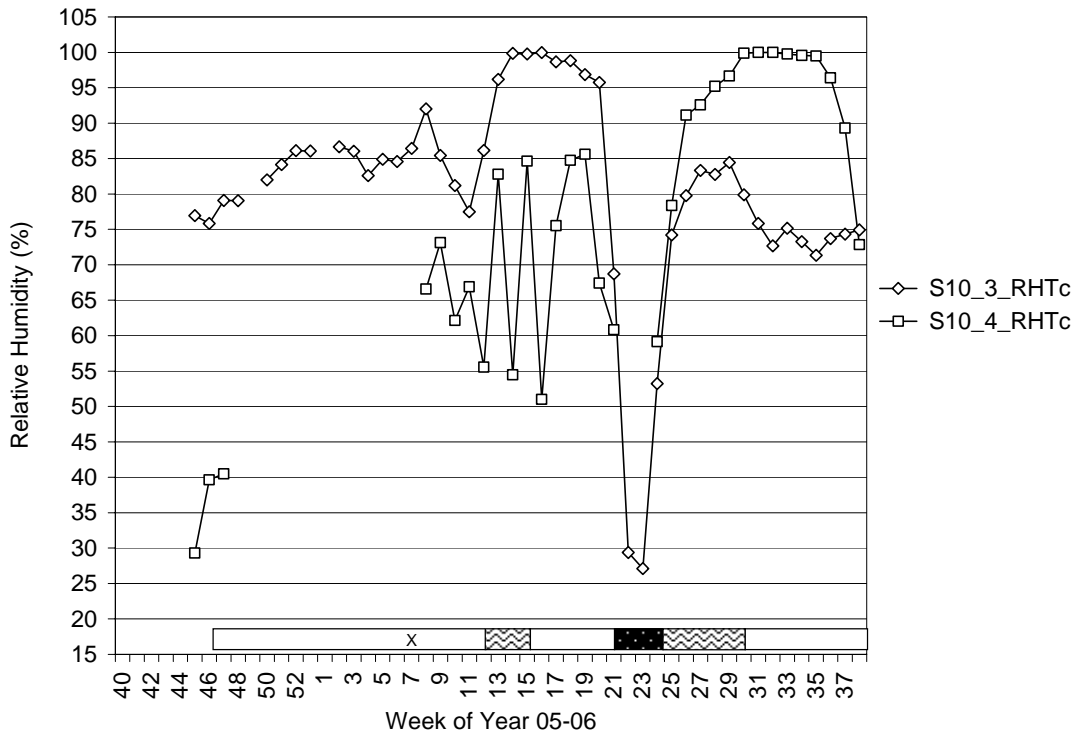


Figure B S10-3 S10 - Temperature

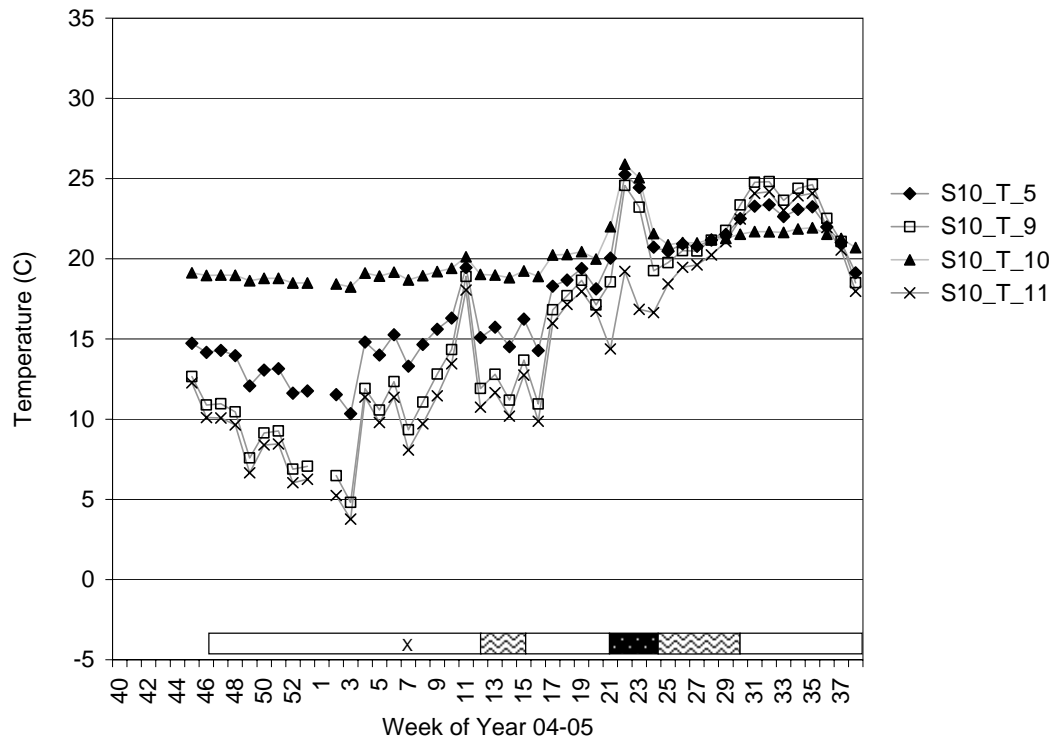
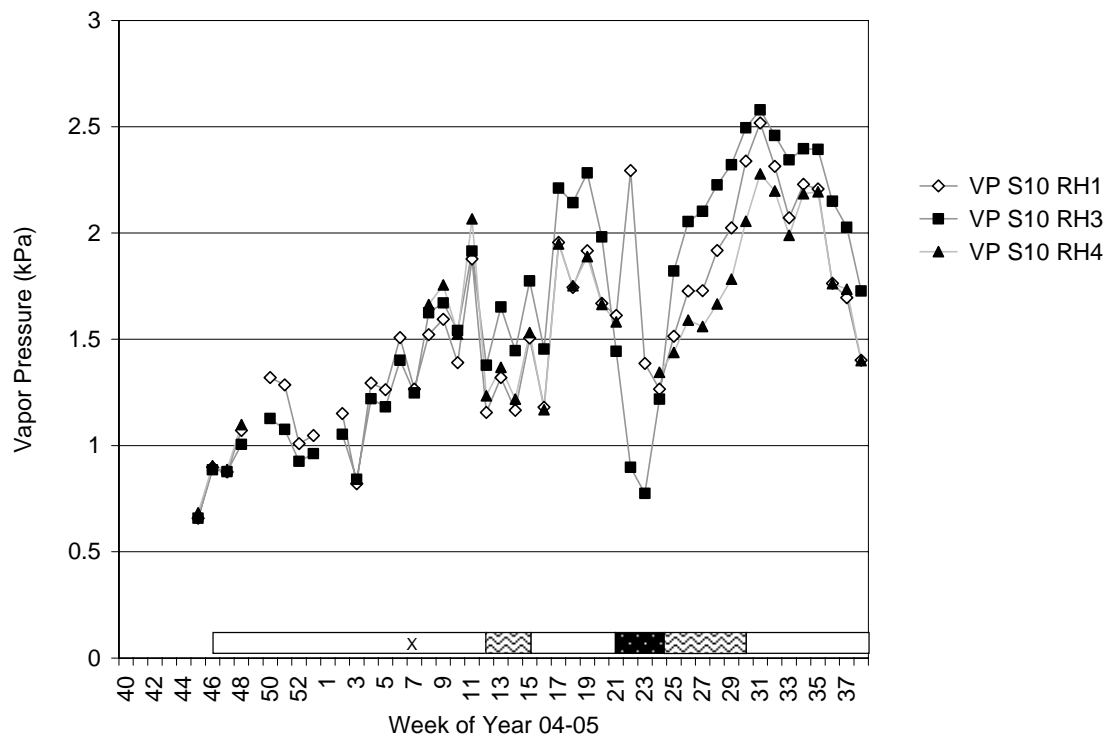
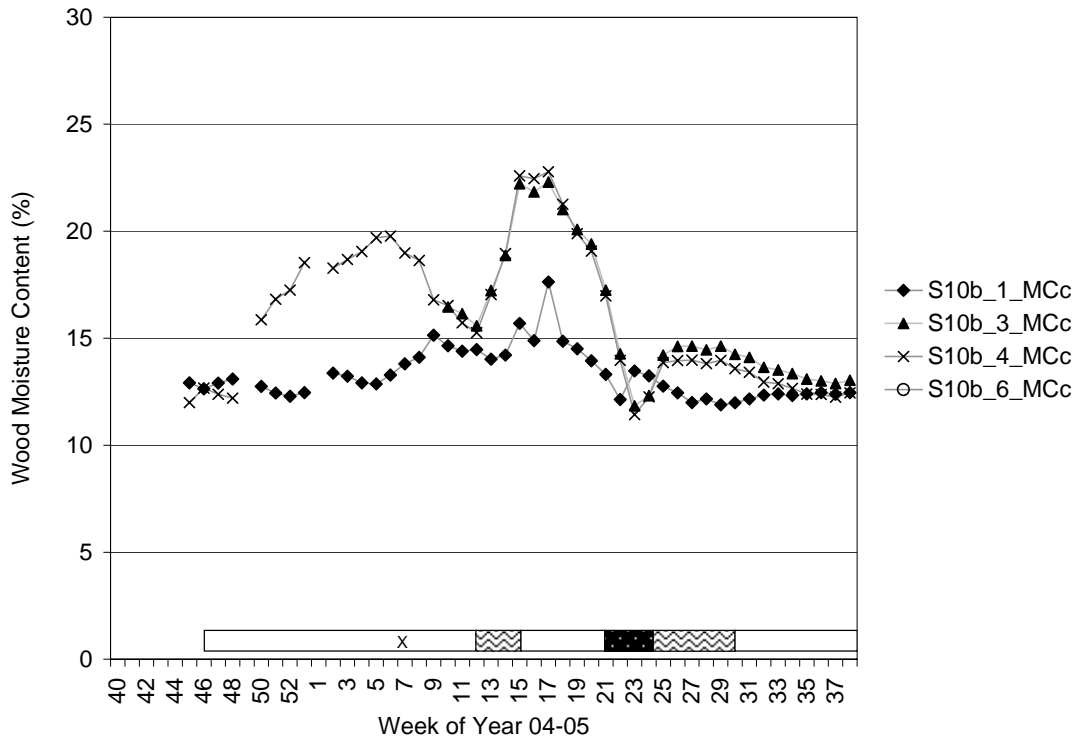


Figure B S10-4 S10 - Vapor Pressure



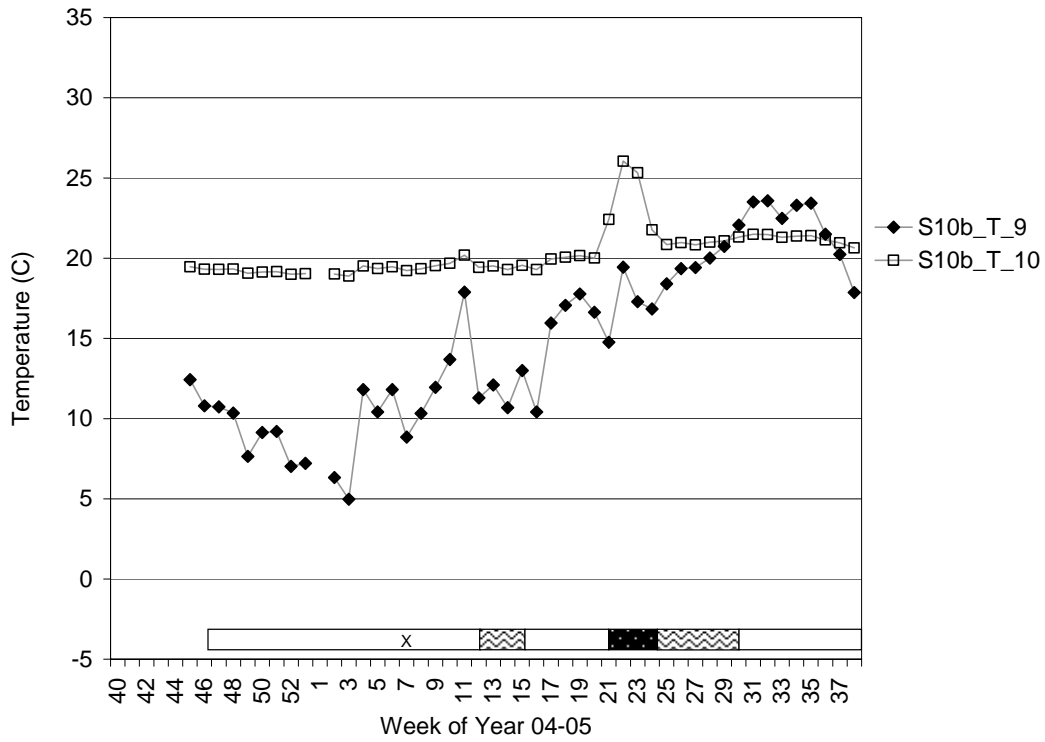
**Figure B S10b-1 S10b – Wood Moisture Content**



**Figure B S10b-2 S10b – Cavity Relative Humidity**



**Figure B S10b-3 S10b - Temperature**



**Figure B S10b-4 S10b – Vapor Pressure**

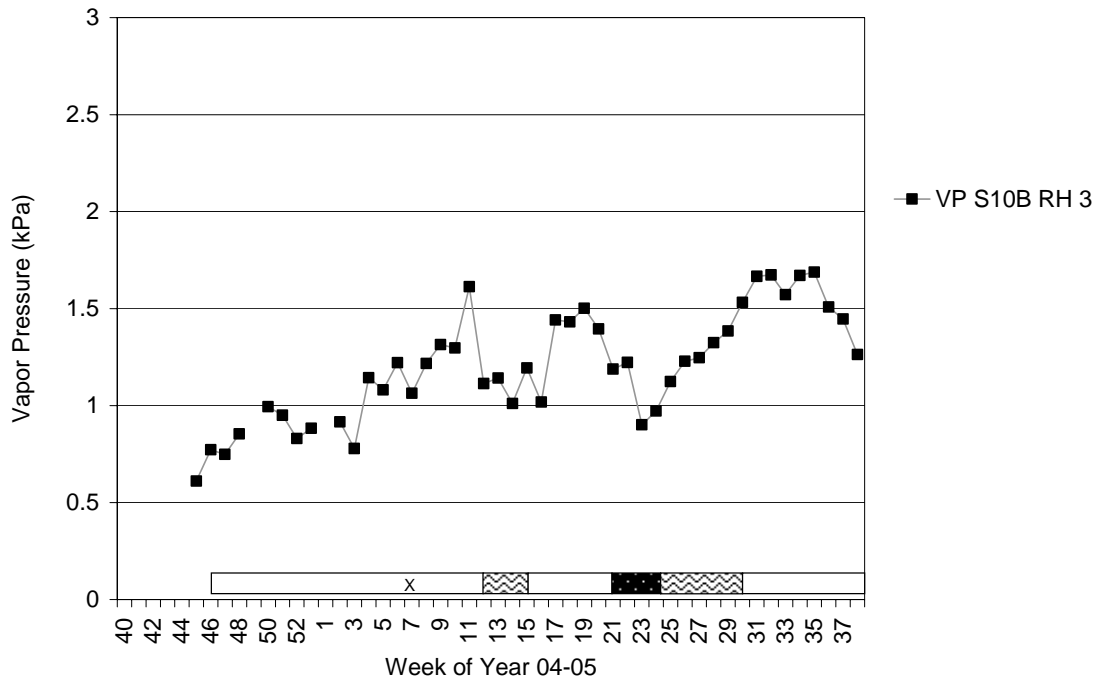


Figure B S11-1

S11 – Wood Moisture Content

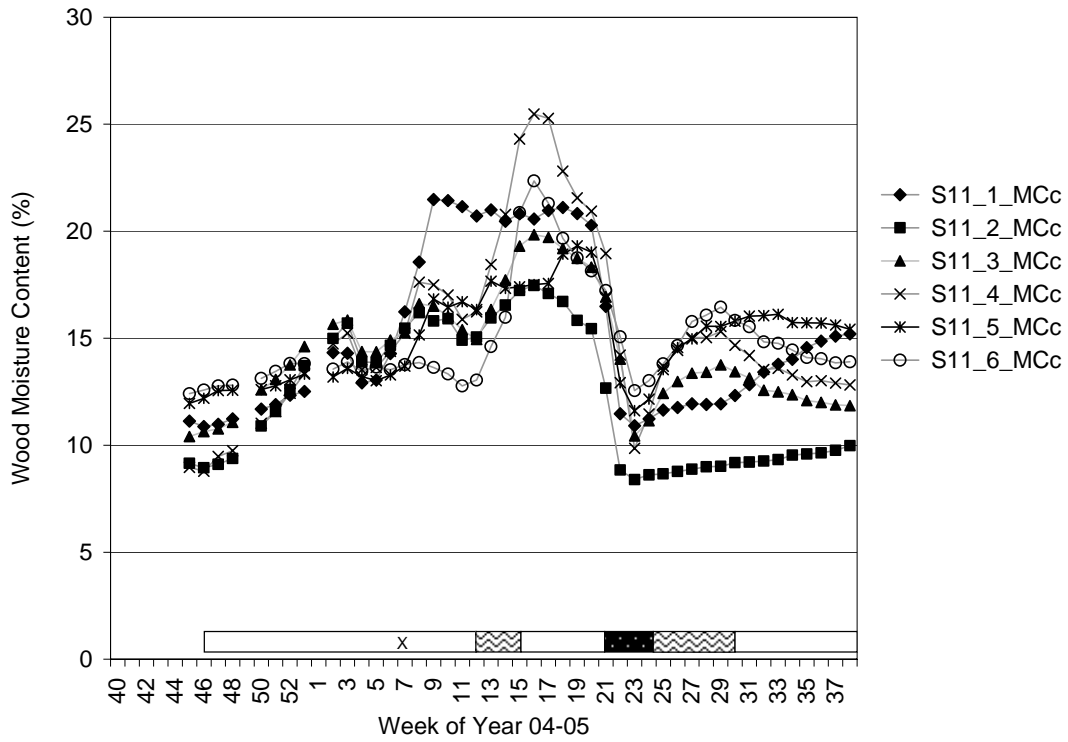


Figure B S11-2

S11 – Cavity Relative Humidity



Figure B S11-3

S11 - Temperature

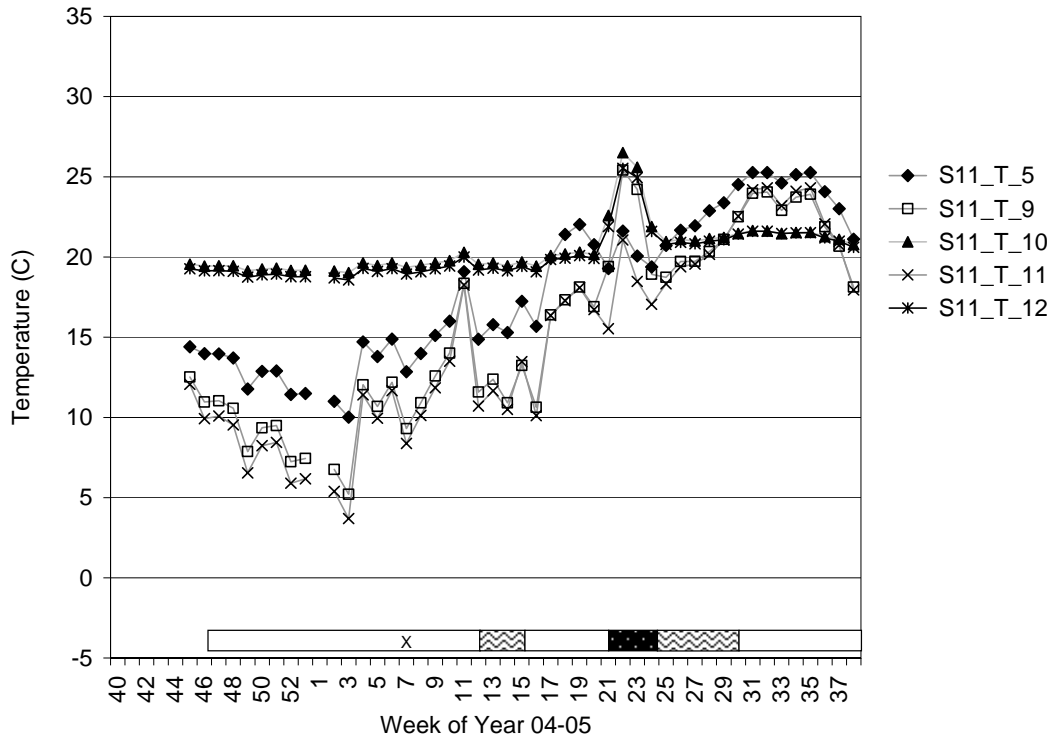


Figure B S11-4

S11 - Vapor Pressure

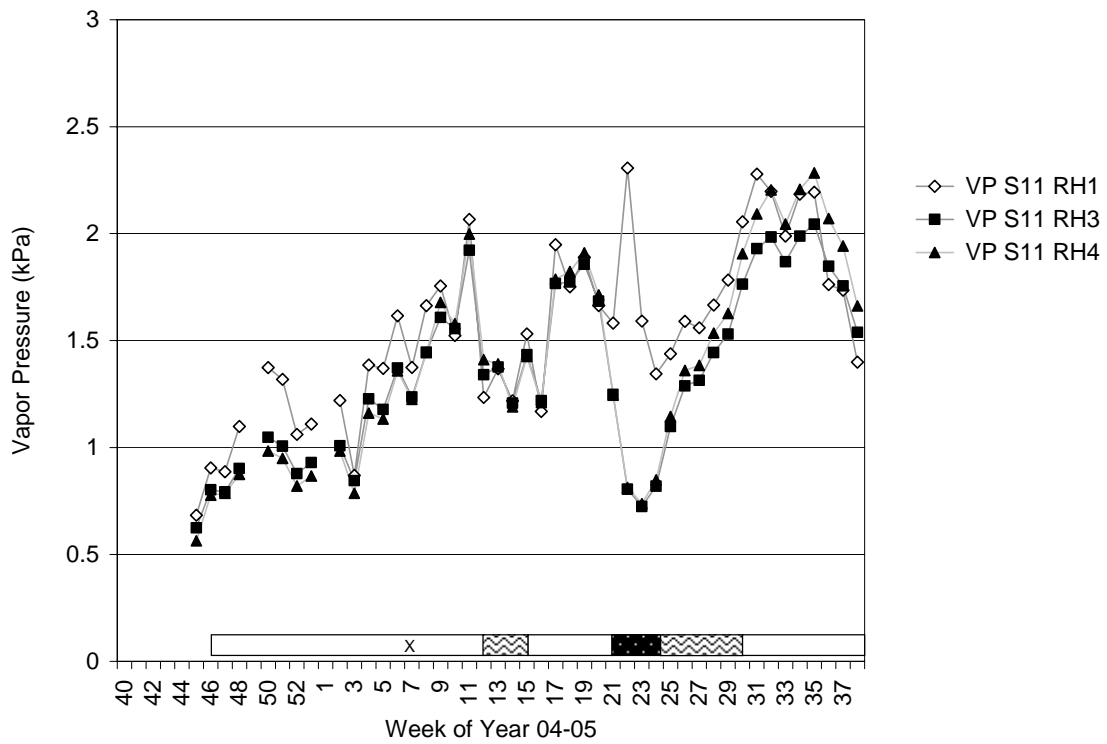


Figure B S12-1

S12 – Wood Moisture Content

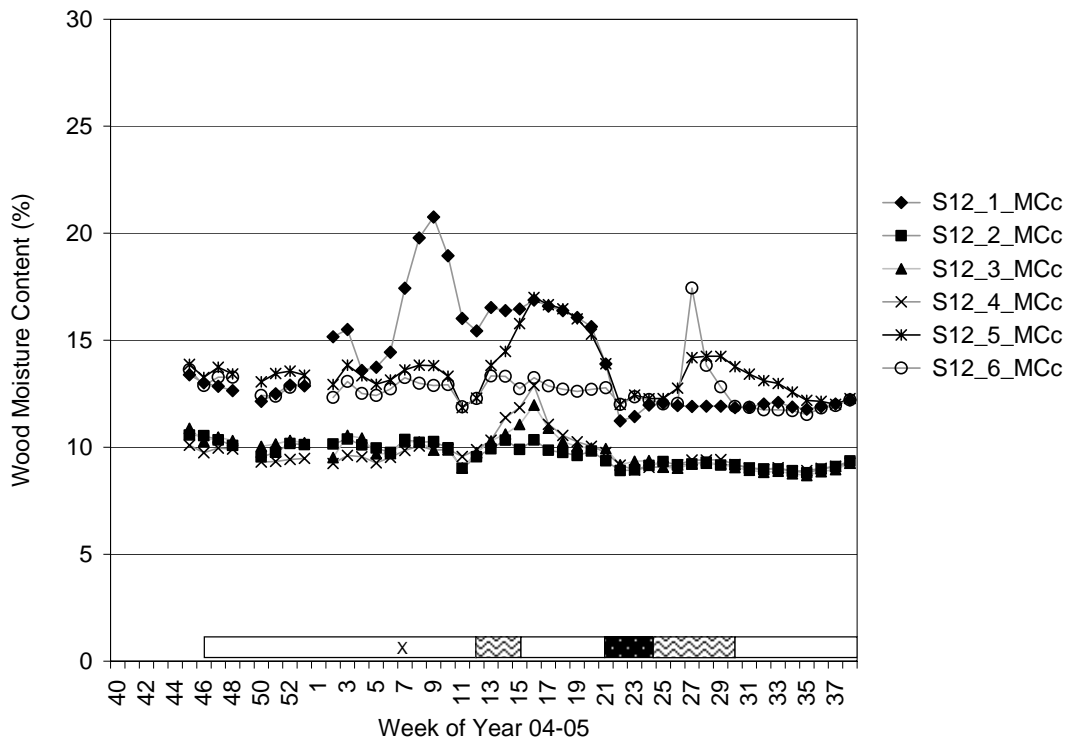


Figure B S12-2 S12 – Cavity Relative Humidity

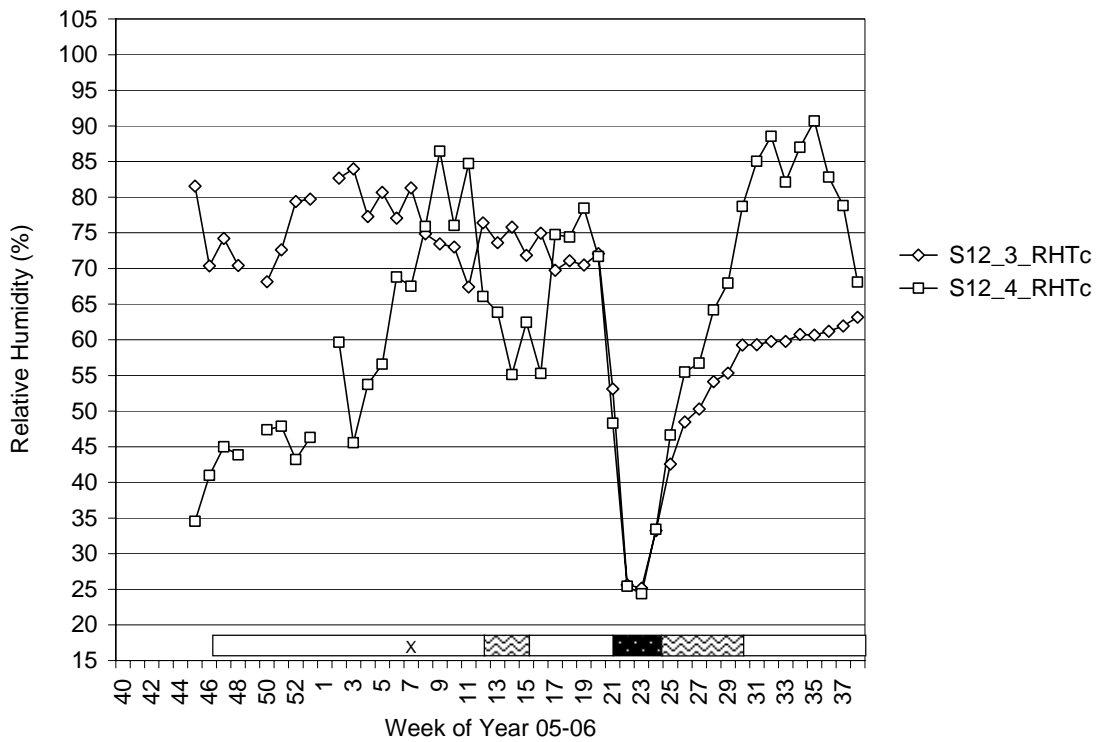


Figure B S12-3 S12 - Temperature

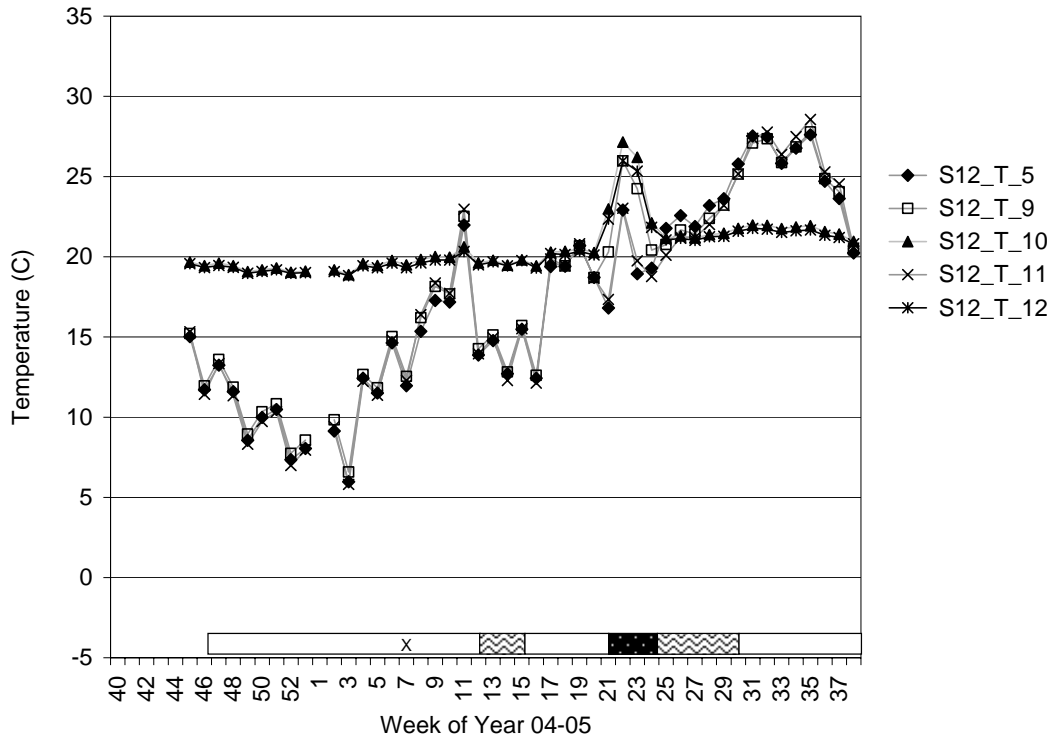
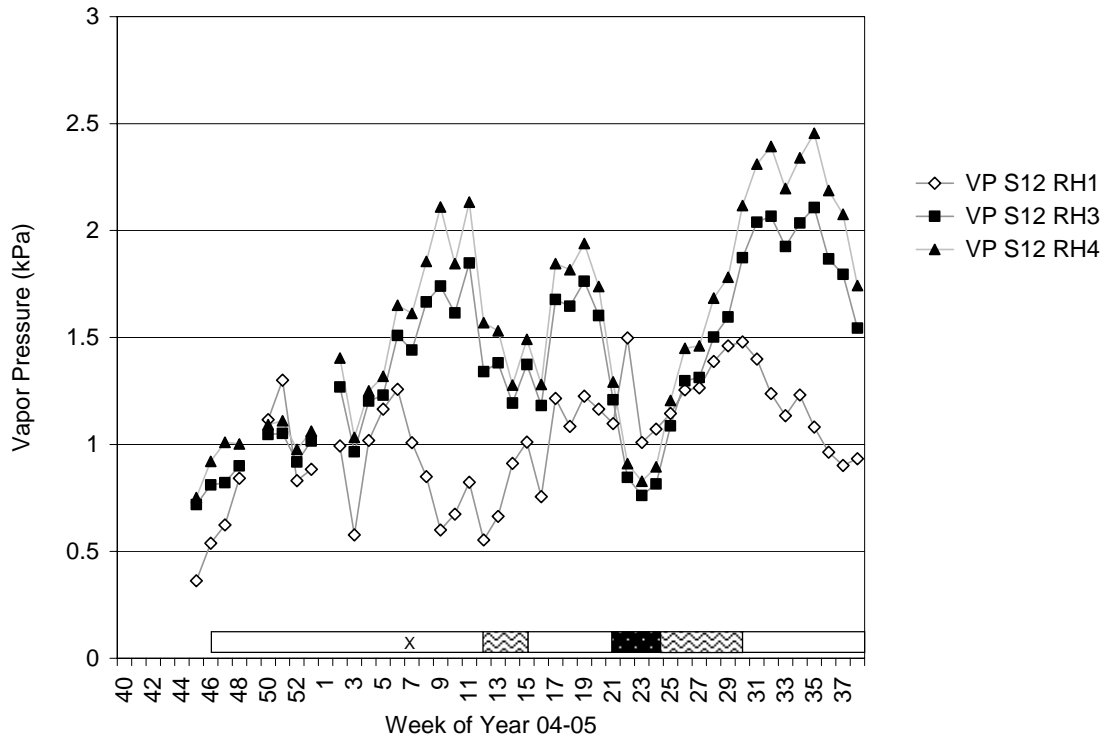
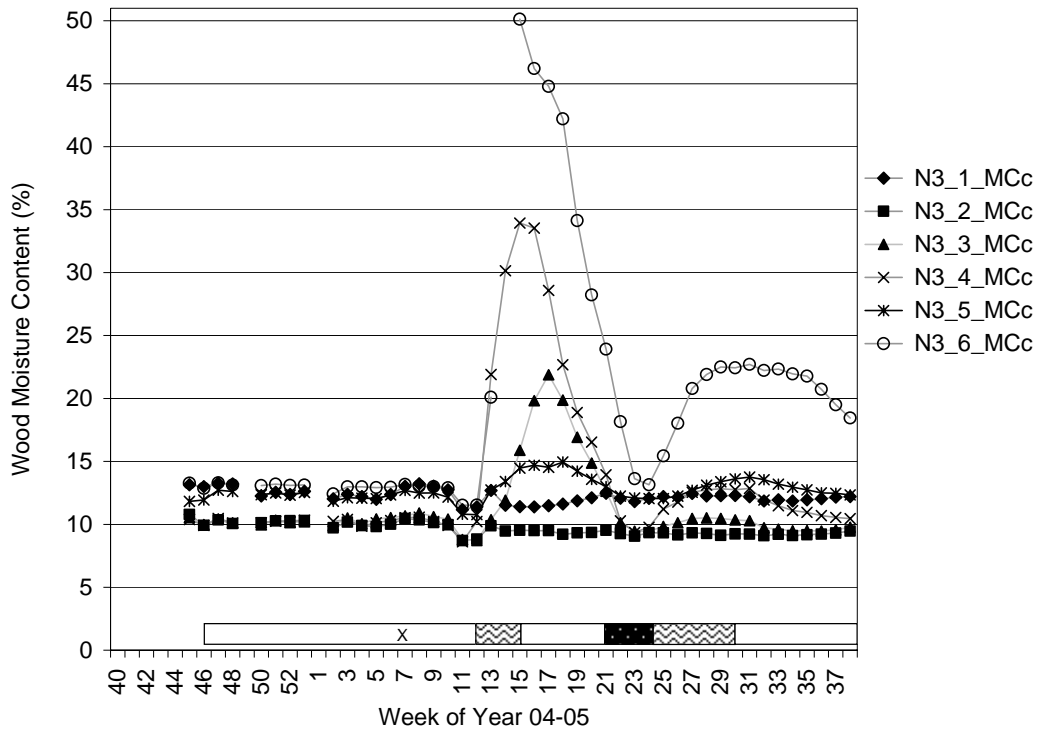


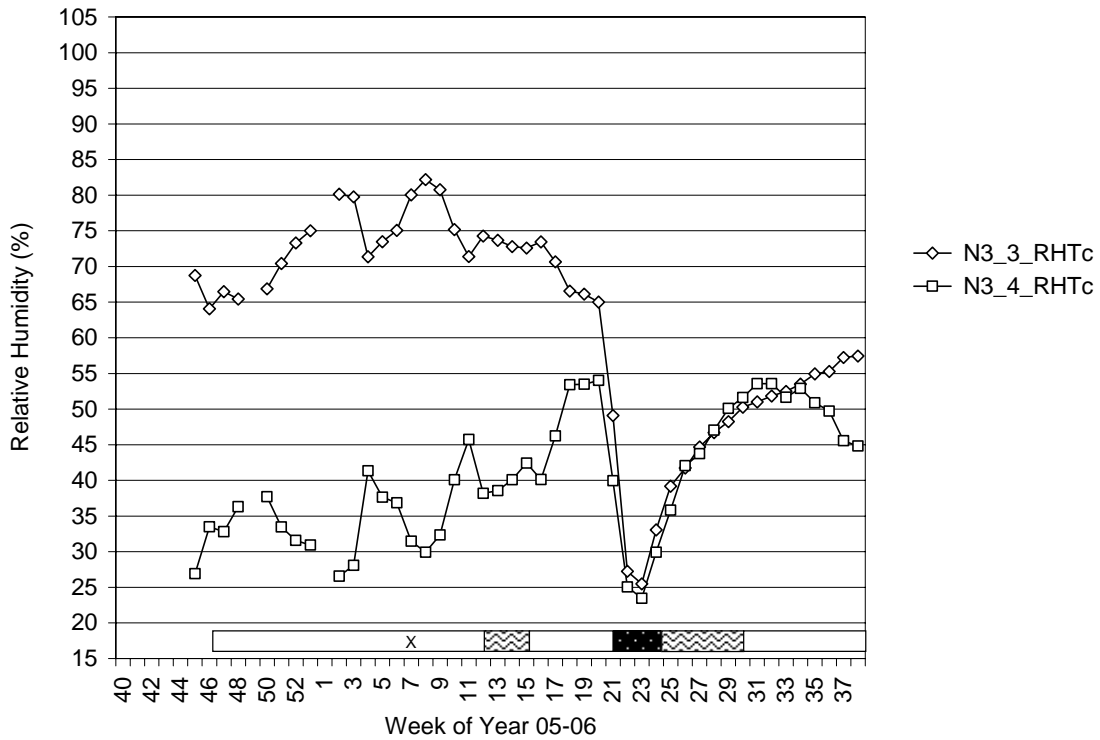
Figure B S12-4 12 – Vapor Pressure



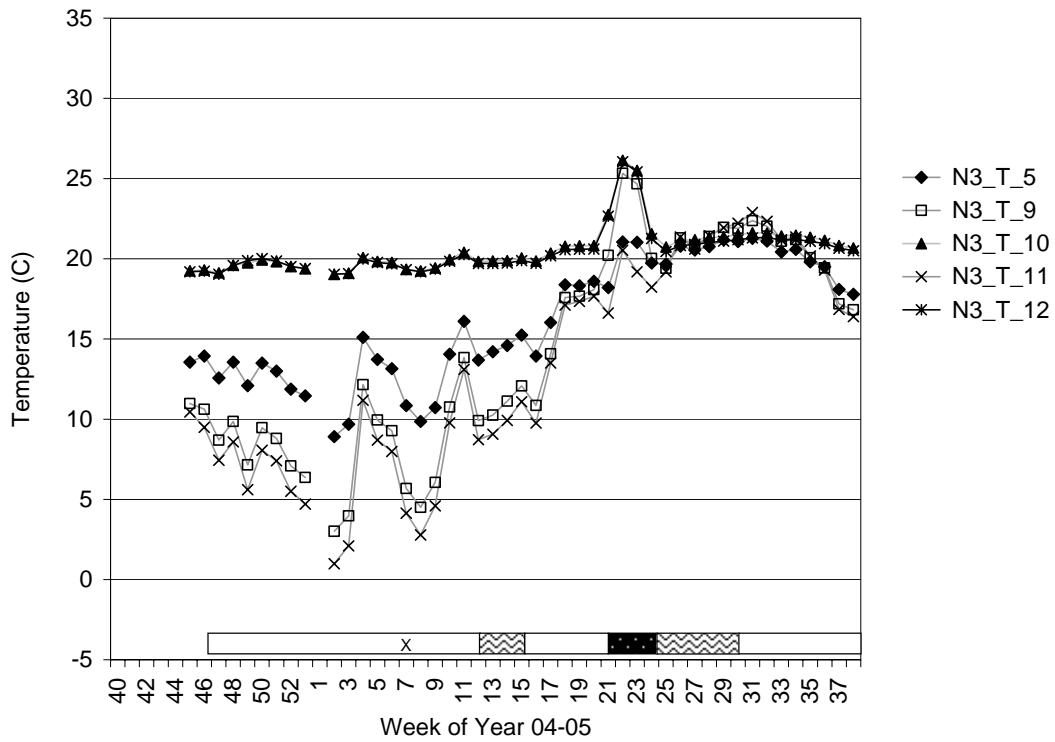
**Figure B N3-1 N3 – Wood Moisture Content**



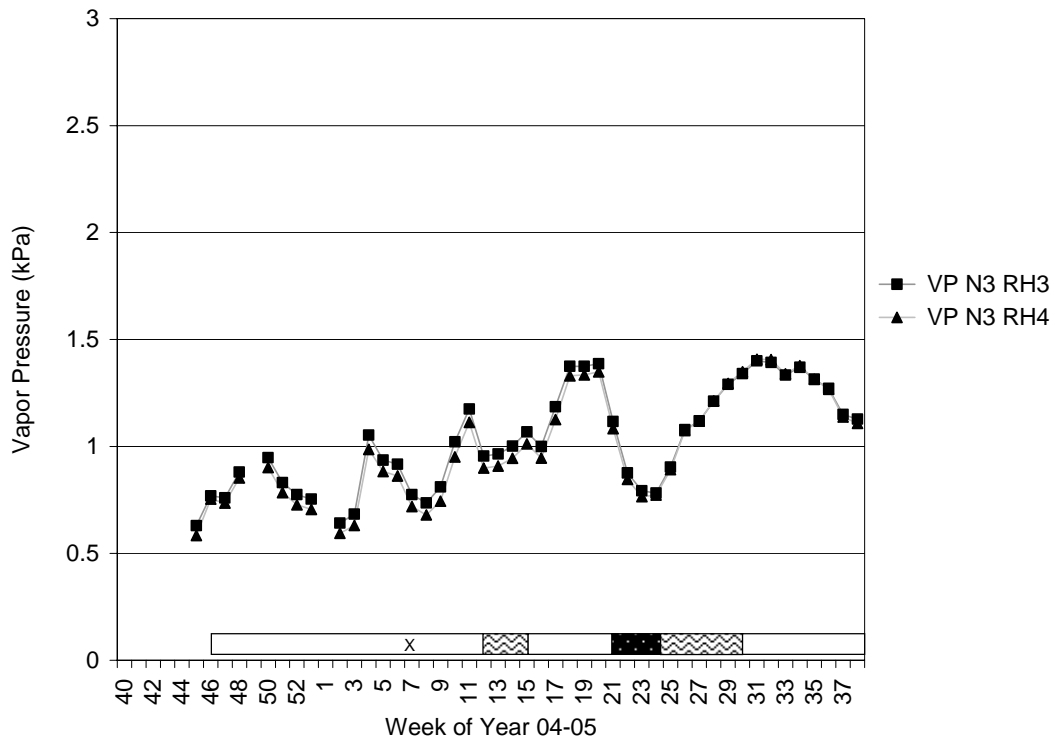
**Figure B N3-2 N3 – Cavity Relative Humidity**



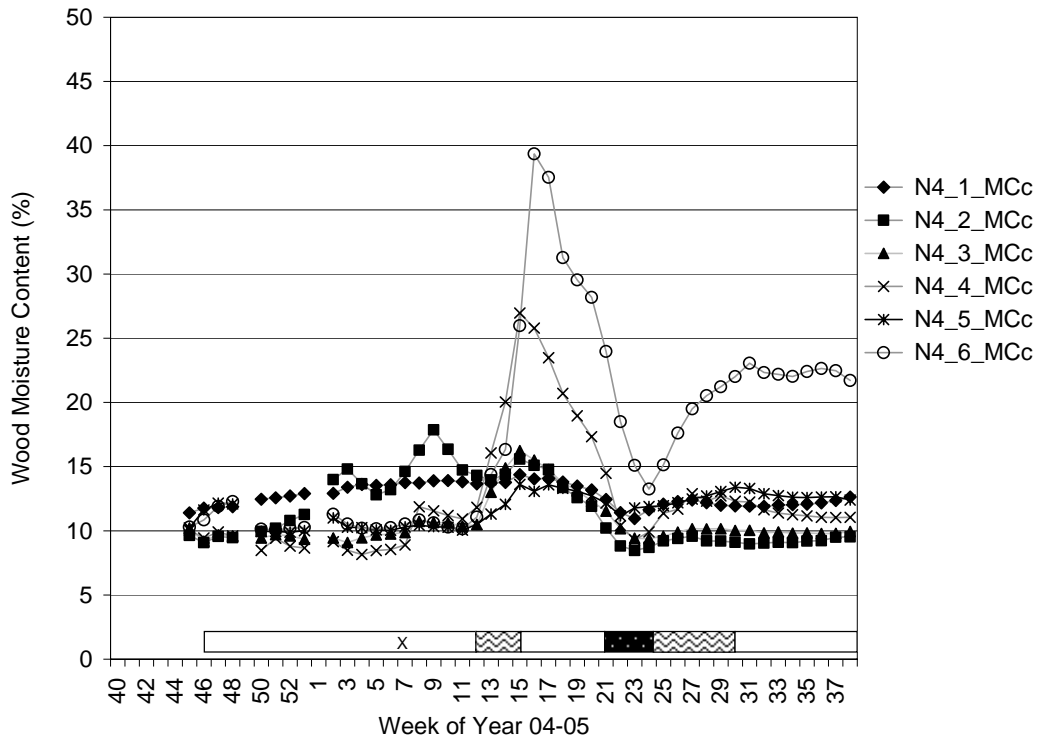
**Figure B N3-3 N3 - Temperature**



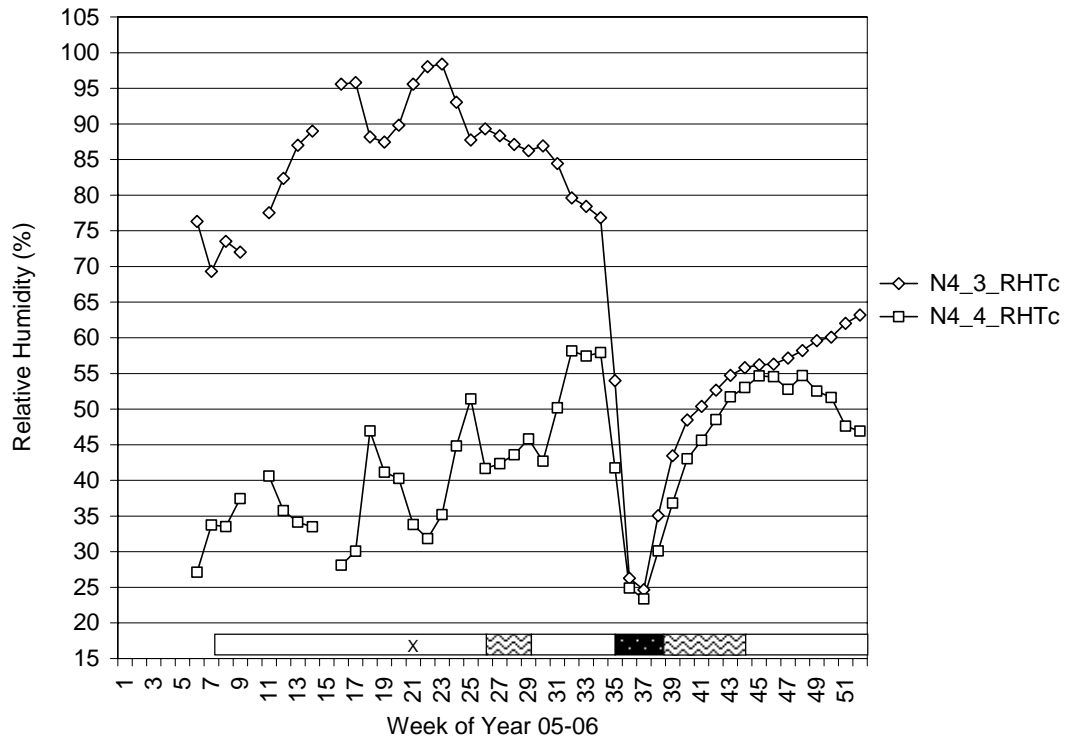
**Figure B N3-4 N3 – Vapor Pressure**



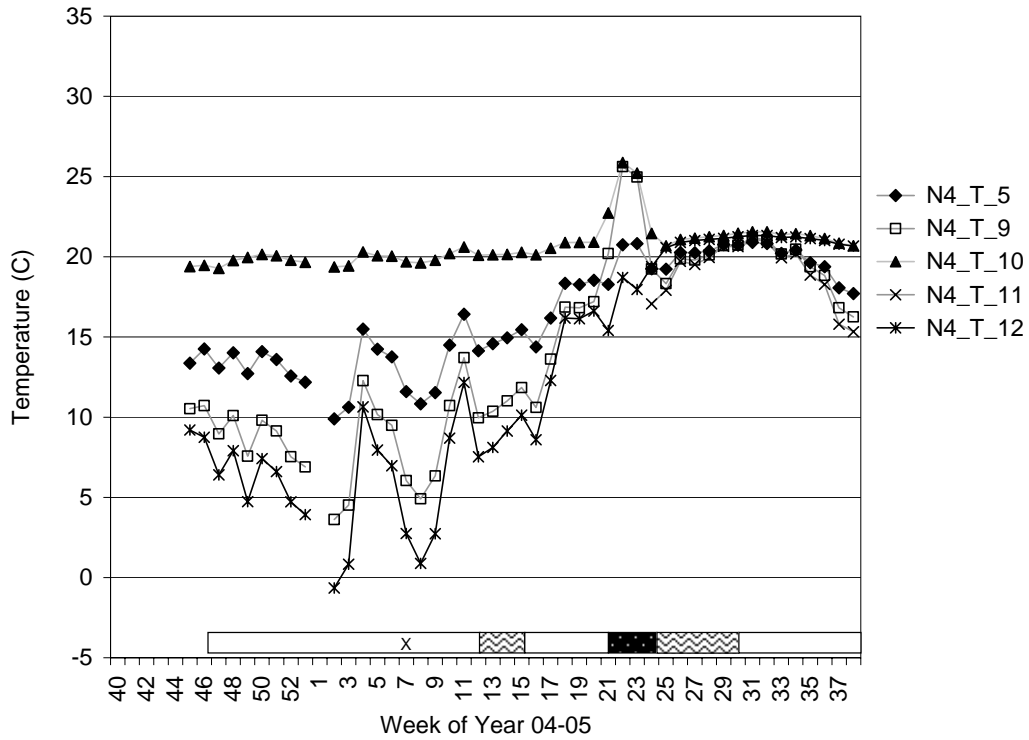
**Figure B N4-1 N4 – Wood Moisture Content**



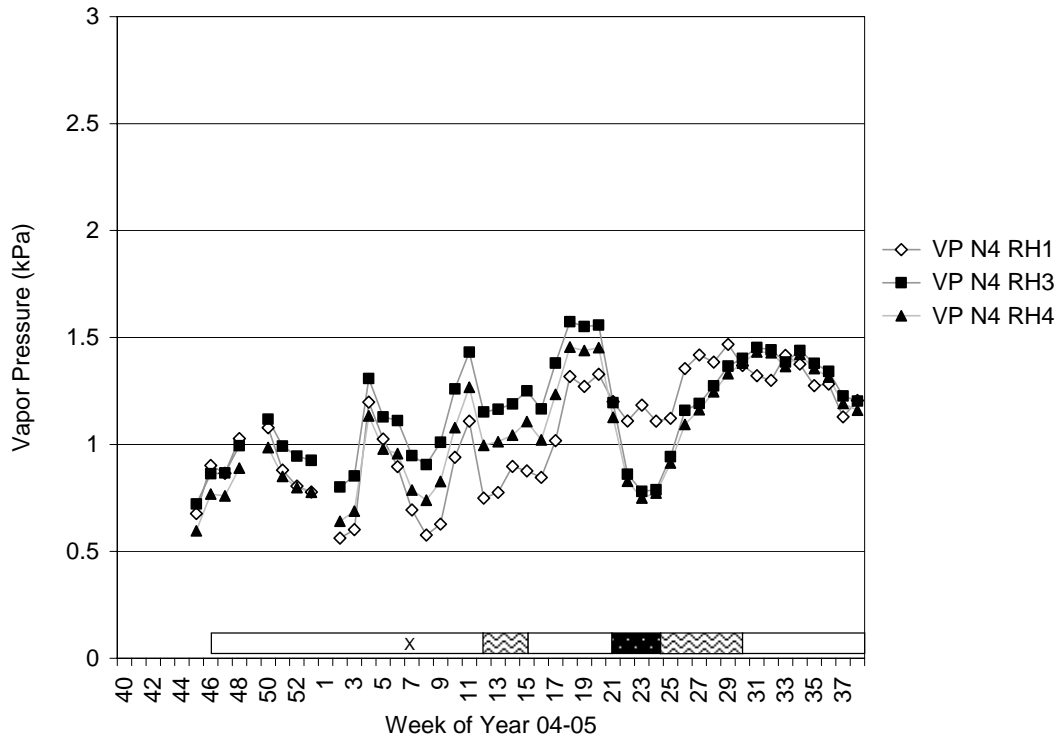
**Figure B N4-2 N4 – Cavity Relative Humidity**



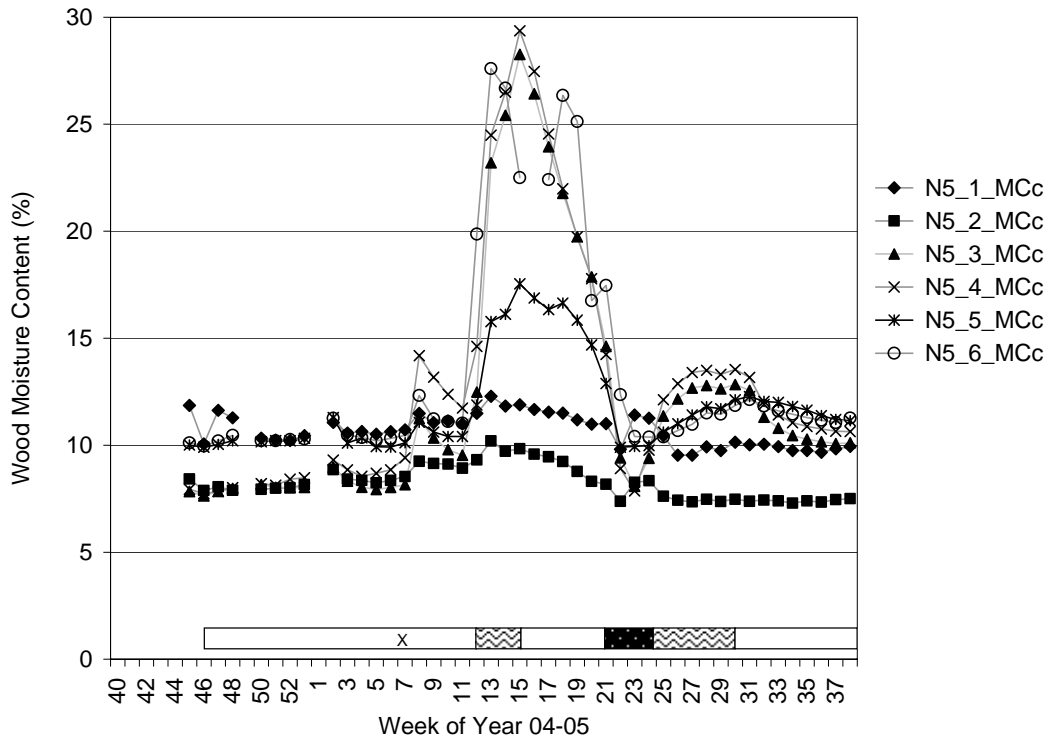
**Figure B N4-3 N4 - Temperature**



**Figure B N4-4 N4 – Vapor Pressure**



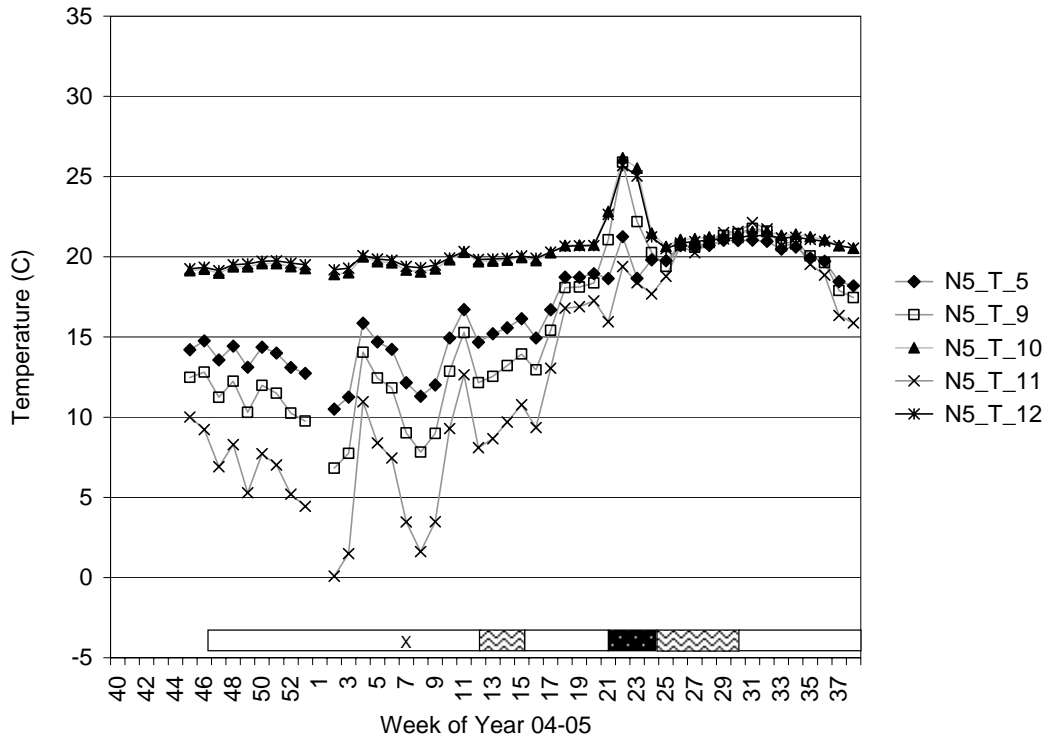
**Figure B N5-1 N5 – Wood Moisture Content**



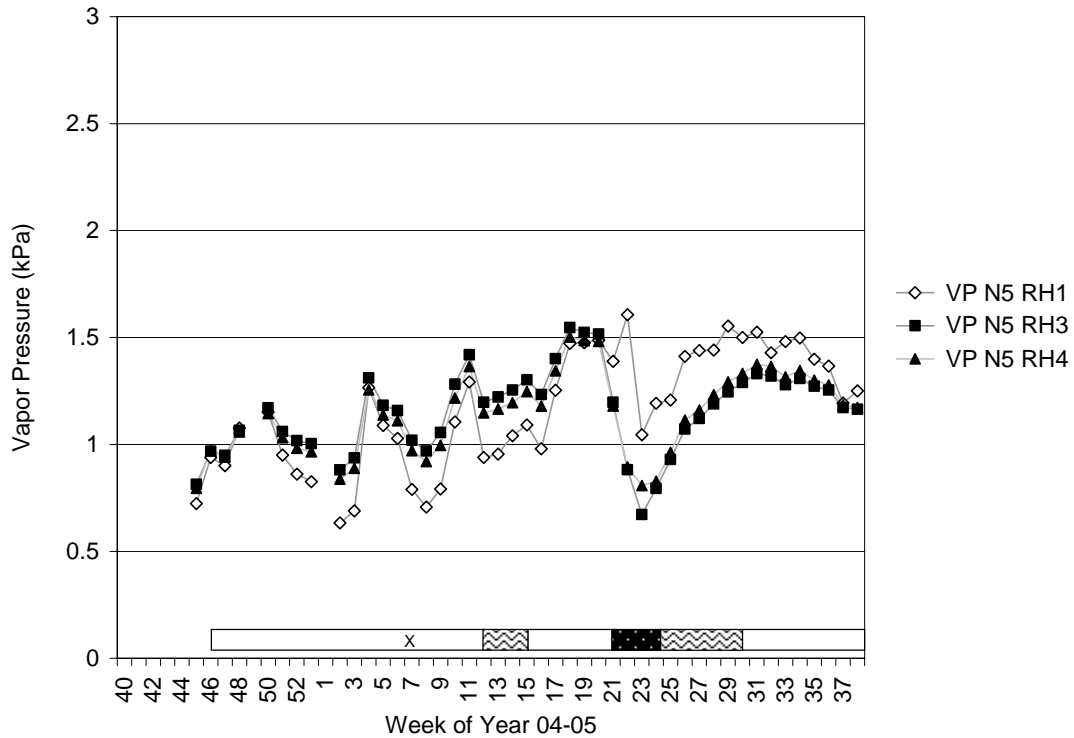
**Figure B N5-2 N5 – Cavity Relative Humidity**



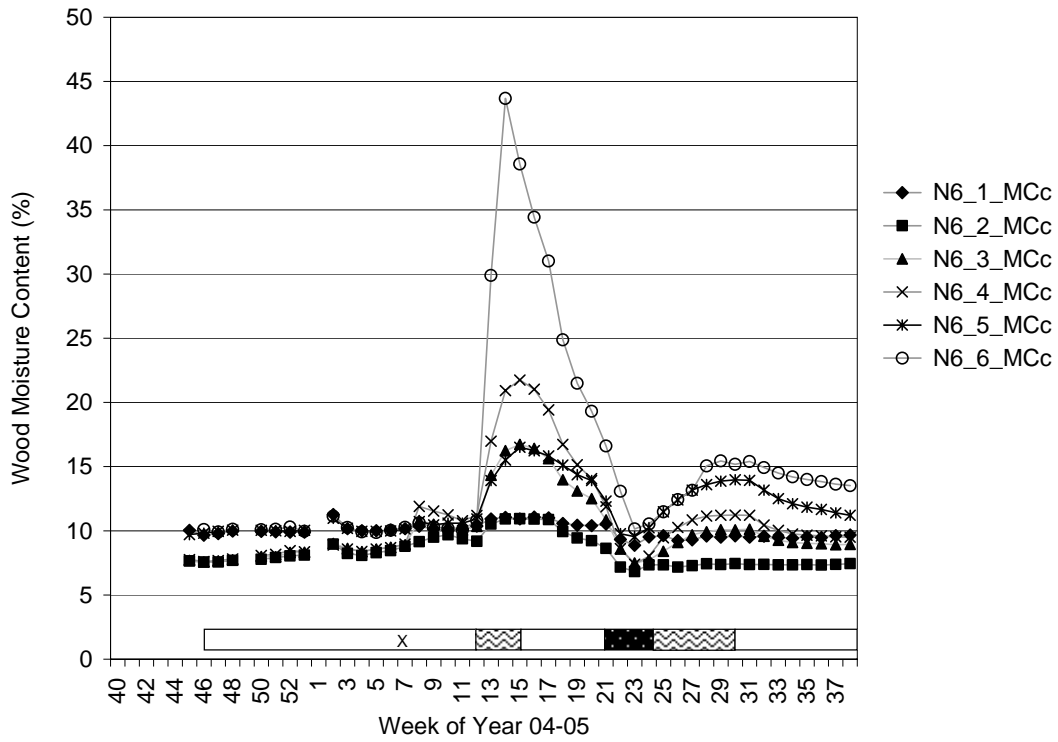
**Figure B N5-3 N5 - Temperature**



**Figure B N5-4 N5 – Vapor Pressure**



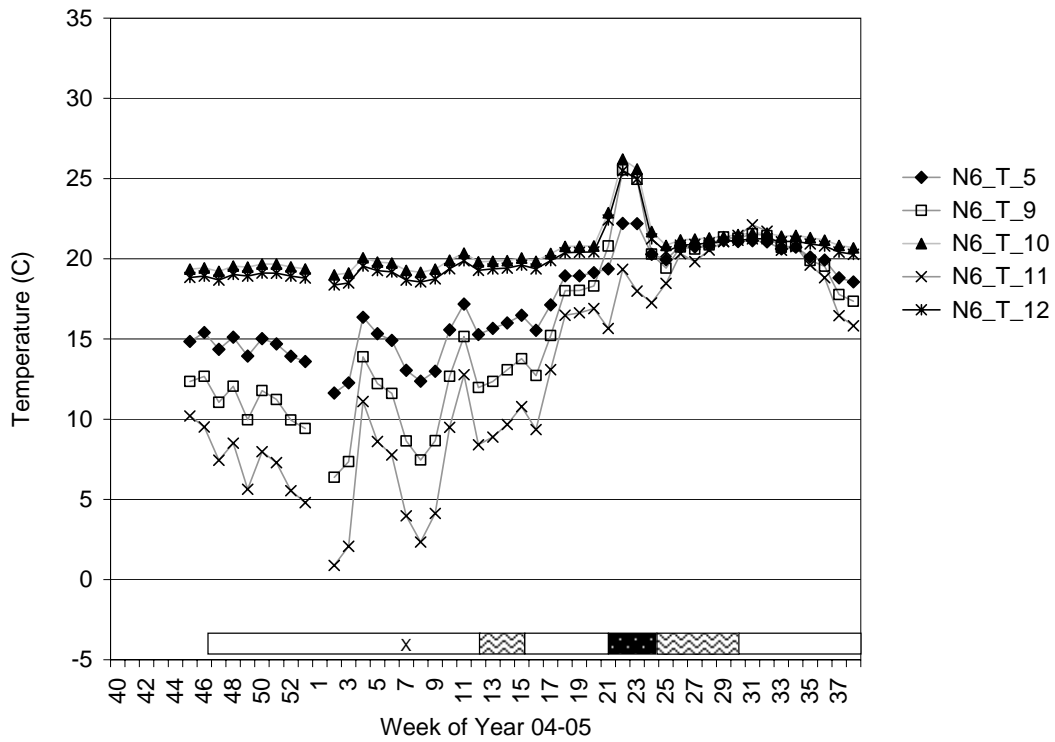
**Figure B N6-1 N6 – Wood Moisture Content**



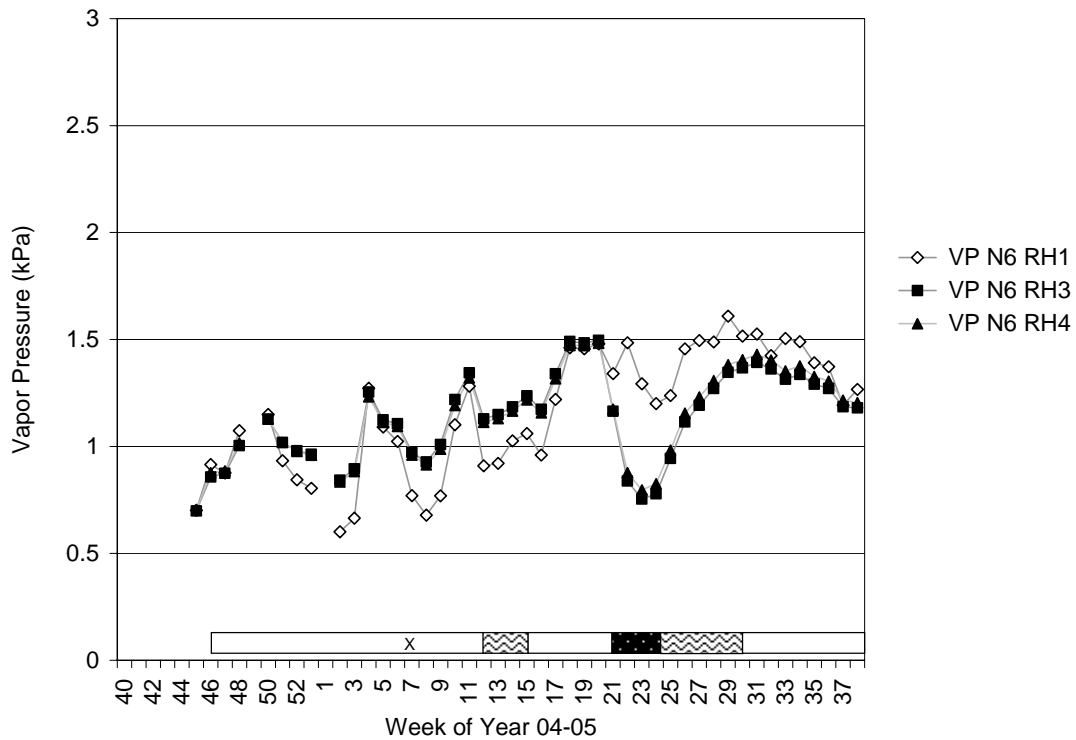
**Figure B N6-2 N6 – Cavity Relative Humidity**



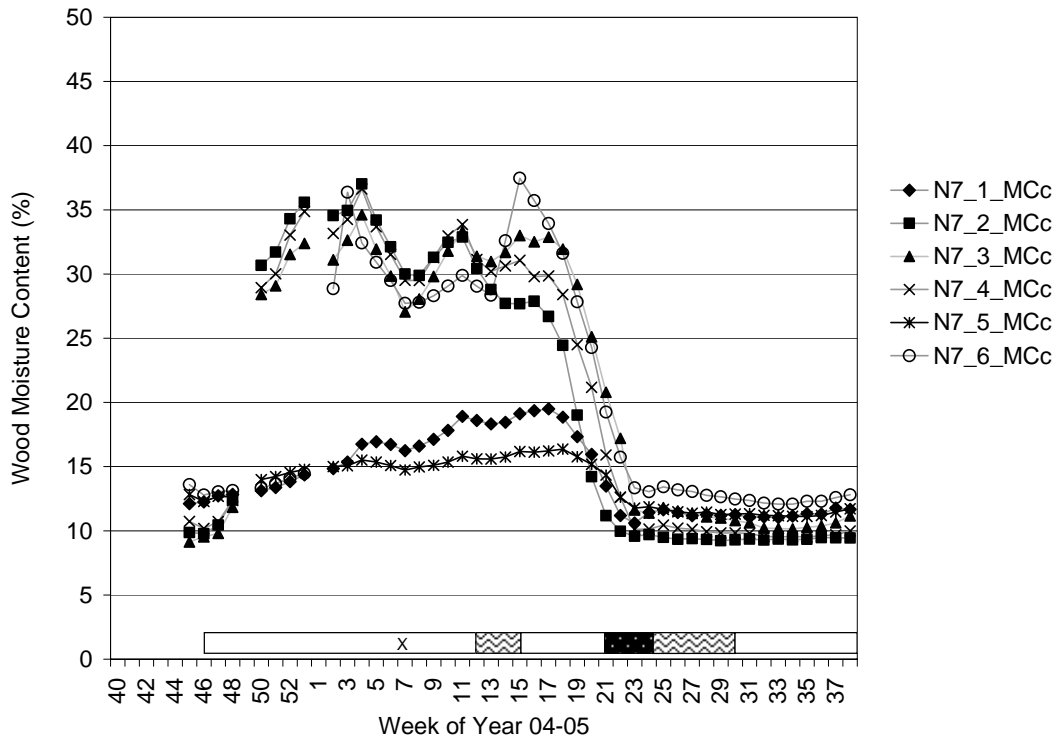
**Figure B N6-3 N6 - Temperature**



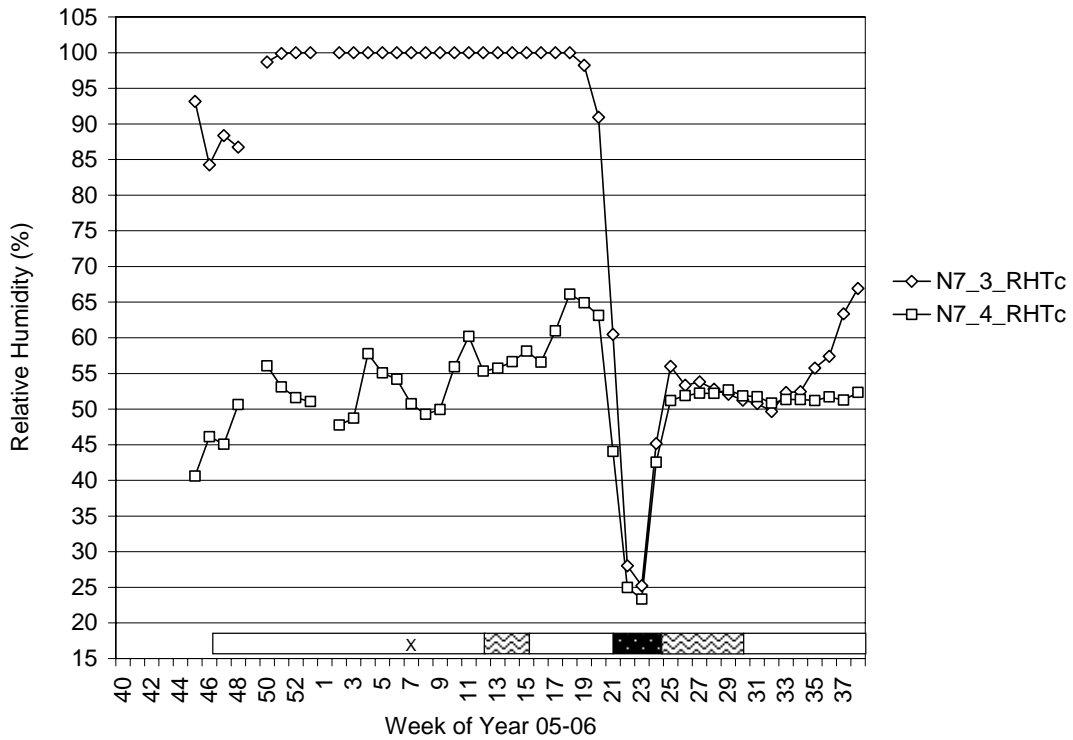
**Figure B N6-4 N6 – Vapor Pressure**



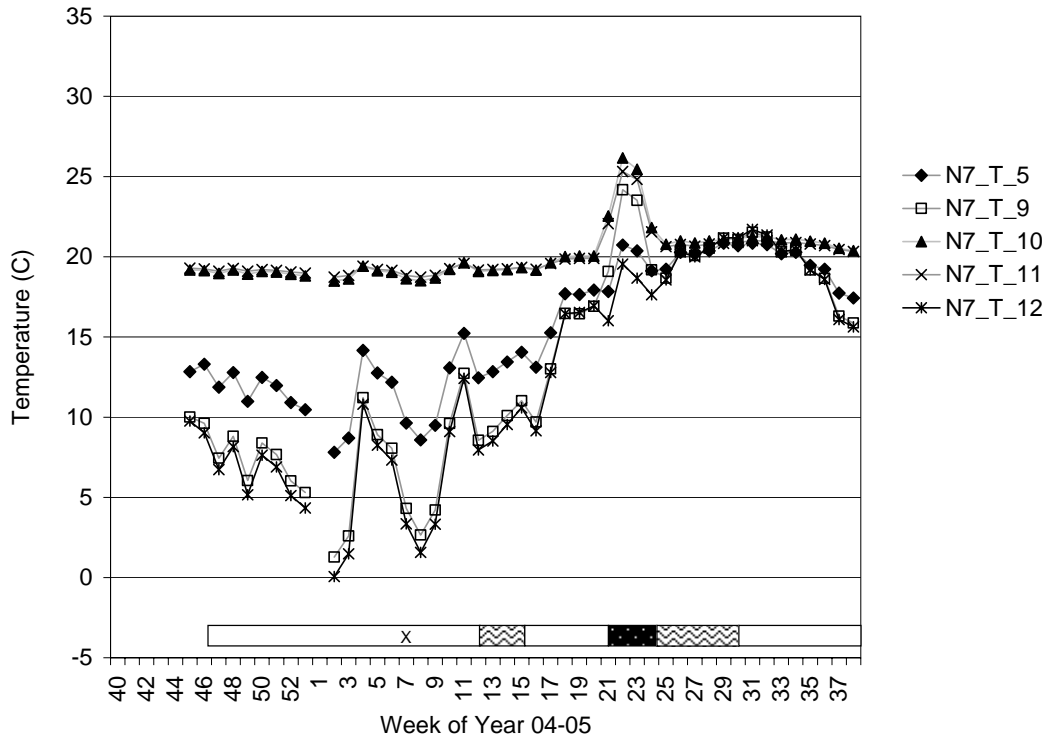
**Figure B N7-1 N7 – Wood Moisture Content**



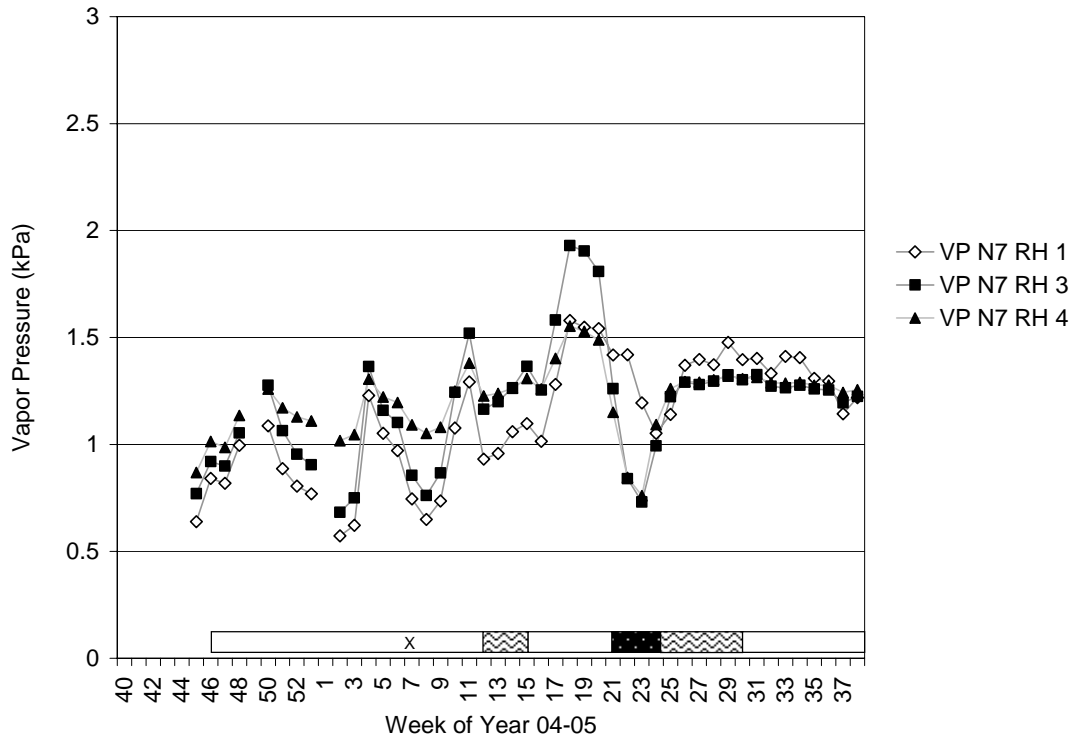
**Figure B N7-2 N7 – Cavity Relative Humidity**



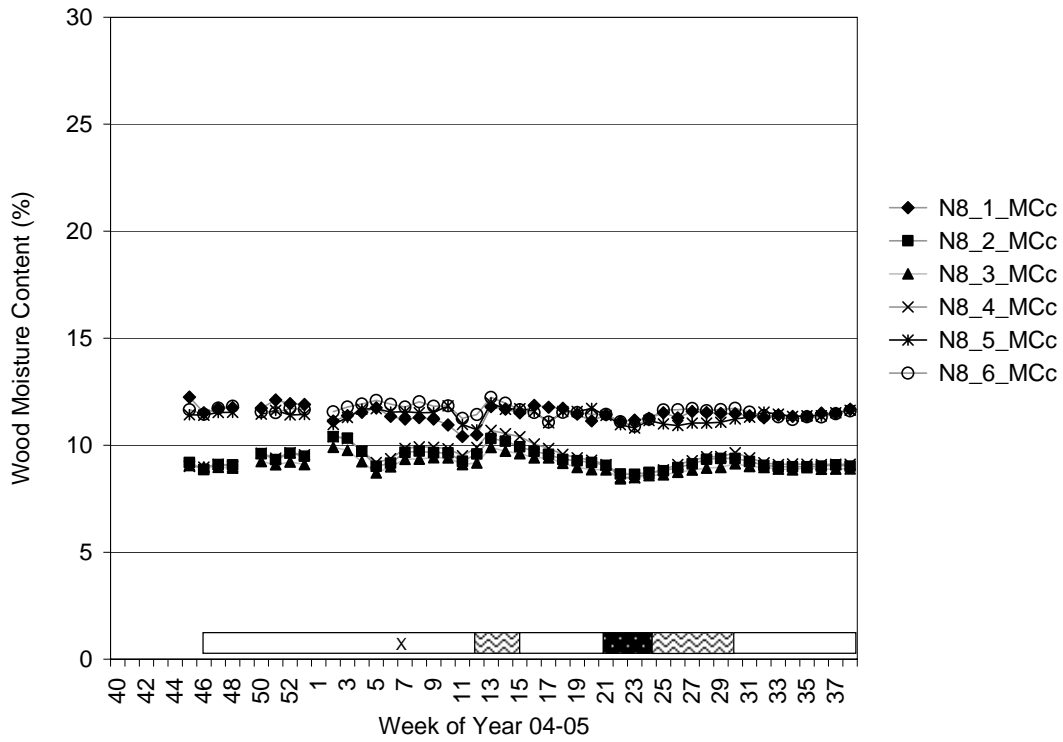
**Figure B N7-3 N7 - Temperature**



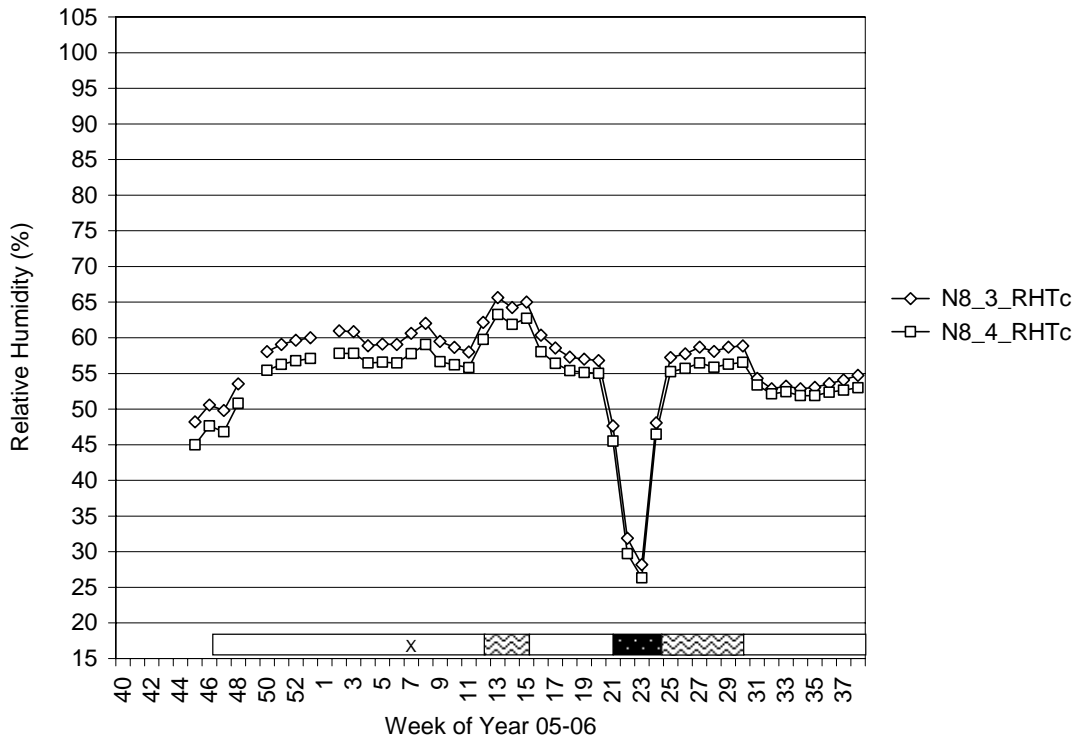
**Figure B N7-4 N7 – Vapor Pressure**



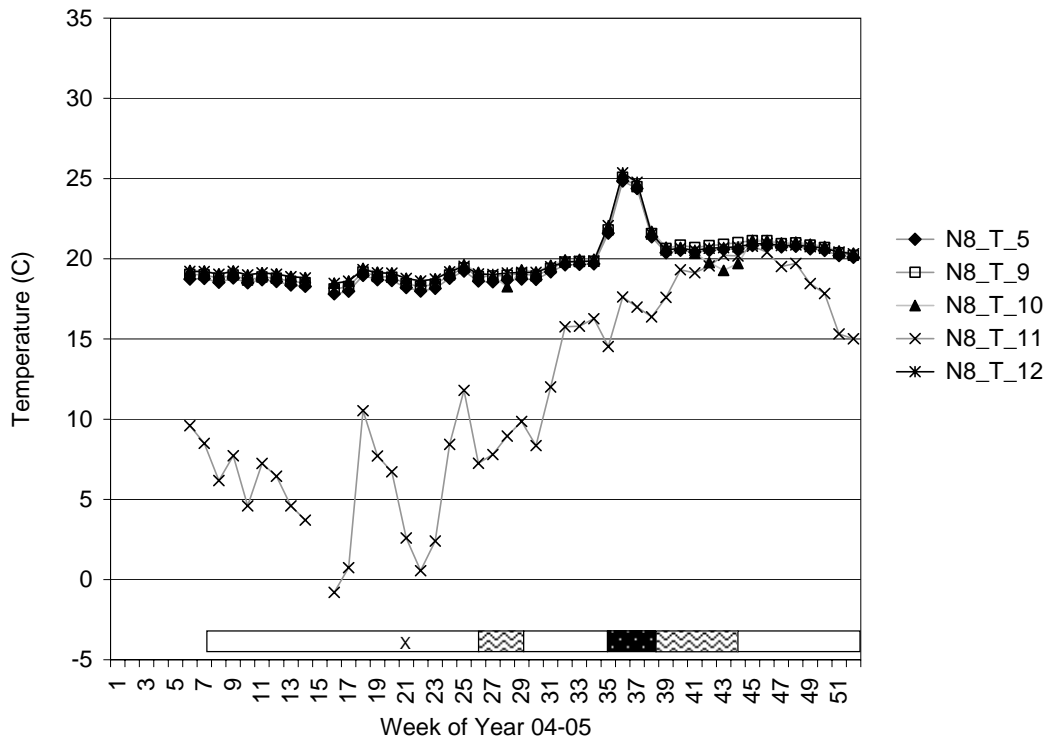
**Figure B N8-1 N8 – Wood Moisture Content**



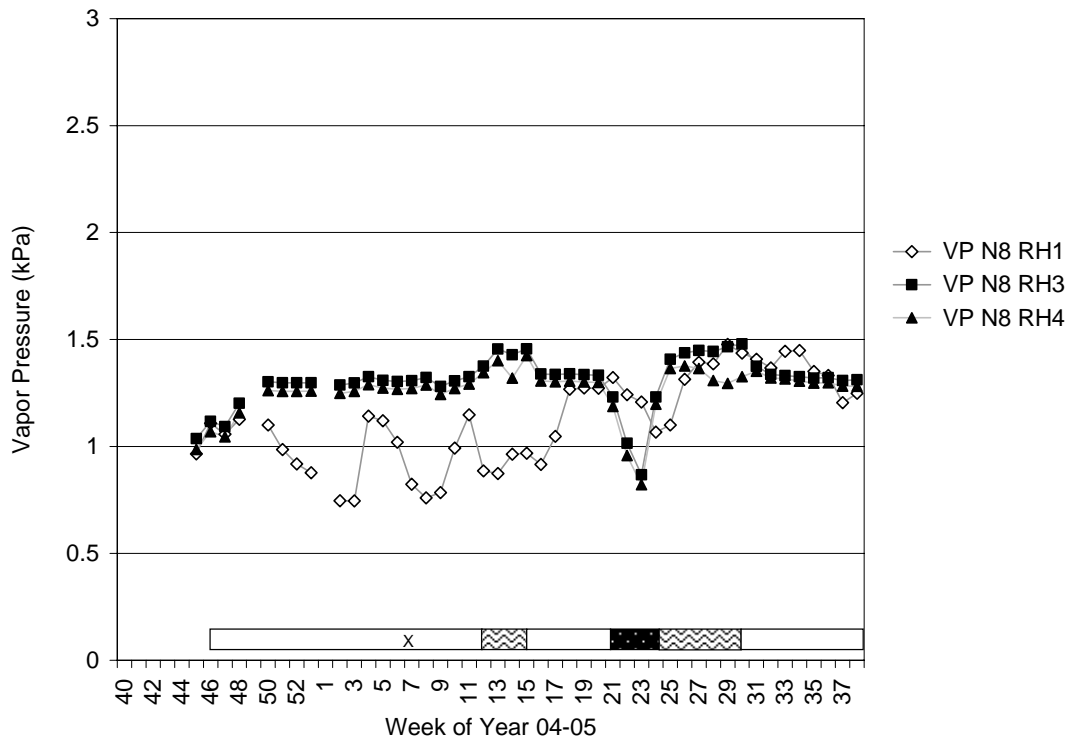
**Figure B N8-2 N8 – Cavity Relative Humidity**



**Figure B N8-3 N8 - Temperature**

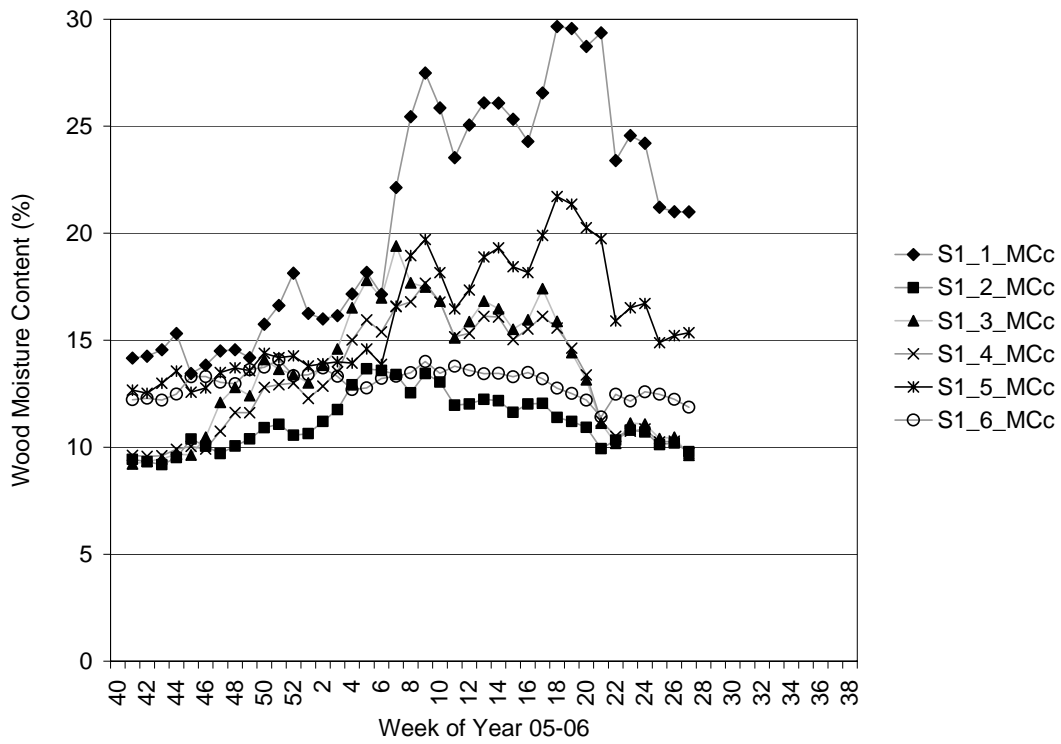


**Figure B N8-3 N8 – Vapor Pressure**



**Appendix C**  
**Test Cycle 3 Figures**  
**October 1, 2005 to June 30, 2006**

**Figure C S1-1 S1 – Wood Moisture Content**



**Figure C S1-2 S1 – Cavity Relative Humidity**

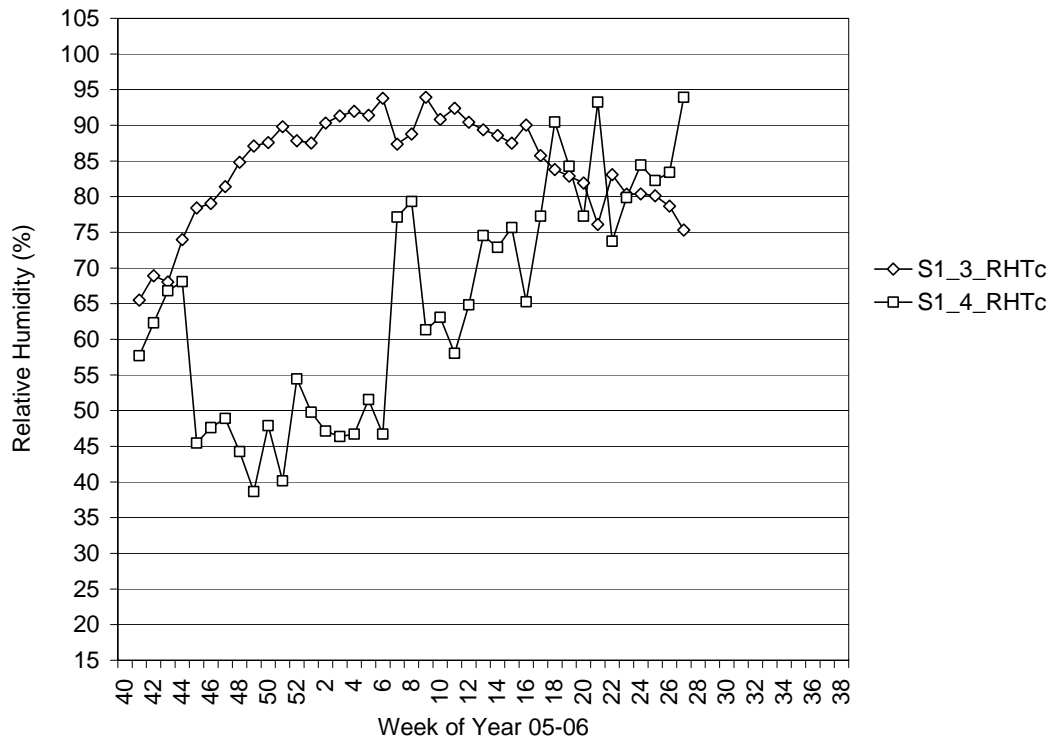


Figure C S1-3 S1 - Temperature

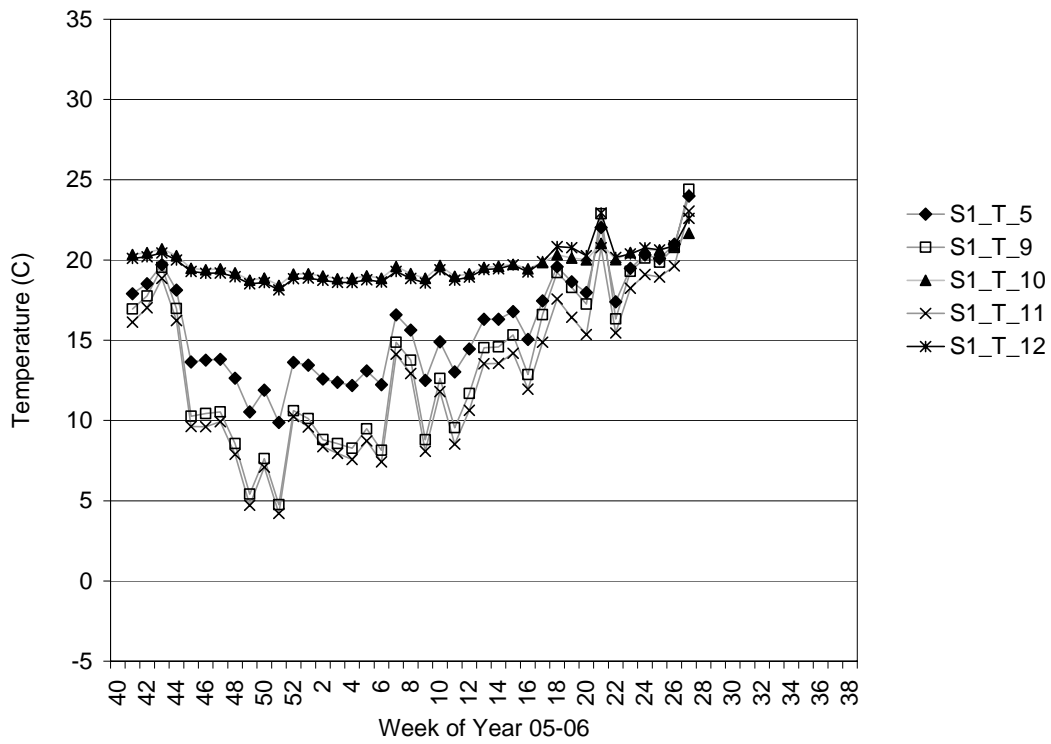
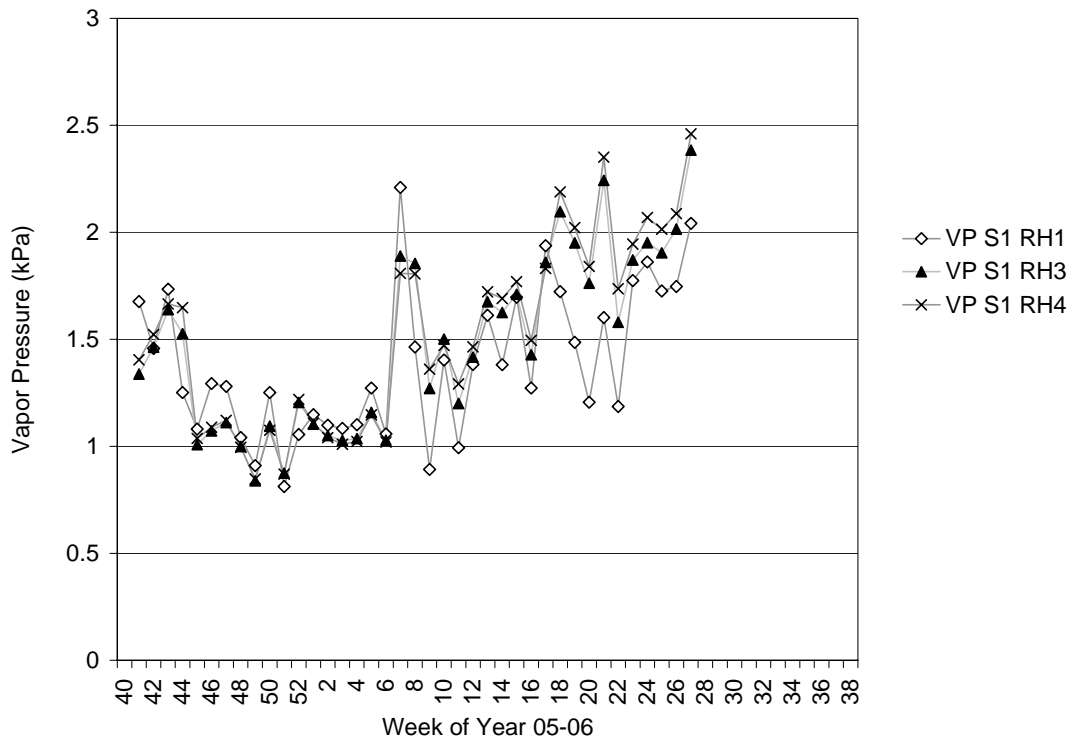
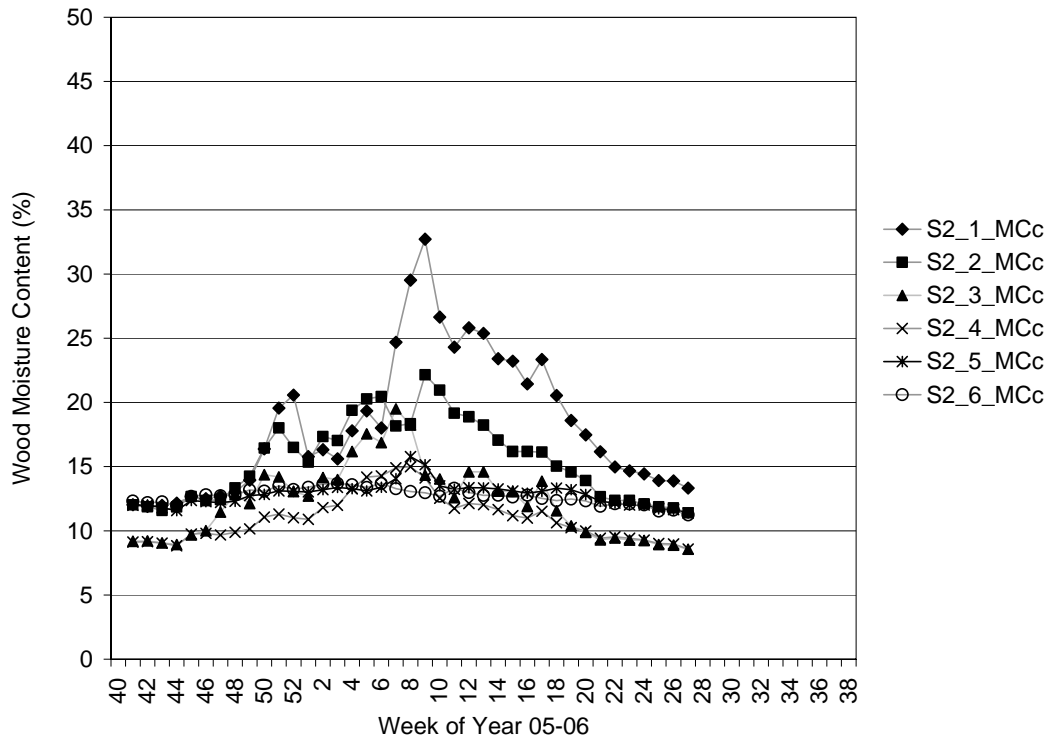


Figure C S1-4 S1 - Vapor Pressure



**Figure C S2-1 S2 – Wood Moisture Content**



**Figure C S2-2 S2 – Cavity Relative Humidity**

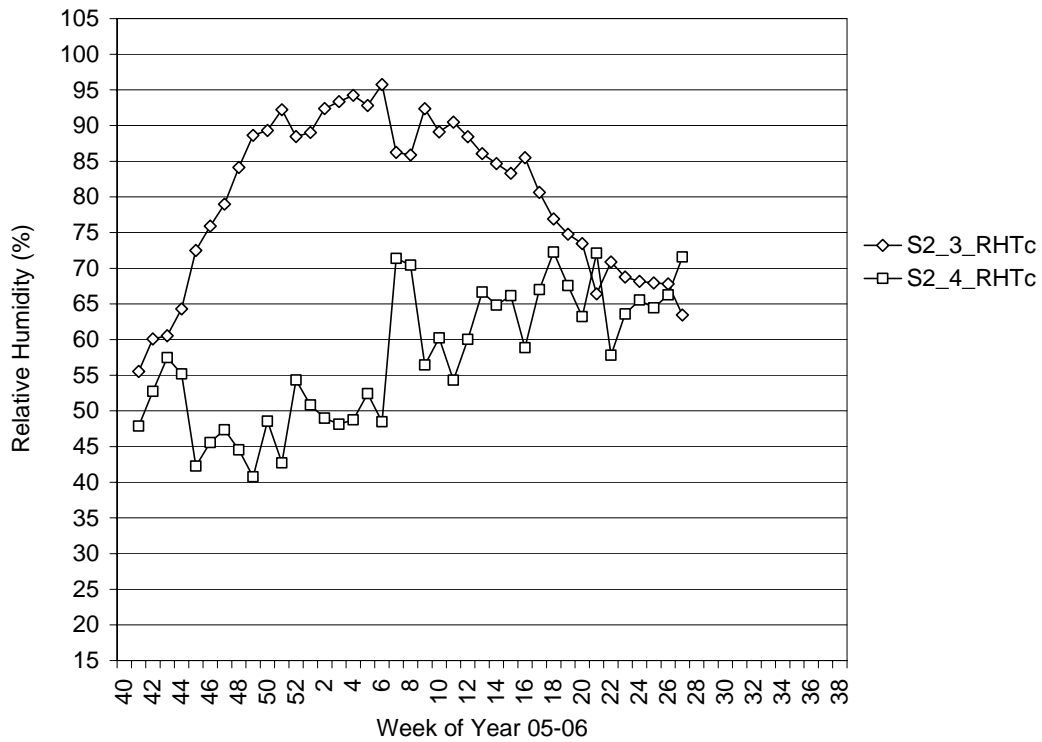


Figure C S2-3 S2 – Temperature

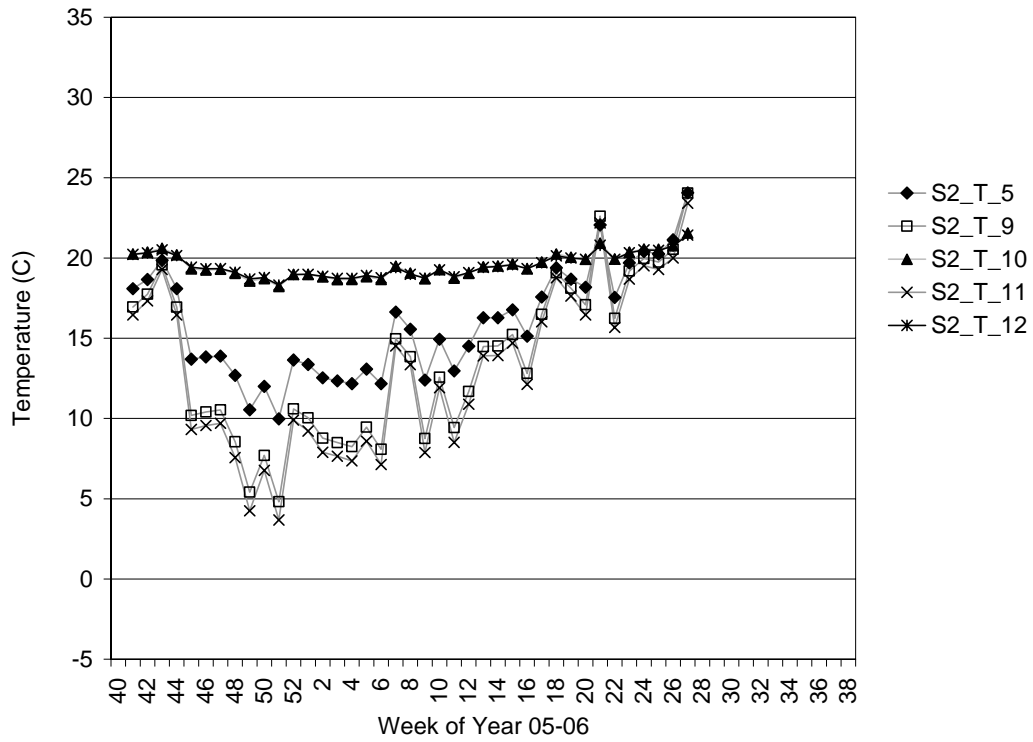
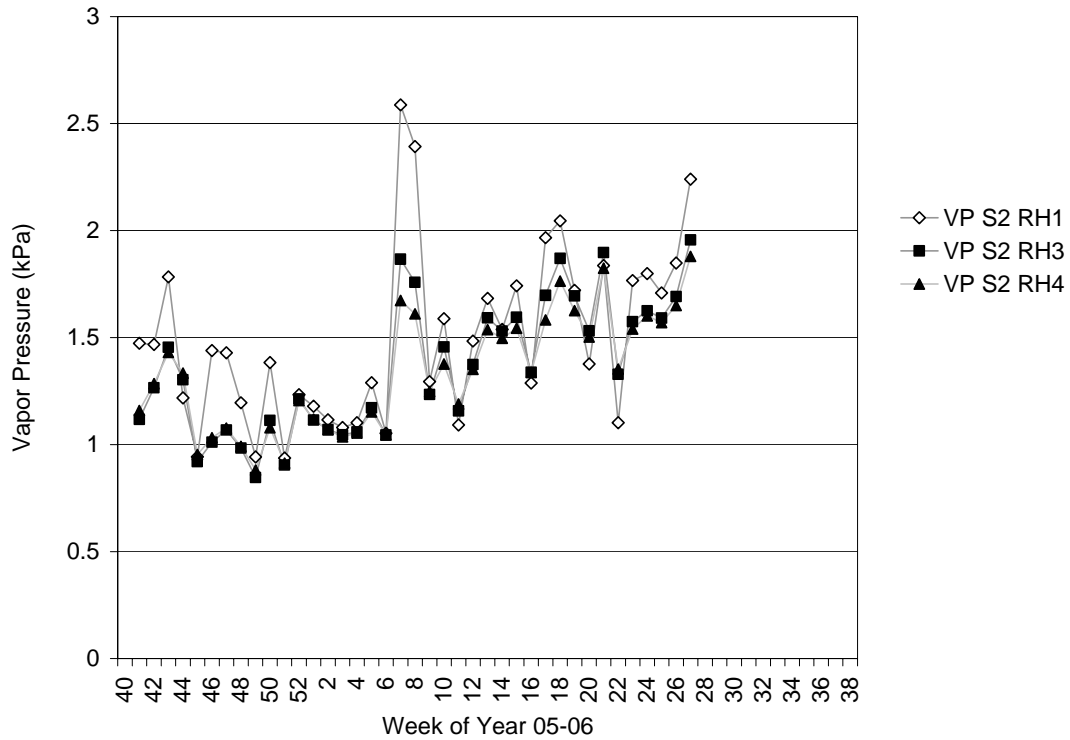
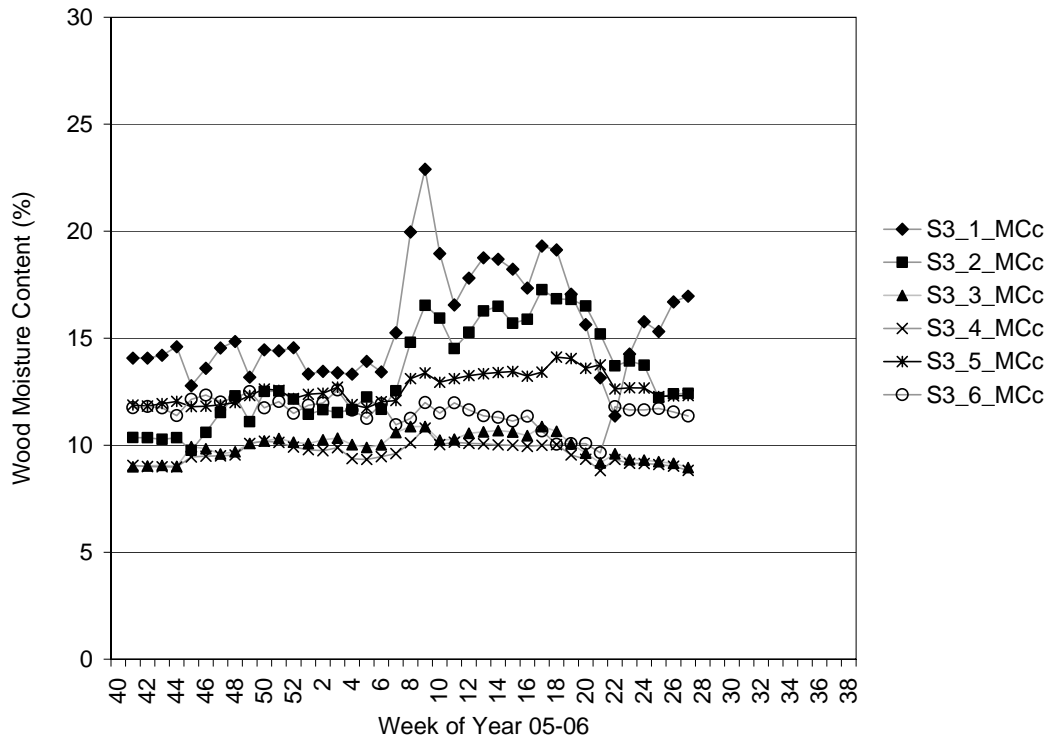


Figure C S2-4 S2 -- Vapor Pressure



**Figure C S3-1 S3 – Wood Moisture Content**



**Figure C S3-2 S3 – Cavity Relative Humidity**

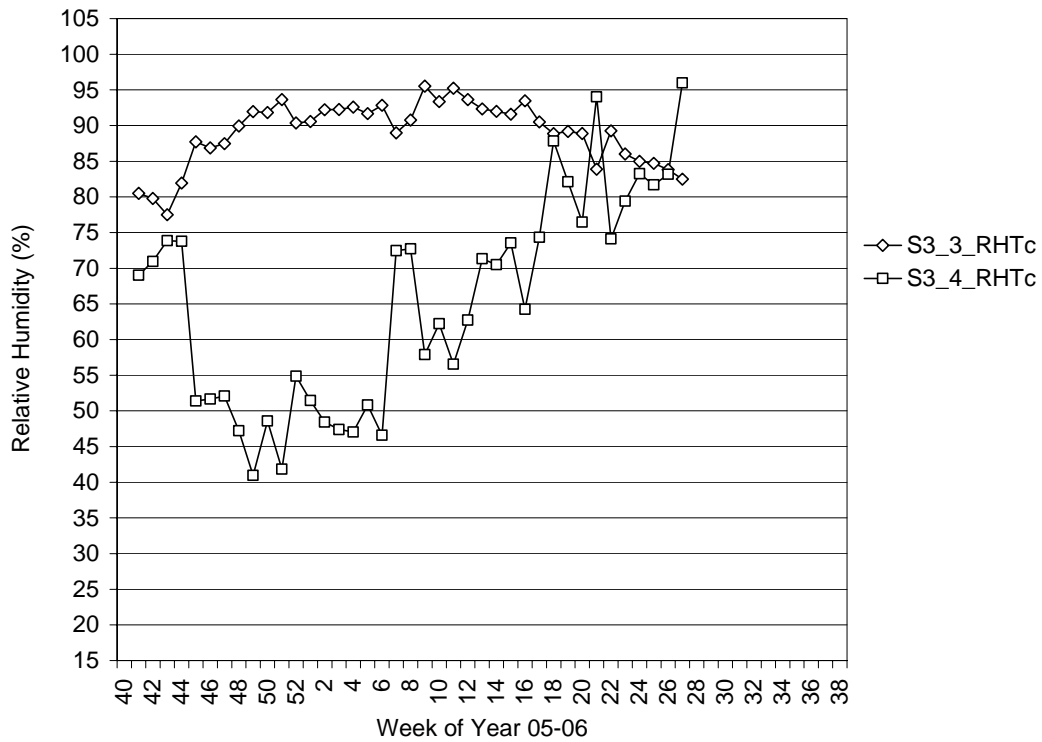


Figure C S3-3 S3 - Temperature

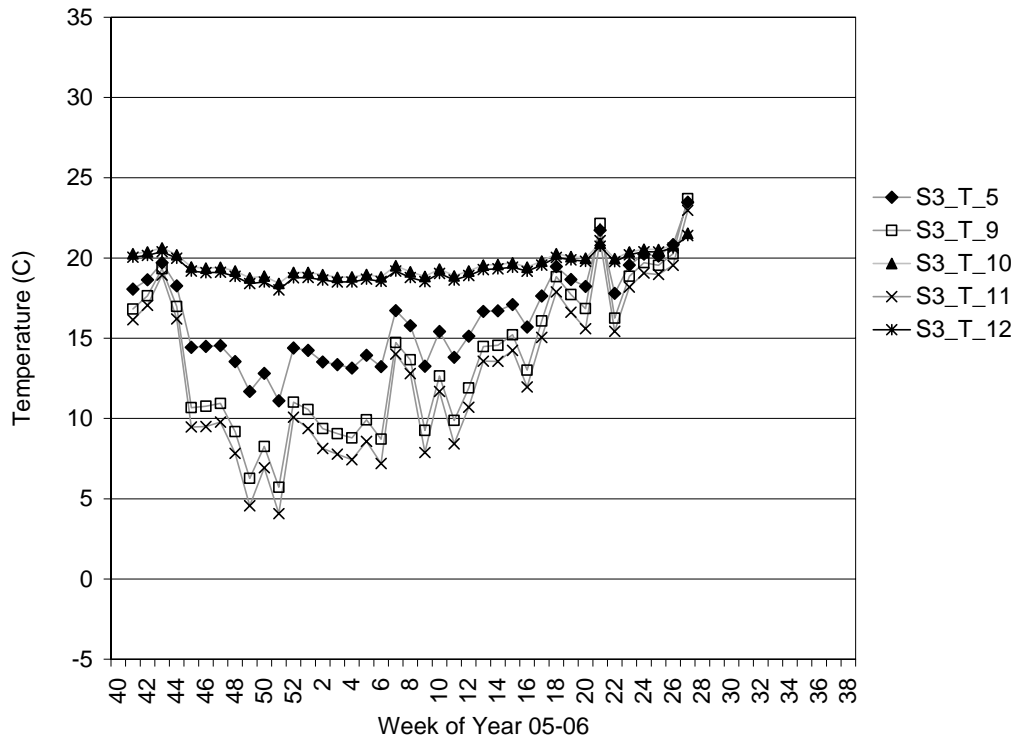
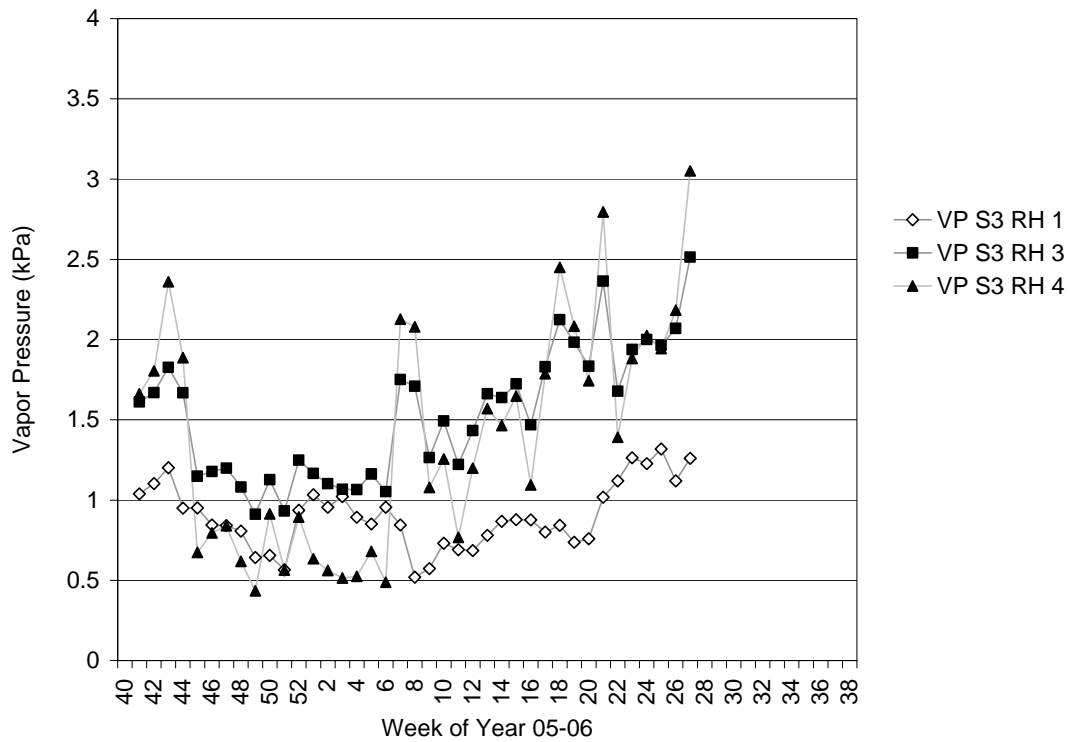
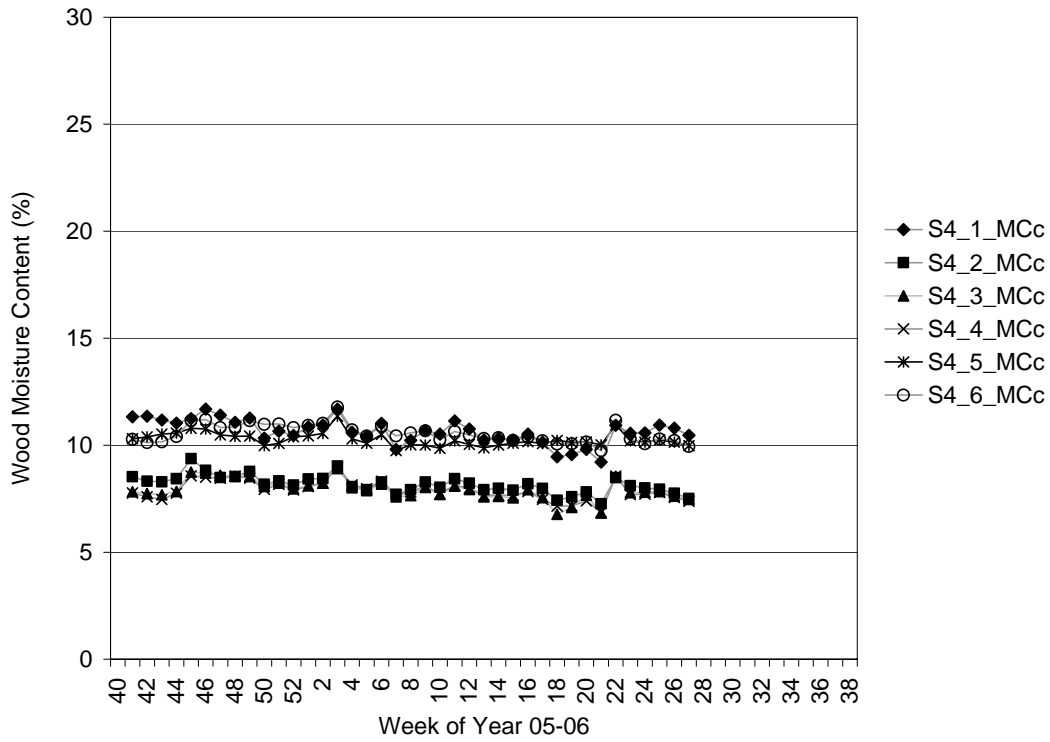


Figure C S3-4 S3 - Vapor Pressure



**Figure C S4-1 S4 – Wood Moisture Content**



**Figure C S4-2 S4 – Cavity Relative Humidity**

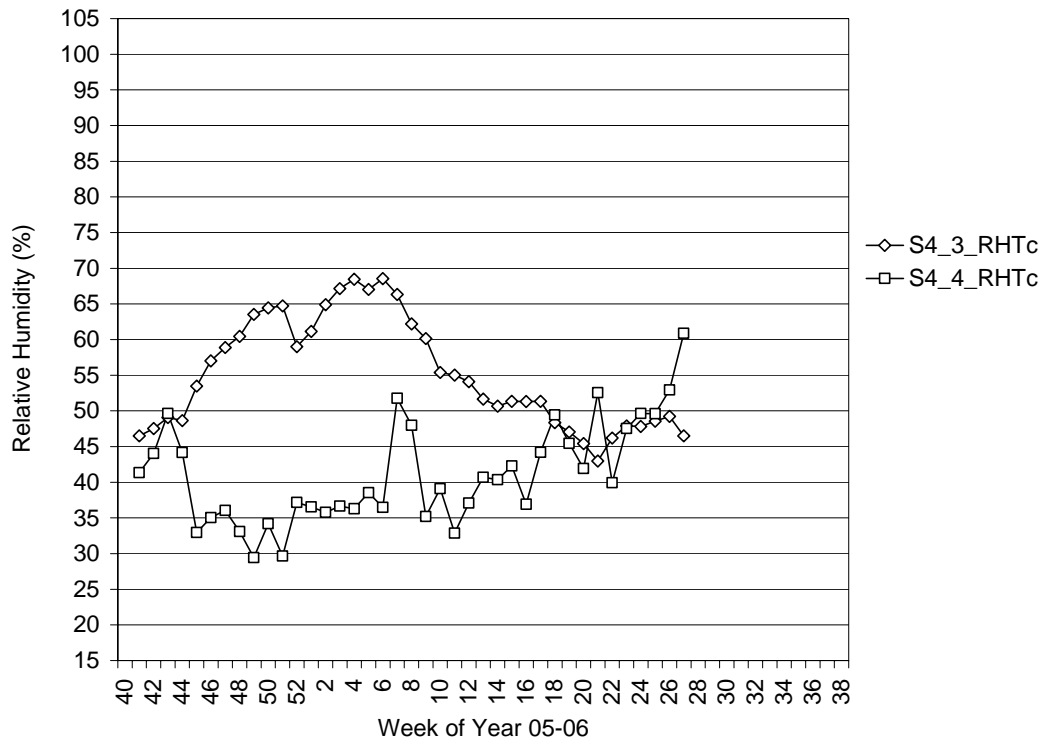


Figure C S4-3 S4 - Temperature

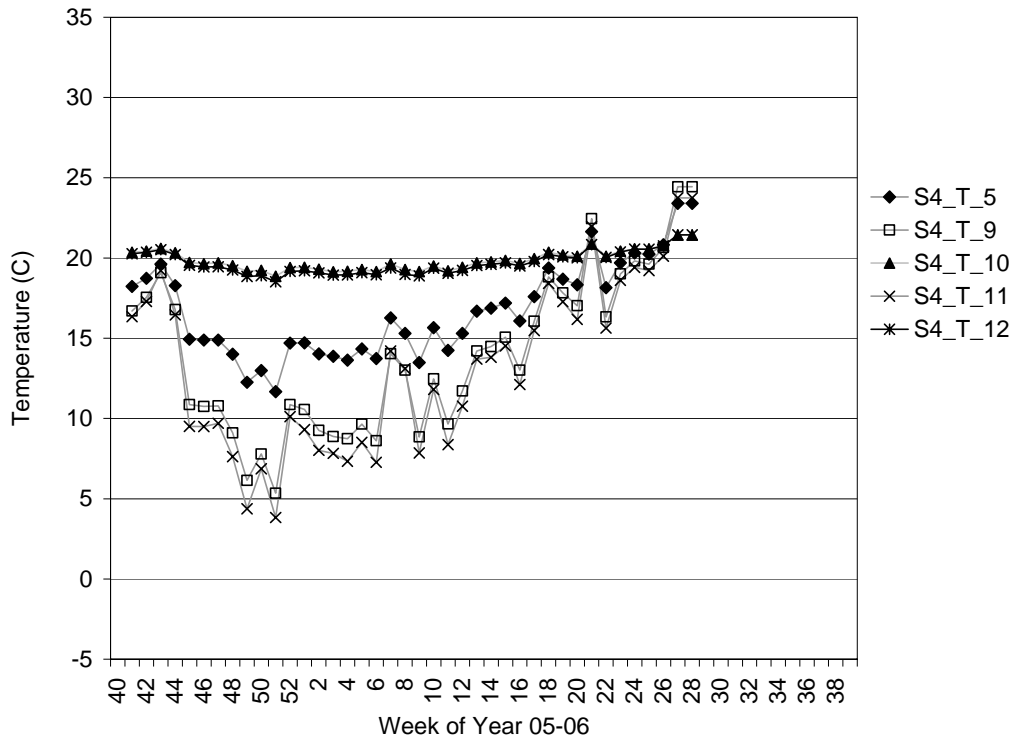
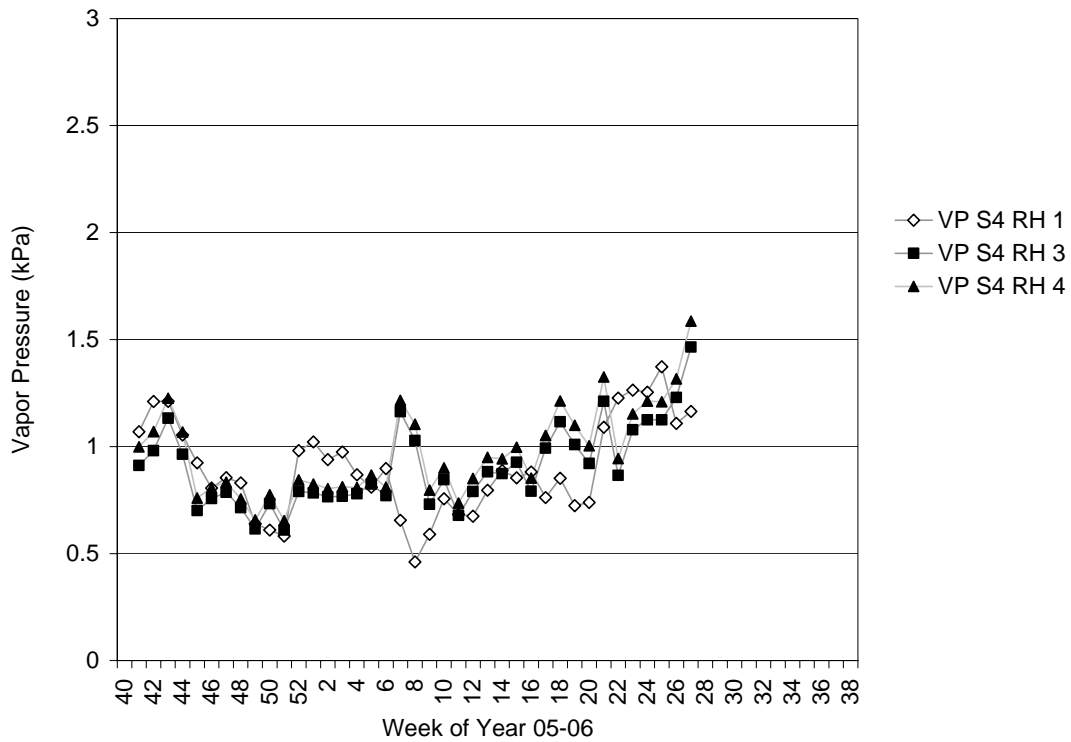
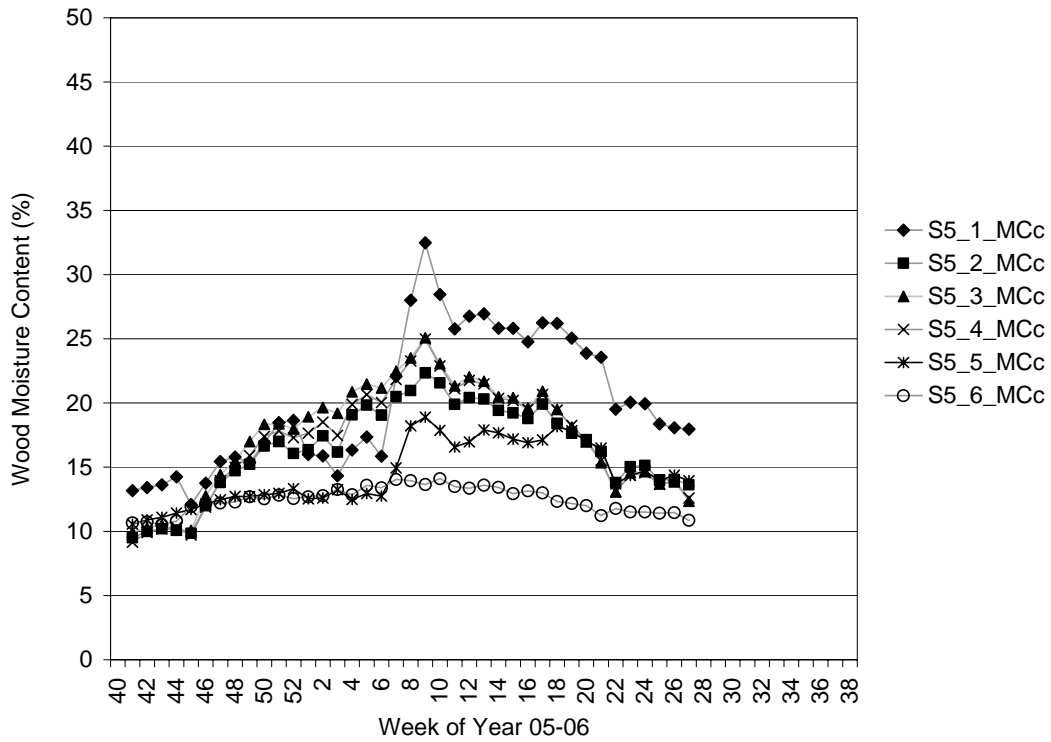


Figure C S4-4 S4 - Vapor Pressure



**Figure C S5-1 S5 – Wood Moisture Content**



**Figure C S5-2 S5 – Cavity Relative Humidity**

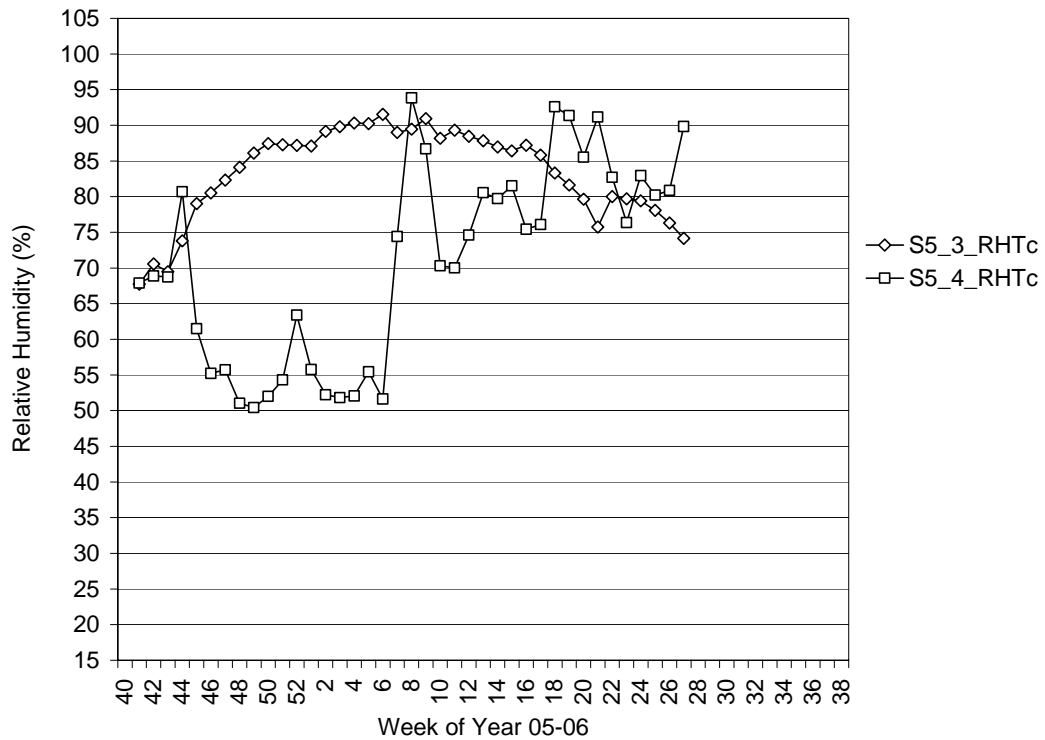


Figure C S5-3 S5 -- Temperature

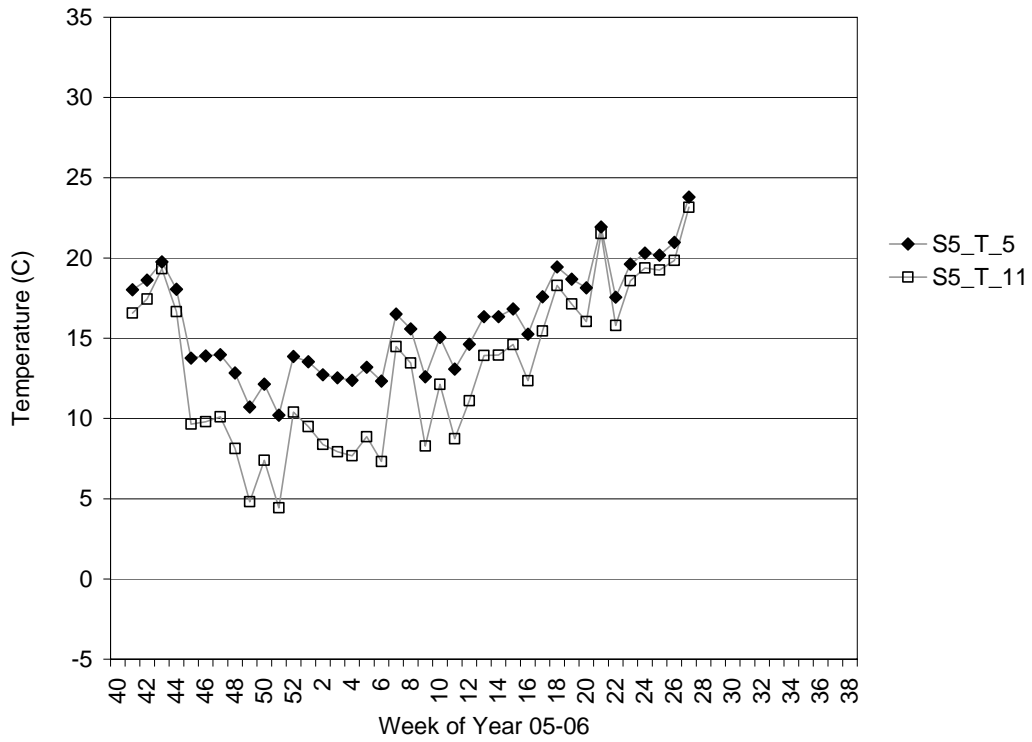


Figure C S5-4 S5 -- Vapor Pressure

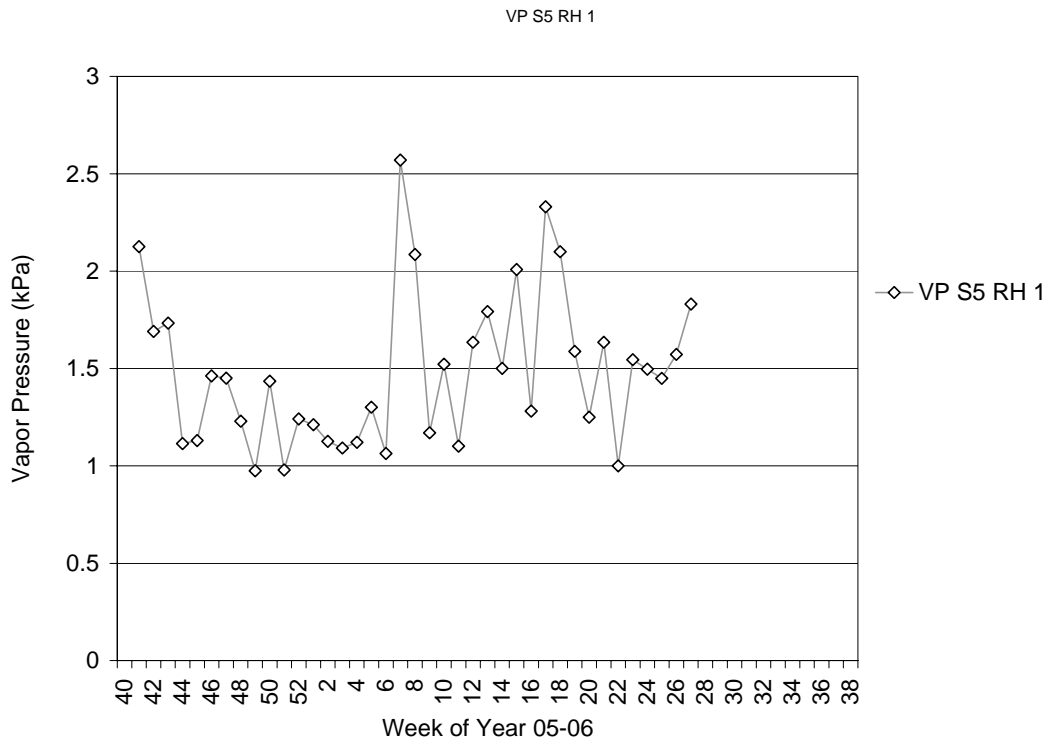


Figure C S6-1

S6 – Wood Moisture Content

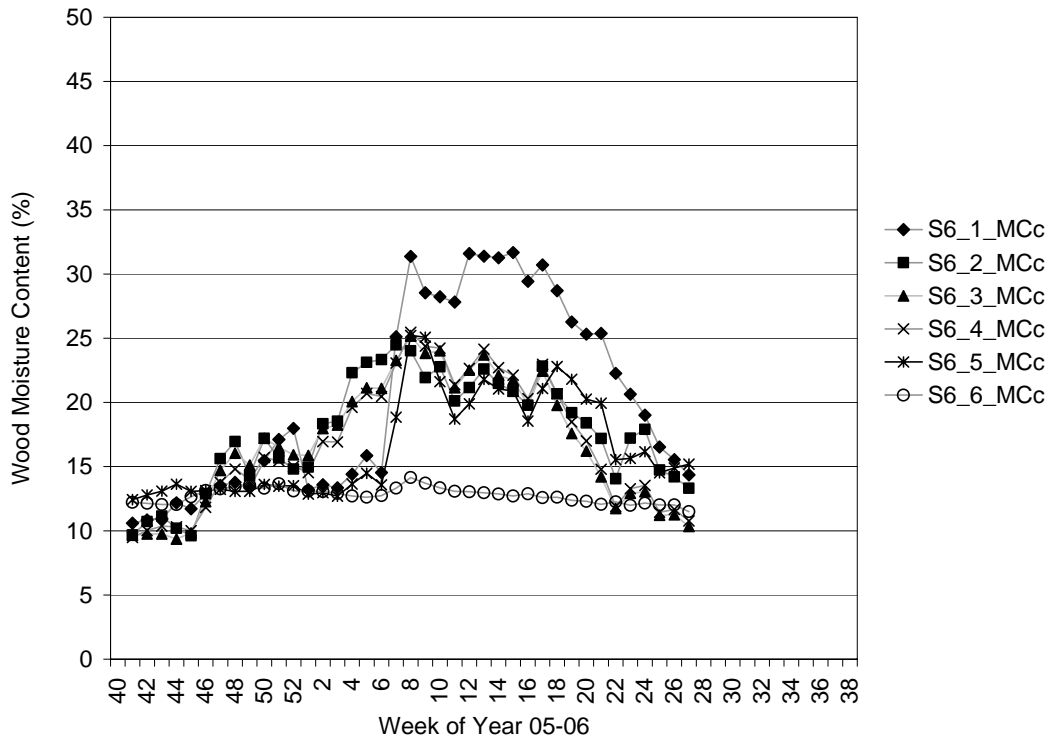


Figure C1 S6-2

S6 – Cavity Relative Humidity

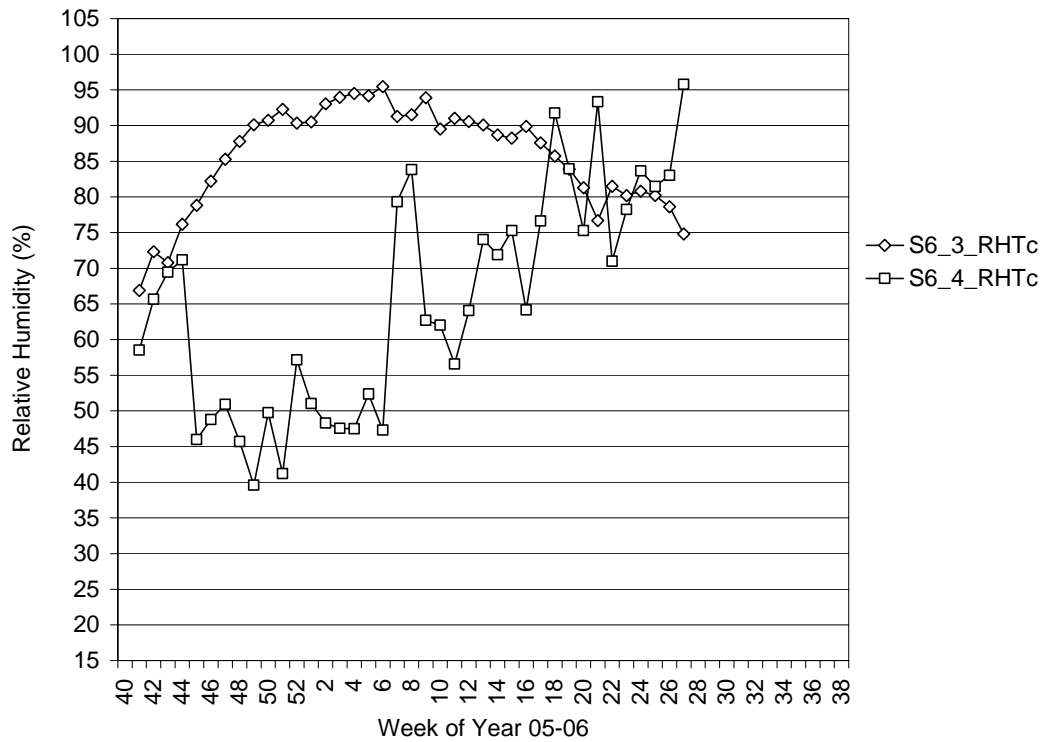


Figure C S6-3

S6 - Temperature

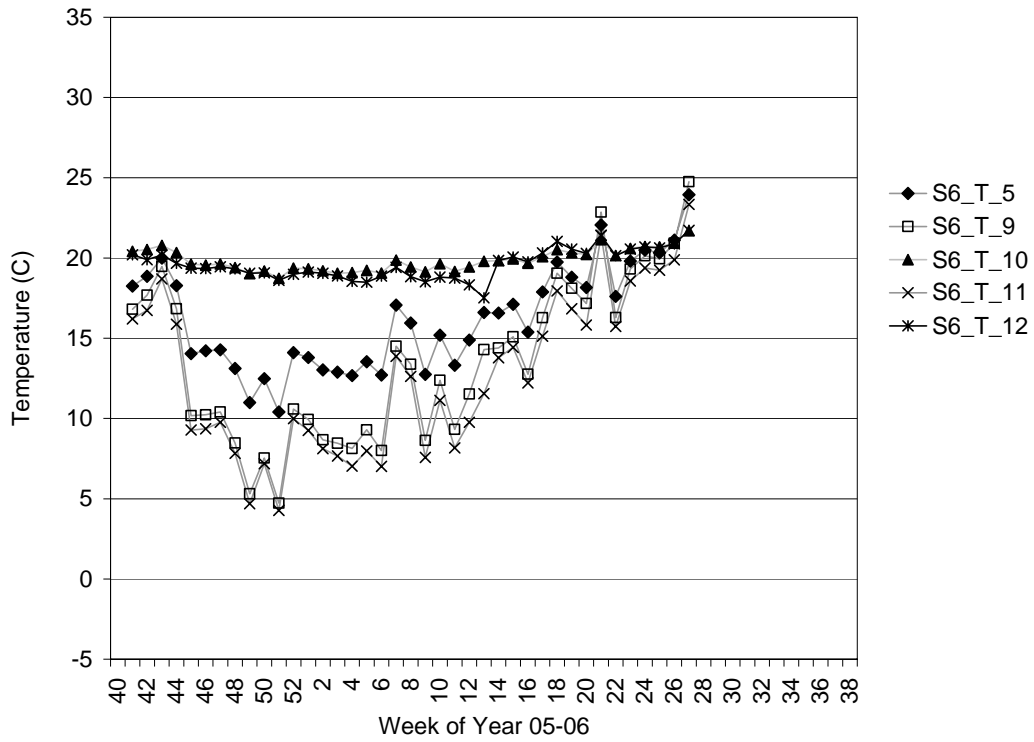
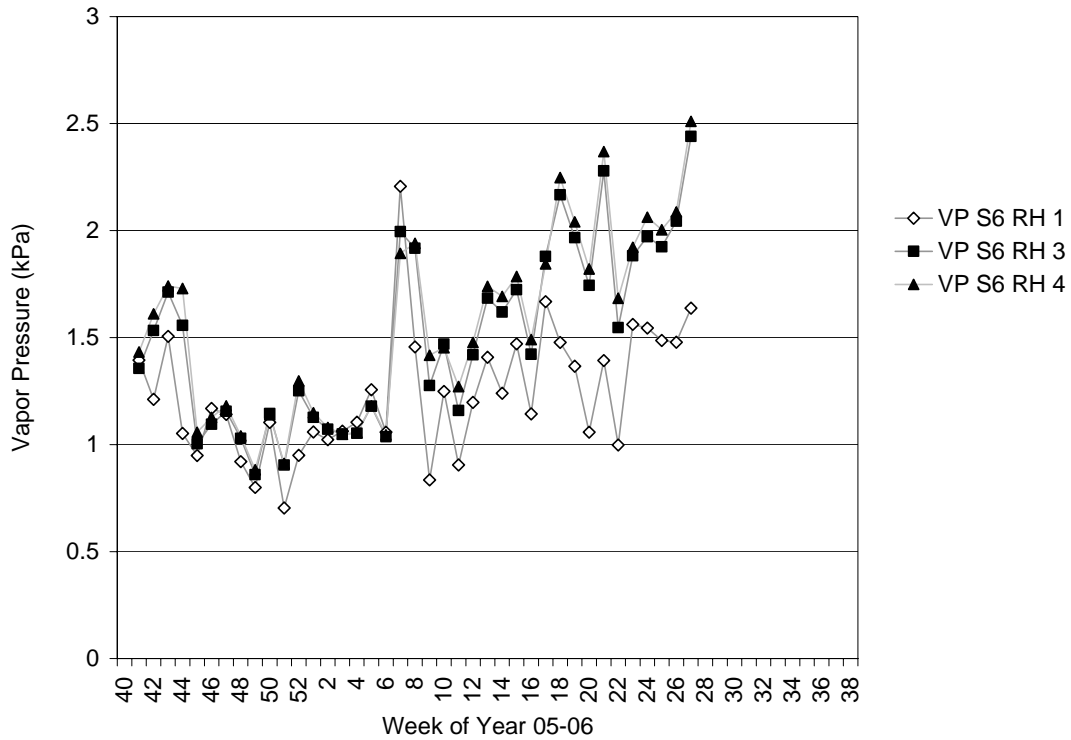
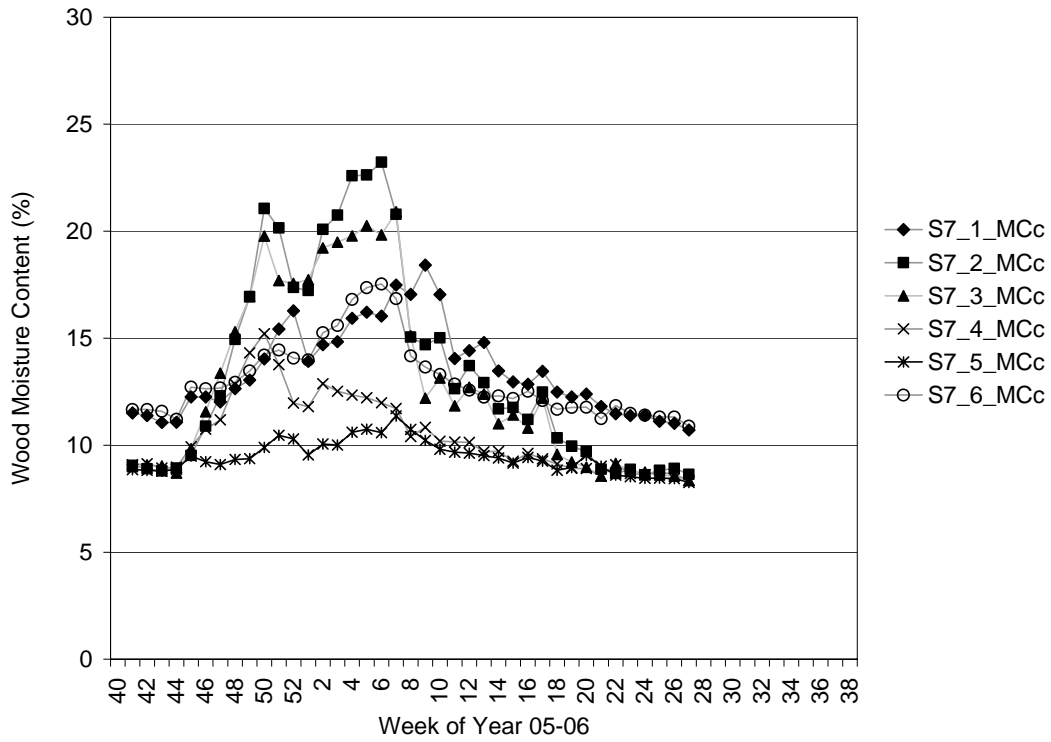


Figure C S6-4

S6 - Vapor Pressure



**Figure C S7-1 S7 – Wood Moisture Content**



**Figure C S7-2 S7 – Cavity Relative Humidity**



Figure C S7-3 S7 - Temperature

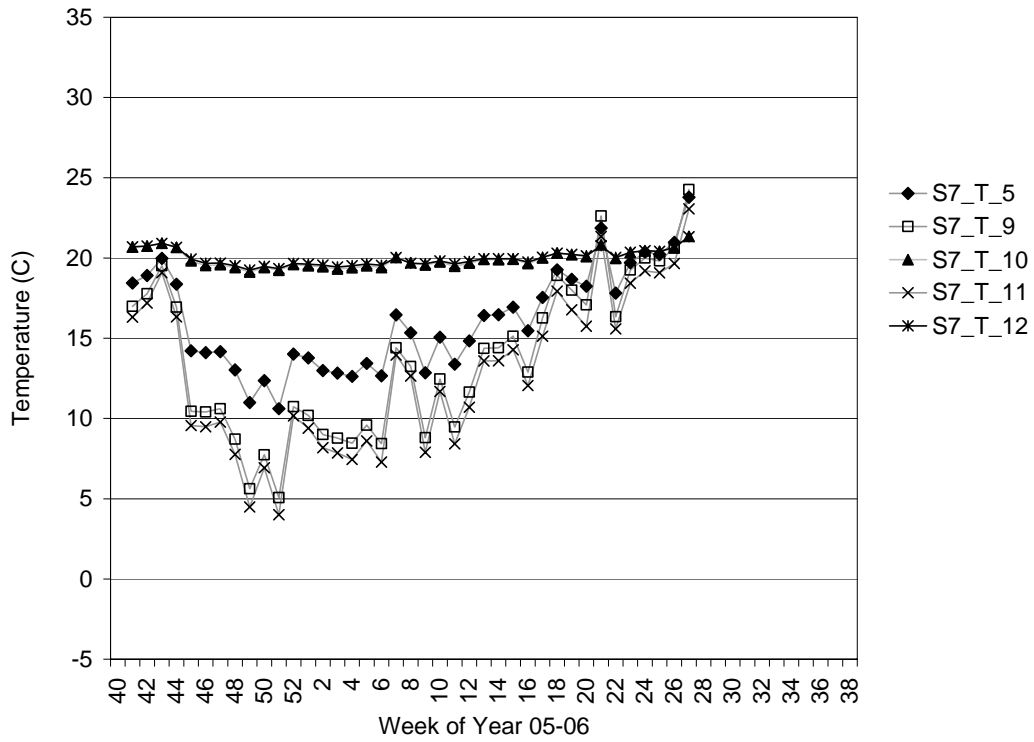
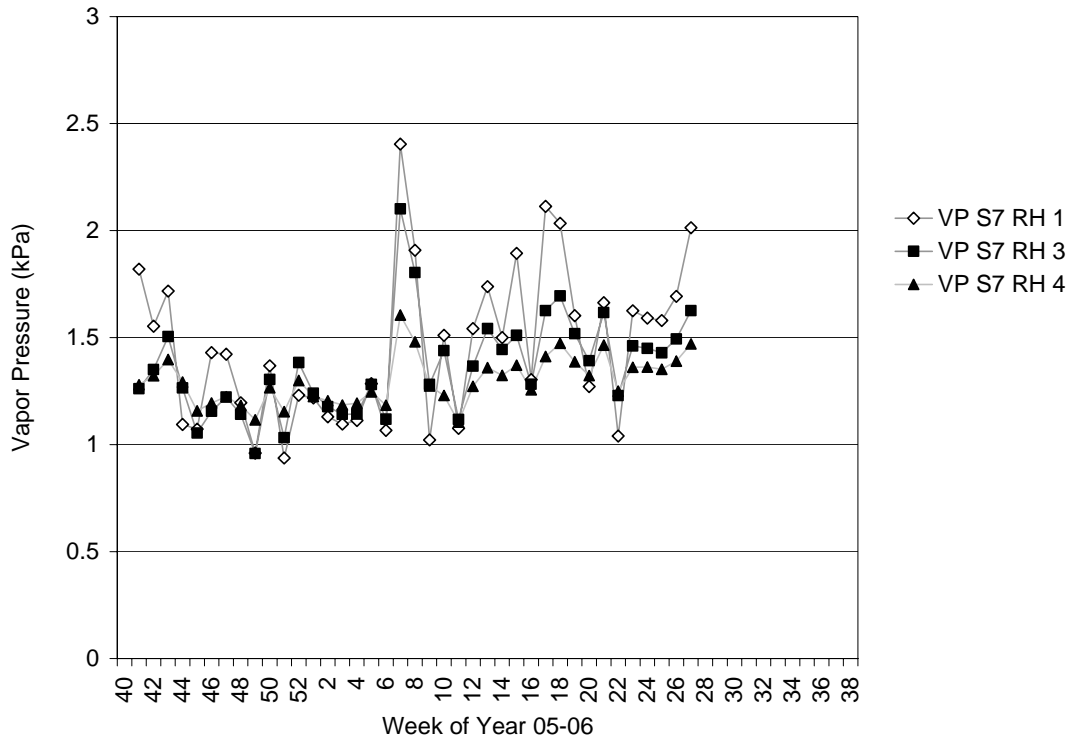
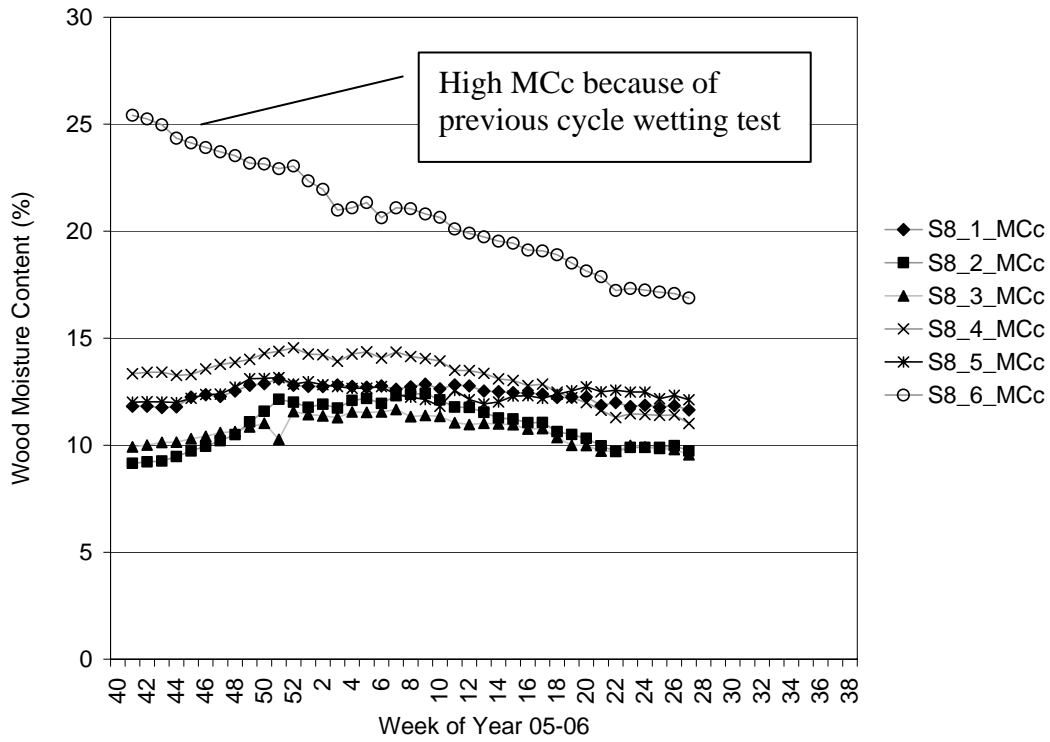


Figure C S7-4 S7 - Vapor Pressure



**Figure C S8-1 S8 – Wood Moisture Content**



**Figure C S8-2 S8 – Cavity Relative Humidity**



Figure C S8-3 S8 - Temperature

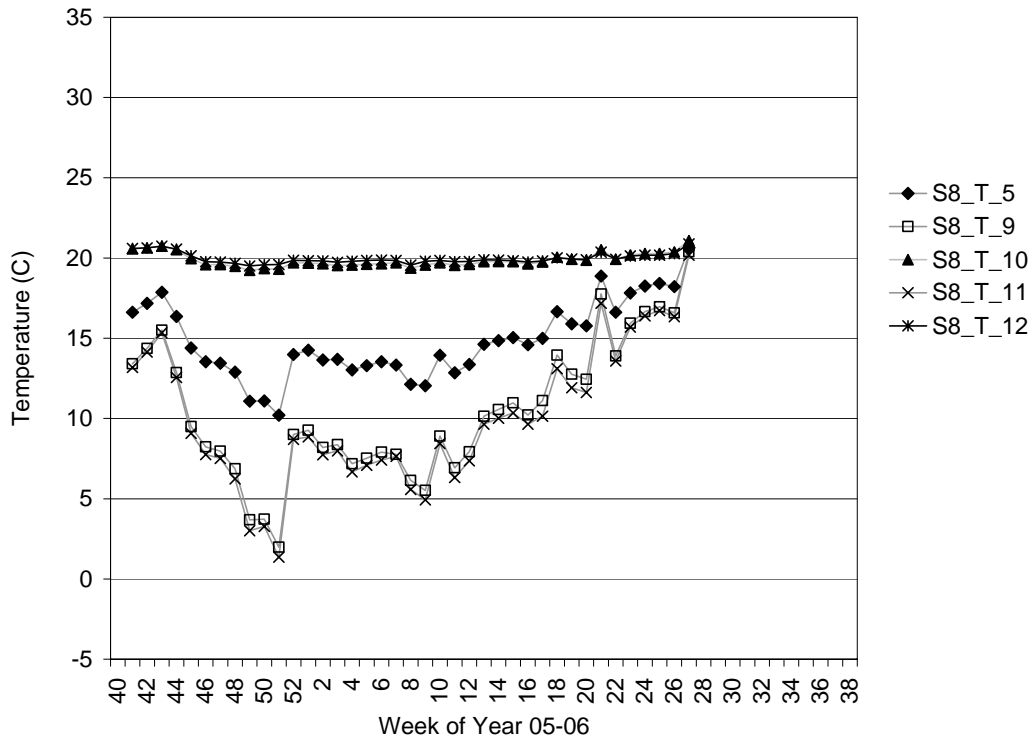
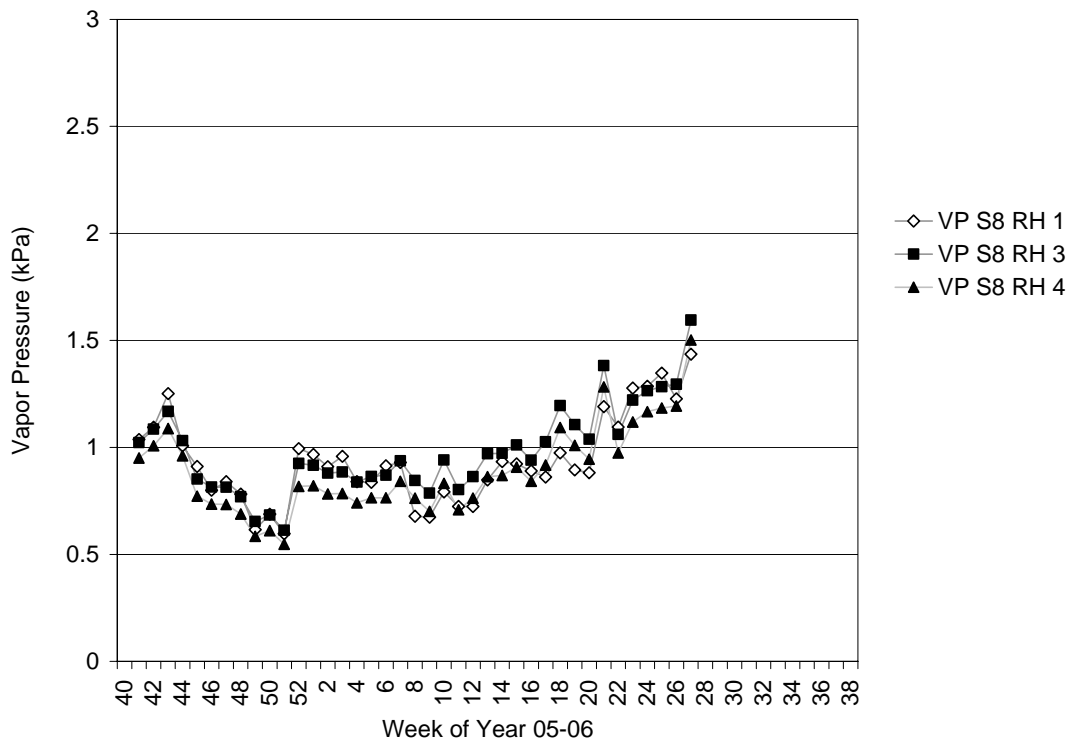
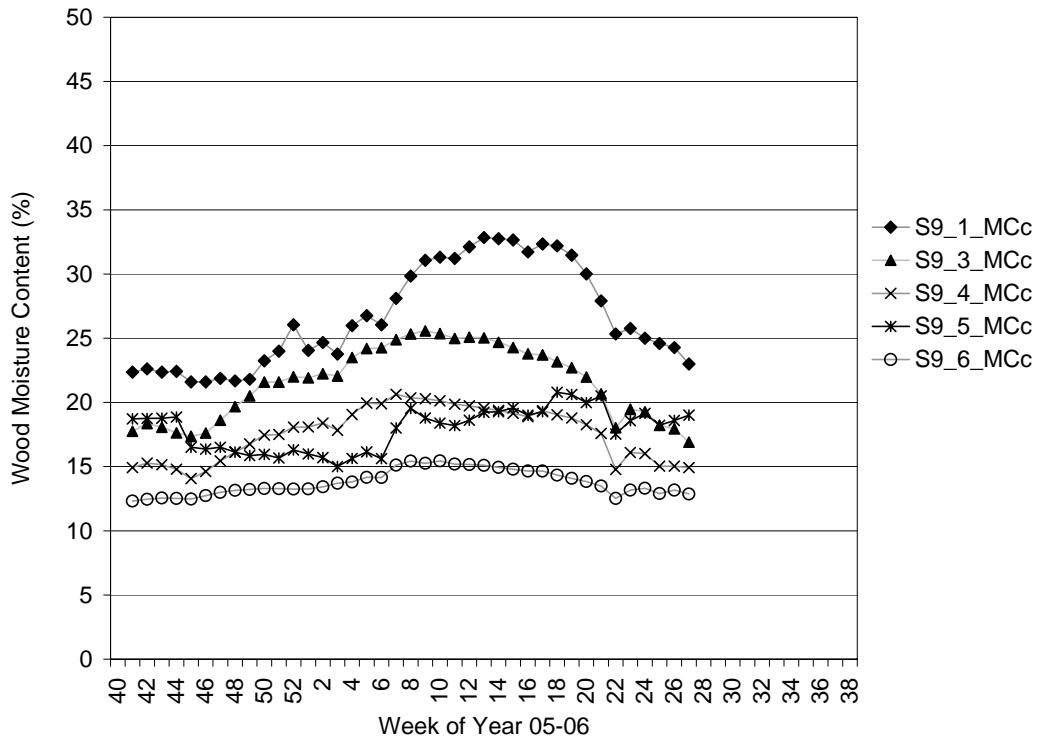


Figure C S8-4 S8 – Vapor Pressure



**Figure C S9-1 S9 – Wood Moisture Content**



**Figure C S9-2 A9 – Cavity Relative Humidity**

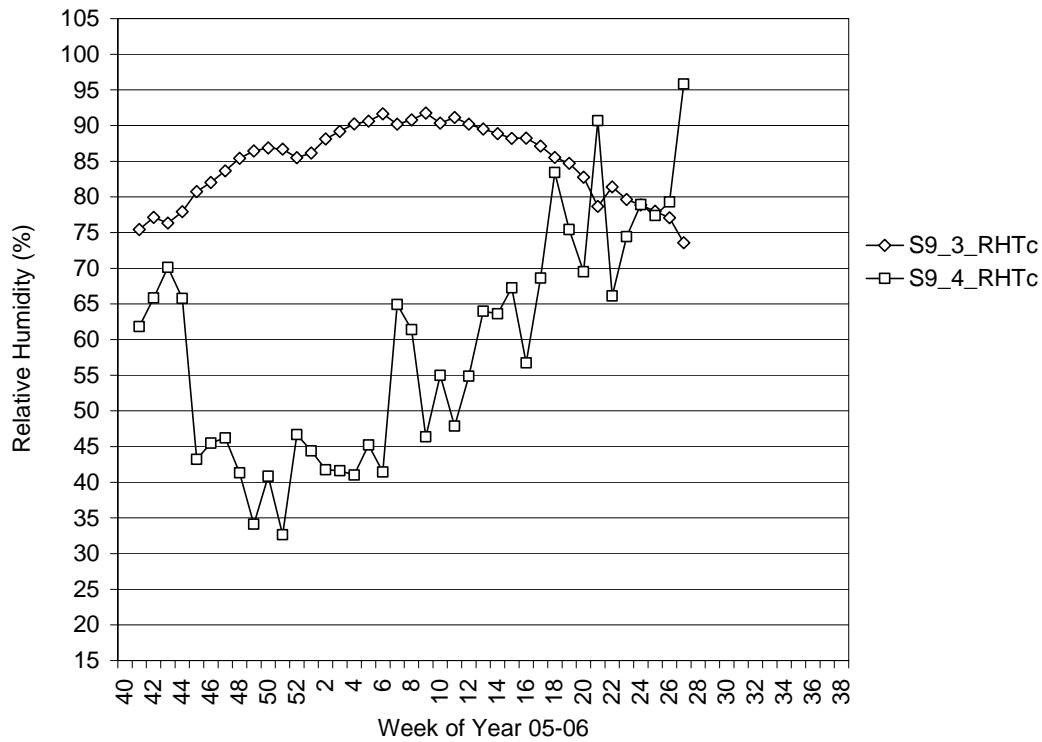


Figure C S9-3 A9 - Temperature

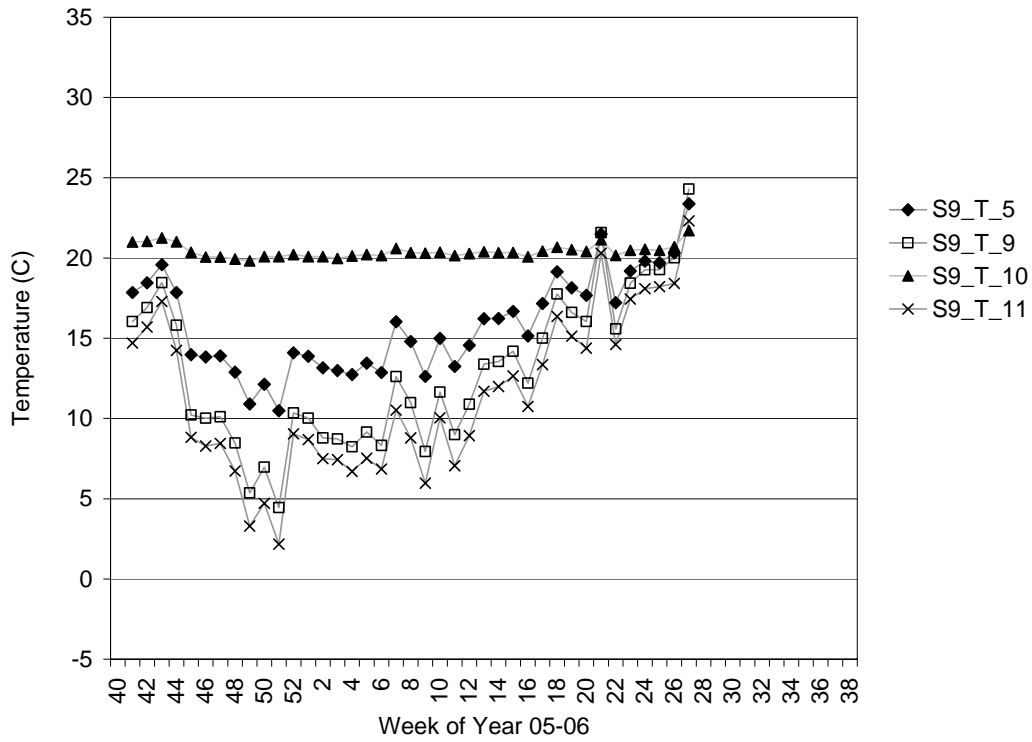
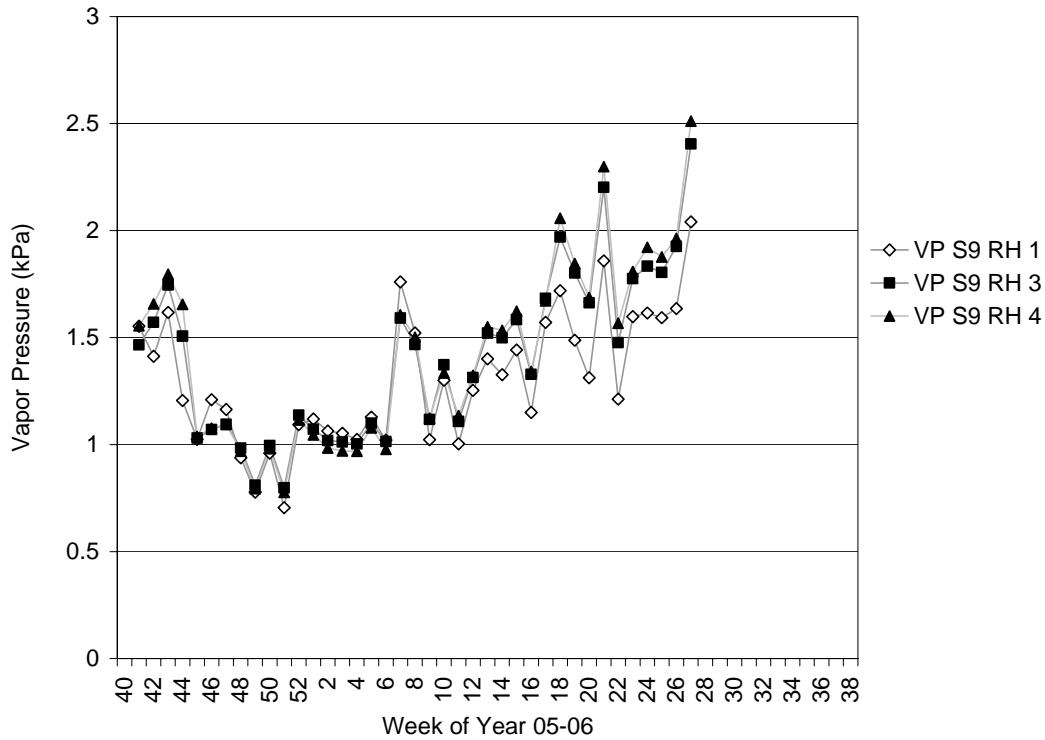
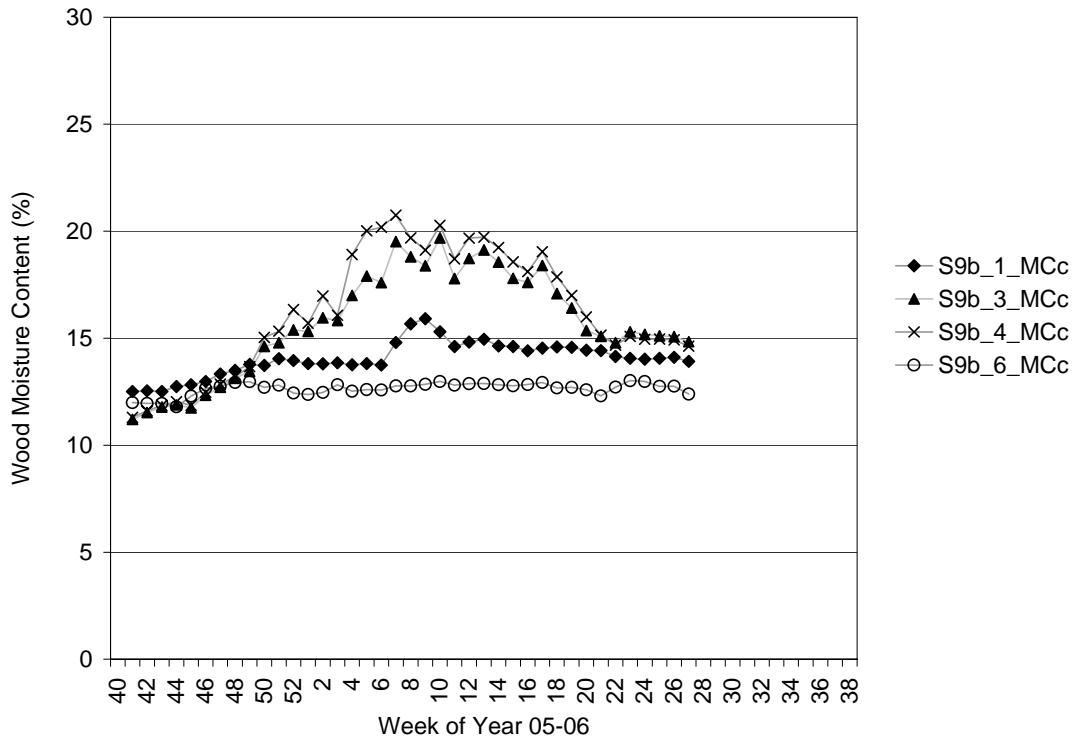


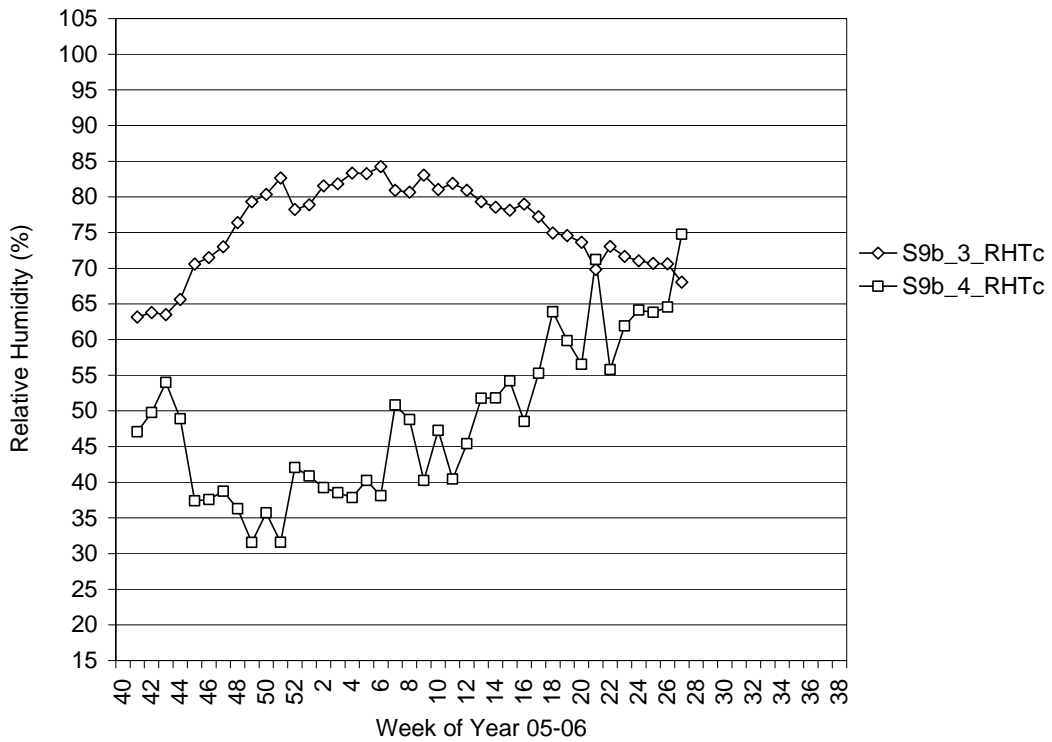
Figure C S9-4 S9 – Vapor Pressure



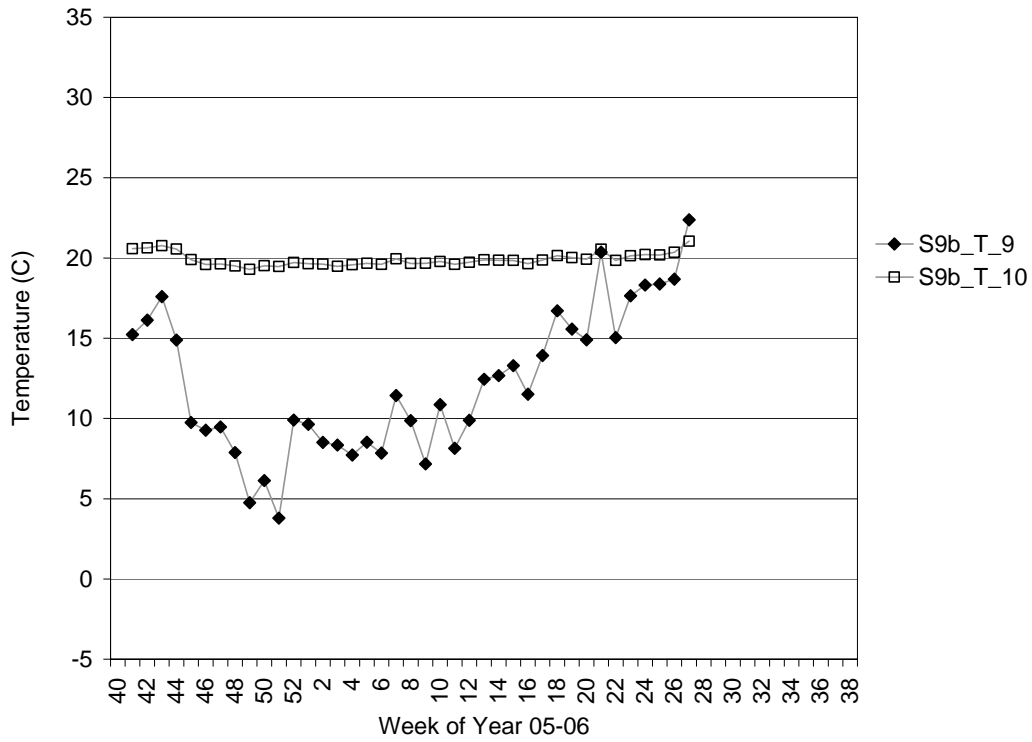
**Figure C S9b-1 S9b – Wood Moisture Content**



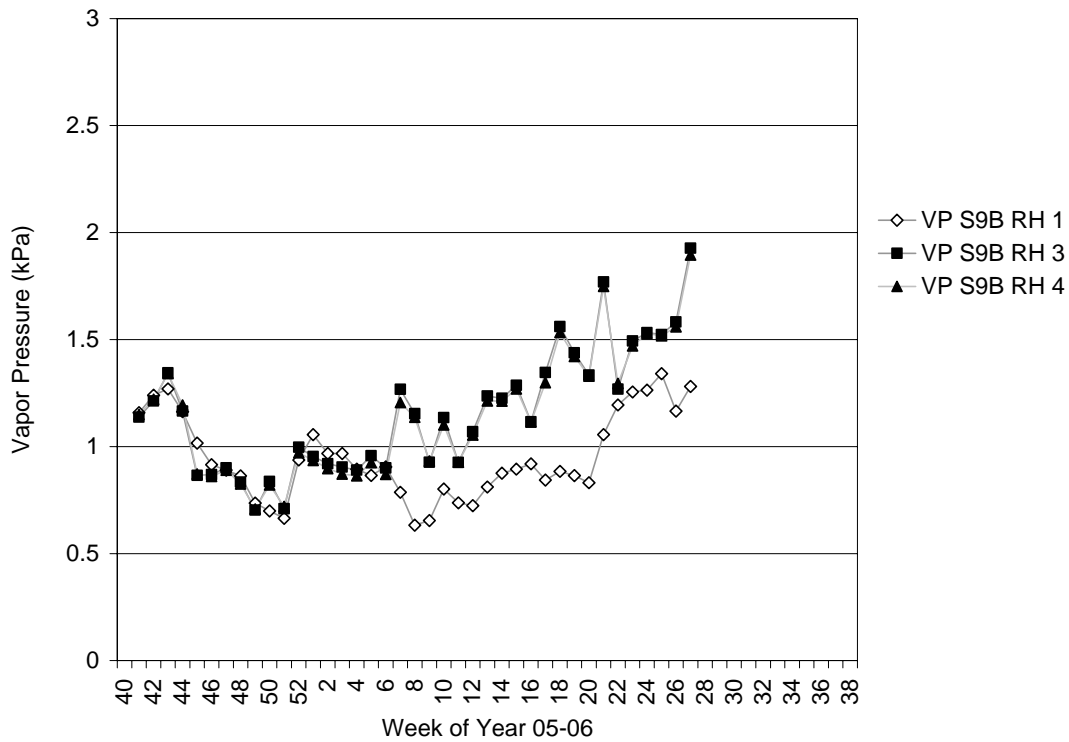
**Figure C S9b-2 S9b – Cavity Relative Humidity**



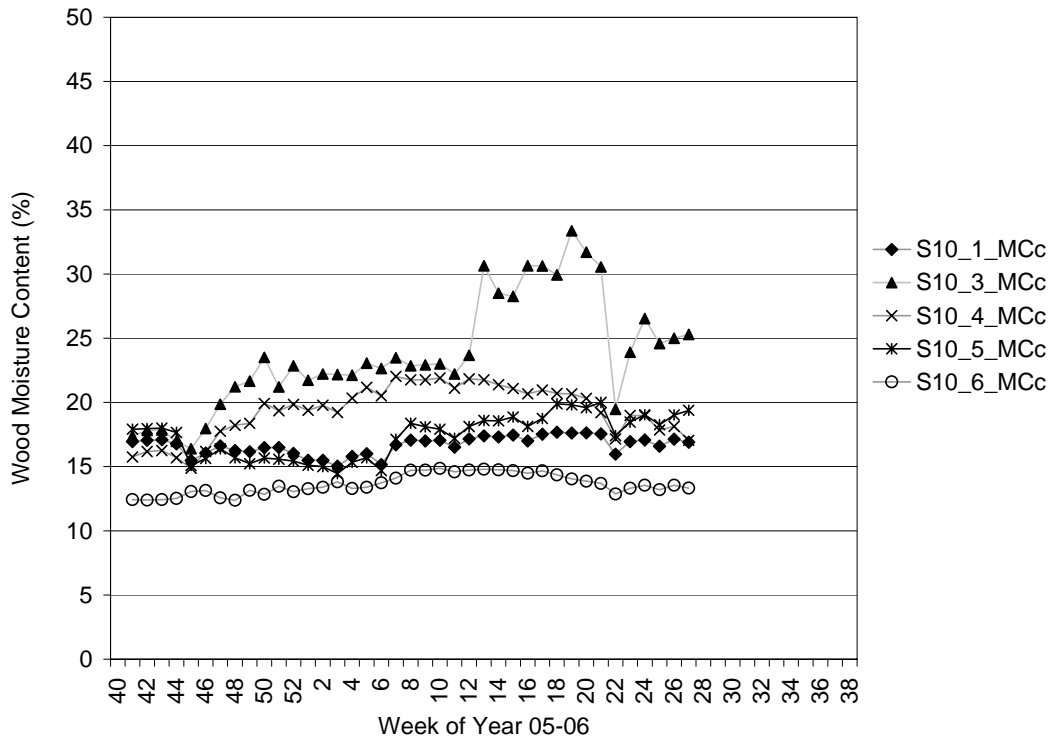
**Figure C S9b-3 S9b - Temperature**



**Figure C S9b-4 S9b - Vapor Pressure**



**Figure C S10-1 S10 – Wood Moisture Content**



**Figure C S10-2 S10 – Cavity Relative Humidity**

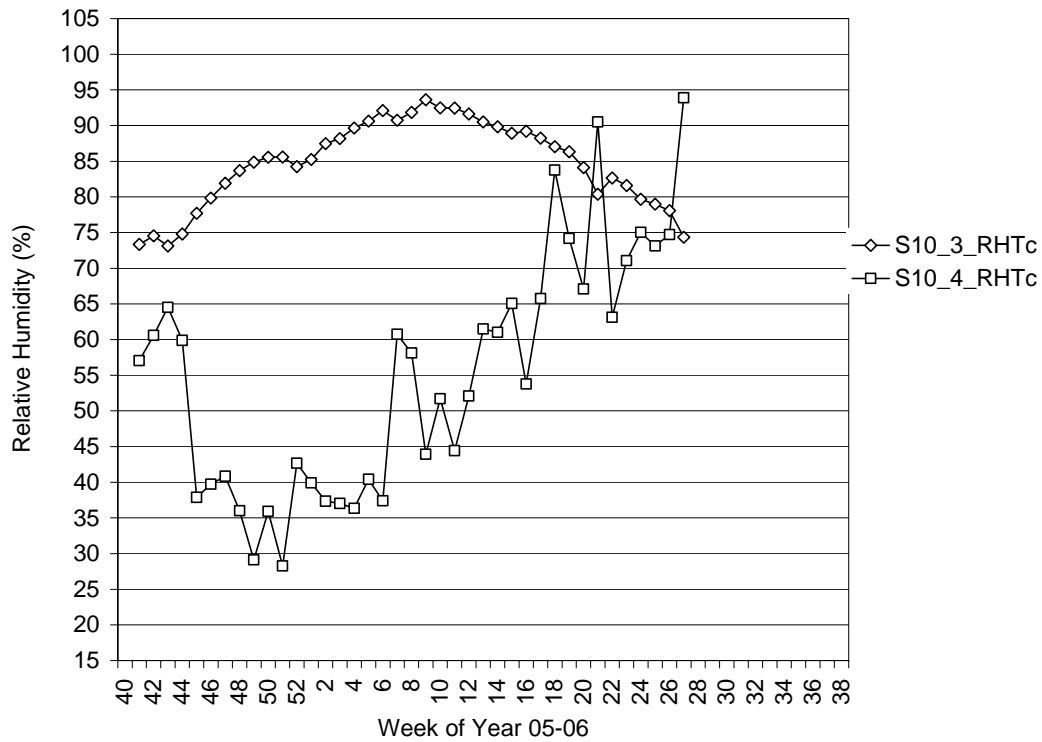


Figure C S10-3 S10- Temperature

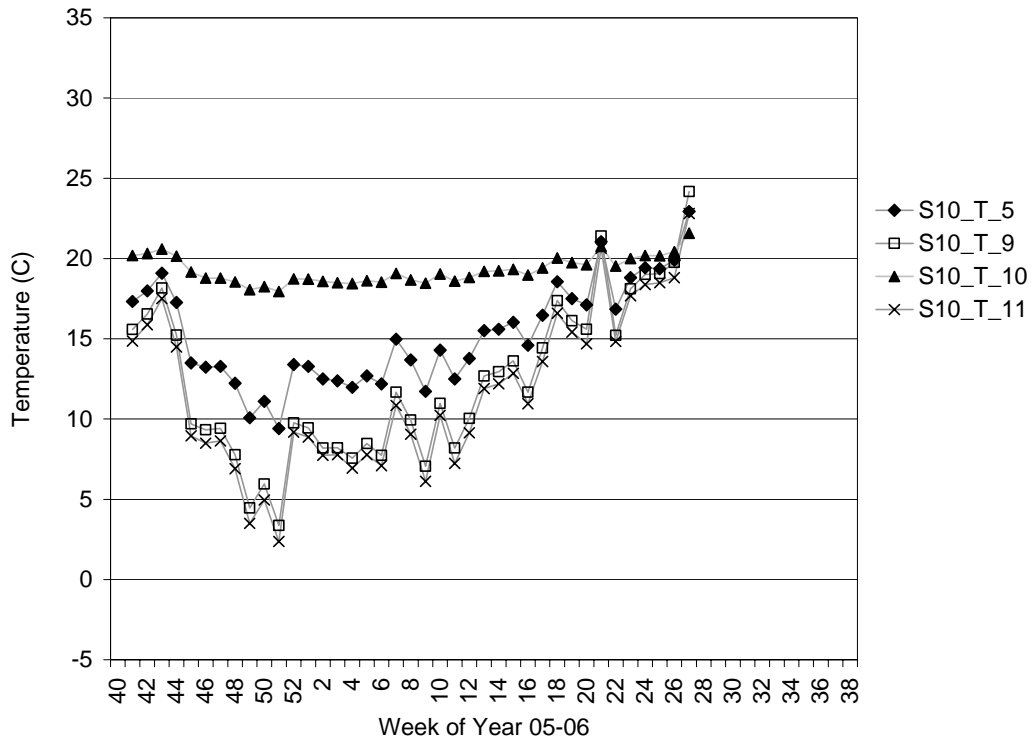
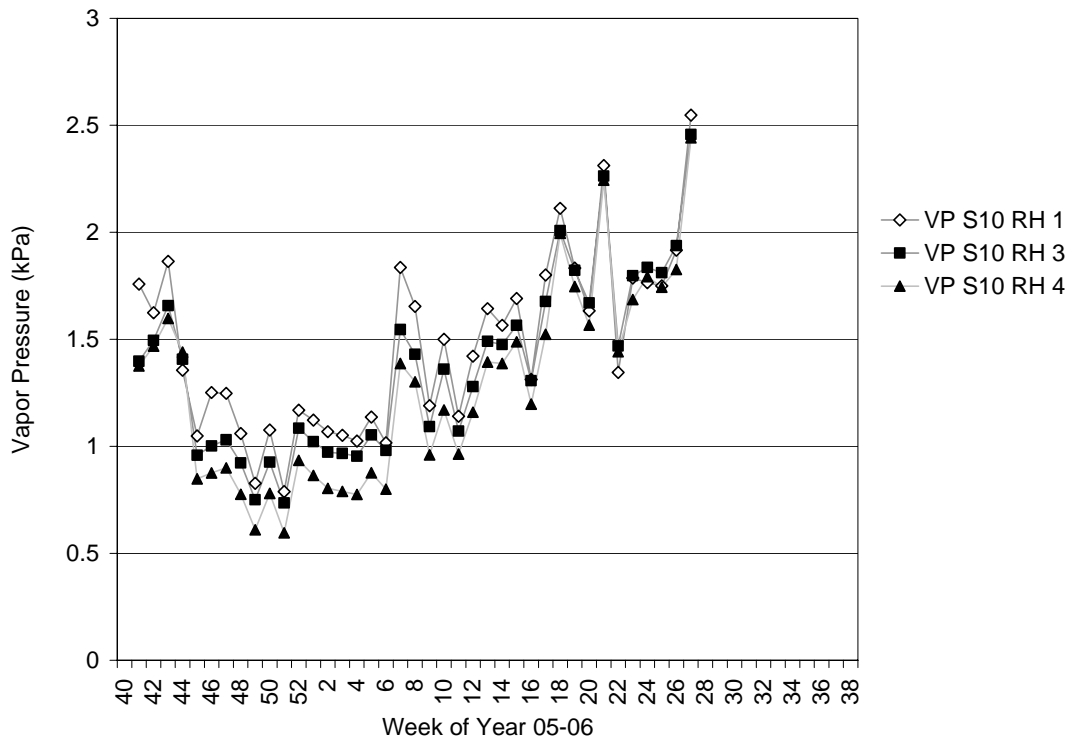
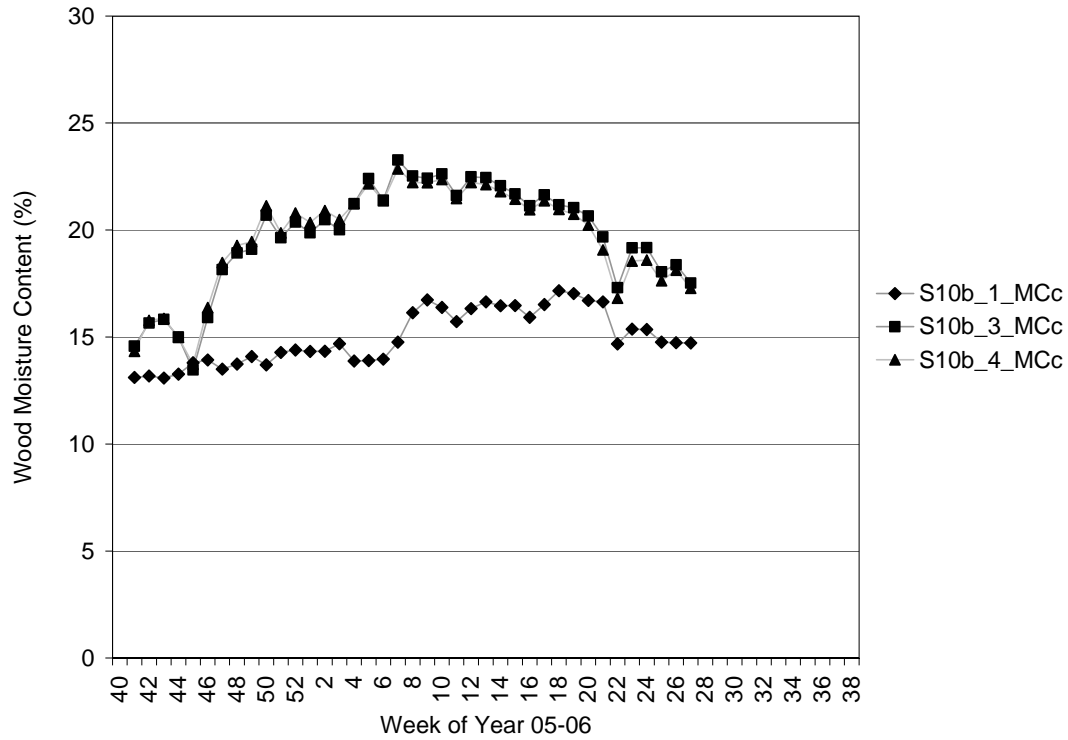


Figure C S10-4 S10 – Vapor Pressure



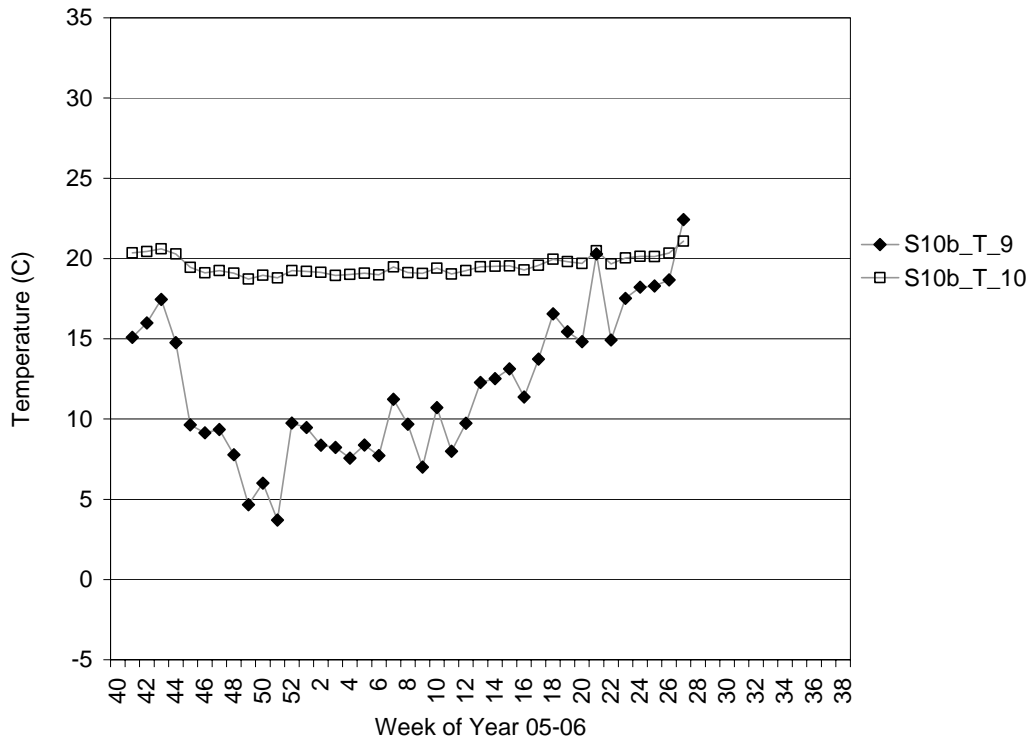
**Figure C S10b-1 S10b – Wood Moisture Content**



**Figure C S10b-2 S10b – Cavity Relative Humidity**



**Figure C S10b-3 S10b - Temperature**



**Figure C S10b-4 S10b – Vapor Pressure**

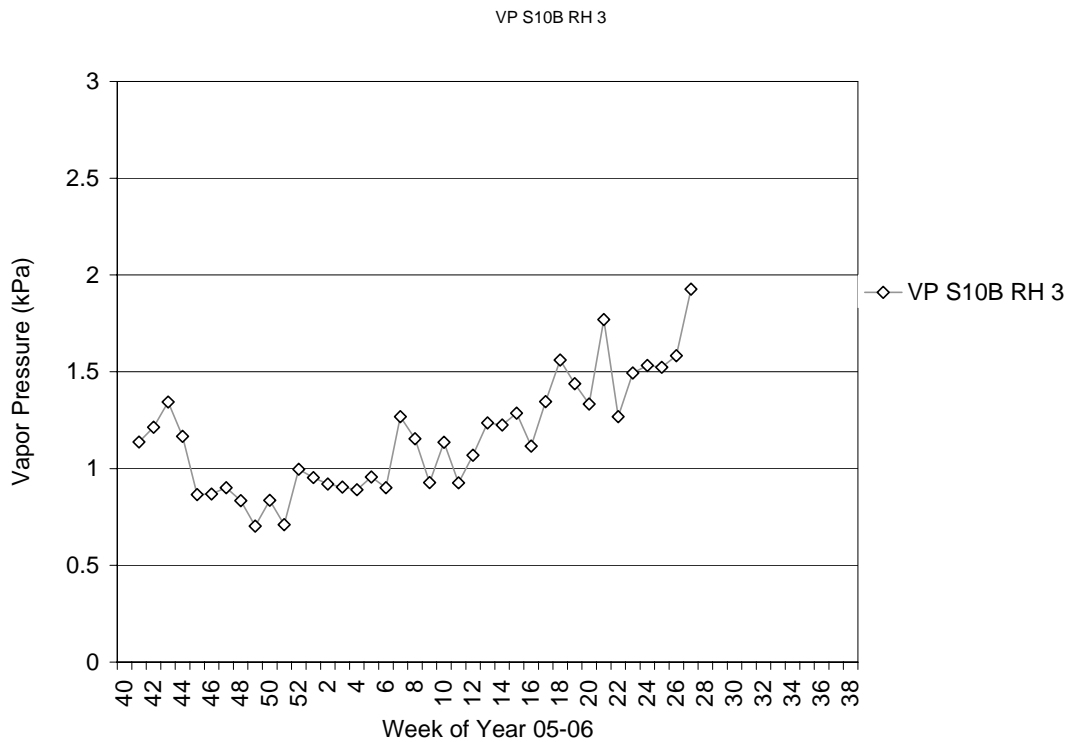


Figure C S11-1

S11 – Wood Moisture Content

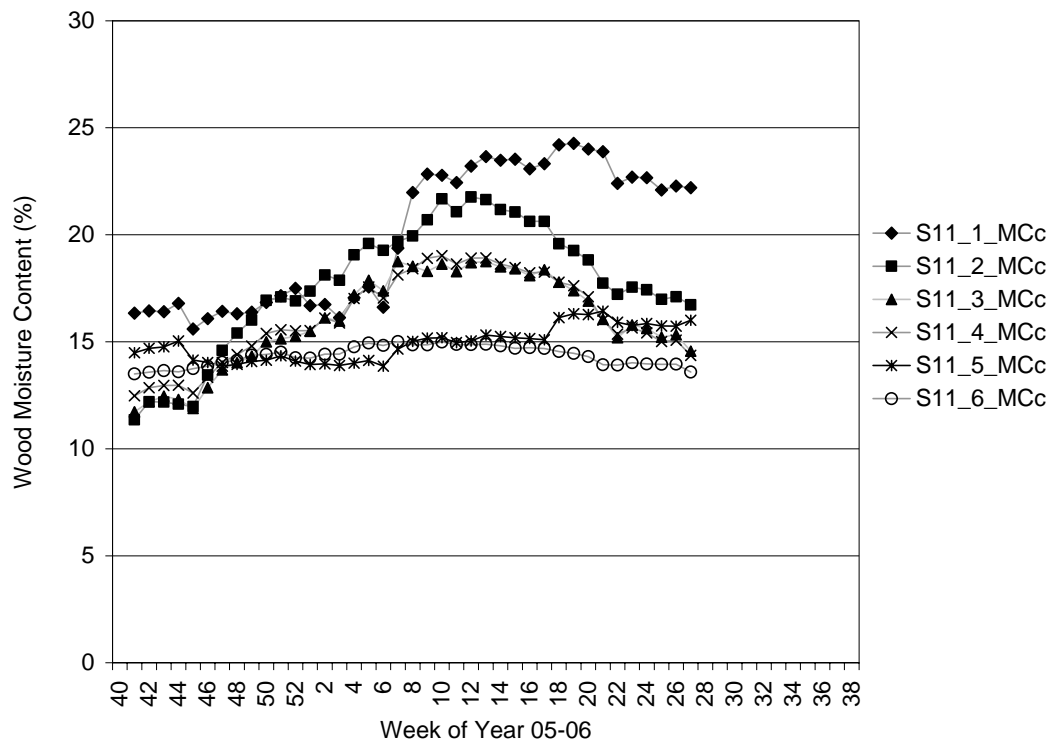


Figure C S11-2

S11 – Cavity Relative Humidity



Figure C S11-3

S11 - Temperature

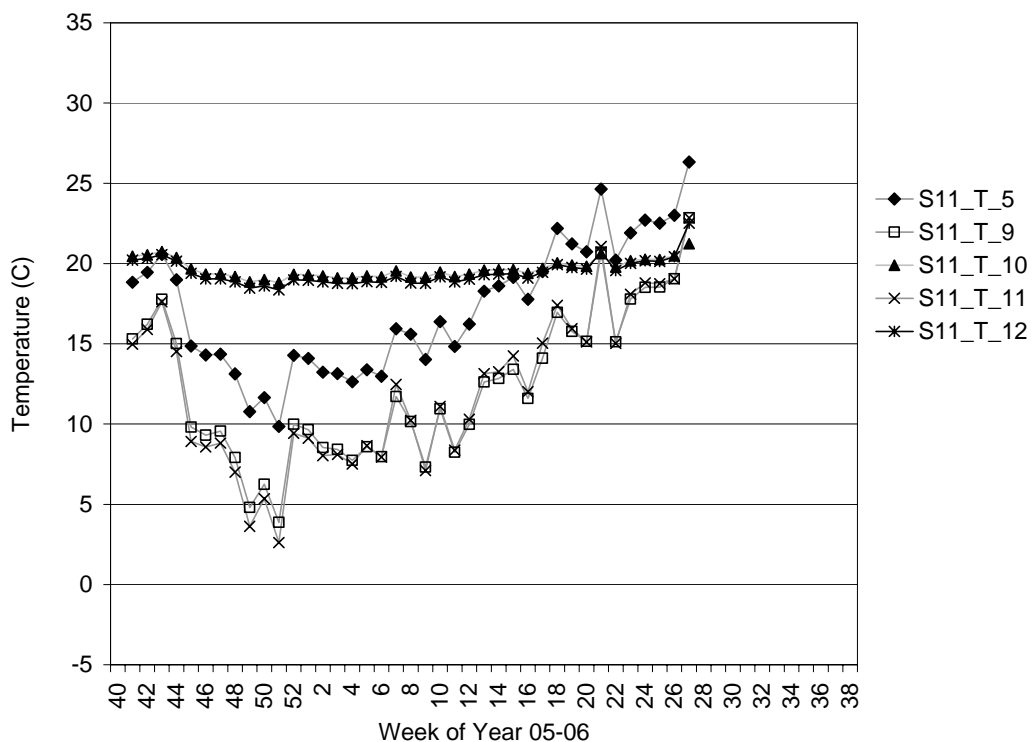


Figure C S11-4

S11 - Vapor Pressure

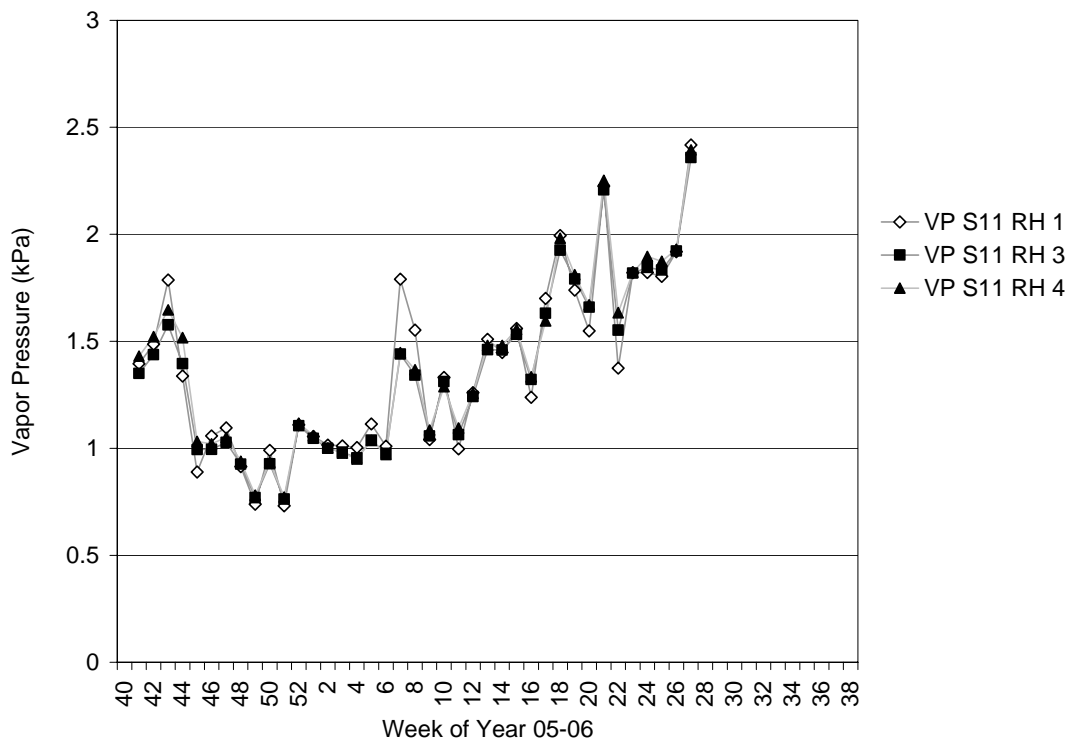


Figure C S11-1 S12 – Wood Moisture Content

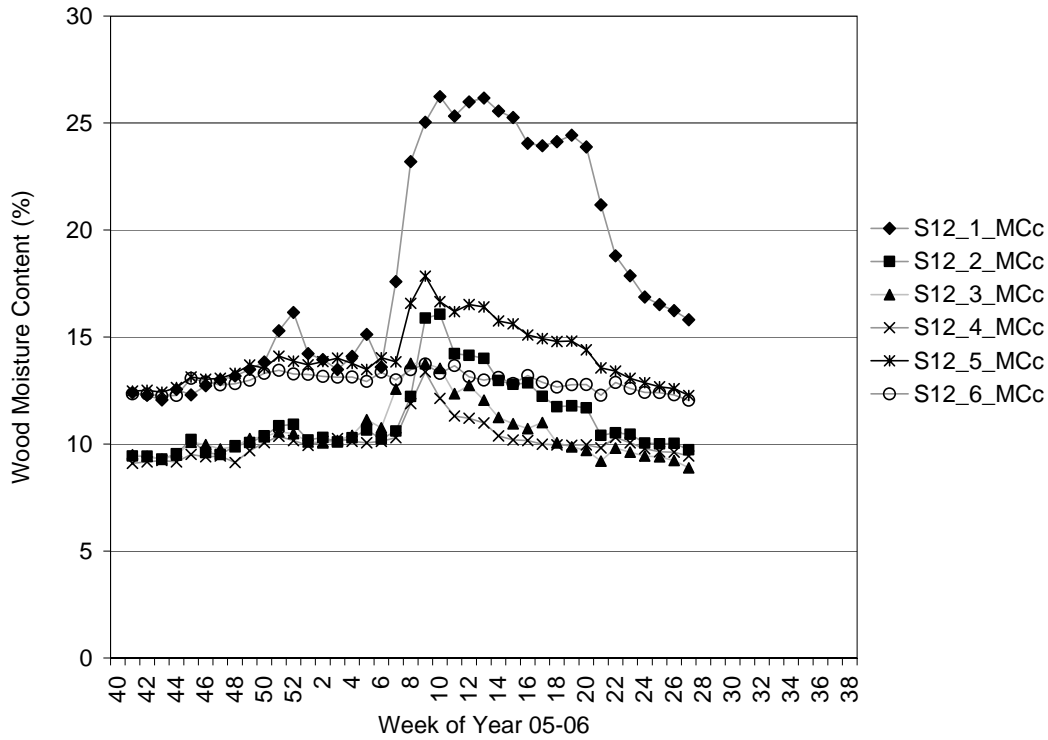


Figure C S11-2 S12 – Cavity Relative Humidity

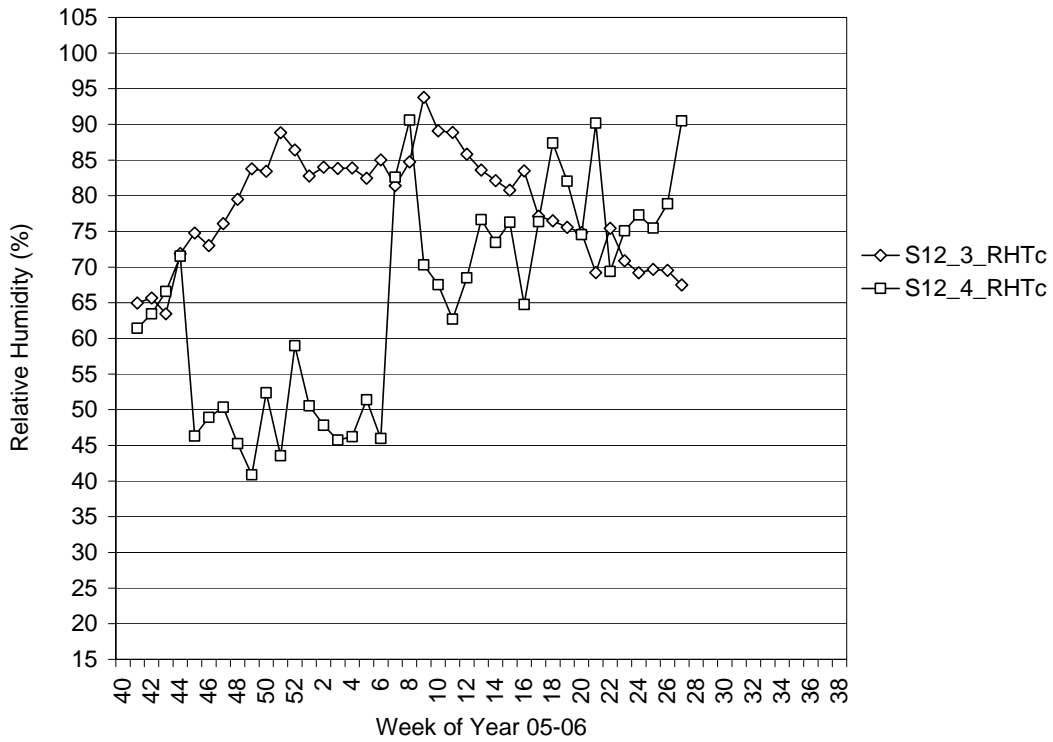


Figure C S11-3

S12 - Temperature

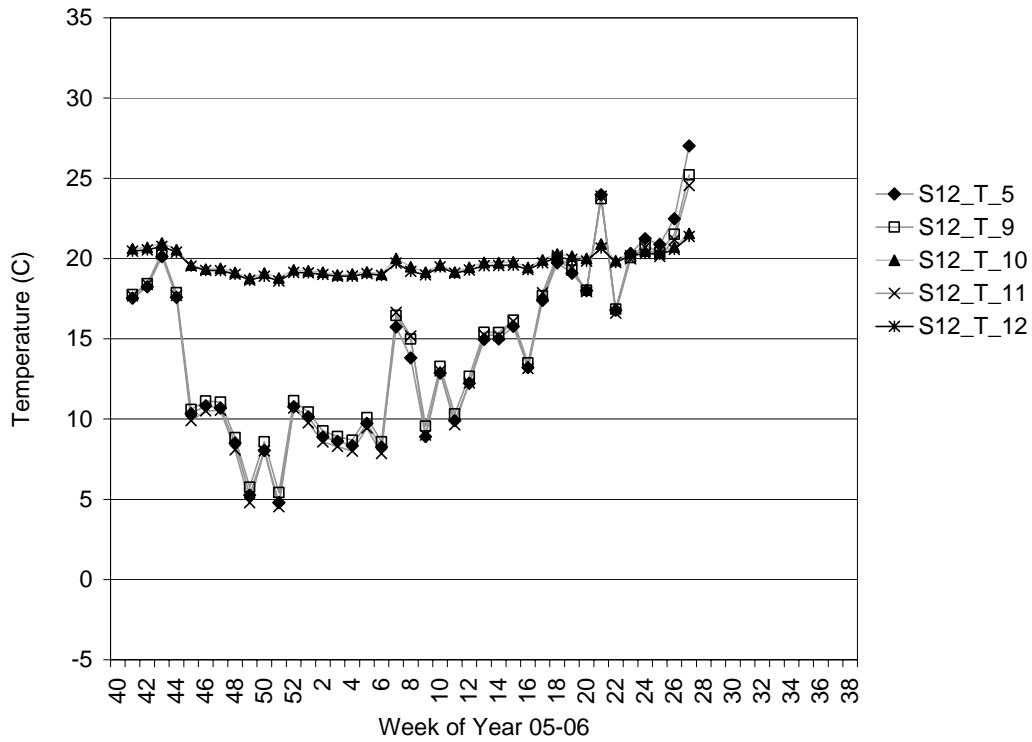


Figure C S11-4

S12 - Vapor Pressure

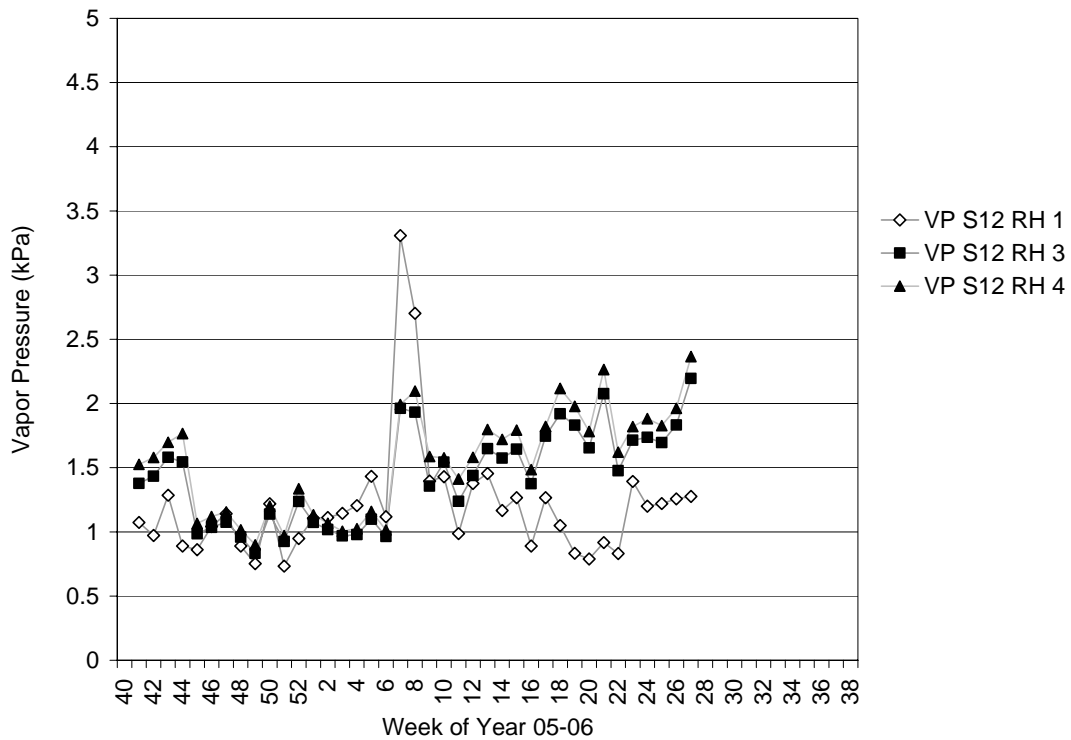


Figure C N3-1

N3 – Wood Moisture Content

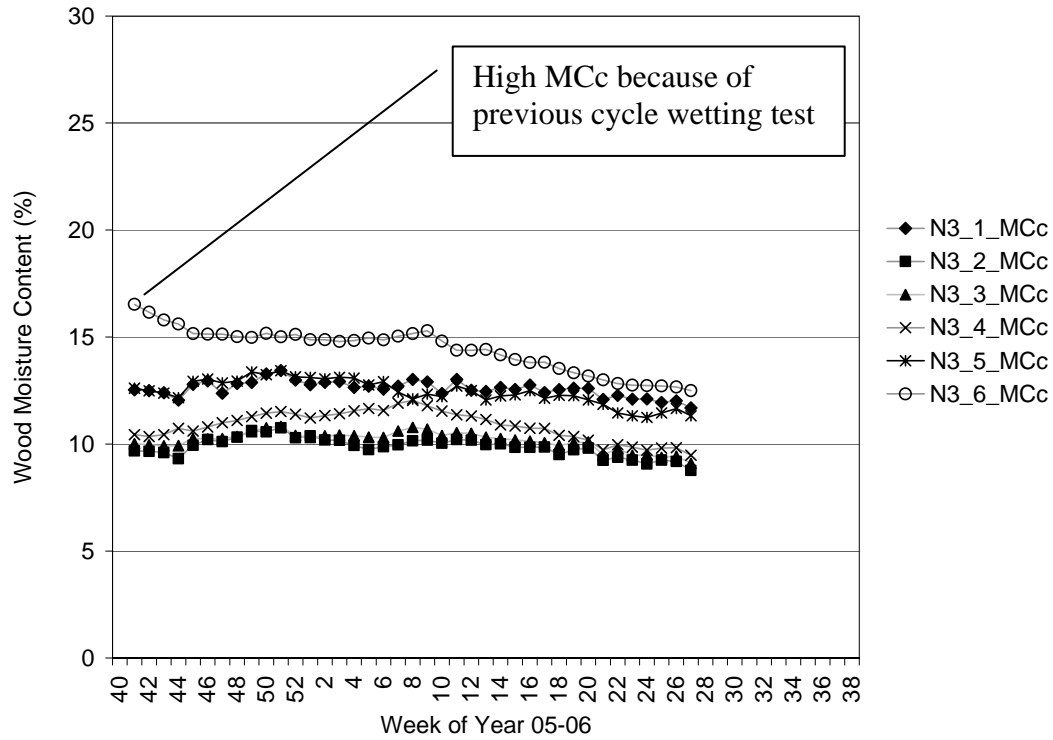


Figure C N3-2

N3 – Cavity Relative Humidity



Figure C N3-3

N3 - Temperature

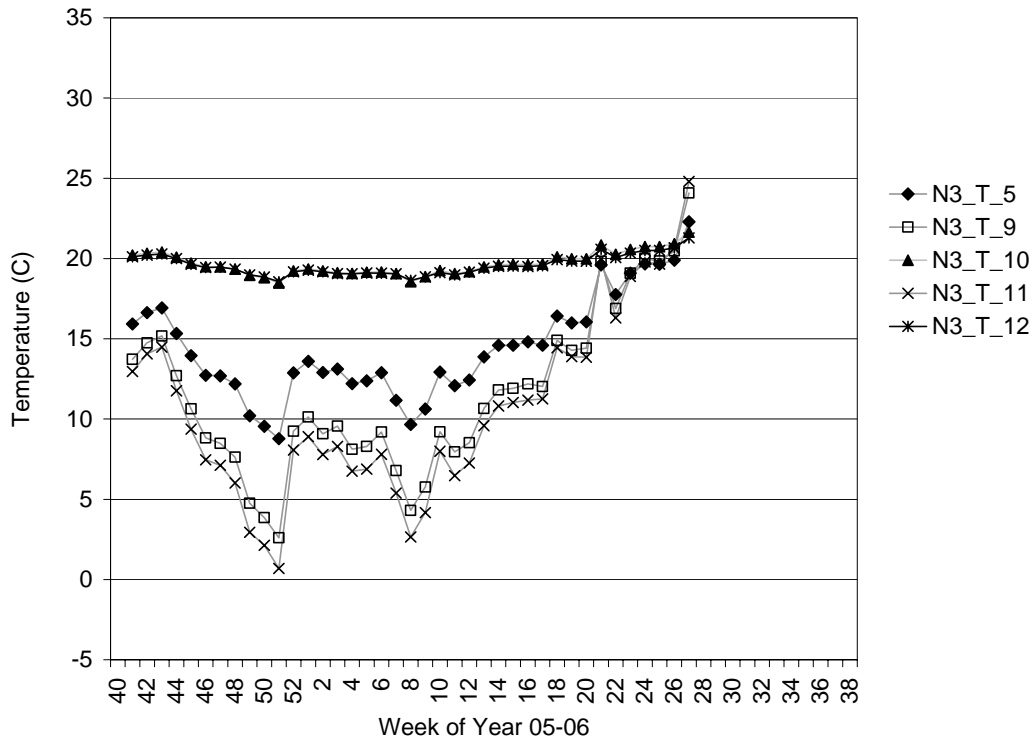


Figure C N3-4

N3 - Vapor Pressure

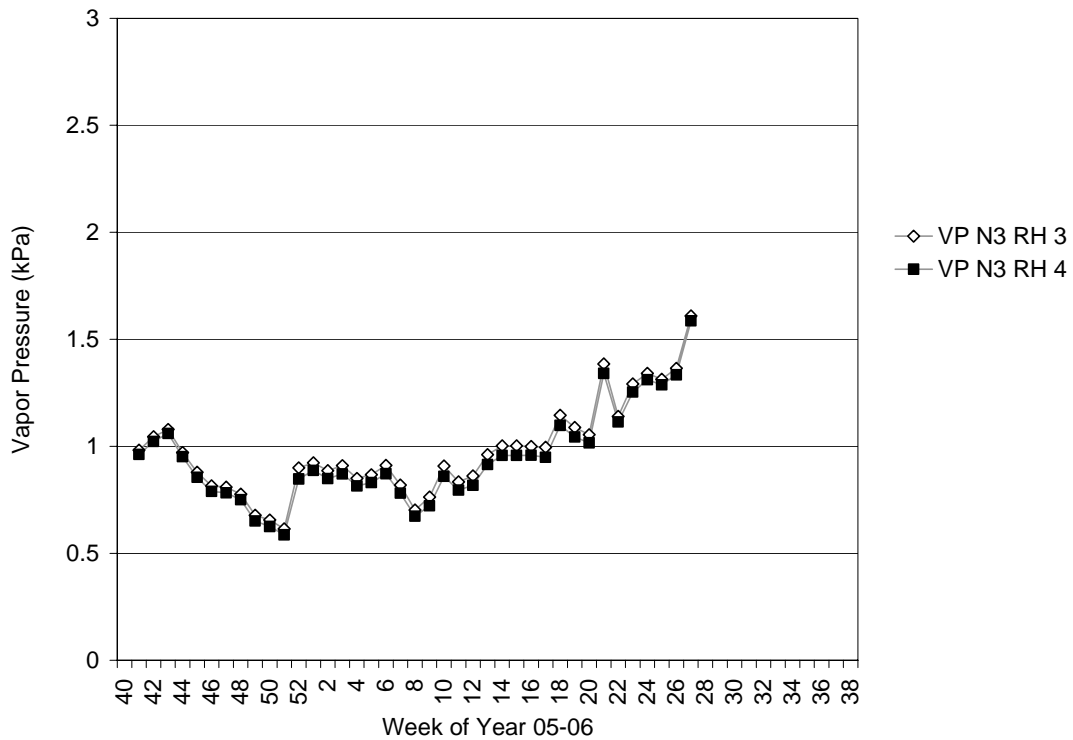


Figure C N4-1

N4 – Wood Moisture Content

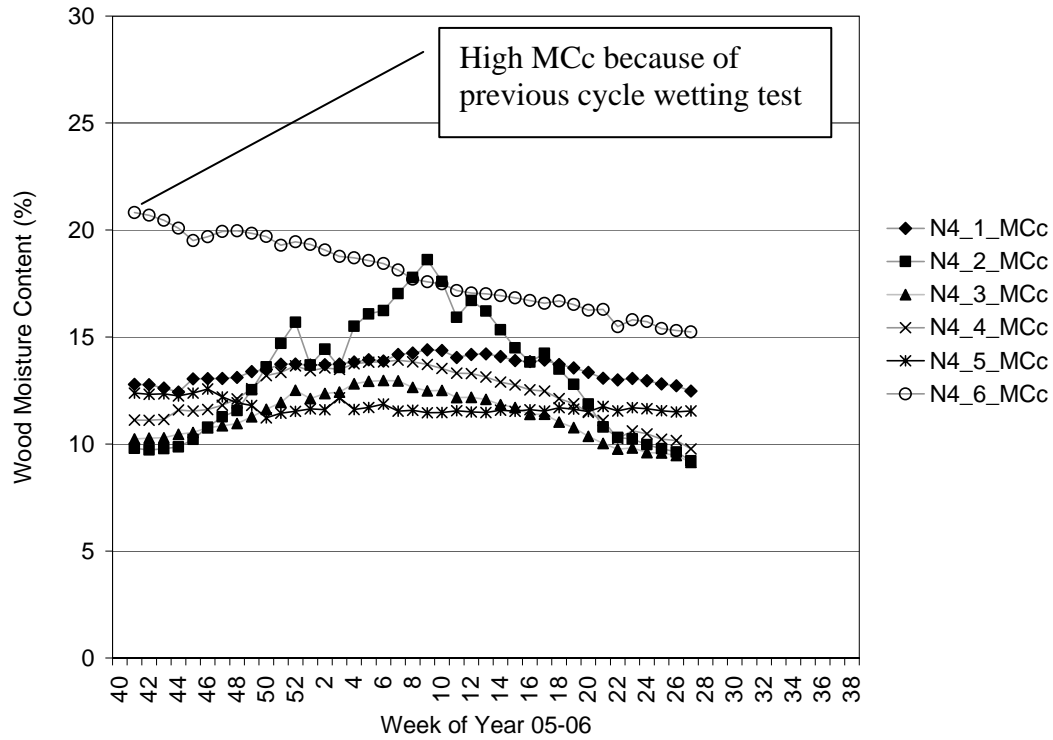


Figure C N4-2

N4 – Cavity Relative Humidity

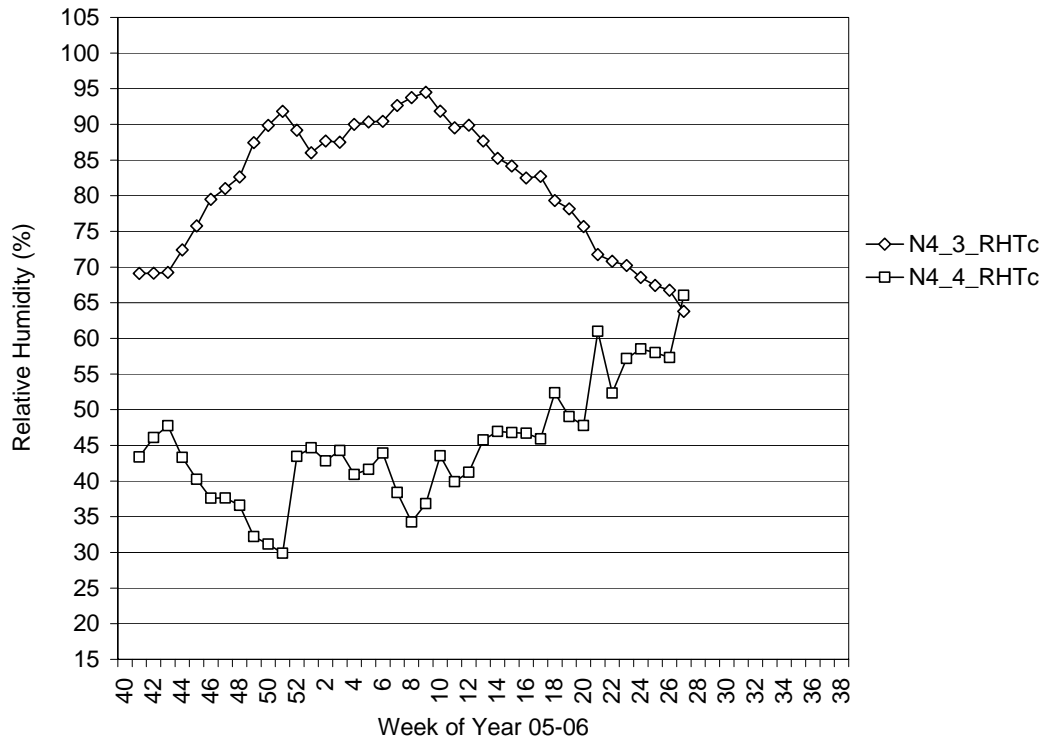


Figure C N4-3

N4 - Temperature

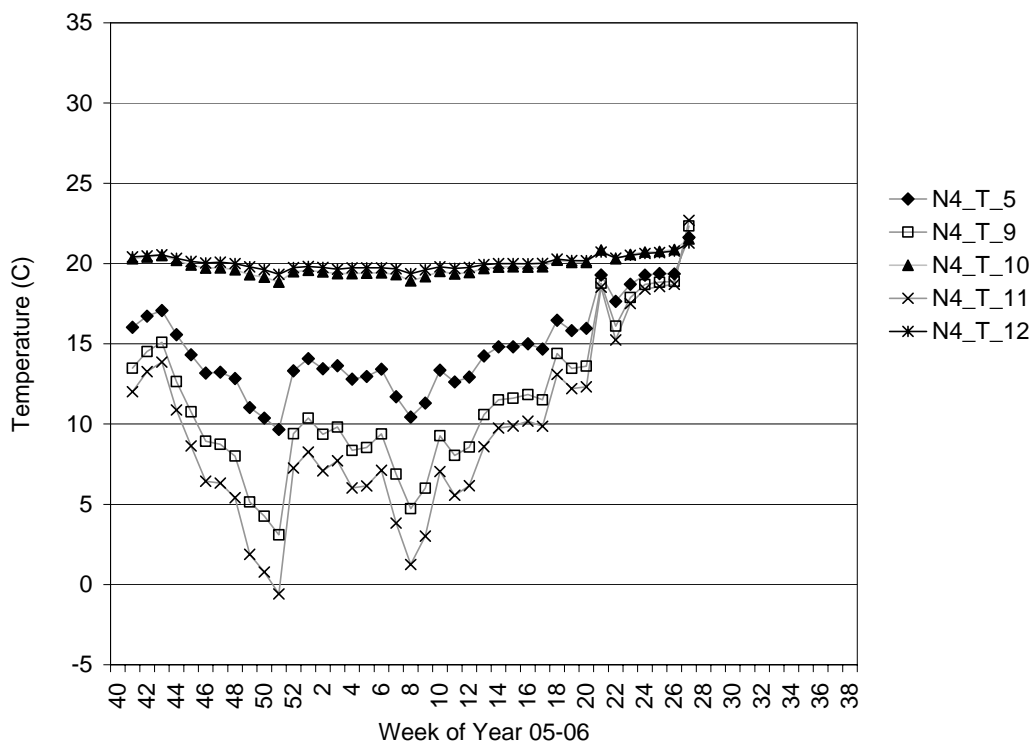


Figure C N4-4

N4 - Vapor Pressure

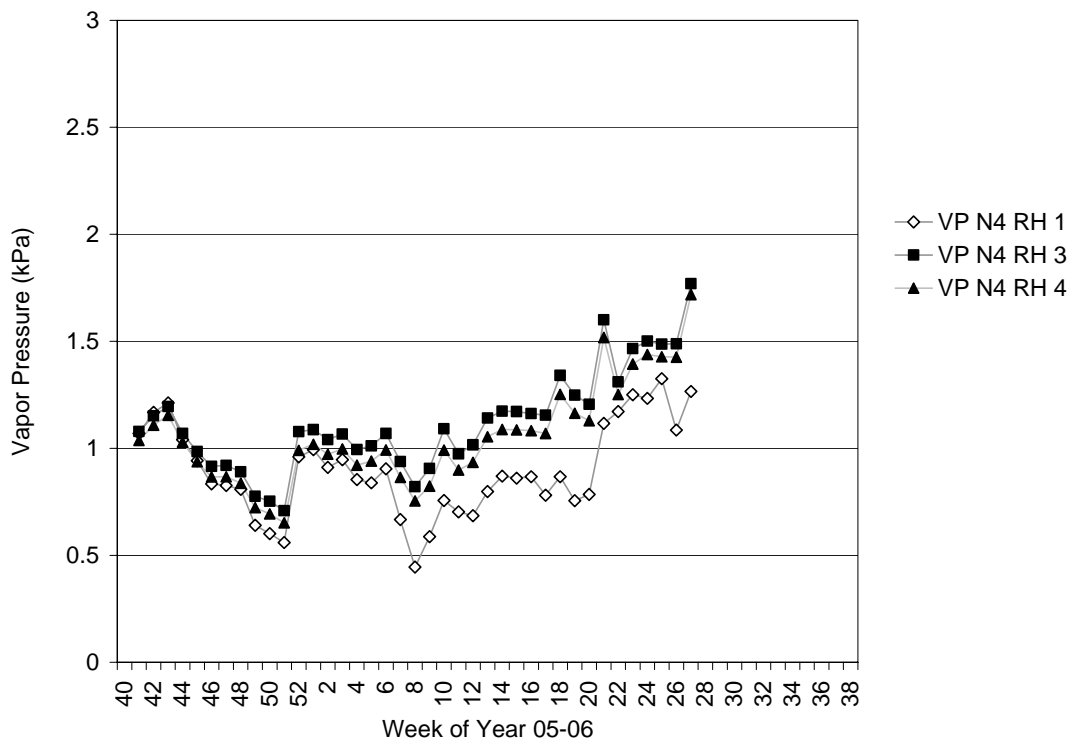


Figure C N5-1

N5 – Wood Moisture Content

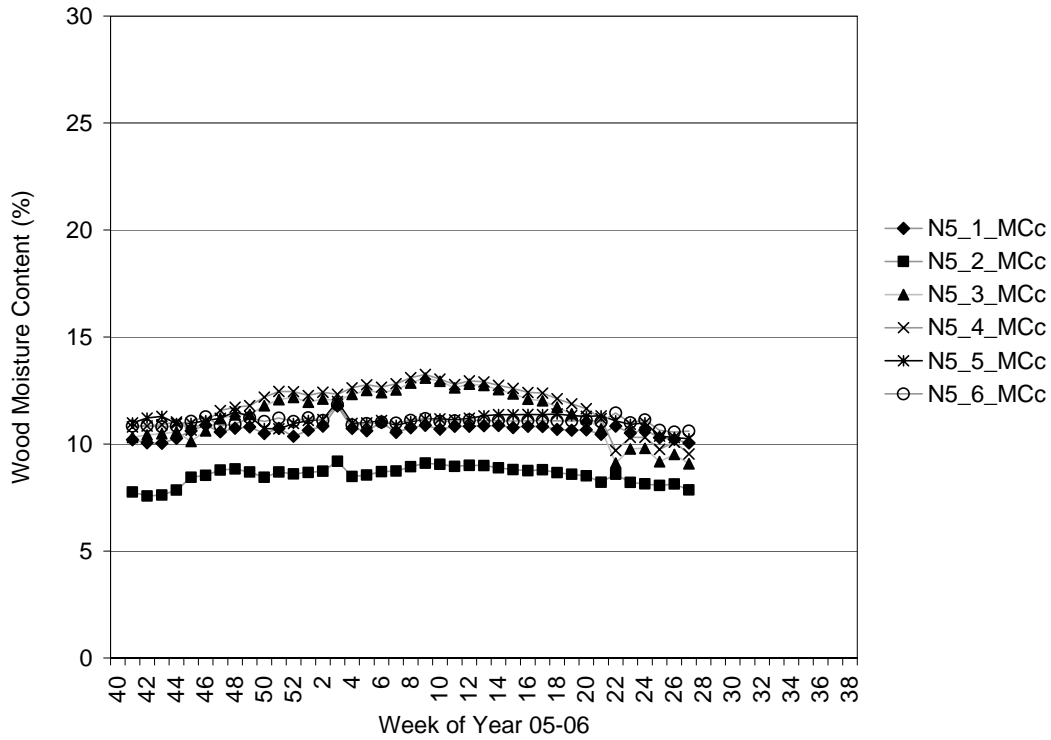


Figure C N5-2

N5 – Cavity Relative Humidity



Figure C N5-3

N5 - Temperature

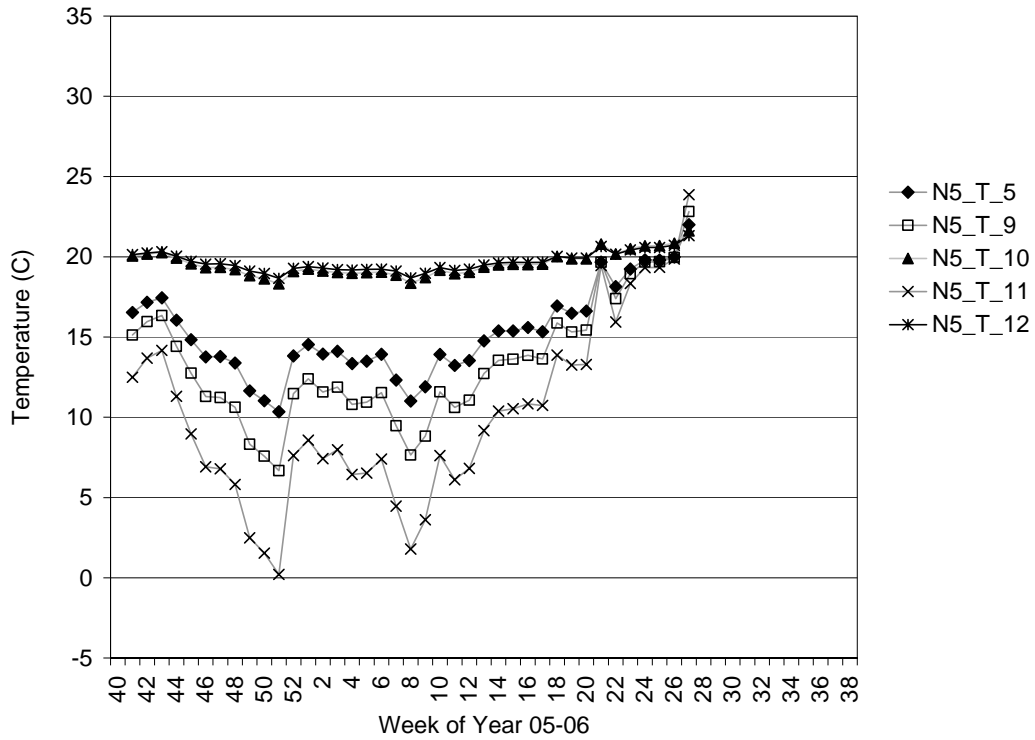


Figure C N5-4

N5 – Vapor Pressure

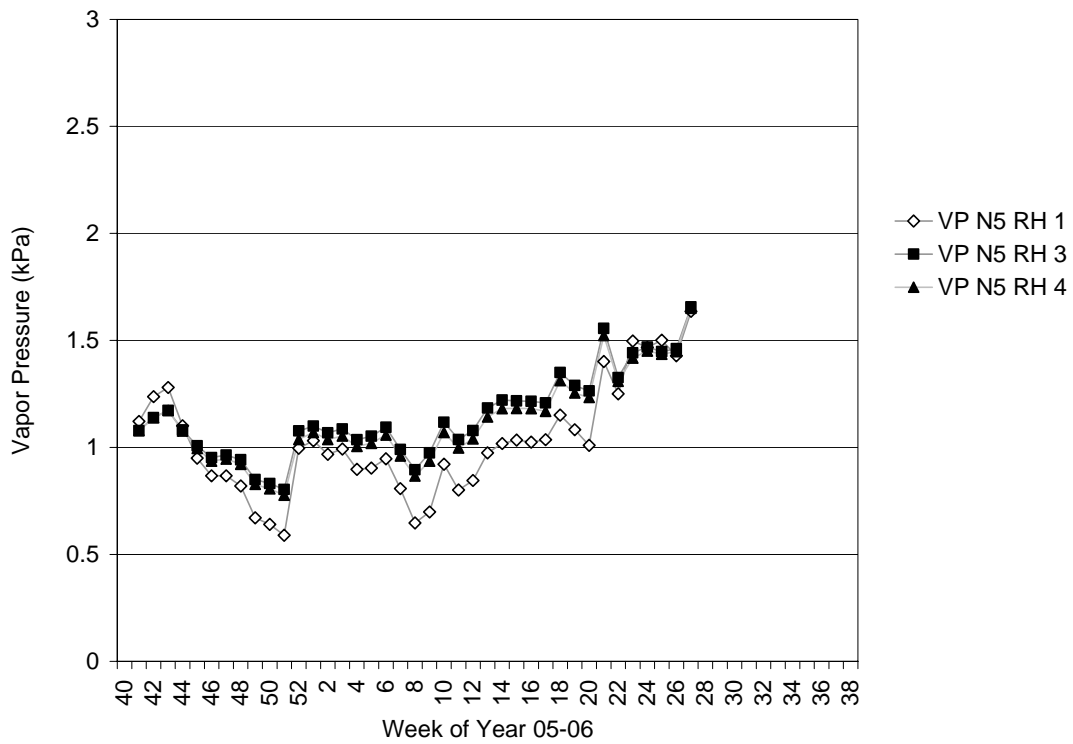


Figure C N6-1

N6 – Wood Moisture Content

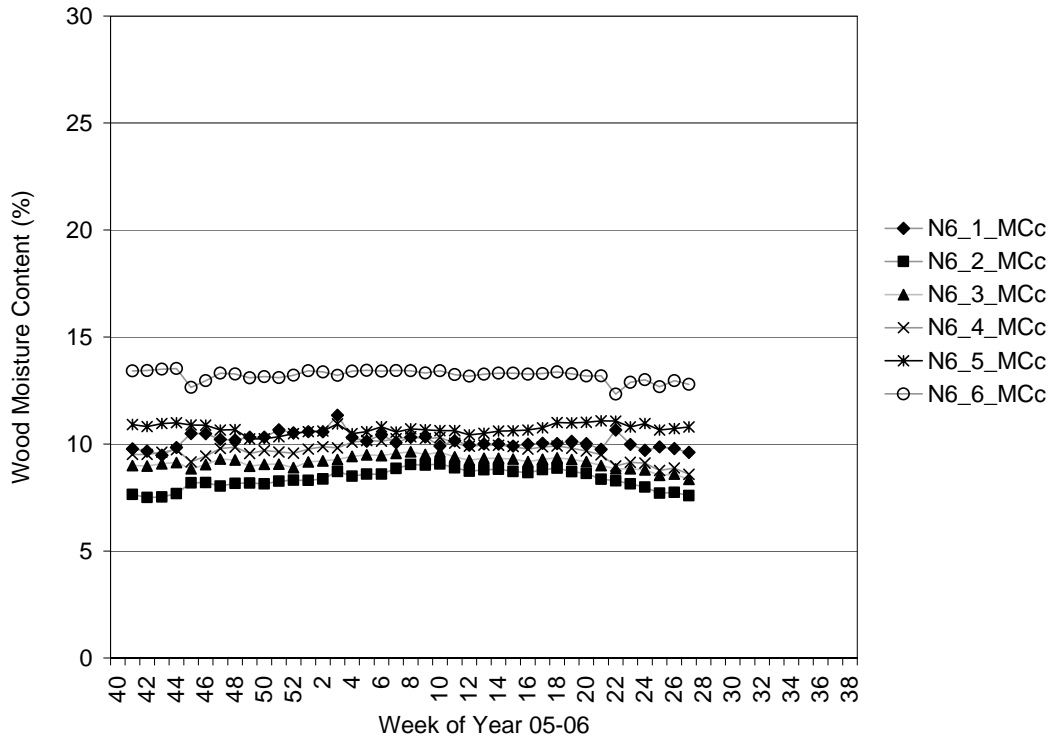


Figure C N6-2

N6 – Cavity Relative Humidity

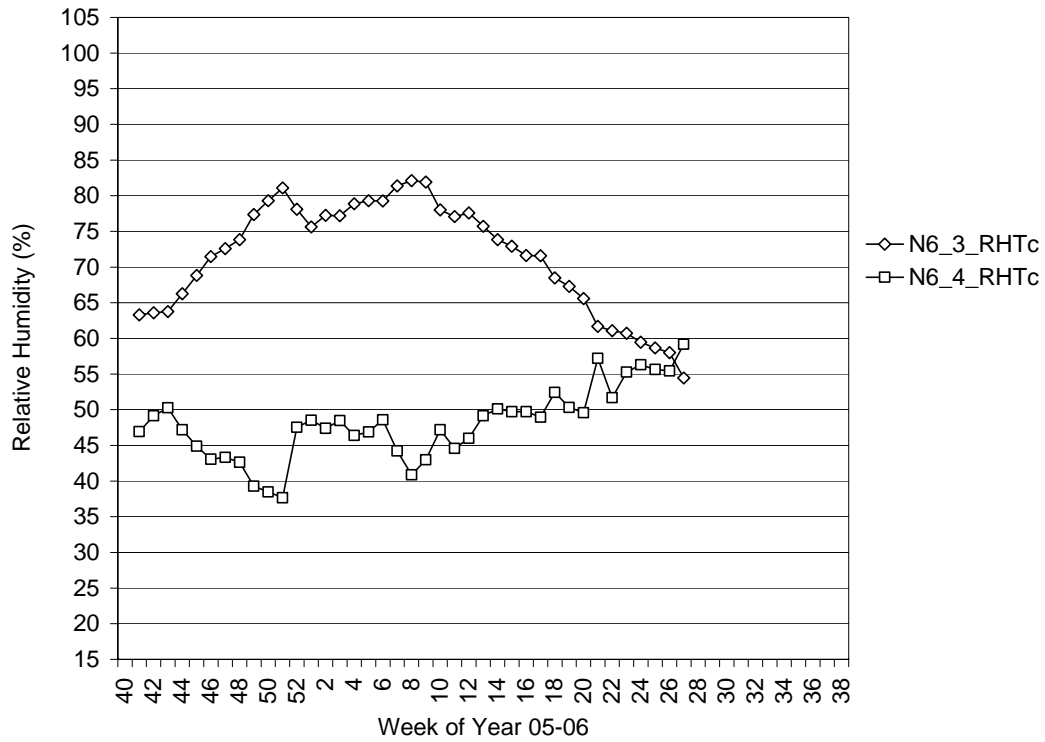


Figure C N6-3

N6 - Temperature

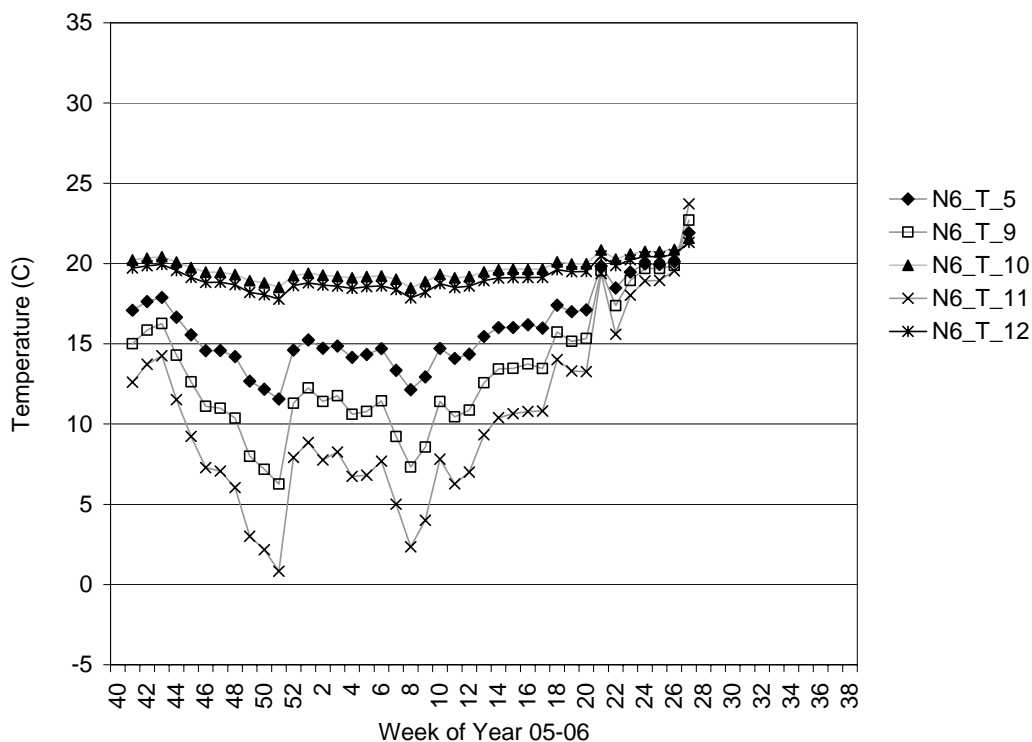


Figure C N6-4

N6 - Vapor Pressure

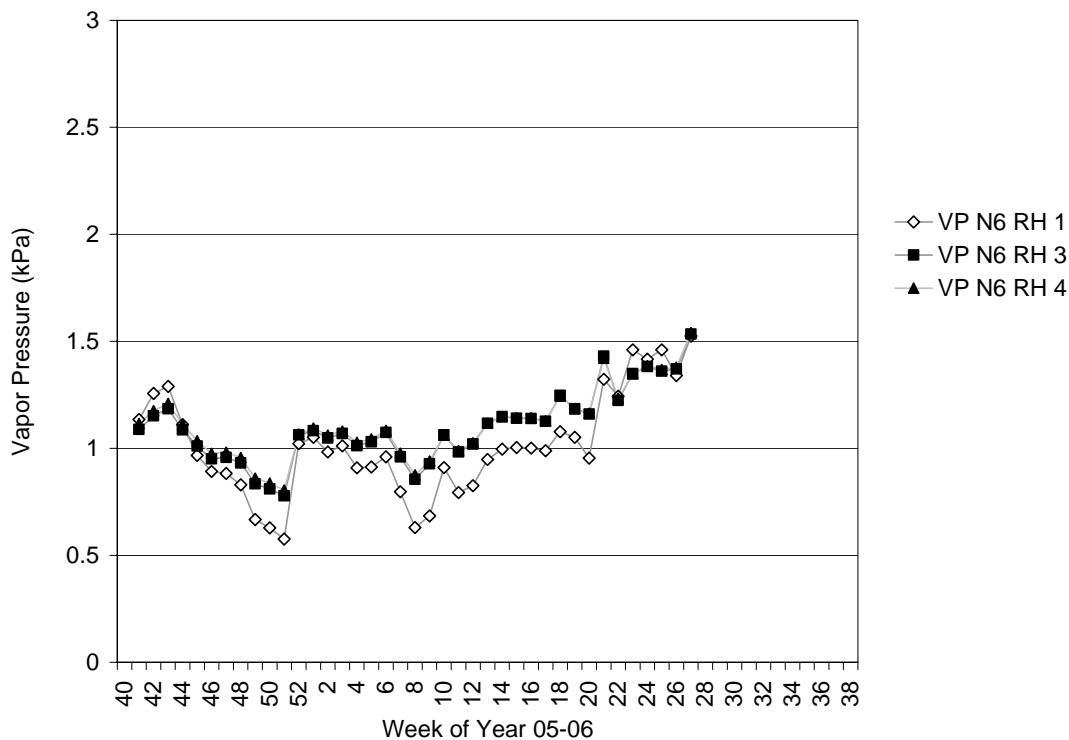


Figure C N7-1

N7 – Wood Moisture Content

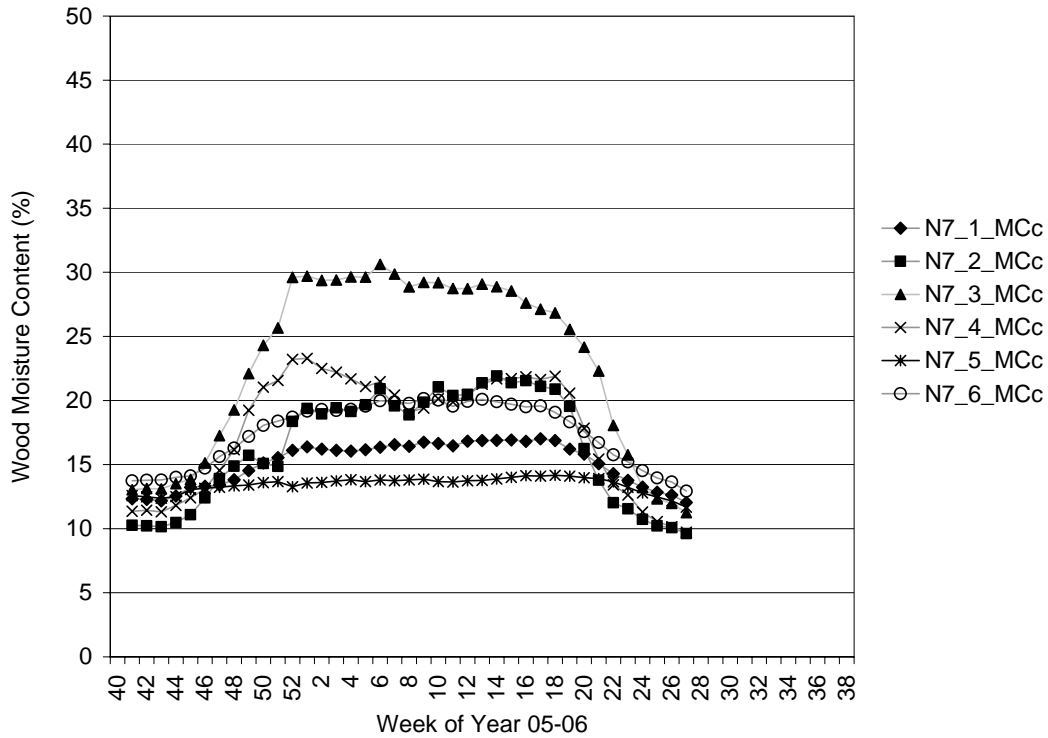


Figure C N7-2

N7 – Cavity Relative Humidity

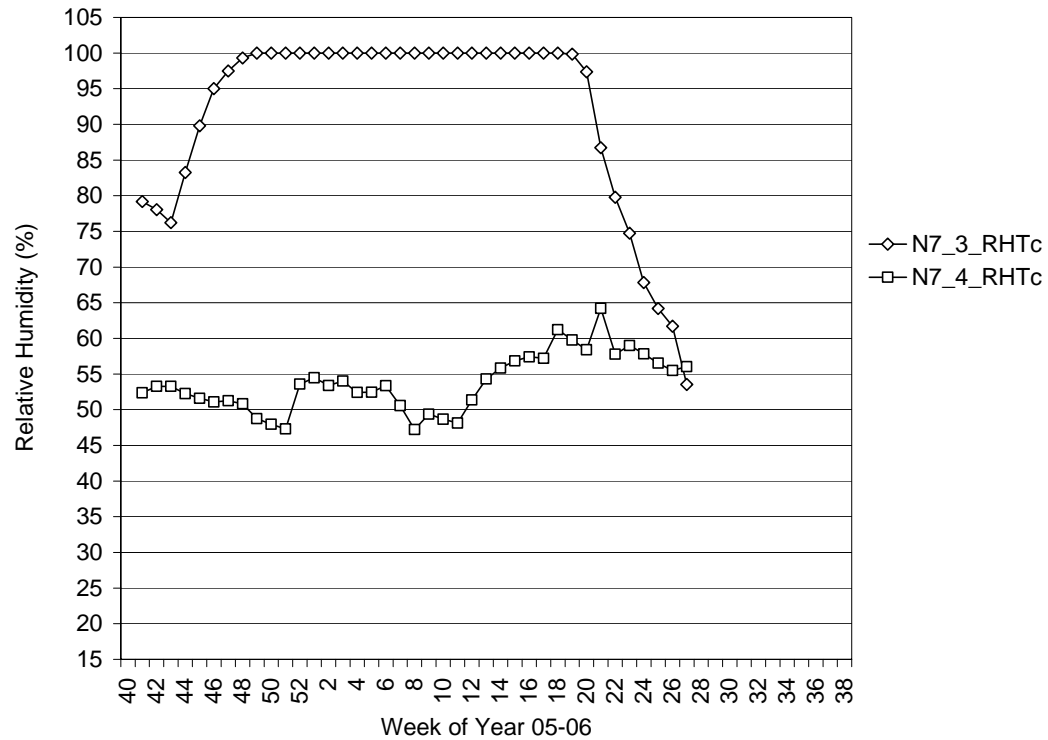


Figure C N7-3

N7 - Temperature

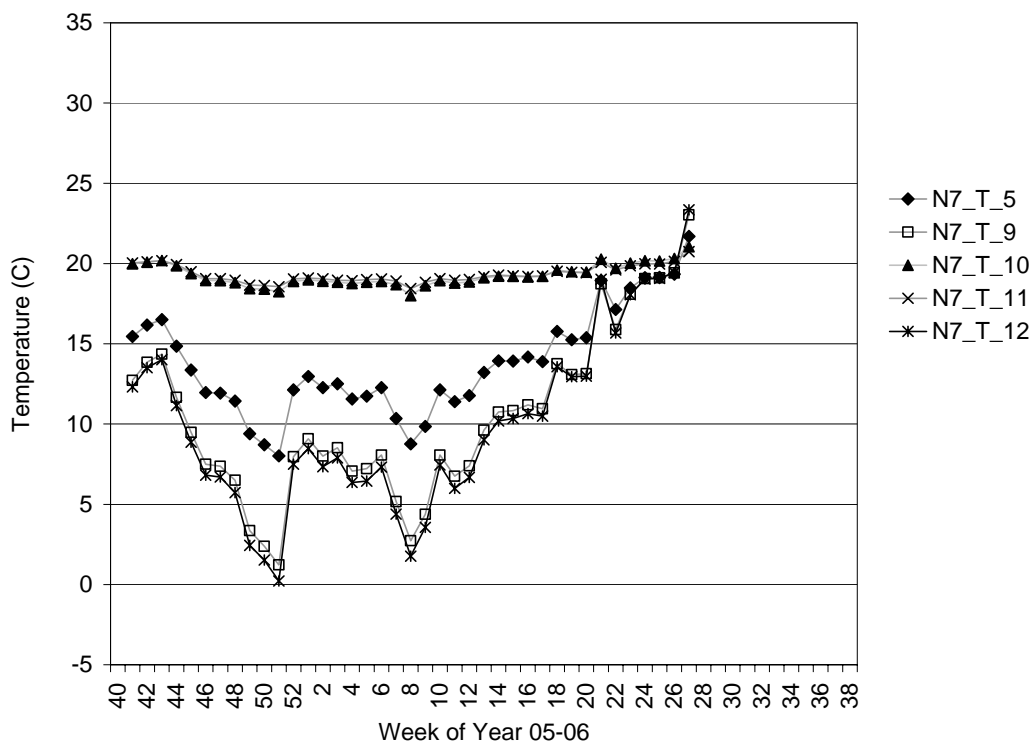


Figure C N7-4

N7 - Vapor Pressure

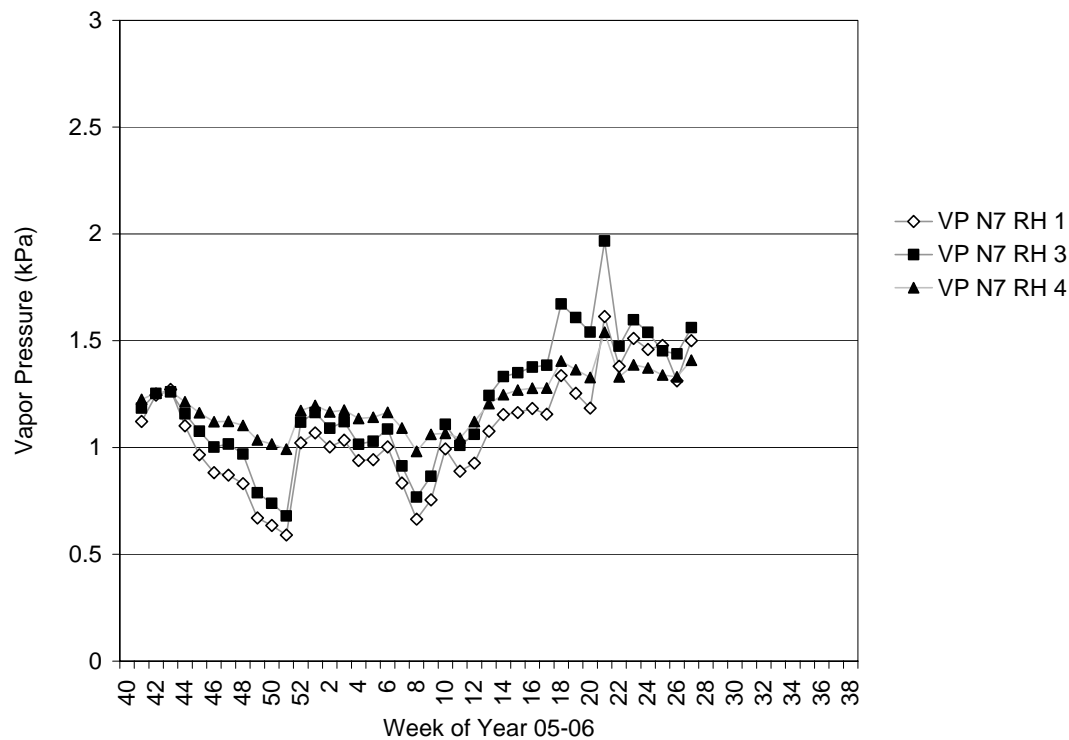


Figure C N81

N8 – Wood Moisture Content

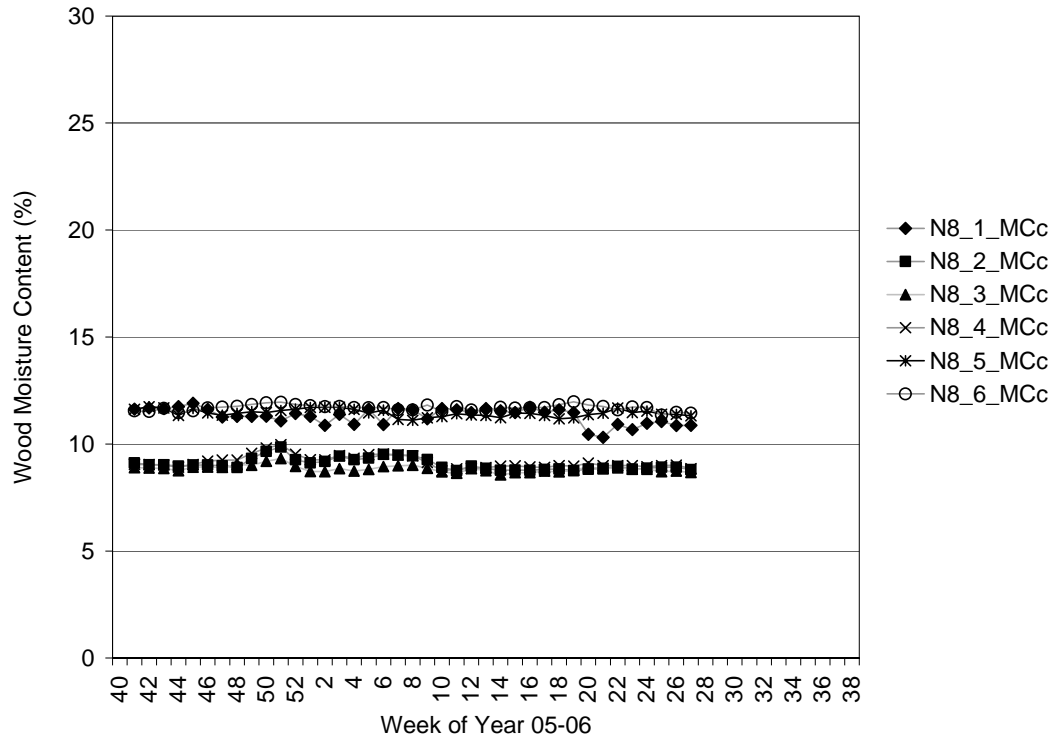


Figure C N8-2

N8 – Cavity Relative Humidity

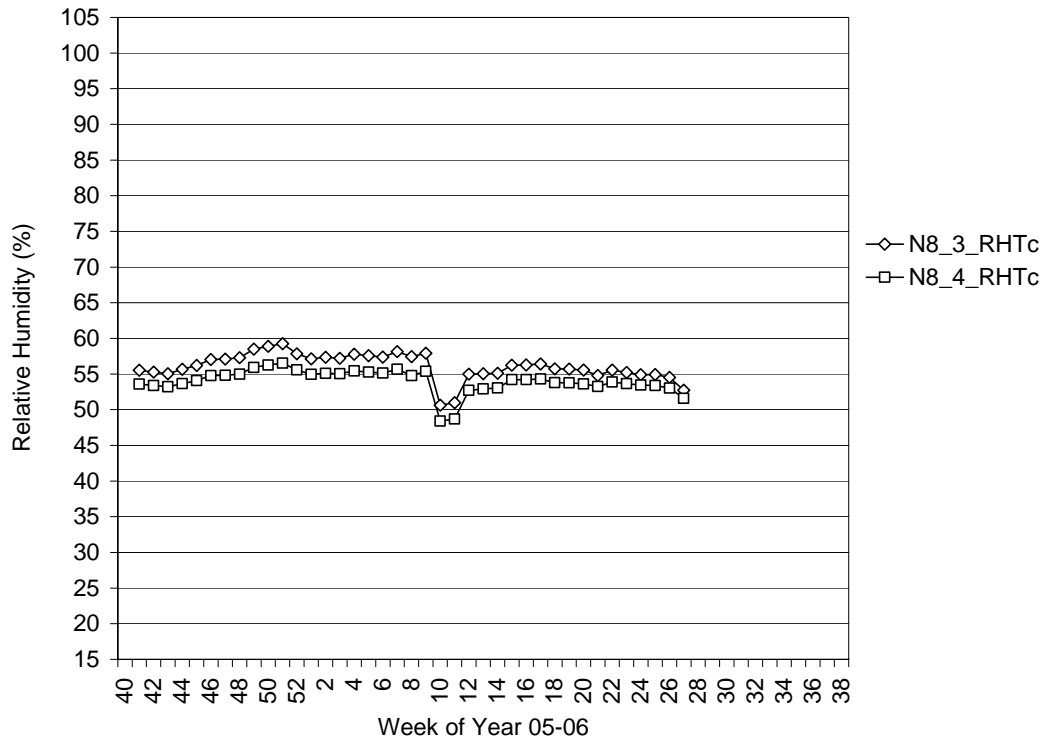


Figure C N8-3

N8 - Temperature

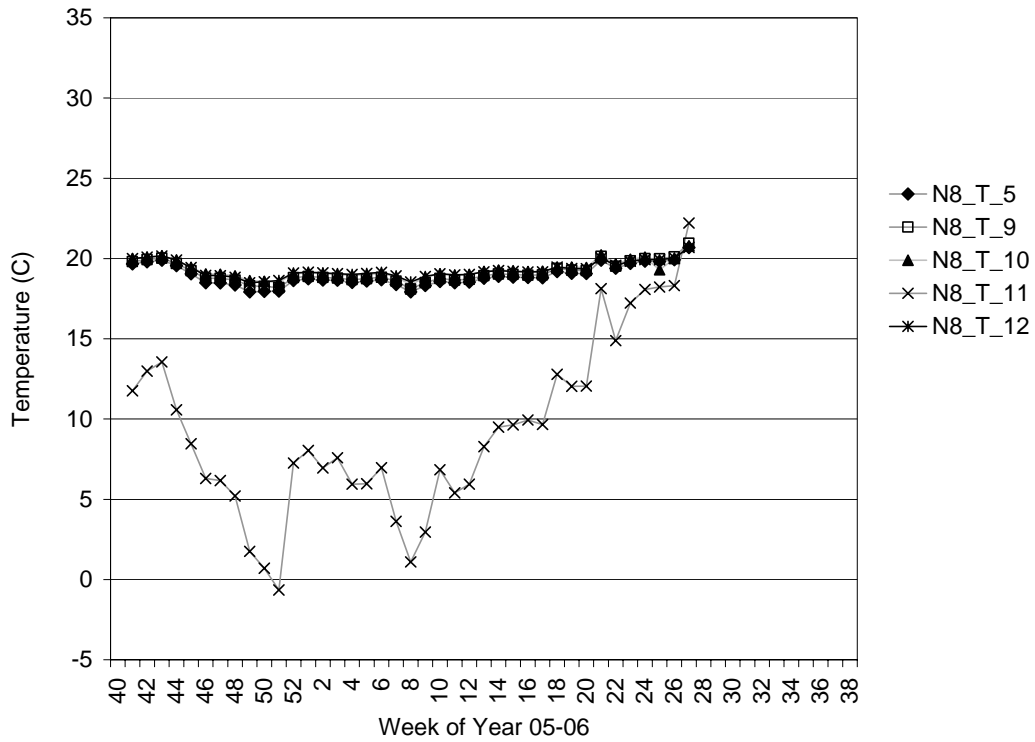
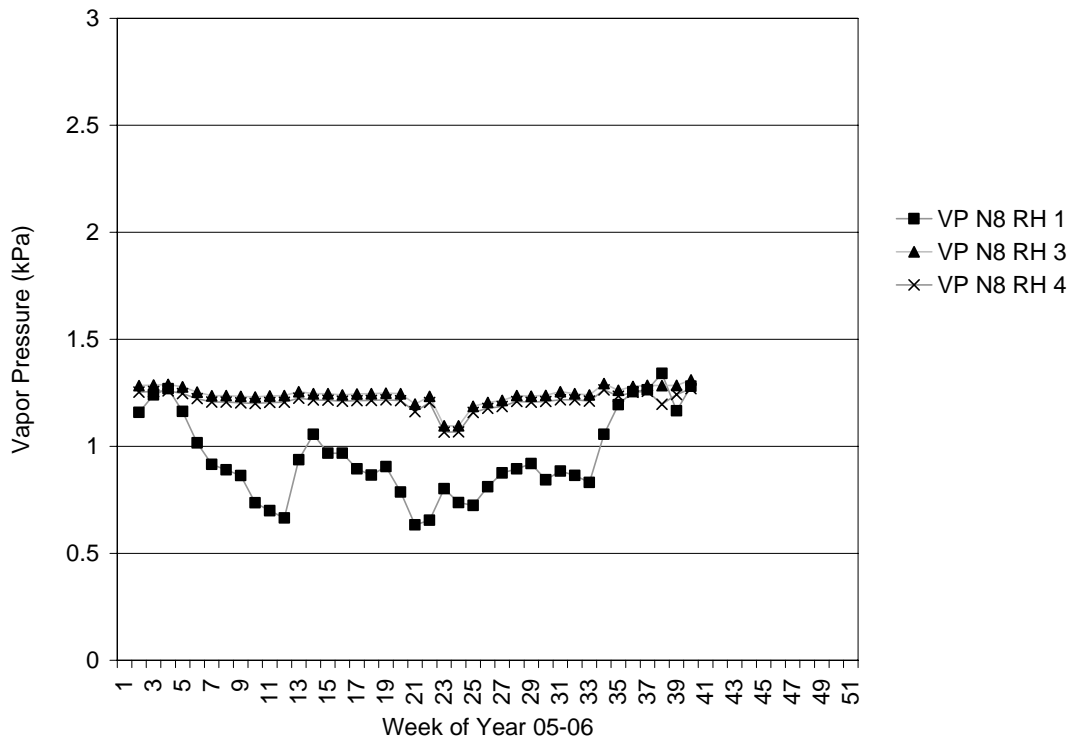


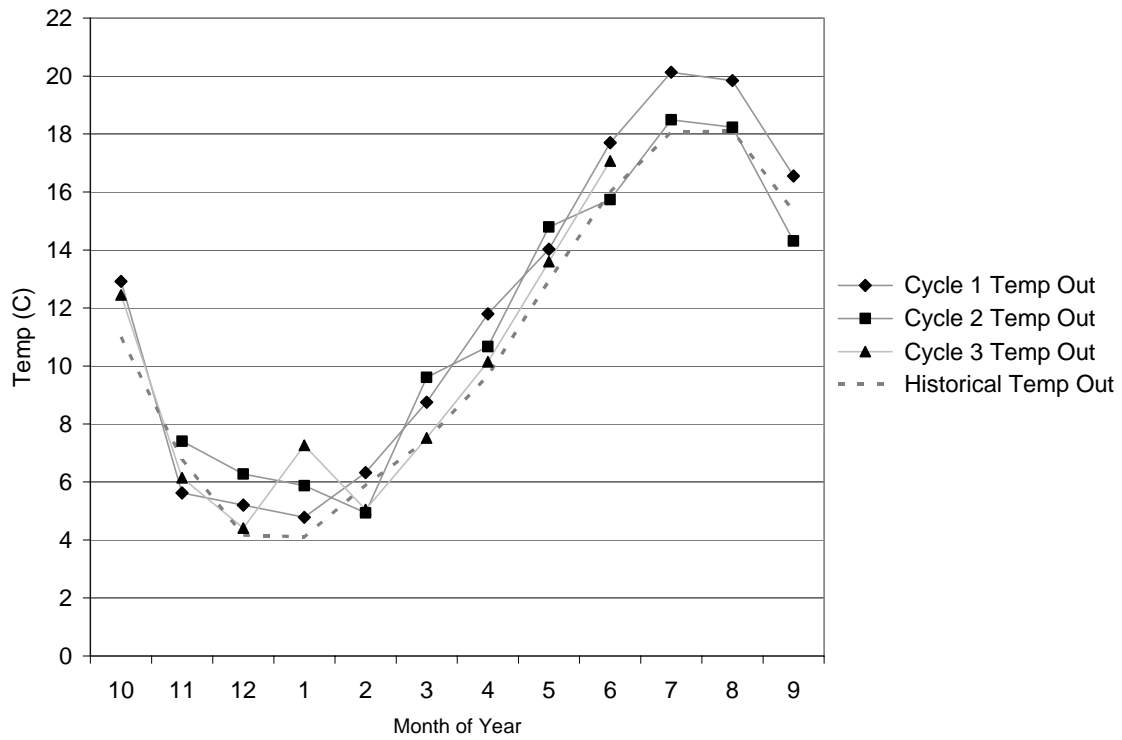
Figure C N8-4

N8 - Vapor Pressure

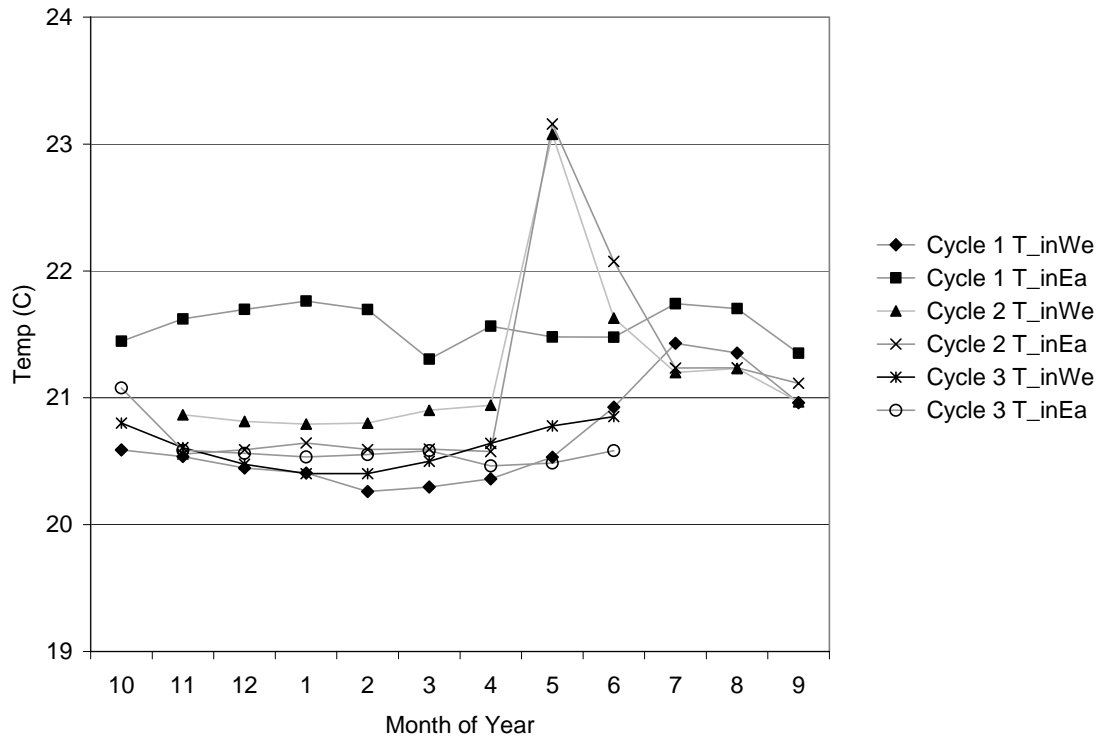


**Appendix D**  
**Indoor and Outdoor Environmental Conditions**  
**October 2003 to June 2006**

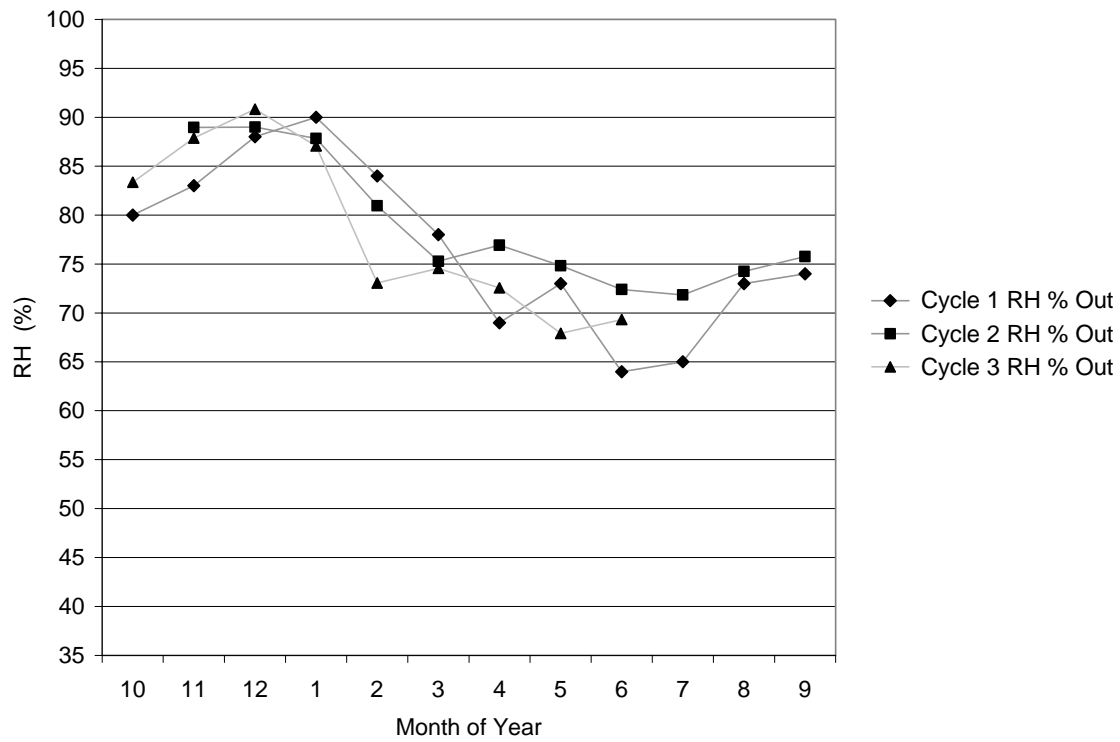
**Figure D1 Outdoor Temperature (C)**



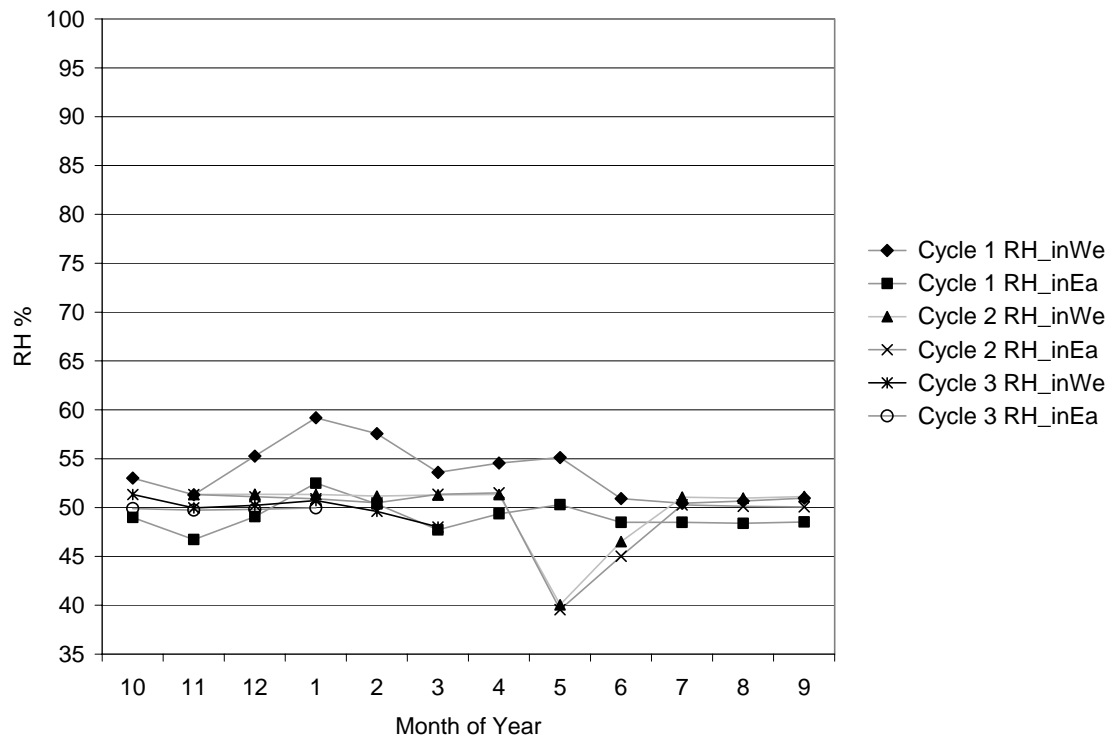
**Figure D2 Indoor Temperature (C)**



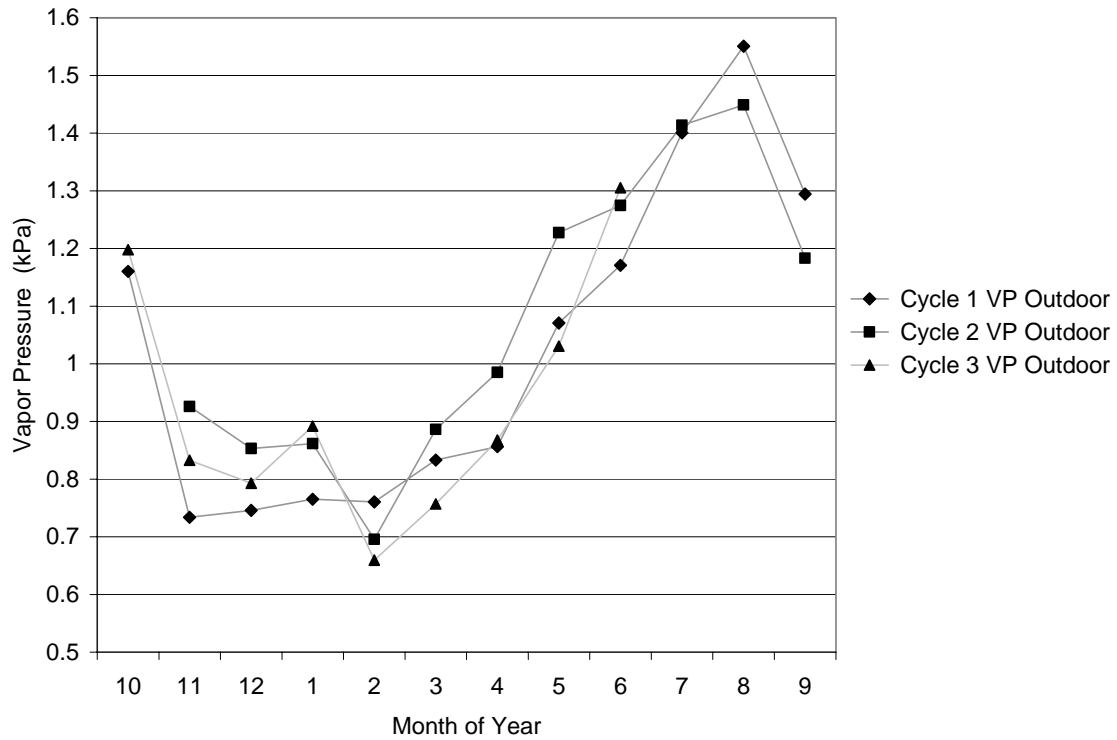
**Figure D3 Outdoor Relative Humidity (%)**



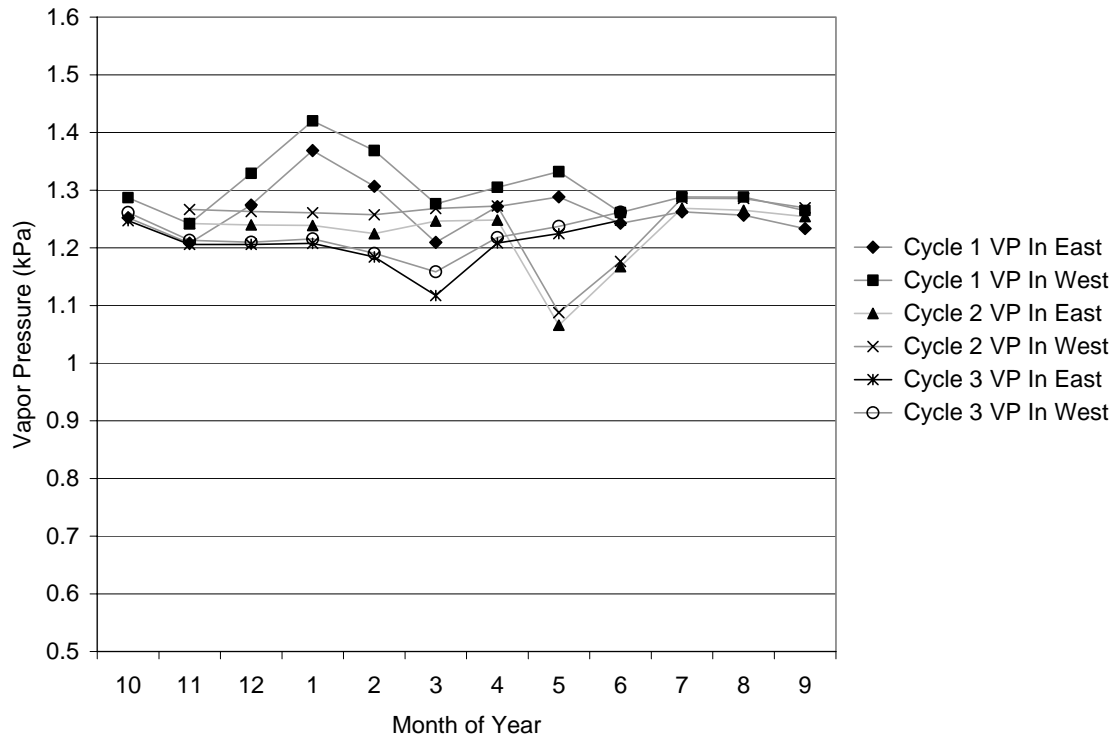
**Figure D4 Indoor Relative Humidity**



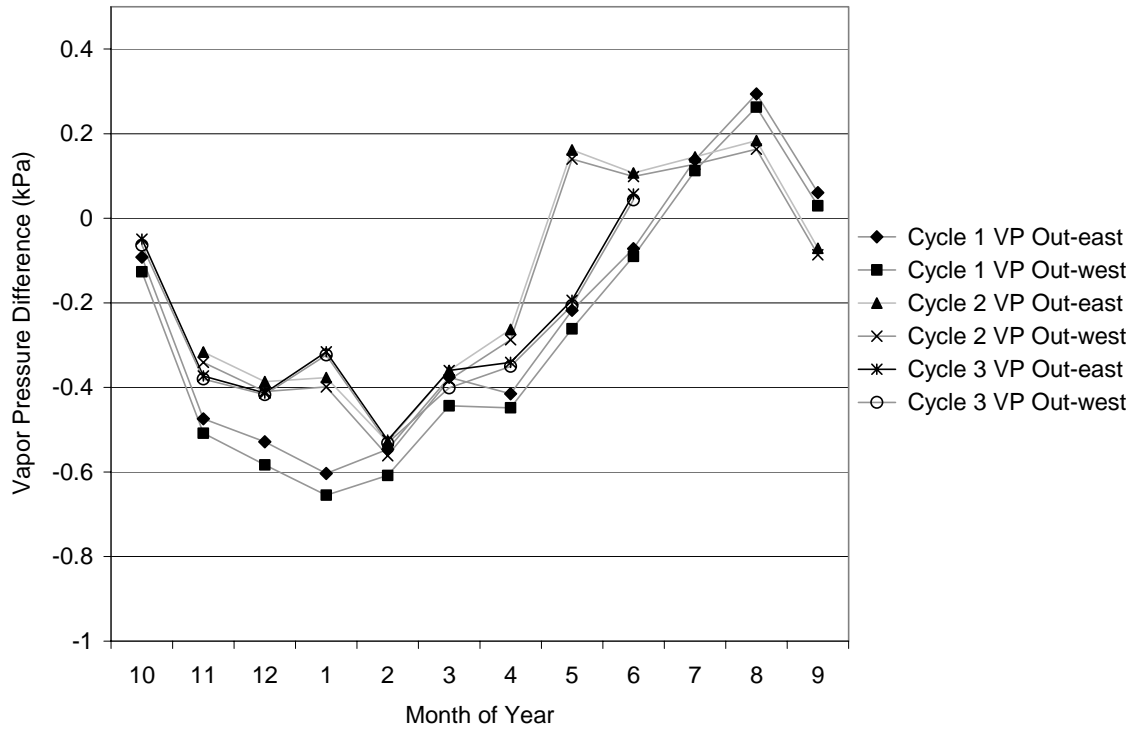
**Figure D5 Vapor Pressure Outdoors (kPa)**



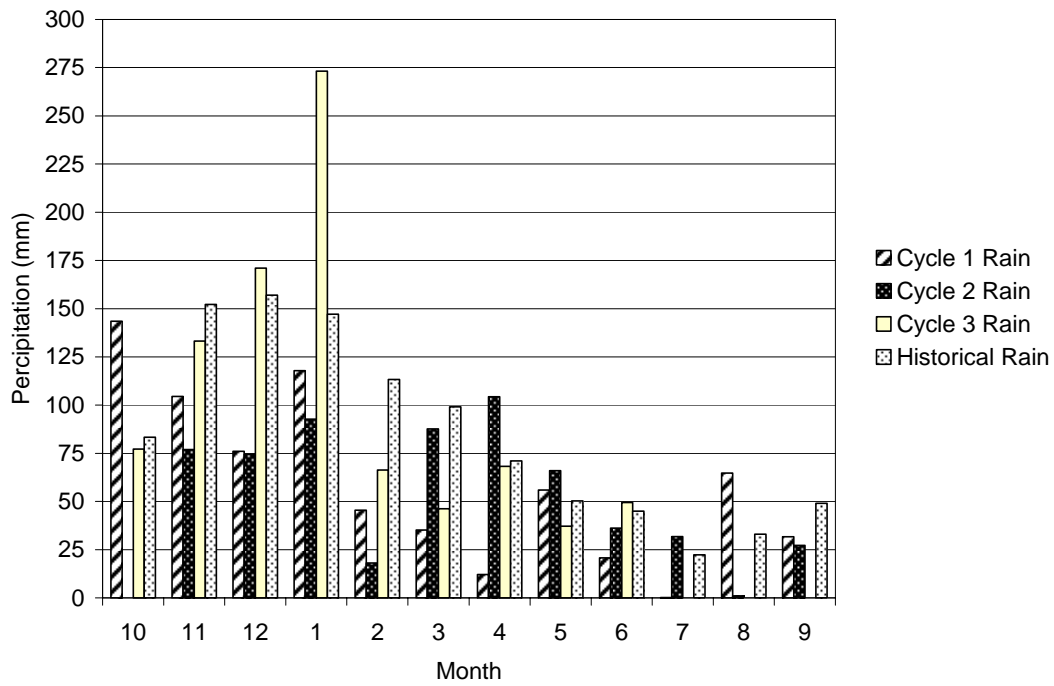
**Figure D6 Vapor Pressure Indoors (kPa)**



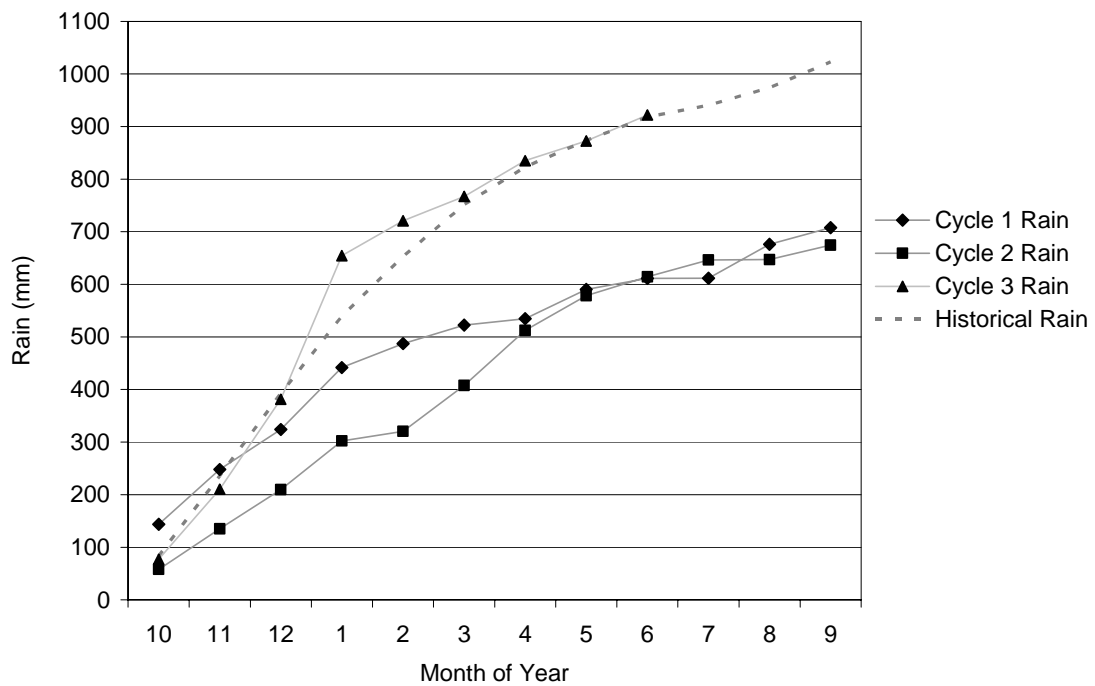
**Figure D7 Vapor Pressure Difference (Outdoors – Indoors)**



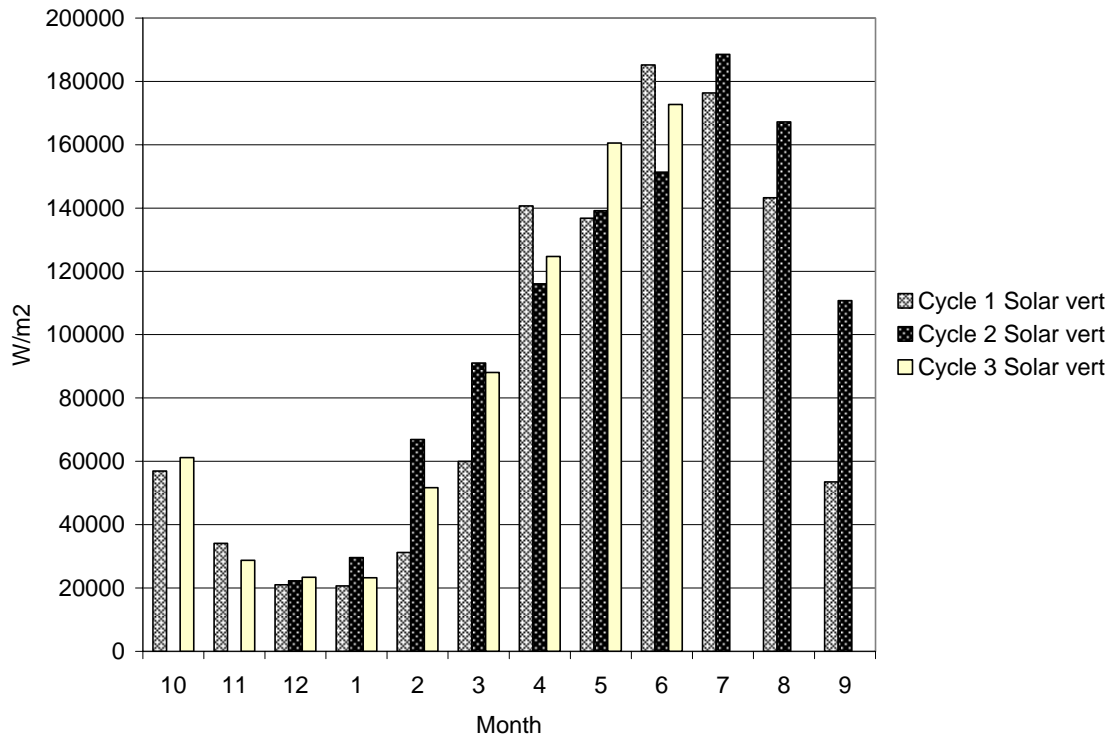
**Figure D8 Sum of Precipitation**



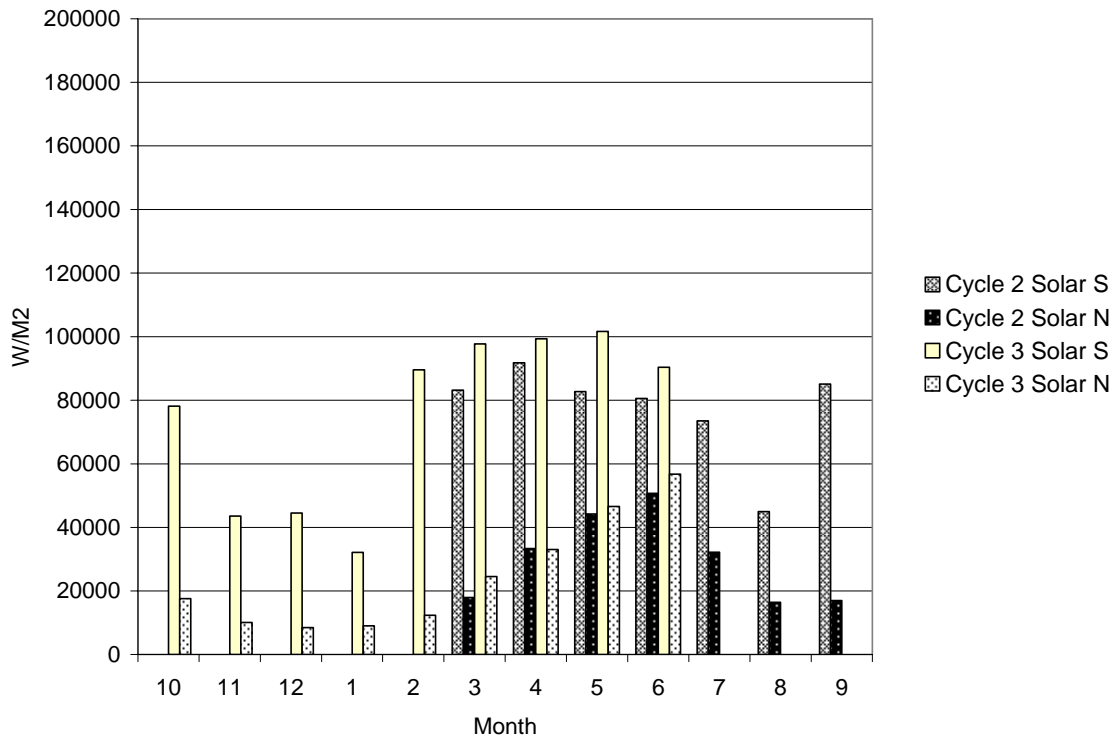
**Figure D9 Cumulative Precipitation**



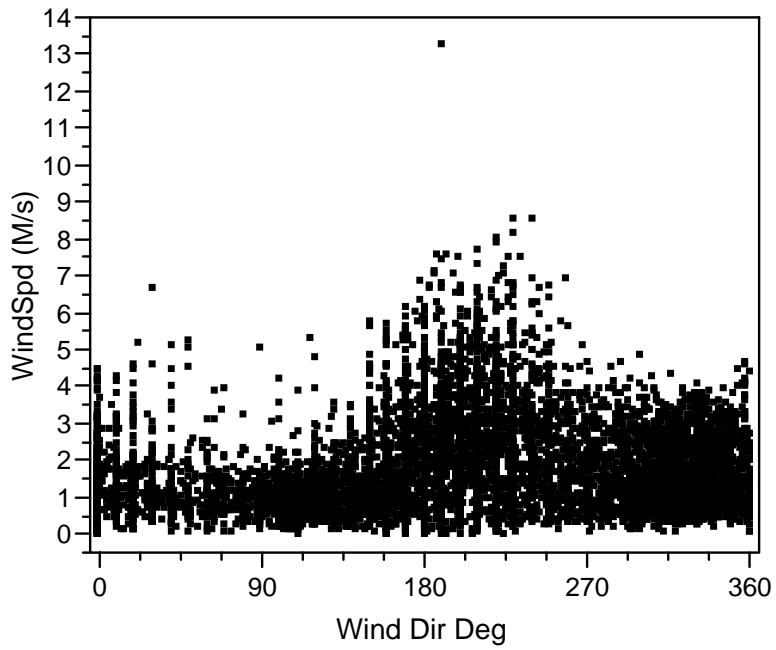
**Figure D10 Sum of Vertical Solar Radiation (W/m<sup>2</sup>)**



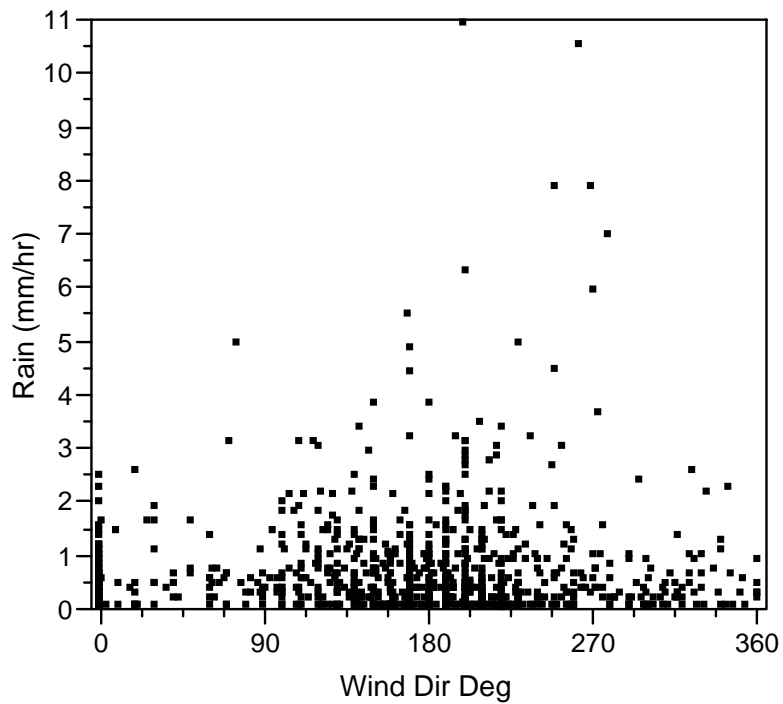
**Figure D11 Sum of Horizontal Solar Radiation (W/m<sup>2</sup>)**



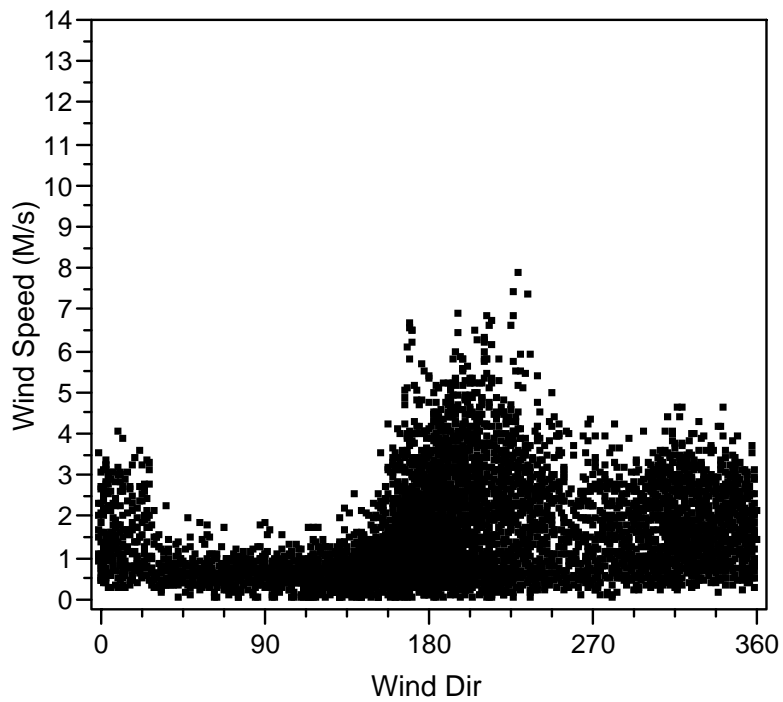
**Figure D12**      **Cycle 1 - Wind Speed by Wind Direction**



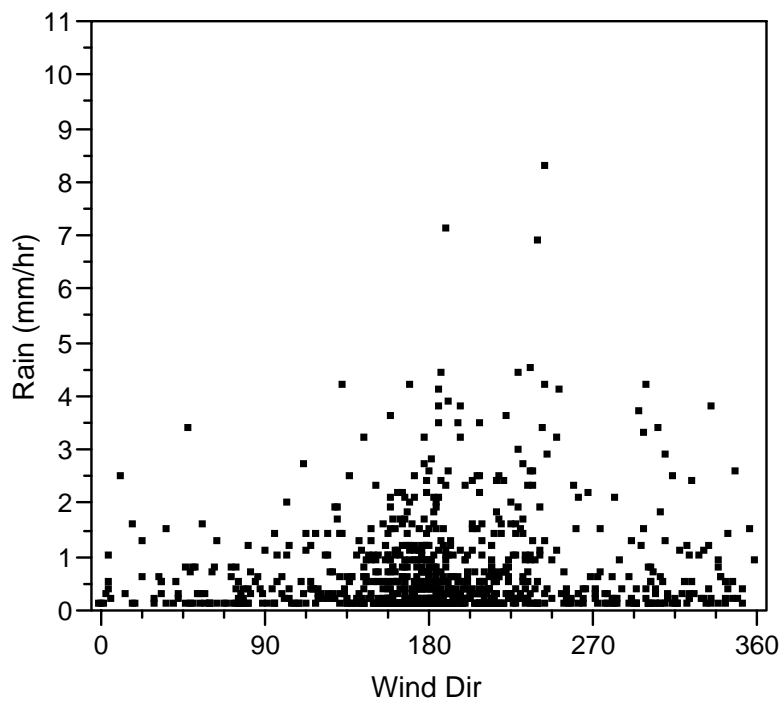
**Figure D13**      **Cycle 1 – Precipitation by Wind Direction**



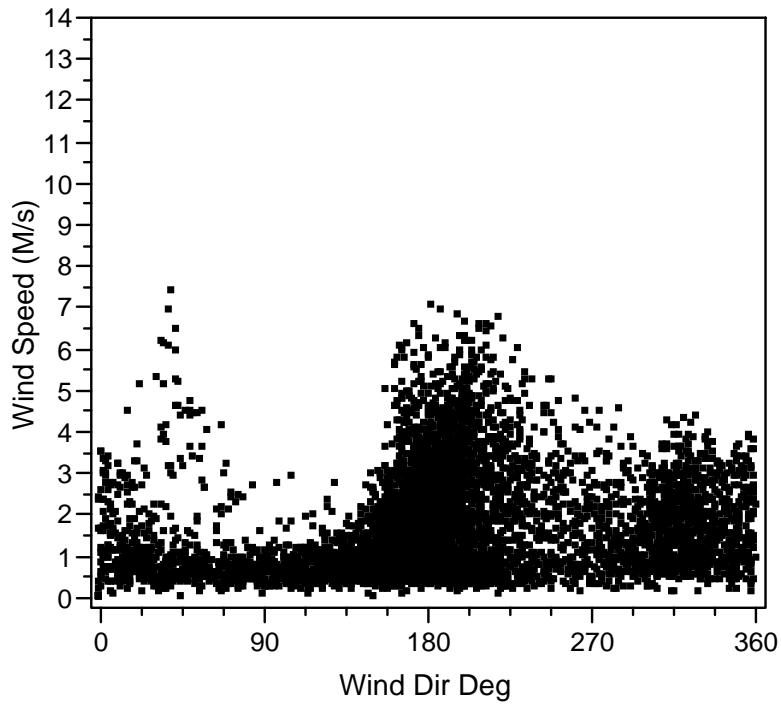
**Figure D14**      **Cycle 2 - Wind Speed by Direction**



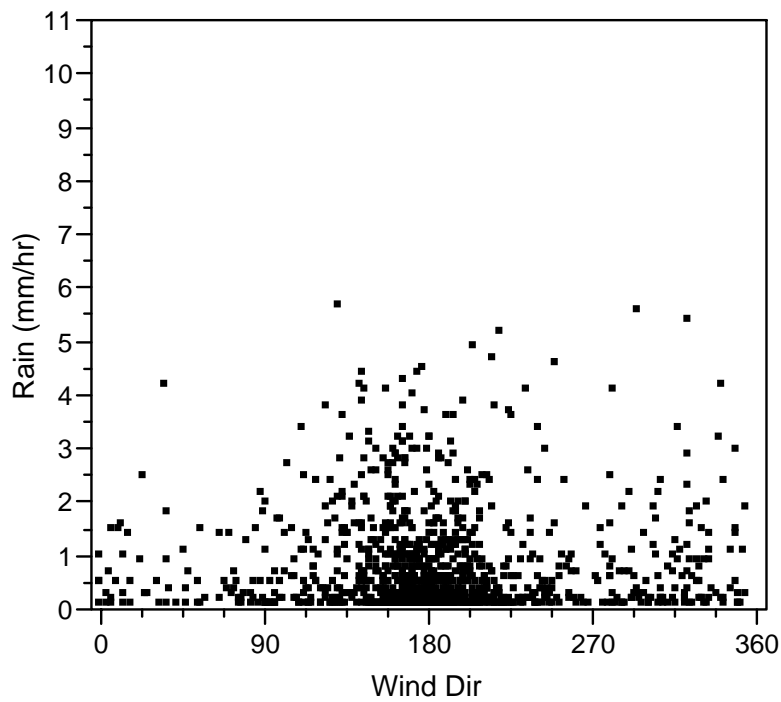
**Figure D15**      **Cycle 2 - Precipitation by Wind Direction**



**Figure D16**      **Cycle 3 - Wind Speed by Wind Direction**



**Figure D17**      **Cycle 3 – Precipitation by Wind Direction**



# **Developing Innovative Wall Systems that Improve Hygrothermal Performance of Residential Buildings**

Report Type: **Final ORNL Contributions Report**

Reporting period start date: **August 2002**

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## ABSTRACT

This document serves as the final report documenting work completed by Oak Ridge National Laboratory, (ORNL), through a collaborative venture with the Washington State University (WSU) under U.S. Department of Energy, (DOE), Grant, Developing Innovative Wall Systems that Improve Hygrothermal Performance of Residential Buildings. This project was conducted in collaboration with Washington State University (WSU), and includes the participation of several industry partners including Weyerhaeuser, APA – The Engineered Wood Association, CertainTeed Corporation and Fortifiber. This document summarizes work completed by Oak Ridge National Laboratory between August 2002 through 2006.

ORNL's primary role was to provide the scientific backbone to the development of this moisture engineering wall testing facility, co-review and develop with WSU the wall designs, develop a field testing approach that was adopted to monitor the hygrothermal response of wall systems. During the project period ORNL constructed walls for the test facility, initially secured and specified the instrumentation package, installed the first series of instrumentation, co-developed a second and third matrix of test wall designs with our WSU partners and industry partner, and analyzed and reviewed the measured data from test wall specimens.

At the end of the first year monitoring, ORNL prepared and submitted a draft report to WSU, and participated twice in DOE project reviews. Results have also been disseminated to the public, and Industry partners.

This report will attempt to avoid duplication of report 1 submitted by Washington State University (WSU) on the development of the Natural Exposure Testing (Task 2) of the statement of work between DOE and ORNL. The focus of this report is on the development of results during the hygrothermal material and wall performances activities important when employing hygrothermal modeling.

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The City of Seattle, Department of Construction and Land Use, specifically the role by Mr. Michael Aoki-Kamer, is to be considered the precursor to this research project. The building envelope committee, and the numerous contributions from this committee was instrumental in defining the original need, and framework of this project and should be fully acknowledged.

The continuous contributions of WSU Principals (Chuck Murray and Bob Tichy) were critical contributors for the success of this research project. They managed the test facility, troubleshooting and maintaining the facility on a daily basis. Industry partners Fred Baker, Fortifiber, Stanley D. Gatland, CertainTeed, Dave Gromala, Weyerhaeuser Wood Technology Center, Dan Hanson, Weyerhaeuser Wood Technology Center, Frank Nunes Lath & Plastering Institute of N California, Steve Zylkowski, APA, Engineered Wood Products Association contributions are also fully acknowledged.

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Marcin Pazera, MP Associates, Canada  
Teresa Williams, Oak Ridge National Laboratory (Review of Document)

## **INTRODUCTION**

Washington State University (WSU) and Oak Ridge National Laboratory (ORNL) have implemented a research protocol to analyze hygrothermal response of wall assemblies. The protocol utilizes three primary evaluation methods. These include experimental testing of full-scale walls in the natural environment, characterization of building materials response to moisture, and long term predictive evaluation of heat and moisture transport through building components using advanced computer modeling techniques.

## EXECUTIVE SUMMARY

This document serves as the Topical Report documenting of work completed by Washington State University, (WSU), under U.S. Department of Energy Grant, Developing Innovative Wall Systems that Improve Hygrothermal Performance of Residential Buildings. This project was conducted in collaboration with Washington State University (WSU), and includes the participation of several industry partners including Weyerhaeuser, APA – The Engineered Wood Association, CertainTeed Corporation, and Fortifiber. This document summarizes work completed by Washington State University August 2002 through June 2006.

This project developed and implemented the first ever moisture engineering analysis to quantify the important moisture control elements in wood frame building assemblies that are energy efficient. The intention of this project was to investigate a number of wall designs that could passively (without additional energy penalty) be deployed to provide moisture tolerant wall systems in the climate of the Pacific Northwest.

At the same time, as these walls represent only a small number of walls used in the Northwest and field data provide limited transferability to other locations, the data was to be used to benchmark hygrothermal modeling. With a validated model, any wall can be modeled and the impact of various climates can be investigated in a more cost effective manner. To achieve this end, a number of laboratory testing of building material hygrothermal properties were performed, laboratory validation data for the ventilation characteristics at the same time as Puyallup field data were generated. The results of the project report include:

- hygrothermal material property data,
- review of the quality of the field data for modeling purposes,
- preliminary benchmarking hygrothermal models against laboratory and field data.

ORNL primary role was to perform an analysis of the key building science findings, detailed analysis of the quality of the field data, and the validation of models and incorporation of the results for further development of moisture modeling tools.

# **TASK1: HYGROTHERMAL MATERIAL PROPERTY CHARACTERIZATION**

## **MATERIAL PROPERTIES**

### **Introduction**

In this part of the report, the hygrothermal material properties for a selected number of materials used in the NET wall facility and measured at the Oak Ridge National Laboratory are presented. Material properties are needed for a number of strategic reasons. The first is to provide the transport coefficients for the advanced hygrothermal modeling activity, and secondary, to provide insight on the various field observed differences in the wall performances. Measurement of the hygrothermal material properties at ORNL involved the participation of Ken Wilkes, Phil Childs, Jerry Atchley and Achilles Karagiozis. Materials were shipped to ORNL by Mr. Murray (WSU) that were randomly selected during the construction period of the walls. The majority of the material properties reported have been completed but some still are undergoing measurements at ORNL (suction isotherms). The results presented is the progress to date on the various materials that have been measured.

This report gives results of the DOE-WSU Award Number: DE-FC26-02NT41498, on *Developing Innovative Wall Systems that Improve Hygrothermal Performance of Residential Buildings* project in which several hygrothermal properties were measured on the same building materials used in the wall construction at the Puyallup test facility. The properties that were measured were water vapor permeance, sorption isotherm, suction isotherm, and liquid uptake. Table 2 lists the material used in the investigation.

## **EXPERIMENTAL PROCEDURES**

A number of key hygrothermal material properties are needed to characterize the transport of moisture through building envelope systems. These material properties need to be measured as a function of the driving potential. Below is a list naming the most important ones that have been measured at the ORNL advanced hygrothermal material property laboratory:

- 1) Sorption isotherms in the hygroscopic regime (as a function of relative humidity)

- 2) Suction isotherms in the capillary regime (as a function of moisture content/RH)
- 3) Water vapor permeance in both regimes (as a function of relative humidity)
- 4) Liquid diffusivity in the capillary regime (as a function of moisture content)
- 5) Thermal conductivity (dry state) data taken from ORNL database or WUFI/ME database

In Figures 1 through 8 the test facility with the various measurement apparatus is shown. Material sample are also displayed to indicate the material sample size used.



Figure 1: Climate Controlled (T& RH) Chamber



Figure 2: Desiccant Temperature Control Drying Oven



Figure 3: Water Vapor Permeance Test Specimens



Figure 4: Pressure Plate Apparatus



Figure 5: Liquid Uptake Apparatus

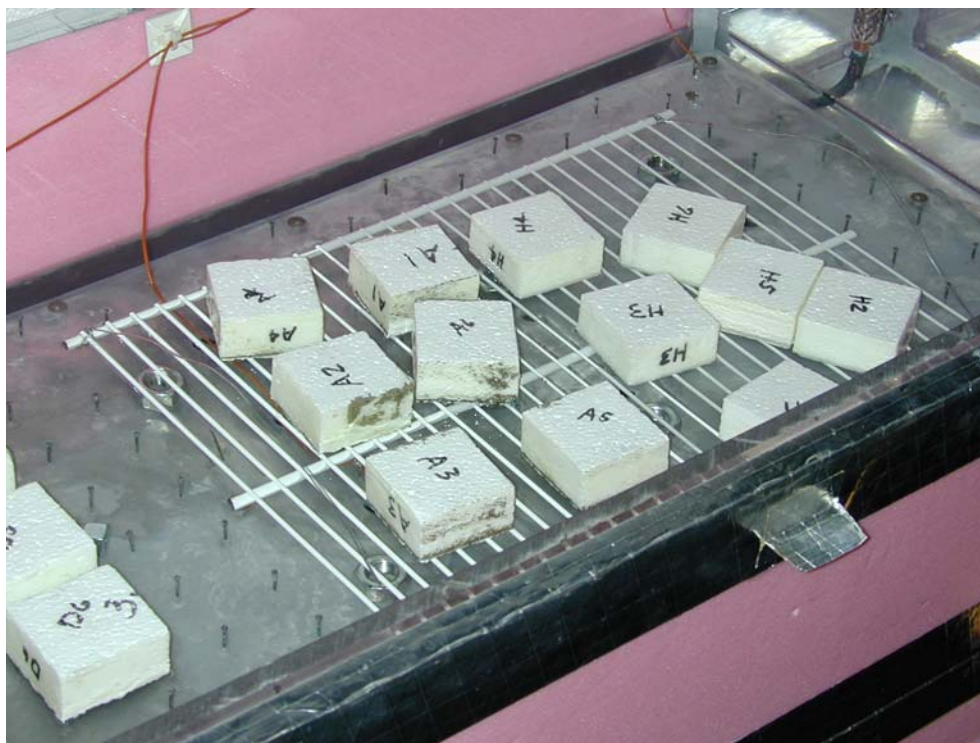


Figure 6: Samples for Liquid Uptake Measurements

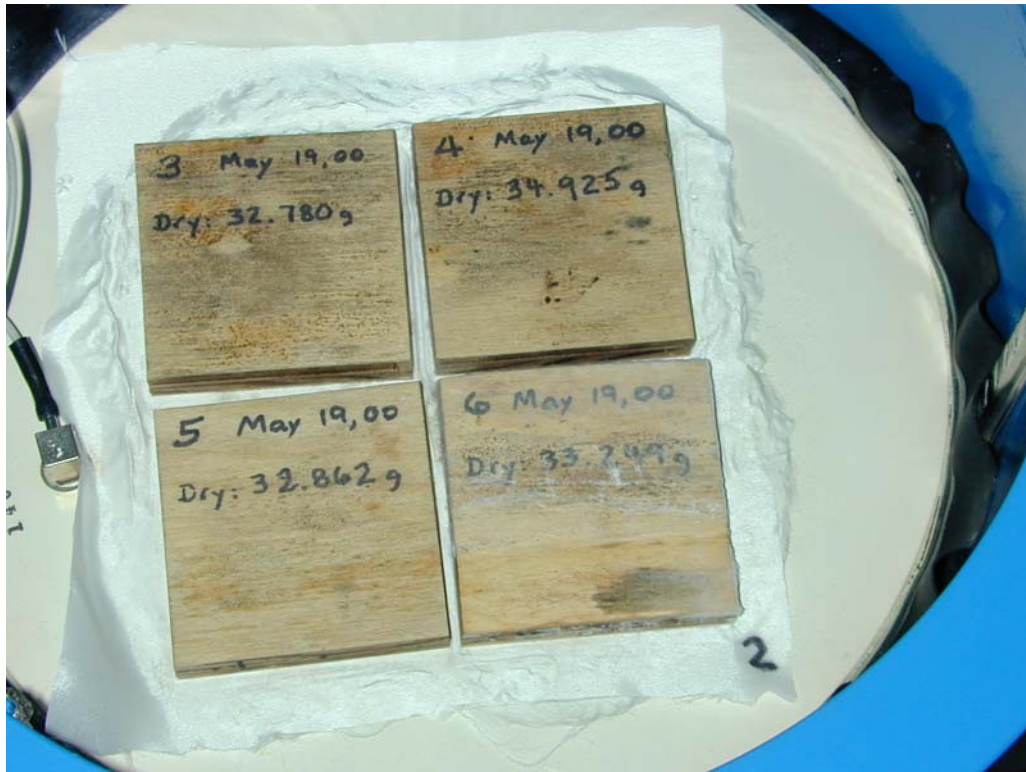


Figure 7: Samples for Capillary Suction Isotherms



Figure 8: Samples for Hygroscopic Sorption Isotherms

## Water Vapor Permeance Measurements

Water vapor permeance measurements were made according to ASTM E 96-00, Standard Test Methods for Water Vapor Transmission of Materials. Both wet and dry cup measurements were performed. Specimens were sealed with wax to the openings of PVC cups. The cups had internal diameters of about 5.55 inches, and the walls and bottoms of the cups were about 0.5 inch thick. The cups contained either distilled water (to provide 100% RH inside the cup) or anhydrous calcium chloride desiccant that had been baked at 400°F (204°C) (to provide near 0% RH inside the cup). The air space between the specimen and the water was about 0.5 inch, and was about 0.25 inch between the specimen and the desiccant. Different specimens were used for the wet and dry cup measurements. The cups were placed in environmental chambers that were maintained at 73.4°F (23°C) and at relative humidities of 50%, 70%, or 90%.

**Principle:** Water vapor transport is determined using standardized isothermal tests. Mass change i.e., loss or gain, is determined gravimetrically and with the knowledge of the boundary conditions water vapor permeability can be calculated.

$$Permeance (WVP) = \frac{\dot{Q}_{vapor}}{\Delta P_v} = \frac{\dot{Q}_{vapor}}{P_{vsat} (RH_{Dish} - RH_{Chamber})} \quad (1)$$

A typical dry cup test set-up is shown in Figure 9. Material being tested is placed in a horizontal direction between two environments having the same temperature with the relative humidity corresponding to near 0% and 50% RH on the opposite side of the specimen being tested. The tests should be performed in an environmental chamber having temperature and relative humidity control i.e., 23°C and 50% RH. On the opposite side of the material, the RH can be maintained at near 0% with the use of moisture sorbent such calcium sulfate ( $CaSO_4$ ) to store the transported moisture. At predefined time intervals, the cups were removed from the chamber during testing for a short duration to obtain gravimetric readings. The values published in literature for the generated vapor pressure at the surface of the calcium chloride (sulfate) correspond to near 0% RH. These values are also recommended as reference values to be used in determining vapor pressure. The accuracy of these values is however questionable since measuring the RH at the surface of the desiccant directly is not possible.

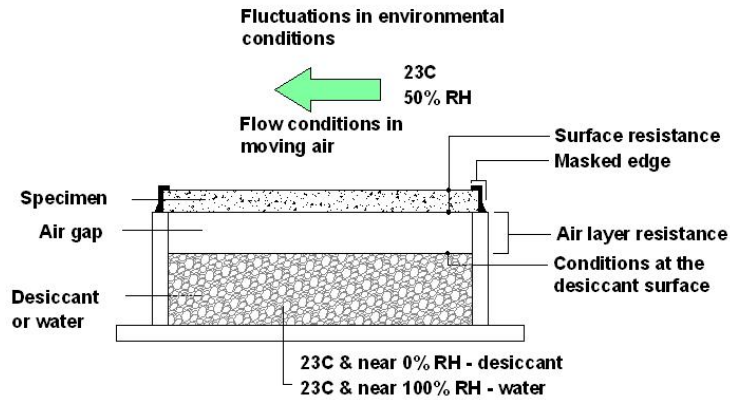


Figure 9: Wet cup test setup is similar to the dry cup setup

Wet cup test setup is similar to the dry cup setup. With one exception, the moisture sink is replaced with a moisture source i.e., distilled water. Distilled water is used to generate near 100% RH. The cups are kept in an environmental chamber with temperature and relative humidity controlled at  $23 \pm 0.1^\circ\text{C}$  and  $50 \pm 1\%$  RH, respectively.

In North America, water vapor transmission (WVT) test method was first standardized in 1953 (Hansen and Bertelsen, 1989). Based on the research findings of Joy and Wilson (1965) recommendations relating to the design and the selection of appropriate materials for use in cup fabrication, as well as adequate sealing techniques, and desirable properties of the sealants were implemented in the E96 standard. Joy and Wilson (1966) identified that masked edge effects introduced errors in range of up to 20% in WVT measurements. Experimental results performed on a 0.5 inch (12.5 mm) material confirmed that increasing masked edge from 0.125 inch to 0.625 inch (15.875 mm) in thickness increased WVT by 20%. An empirical correlation was developed and the quantity of excess WVT was expressed as a function of ratio of material thickness and masked edge. This empirical correlation confirmed the validity of masked edge correction introduced by Greebler (1952).

$$\text{Percent excess WVT} = \frac{400z}{\pi X} \log_e \left( \frac{2}{1 + e^{-(2\pi b / z)}} \right)$$

where;  $z$  = specimen thickness (2)

$b$  = width of masked edge

$X$  = four times the test area divided by the perimeter

Babbitt (1939) was first to highlight the significance of the resistance offered by the still air layer inside the cup, and its effect on the calculated apparent resistance. Babbitt performed WVT tests with multiple layers of fiber board and kraft paper, and plotted the calculated resistance i.e., inverse of permeance, as a function of number of material layers. Through extrapolating the linear regression to zero layers he was able to show that the air space offered additional resistance. This meant that the vapor pressure drop across the sample was lower than the total vapor pressure drop between the desiccant and the external environment. Hansen and Lund (1990) demonstrated that increasing the air layer thickness from 5 mm (0.197 inch) to 25 mm (0.984 inch) reduced the vapor pressure at the boundary of the specimen. Burch et al., (1992) showed empirically that the rate of WVT became increasingly inaccurate with an error of more than 20% for highly permeable materials. A correction for air layer thickness can be performed using Schirmer equation (CEN TC 89, 1994):

$$\delta_{\text{AIR}} = \frac{2.306 \times 10^{-5}}{R_v T} \left( \frac{p_o}{p} \right) \left( \frac{T}{273} \right)^{1.81} \quad (3)$$

Where T is temperature [K],  $\delta$  is water vapor permeability in air [kg/msPa], p is barometric pressure [Pa],  $p_o$  is standard barometric pressure [101300 Pa] and  $R_v$  is the gas constant for air 461.9 [J/kgK]. Equation 2 highlights the fact that water vapor permeability in air ( $\delta_{\text{AIR}}$ ) is dependent on the temperature and the barometric pressure during the test. The above equation shows that water vapor permeability in air is directly proportional to changes in temperature and indirectly proportional to changes in barometric pressure. In test conditions with lower mean barometric pressure, the ratio of standard barometric pressure ( $p_o$ ) to the mean barometric pressure (p) is greater than one. The water vapor permeability of air and material can be assumed to vary equally with the barometric pressure.

The boundary conditions for the tested specimen are created by the gradient of water vapor concentration on the opposite surfaces of the specimen. The test precision is dependent on the stability and reproducibility of this gradient. In isothermal conditions, temperature stability dictates the variability of the driving potential for transport. Joy and Wilson (1965) noted that stability of the driving potential is affected by the stability of vapor pressures on opposite sides of the specimen. Currently, information related to tolerances of boundary conditions in WVT test does not exist. The ASTM E96 WVT standard does not provide guidelines on variability of boundary conditions in WVT test with highly permeable construction materials. However, such

knowledge is required to generate repeatable and reproducible results. Two critical aspects that must be verified:

- Reproducibility of vapor pressures
- Ability to maintain stable vapor pressures throughout the test

In addition another shortcoming relates to the fact that no limits are specified on the suitable range of permeabilities that can be measured with the dry cup test method. The WVT E96 standard test method can be applied to measure water vapor transmission for any construction material. However, the standard lacks information on performance and handling of the desiccant. We believe that currently insufficient information exists, which could lead to calculations which underestimate the transport coefficient. In the modeling analysis, the measured ASTM E96 data were analyzed to provide the actual transport coefficients.

### **Sorption Isotherm (Hygroscopic Regime)**

Determination of sorption isotherms is based on well established thermodynamic principles. In an enclosed system, a hygroscopic material will reach equilibrium moisture content with the surrounding environment. When the initial moisture content in the material is lower than the equilibrium moisture content (i.e. relative humidity in the surrounding environment), water vapor is absorbed from the air in the surrounding space resulting in an increase of the specimen's mass. As long as moisture continues to be absorbed, the mass of the specimen will continue to increase until equilibrium conditions are reached. The rate at which this increase takes place decreases as the equilibrium is being approached. Consequently, when the initial moisture content of the material is higher than the equilibrium moisture content the specimen moisture desorbs from the material and its mass decreases until equilibrium is reached under desorption. The change in mass is determined gravimetrically using an analytic balance. Material storage in a hygroscopic range can be quantified for moisture contents ranging from near 0% RH up to approximately 95% RH.

Sorption isotherm measurements were made according to ASTM C 1498-04, Standard Test Method for Hygroscopic Sorption Isotherms of Building Materials. Triplicate specimens consisted of about 15 grams (0.0331 lb) each of material cut into small pieces. The specimens were placed into 60 mL flint glass jars with tightly-fitting polypropylene lids from which the cardboard liners had been removed. The lids were placed on the jars for weighings on a balance that had a capacity of 5 kg (11.023 lb) and a resolution of 1 mg (2.2046E-6 lb). The

gypsum specimens were dried at 73.4°F (23°C) in an oven that was tightly sealed and was continuously flushed with compressed air piped in from the laboratory's power plant. The compressed air was dried at the power plant to a dew point that varied between -40°F and -60°F (-40°C and -51°C), depending upon the condition of the drying columns. This corresponds to a relative humidity of about 0.5% or less. After drying, the specimens were placed in air-tight desiccators containing saturated salt solutions that maintained RH between 11.3% and 97.4% at a temperature of 73.4°F (23°C). The desiccators were placed inside controlled temperature/humidity cabinets where the temperature was controlled at 73.4 " 0.2°F (23.0 " 0.1°C). Measurements were started at the lowest RH, and after equilibrium was reached, the specimens were transferred to the next higher RH until measurements had been made over the range of RH. After tests at the highest RH, measurements were repeated in the reverse order to obtain desorption isotherms. The moisture content reported is the average of the three specimens.

The equilibrium conditions of the air space inside the environment are dependent on a number of factors, including but not limited to:

- Temperature instability of the environment in which the test is being conducted,
- Purity of solute i.e., salts utilized,
- Mass ratio of solute to solvent utilized in preparation of the solutions,
- Contamination of the solutions,
- Ratio of surface area of the solution to the volume of the space surrounding the specimens, and
- Frequency of opening the enclosed space to obtain gravimetric readings.

The key factor affecting precision of sorption measurements is the ability of maintaining stable vapor pressure in the air space surrounding the test specimens. More specifically this requires stability of both temperature and relative humidity. The equation utilized in calculation of ( $P_{SAT}$ ) is given in the ASHRAE Handbook of Fundamentals (2005).

The actual vapor pressure is calculated from the knowledge of moisture content in the air i.e., from the knowledge of mass (quantity) of moisture in given mass (quantity) or volume of dry air, or from the knowledge of relative humidity. Although the former approach is more elaborate, in the latter approach the relative humidity can be directly measured using RH/T sensors. The measured humidity can be expressed on a fractional basis and when multiplied with saturation vapor pressure for the same temperature, actual vapor pressure is obtained.

The stability of the vapor pressure in the surrounding air space is one of the most critical factors in sorption isotherm measurements.

In approach followed saturated salt solutions are utilized in controlling vapor pressure of the air inside a closed volume. Although, the time response is slower, this approach is much more economic. Typically, airtight desiccators containing saturated salt solutions are utilized. Figure 10 shows a sorption isotherm set-up with continuous and automatic weighing capability. The vapor pressure generated is a function of the type of salt used as well as the operating temperature during the test. Table 1 lists different salts and the corresponding vapor pressures at an operating temperature of 25°C.

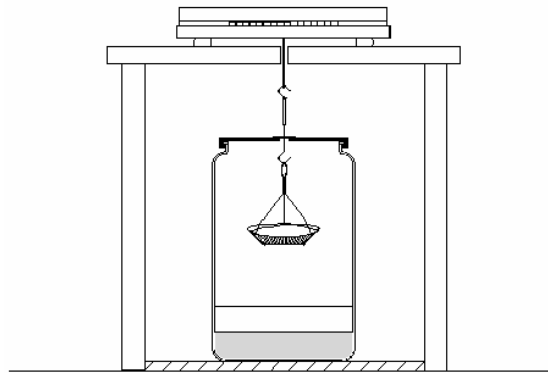


Figure 10: Experimental set-up utilized in conducting sorption isotherm measurements (Pazera et al [2006] [2004])

Table 1: Relative humidity corresponding to different saturated salt solutions at 25°C.

Type of salt	RH [%] at 25°C	Type of salt	RH [%] at 25°C
Cesium fluoride	$3.39 \pm 0.94$	Sodium bromide	$57.57 \pm 0.40$
Lithium bromide	$6.37 \pm 0.52$	Cobalt chloride	$64.92 \pm 3.50$
Zinc bromide	$7.75 \pm 0.39$	Potassium iodide	$68.86 \pm 0.24$
Potassium hydroxide	$8.23 \pm 0.72$	Strontium chloride	$70.85 \pm 0.04$
Sodium hydroxide	$8.24 \pm 2.1$	Sodium nitrate	$74.25 \pm 0.32$
Lithium chloride	$11.30 \pm 0.27$	Sodium chloride	$75.29 \pm 0.12$
Calcium bromide	$16.50 \pm 0.20$	Ammonium chloride	$78.50 \pm 0.40$
Lithium iodide	$17.56 \pm 0.13$	Potassium bromide	$80.89 \pm 0.21$
Potassium acetate	$22.51 \pm 0.32$	Ammonium sulfate	$80.99 \pm 0.28$
Potassium fluoride	$30.85 \pm 1.30$	Potassium chloride	$84.34 \pm 0.26$
Magnesium chloride	$32.78 \pm 0.16$	Strontium nitrate	$85.06 \pm 0.38$
Sodium iodide	$38.17 \pm 0.50$	Potassium nitrate	$93.58 \pm 0.55$
Potassium carbonate	$43.16 \pm 0.39$	Potassium sulfate	$97.30 \pm 0.45$
Magnesium nitrate	$52.89 \pm 0.22$		

Upon reaching equilibrium, plotting moisture content as a function of relative humidity generates sorption isotherm. Figure 11, shows a typical construction material with the hygroscopic and capillary regions.

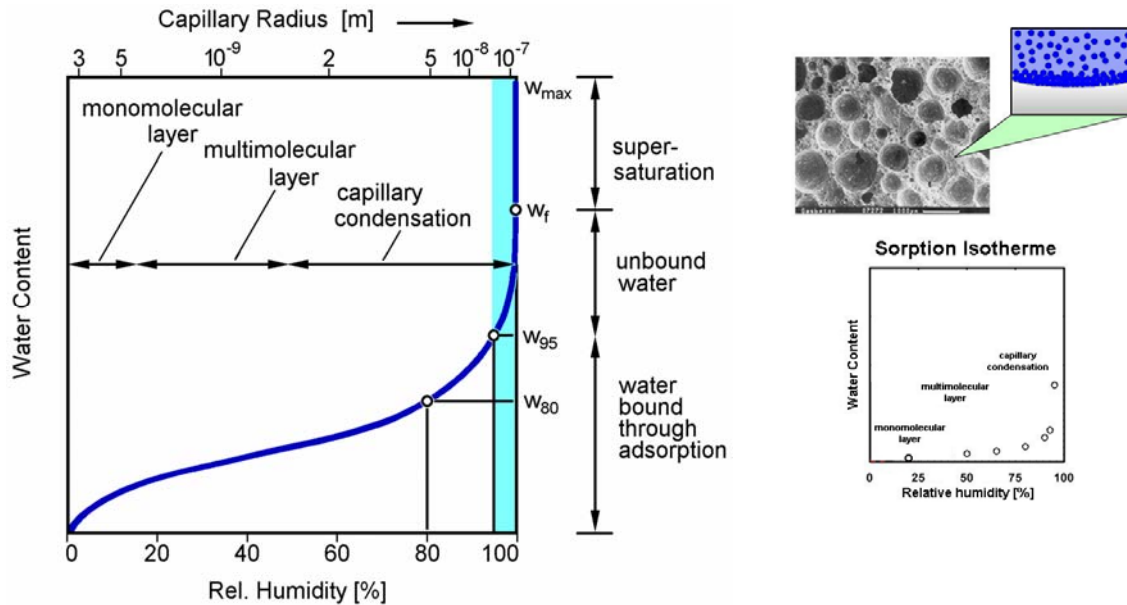


Figure 11: Sorption-Suction Isotherms

**Facility & Equipment:** Based on knowledge and experience gained during the development of sorption isotherm measurement methodology, the closed desiccator system was found not only most feasible but also least prone to experimental errors. To provide and maintain adequate temperature control, the desiccators were stored (kept) inside a temperature controlled chamber. Because the desiccators themselves are a closed system there is no need to control relative humidity inside the chamber. The chamber was maintained at a constant  $23 \pm 0.05^\circ\text{C}$  ( $73.4^\circ\text{F} \pm 0.09$ ) using a dedicated HVAC system.

**Test Procedure:**

1. Prepare the specimens accordingly. First, cut down or break the specimen into smaller chunks to an approximate size ranging between  $\frac{1}{4}$  inch (6.25 mm) and  $\frac{1}{2}$  inch (12.5 mm) in diameter.
2. Weigh the specimens and place them in the desiccator for drying until the weight stabilizes i.e.: until the change in weight is less than 0.2% in two subsequent readings taken on two consecutive days.
3. Prepare saturated salt solutions in accordance with an ASTM standard (provide the title of this standard). The ratio of solvent to the solute can be obtained from the Physics and Chemistry Reference Book. To ensure that the saturation is saturated and maintains to be saturated for the duration of the test increase the quantity of salt crystals (solute) by putting two-three times the amount required in the standard. This over-saturation is critical as it impacts the stability of relative humidity inside the desiccators.
4. Pour the saturated salt solution into the glass ball, and stir continuously for several minutes. Place the glass bowl inside the dessicator, close the lid and place it into the sorption chamber. This takes between 2-4 days and is dependent on the number of factors including; initial temperature of the water, and the type of salt.
5. Take the specimens out of the room temperature desiccator chamber, and store in an air tight dessicator containing desiccant and allow the specimens to cool down. The desiccant functions as a moisture sink and maintains very low (near 0%) relative humidity of the air space surrounding the specimens. Once cooled weigh the specimens and determine the difference in weight with the previous reading.
6. Close the lid using clips and place the set-up in the sorption chamber. This denotes the start of the test.
7. Allow the test to run for 14 days, and then obtain intermittent weights for the specimens. After the weighing replace the specimens back into the dessicator and continue to run the test for another 7 days. Obtain another set of gravimetric readings by weighing the specimens again. Compare the difference in weight change if the weight continues to increase significantly place the specimens back in the desiccators and continue to run the test. The limit for in weight change corresponding to the equilibrium conditions.

A somewhat different procedure was used for the cement board because of measurement difficulties caused by effects that have been attributed to carbonation reactions.[1] For this material, separate specimens were tested for each humidity level, instead of carrying one set of specimens through the sequence of humidities.

## **Suction Isotherm**

### **Pressure Plate Measurements**

Suction isotherm measurements are also not covered by an ASTM standard. The method is described as follows. Specimens were about 2 inch (50 mm) squares, and were saturated by being placed under about 4 inches (101.6 mm) of distilled water. The specimens were placed in pressure plate apparatuses (similar to those described in ASTM D 2325, Standard Test Method for Capillary-Moisture Relationships for Coarse- and Medium-Textured Soils by Porous-Plate Apparatus, and ASTM D 3152, Standard Test Method for Capillary-Moisture Relationships for Fine-Textured Soils by Pressure-Membrane Apparatus) where applied air (or nitrogen) pressures ranged from just above atmospheric to about 10 atmospheres. The relative humidity in the pressure vessels was obtained from the measured air pressure via the chemical potential. Tests were started at the lowest applied pressure (highest relative humidity) and progressed through a series of higher applied pressures. After equilibrium at each pressure, the specimens were removed from the pressure vessels and weighed. After completion of the sequence of pressure tests, the specimens were dried, and the moisture content was calculated as a percentage of the dry weight.

**Principle:** Determination of equilibrium MC at relative humidity above 95% RH is not reliable with the use of sorption isotherm approach. The principles of pressure plate measurements have been well known and widely used for decades in the field of soil science. Each porous plate consists of a porous ceramic plate covered on one side with a thin neoprene diaphragm. Mounted between the diaphragm and the underside of the porous plate is an internal screen, which accommodates the passage of the water. An outlet stem running through the plate connects this passage to an outflow tube fitting, which connects to the atmosphere outside the extractor. Figure 12 illustrates the pressure vessel with a horizontally mounted ceramic pressure plate.

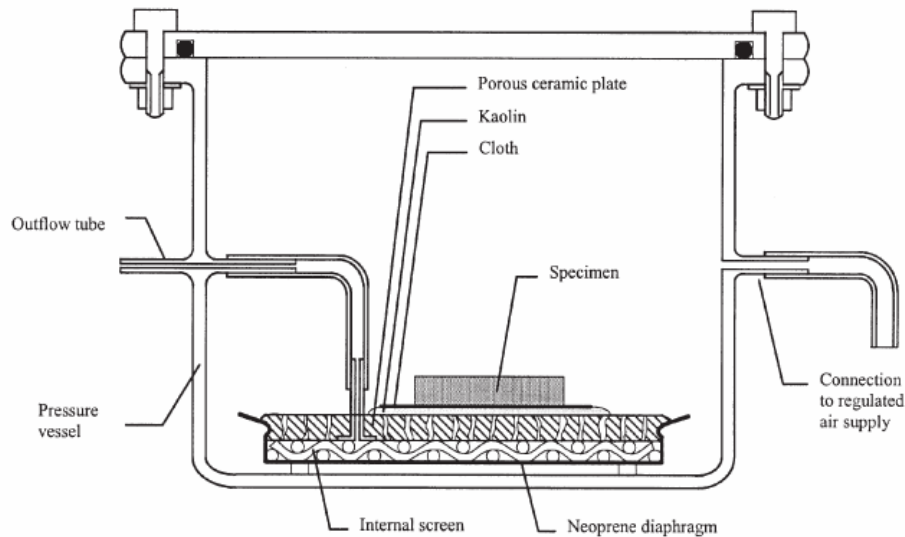


Figure 12: shows a cross-section for a typical pressure plate with a porous material placed on the porous membrane

Therefore pressure plates are utilized to measure equilibrium MC in a high end of the full relative humidity range. A fully saturated specimen (with its lateral sides sealed airtight) is placed on the porous plate inside the test vessel. A kaolin powder is utilized as the interface material between the material being tested and the porous plate to maintain the hydraulic contact. The vessel is closed and the air pressure on the interior of the vessel is slowly increased above atmospheric pressure. Water contained in the range of pores having capillary pressure equivalent to or lower than the air pressure in the surrounding air volume distills from the specimen until equilibrium moisture content is attained. If hydraulic contact is maintained between the specimen and the membrane, the equilibrium MC in the tested specimen will correspond to the pressure drop between air and water (the latter being under pressure). Once the equilibrium moisture content has been reached, air is released from the vessel and the pressure equalized back to the atmospheric. The vessel is opened and the mass of the specimen is determined gravimetrically. Following the gravimetric reading, the specimen is placed back in the vessel, flooded with water to establish hydraulic contact and the air pressure level is increased. During the subsequent readings the level of equilibrium pressure inside the vessel is increased so that more liquid distills out of the specimen. This process is repeated until enough data points from both pressure plates and sorption isotherms combined exist to construct a moisture retention curve.

**Facility & Equipment:** Because of the significant pressures at which these tests are performed (up to 100 Bars or 100 times the atmospheric pressure) off the shelf equipment manufactured by Soil Moisture was used. The laboratory set-up contains regulated air pressure source (either electric air compressor or compressed bottle gas), pressure control manifold, and pressure vessel which contain the ceramic pressure plate. The system shown in the Figure above shows three different extractors being independently run from the same pressure source. The pressure delivered to the vessel is controlled and stepped down using a two stage regulation process. Additionally, two more valves are mounted downstream from each pressure regulator as a safety feature. The extractor was connected to burettes with a tubing measuring 0.125 inch (3.175 mm) I.D.. This collection and monitoring of outflow level enables determination of the equilibrium conditions (a condition at which gravimetric weights of the specimen) can be taken. The equilibrium is attained when no measurable amount of change in the burette reading is observed over a period of many hours or days after the equilibrium is once attained.

### **Liquid Diffusivity**

Liquid diffusivity measurements are not covered by an ASTM standard. The method is described as follows. Specimens were about 2 inches (50 mm) square, and the edges were sealed with epoxy. The finished face of the specimen was brought into contact with a liquid water surface. The epoxied edges prevent liquid water from penetrating the edges and also prevent water from evaporating from the edges, thus ensuring one-dimensional flow of liquid and water vapor in the thickness direction. The specimens were in contact with the water surface for a total of about 4 hours. The specimens were periodically removed from the water tank and weighed. A plot of mass gain versus the square root of the exposure time gives an initial linear portion that is analyzed to calculate the liquid diffusivity.

**Principle:** This measurement (test) is used in estimating capillary liquid transport taking place in the material. When the material is brought in contact with free water surface, liquid begins to enter the pore matrix. The sides of the specimen are sealed with an appropriate sealant to impart 1-D moisture transport. Initially, a small volume of material at the water interface becomes saturated, the gradient begins to build and water is absorbed by capillaries. The degree and the rate of filling of the pore matrix within the material is highly dependent on the porosity of the material, pore size distribution, and other physical factors such as the height of the specimens being tested. In theory, since smaller pores exert greater pressure, these pores

fill with water first. The larger the pores the faster the rate water is absorbed. In reality the complexity of pore structures do not make this process so trivial. These smaller pores will not become filled until water occupies the larger surrounding air spaces. In fact if the air inside the pore matrix cannot be removed, these much smaller voids might never be filled. The appearance of moisture on the top surface of the specimen marks the end of the process dominated by capillary transport. This is often coined as the first stage of water intake process, and it is typically characterized by a rapid increase in mass. Once liquid fills all available open pores via capillary transport, the mass of the specimen continues to increase at a fraction of the rate. This increase corresponds to mass gain caused by redistribution of moisture in the open pore structure as a result of removal and or dissolution of gas phase (i.e., air), from the liquid phase. This is often referred to as the second stage of the free water intake process. Only at the end of this transition zone, the further increase of mass becomes small and entirely dependant on the rate of air removal), indicating that the capillary moisture content has been reached. During the test, gravimetric weights of the specimen are taken at predetermined intervals. The cumulative mass increase per surface area is plotted as a function of the square root of time. The cumulative water inflow is fitted to an empirical model (Equation 1).

$$i = A_0 + A_w t^{1/2} \quad (4)$$

where:  $A_0$  is an intercept,  $A_w$  is the water absorption coefficient

The absorption coefficient is represented by slope of a liquid inflow (determined gravimetrically) through a specific surface area as a function of  $t^{1/2}$ :

$$\Delta m / a = A_w t^{1/2}$$

(5)

where  $\Delta m$  = mass gain of inflowing liquid  
 $a$  = surface area at the inflow  
 $A_w$  = water absorption coefficient

The above model remains valid as long as the following condition is satisfied (Hall and Hoff, 2002):

- The initial water content is uniform and well defined ( $\theta_{\text{DRY}}$ ),
- Flow within the material is strictly one dimensional and water is freely available at the inflow face,
- The material is homogenous,
- The structure of the material remains unaltered by changes in water content, and is dimensionally stable.

The first two conditions are controlled by the experimenter, and the latter two conditions are material dependent. A linear relationship with  $t^{1/2}$  has been confirmed in case of numerous

homogenous building materials. Figure 13 shows a plot of cumulative water inflow as a function of square root of time.

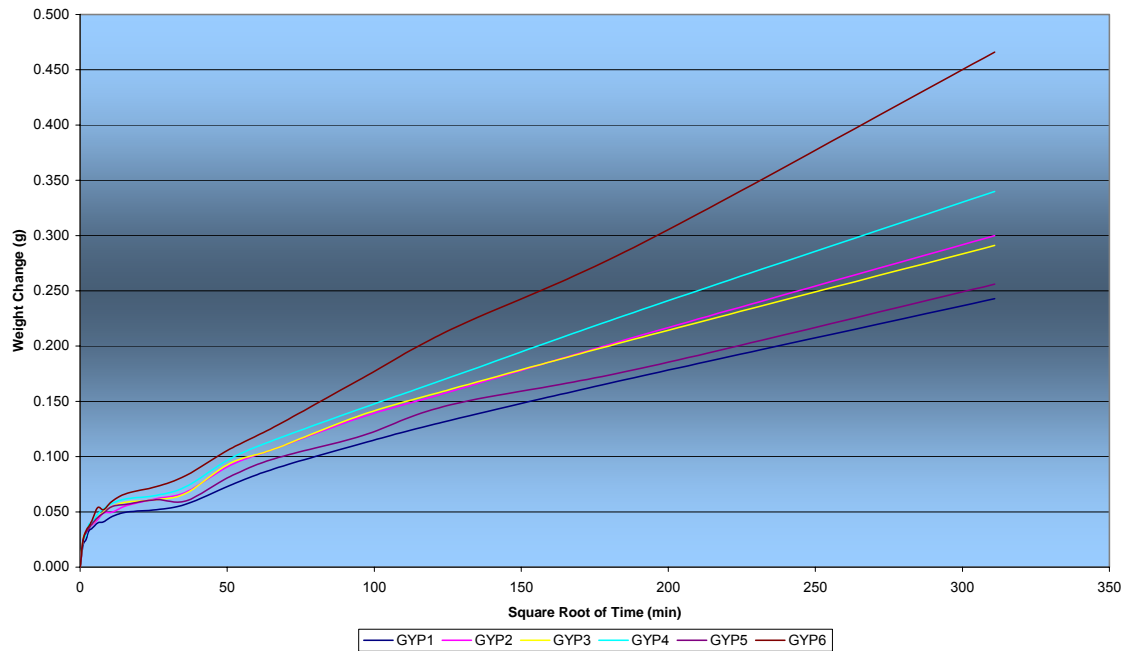


Figure 13: Weight Change plotted as functions of square root of time (min) for a 0.5 inch gypsum board.

**Equipment and Facility:** The water tank and the tank cover shall be of any non-corrosive and non-reactive material, preferably see through such as acrylic or glass, as shown in Figure 5 and 6. The water tank is located on a supporting table with adjustable legs for leveling. The water level is controlled with a float, which cuts off the water supplied to the tank. The float is mounted at an adequate height inside the tank so that the flow of water is cut off when the water level is 2 mm above the specimen supports. An external, small volume water pump provides water circulation through the tank to ensure uniform temperature distribution of water.

The test conducted had temperature between 23 and 25°C (73 and 77°F), and shall be maintained constant within 1°C (2 °F). Prior to conducting the test, the water to equilibrate with the room temperature. It is also beneficial to maintain constant boundary conditions at the upper surface of the specimen. Maintaining a high relative humidity on the specimen's upper surface is needed for limiting the evaporation from the upper surface. An air tight cover cap was found acceptable.

The material used to seal the lateral sides of the specimen must exhibit the following characteristics; it is not reactive/corrosive, not absorptive, not hygroscopic and not permeable for water vapor and water. It must not lose weight to, or gain weight from, the atmosphere in an amount, over the required period of time, that would affect the test result by more than 0.1%. It cannot readily be absorbed by the specimen as it would reduce the volume of open pores taking part in water uptake. Molten wax, quick setting epoxy, and other low permeance coatings are adequate. The operator performing the test should examine, and select the type of sealant best suited for a particular material. Sealing methods are discussed in section 10 and in ASTM standard E96.

***Test Procedure:***

1. Fill the water column with water and wait until the water level in the tank stabilizes. The quantity (the depth) of the water in the tank is controlled by the float (2). The float has been built in at the level so that the water fill stops when the level in the tank is approximately 1 mm above the specimen support (3), which provide support for the specimens being tested.
2. When the water has stabilized place a cover over the tank to reduce evaporation and allow the temperature of the water to stabilize (equilibrate) with the laboratory room temperature.
3. Prepare the specimens for testing. This part of the procedure includes sampling from a batch; as well as determination of dry weight, width, length, and the thickness of each specimen. Using this information calculate the density for each specimen.
4. Note 1: The materials are dried in a desiccant chamber until there is no significant change in mass during a specific time duration.
5. Note 2: Determine dimensions of the specimens including length, width, and thickness. Determine average dimensions from spot dimensions. For materials less than or equal to 1 inch in any respective dimension obtain 3 spot measurements (i.e., 3 length, 3 width, and 3 thickness). For materials more than or equal to 1.5 inches in any respective dimensions obtain 9 spot measurements (i.e., 9 length, 9 width, and 9 thickness).
6. Epoxy the lateral sides of the specimens to impart one dimensional moisture transport using 5 minute epoxy.
7. Place the specimen in contact with the free water surface. Periodically, remove the specimen from the tank blot the excess water from the lower surface of the specimen and obtain a gravimetric reading. After, the reading is obtained place the specimen back in the tank on the specimen supports. The duration of reading should not last more than

15 seconds, to minimize the disruption and reduce the period of discontinuity of capillary transport process.

8. Obtain the readings in accordance with the schedule provided below. The frequency and the length of the test period is dependant on the type of material being tested and its moisture transport characteristics i.e., the ability (magnitude) of the capillary transport.

### **Thermal Conductivity**

Thermal conductivity measurements were made using a heat flow meter apparatus according to ASTM C 518. The apparatus used has hot and cold plates that are 12 inches square ( $0.0077419 \text{ m}^2$ ) with 3 inch square ( $0.0019358 \text{ m}^2$ ) heat flux transducers in each plate. Tests were performed with a temperature difference of  $20^\circ\text{F}$  ( $11.1^\circ\text{C}$ ) for all materials except the Cement Board and the Gypsum Underlayment. For these two materials, the lower thermal resistances required that the tests be conducted with temperature differences of  $15^\circ\text{F}$  ( $8.3^\circ\text{C}$ ) and  $10^\circ\text{F}$  ( $5.6^\circ\text{C}$ ), respectively. When tested as single boards, many of the products had thermal resistances less than  $0.5 \text{ h}\cdot\text{ft}^2\cdot^\circ\text{F}/\text{Btu}$  ( $0.08805 \text{ m}^2 \text{ K/W}$ ), which is the lower limit for conformance to the C 518 standard. Therefore, tests were performed on single boards and also on stacks of two, three, or four boards, depending upon what could be fitted into the apparatus. Tests on different thicknesses allowed the thermal contact resistance between the specimen and the apparatus plates to be evaluated. Thermal contact resistance was determined to be in the range of  $0.05$  to  $0.08 \text{ h}\cdot\text{ft}^2\cdot^\circ\text{F}/\text{Btu}$ , ( $0.008$  to  $0.01410 \text{ m}^2 \text{ K/W}$ ) and this was used as a correction to the tests on single boards.

Table 2: Material list provided for testing.

<b>Materials Test List:</b>	<b>Included in NET</b>
<b>Framing Lumber</b>	
Kiln Dry Grade J Hem-Fir	Yes
<b>Exterior Sheathing -- 15/32 inch</b>	
OSB -- Aspen	Yes
Plywood – 3 ply -- Doug fir -- Coastal (Oregon)	Yes
Dens Glass Gold	Yes
<b>Siding:</b>	
Stucco: 7/8 + 1/8 Cement finish- hydrated at NET	<b>Yes</b>
½ cedar lap wood siding – stained	<b>Yes</b>
<b>Weather Resistive Barrier</b>	
Grade D Building Paper (30 min)	<b>Yes</b>
<b>Insulation</b>	
R-21 high density fiberglass, un-faced	<b>Yes</b>
1” extruded polystyrene	<b>Yes</b>
<b>Drywall</b>	
½ inch – no finish	<b>No</b>
½ inch – 2 coats acrylic latex	<b>Yes</b>
½ inch – vapor barrier paint + 2 coats acrylic latex	<b>Yes</b>
MemBrain™ –Smart Vapor Retarder	<b>Yes</b>

## RESULTS

ORNL staff (Dr. Wilkes, Mr. Atchley and Mr. Childs) prepared the samples and executed the tests needed to arrive at the standard hygrothermal properties that are commonly presented as a function of the relative humidity or moisture content. These are labeled here as fundamental material properties, and were further processed to derive the transport properties used in the hygrothermal simulation validation activity. The results presented below are those commonly found in ASTM and ASHRAE handbooks and are reported in a number of company literature.

In Figure 14, the measured water vapor permeance (Perms as a function of relative humidity) are shown for the following materials:

- 1) OSB (used as wall sheathing board)
- 2) Plywood (used as wall sheathing board)
- 3) Gypsum board painted with 1 coat of primer and 1 coat of latex paint
- 4) Gypsum board painted with 1 coat of primer and 1 coat of oil paint
- 5) Jumbo-Tex weather resistive barrier paper (used in wall assemblies)
- 6) Jumbo-Tex HD weather resistive barrier paper
- 7) Super Jumbo-Tex weather resistive barrier paper
- 8) Unpainted Gypsum Board
- 9) Painted Cement Board
- 10) MemBrain (climatically tuned vapor retarder)

### Water Vapor Transmission

Plots of mass versus time for the cup/specimen assemblies were obtained from the measure time plots. Each cup was weighed periodically to obtain eight or more readings. Selected portions of the plots were fitted to linear equations, and the slopes were used with the cup opening and inside-outside RH difference to calculate the permeance of the specimen, as given in E-96. At least six data points were used to obtain the slopes.

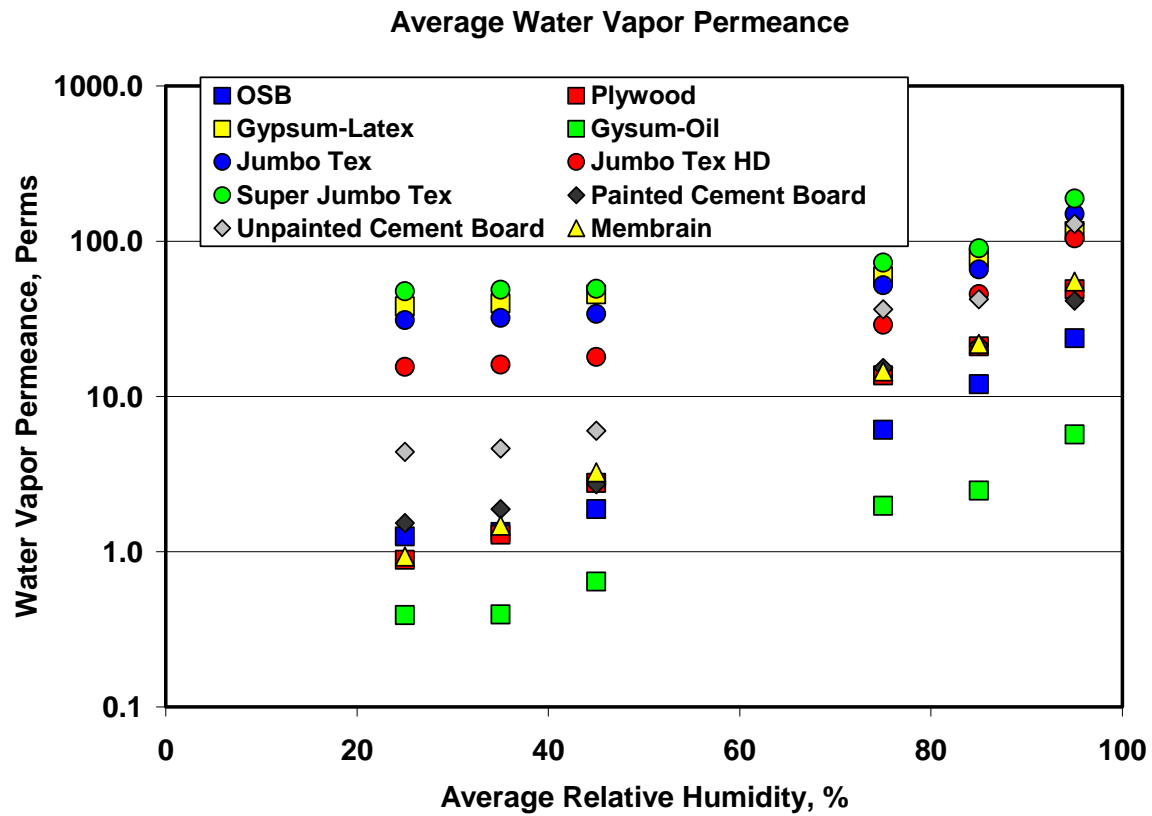
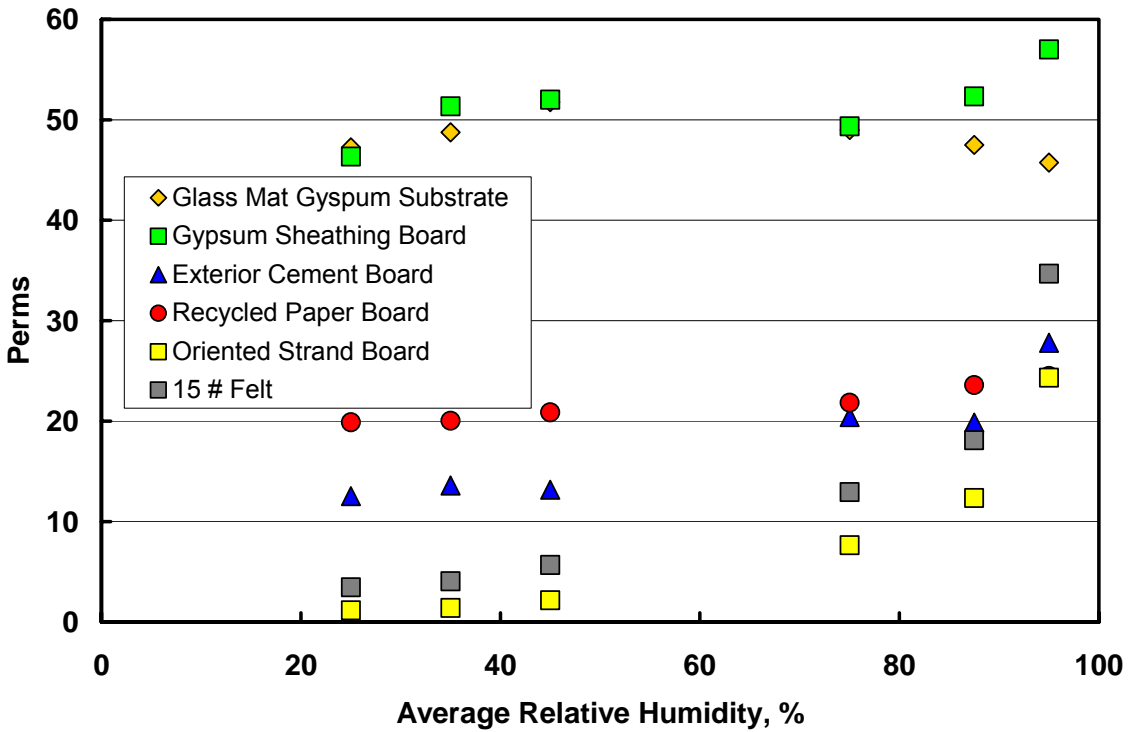


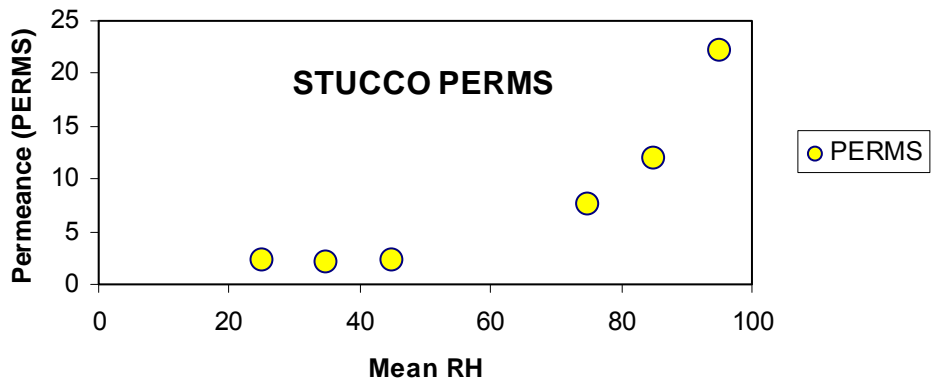
Figure 14: Water Vapor Permeance as a function of the Average Relative Humidity (%)

Some additional material properties that were employed at the Puyallup test facility are depicted in Figure 15. (Original OSB, Glass Mat Gypsum Substrate, Exterior Cement Board, # 15 Felt Paper)

### Water Vapor Permeance of Wall Materials



(a)



(b)

Figure 15: Water Vapor Permeance as a function of the Average Relative Humidity (%). (Some of these were used at the Puyallup Test Facility)

The property values for the water vapor permeances are displayed numerically in Table 3. All these results are not flux corrected but corrected for ASTM E96.

Table 3: Water Vapor Permeance as a function of Relative Humidity

RH, %	OSB	Plywood	Gypsum- Latex	Gypsum- Oil	Jumbo Tex	Jumbo Tex HD	Super Jumbo Tex	Painted Cement Board	Unpainted Cement Board	Membrain
25	1.25	0.89	38.00	0.39	31.00	15.50	47.67	1.53	4.39	0.93
35	1.34	1.29	39.75	0.40	32.00	16.03	48.67	1.88	4.62	1.47
45	1.88	2.78	45.50	0.64	34.00	17.97	49.33	2.72	6.02	3.25
75	6.10	13.65	59.50	1.98	52.00	29.00	72.67	15.28	36.44	14.50
85	12.00	21.00	78.00	2.48	65.67	45.67	90.00	21.42	42.27	21.77
95	23.75	49.00	116.00	5.70	150.00	104.33	188.33	41.36	129.42	54.90

### Sorption Isotherm

Sorption isotherm data for WSU materials are shown in Figure 16. Since the specimens can be weighed to the nearest 1 mg and the specimen mass is about 15 grams, the resolution of the moisture content is about 0.01%. According to ASTM C 1498, moisture content data would be reported to the nearest 0.1%. However, since the moisture contents were so small, the data are reported to the resolution of the measurements.

A number of material properties have been measured for characterizing sorption-suction isotherm

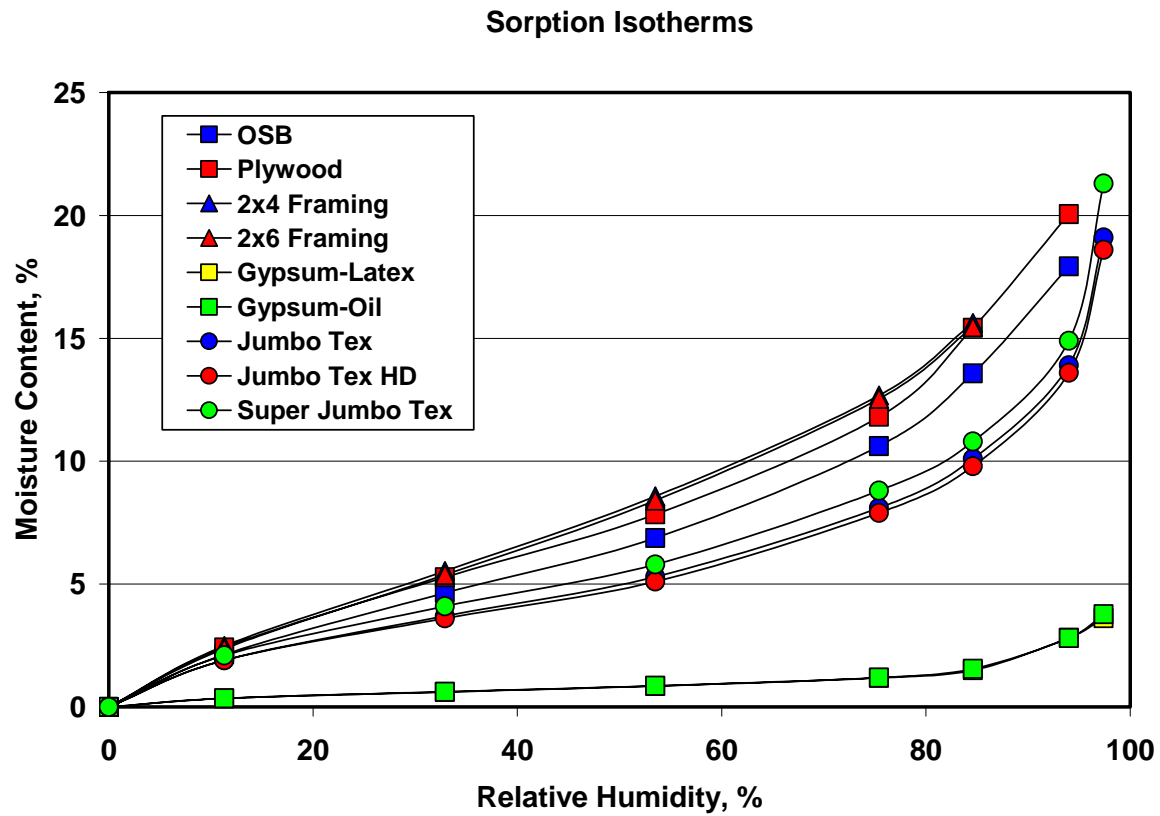


Figure 16: Sorption Isotherms as a function of the Average Relative Humidity (%)

Table 4: Sorption Isotherms as a function of Relative Humidity									
RH, %	OSB	Plywood	2x4 Framing	2x6 Framing	Gypsum-Latex	Gypsum-Oil	Jumbo Tex	Jumbo Tex HD	Super Jumbo Tex
0.0	0	0	0	0	0	0	0.0	0.0	0.0
11.3	2.13	2.42	2.48	2.36	0.35	0.35	1.9	1.9	2.1
32.9	4.64	5.28	5.53	5.38	0.61	0.62	3.7	3.6	4.1
53.5	6.88	7.84	8.57	8.40	0.85	0.86	5.3	5.1	5.8
75.4	10.61	11.80	12.67	12.54	1.19	1.19	8.1	7.9	8.8
84.6	13.57	15.43	15.62	15.45	1.50	1.55	10.1	9.8	10.8
94.0	17.92	20.05			2.81	2.80	13.9	13.6	14.9
97.4					3.61	3.78	19.1	18.6	21.3

### Sorption Isotherms of Wall Materials

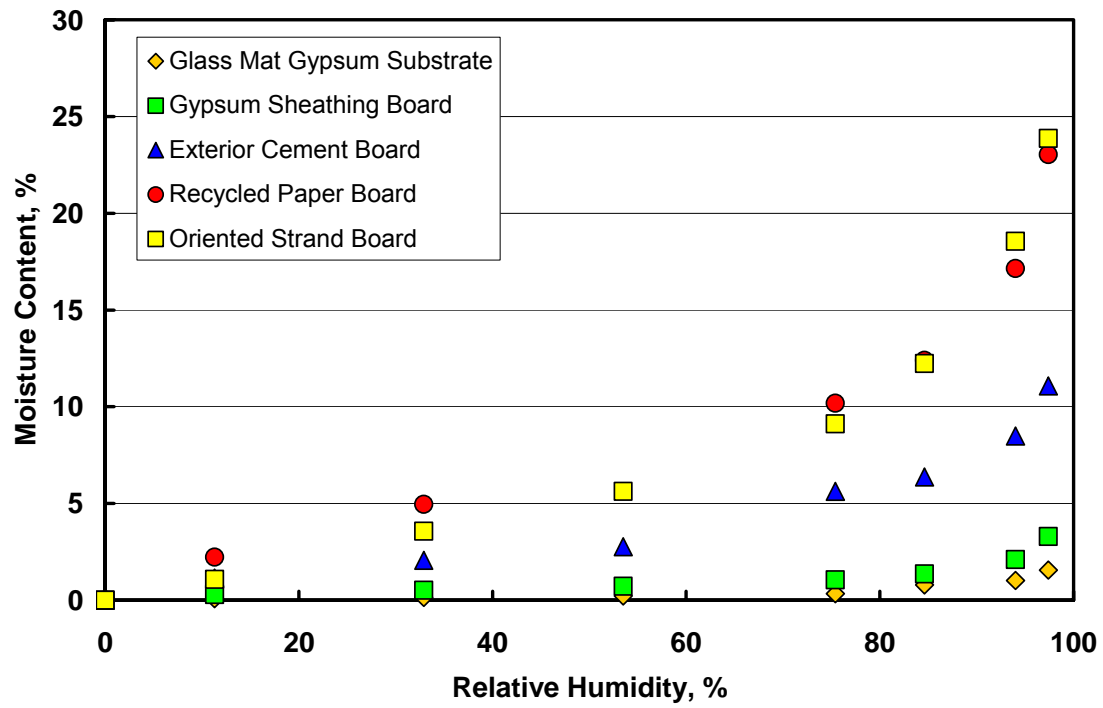


Figure 17: Sorption Isotherms as a function of the Average Relative Humidity (%)

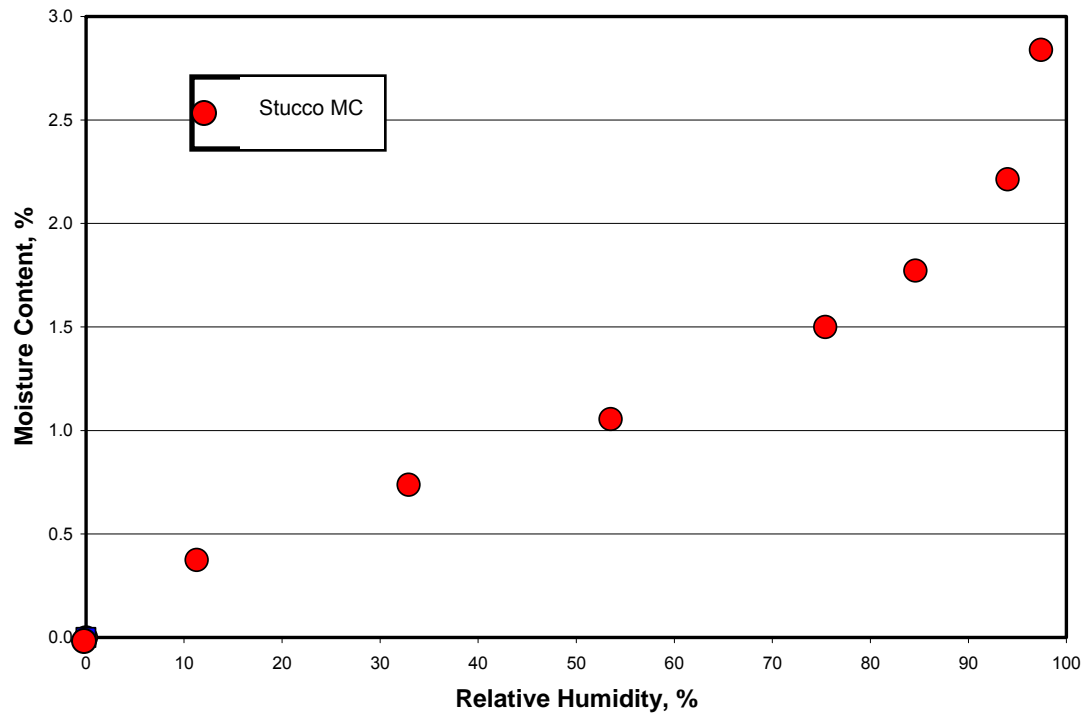


Figure 18: Stucco Sorption Isotherms as a function of the Average Relative Humidity (%)

Table 5: Stucco Suction Isotherm (under test conditions: Stovall (May 2007))

99.998	7.85
99.981	7.41
99.931	7.22
99.784	6.27
99.250	6.34
99.771	6.32
99.282	6.02
97.4	5.27

**Sorption Isotherms for Oriented Strand Board, Plywood, and Framing Lumber**

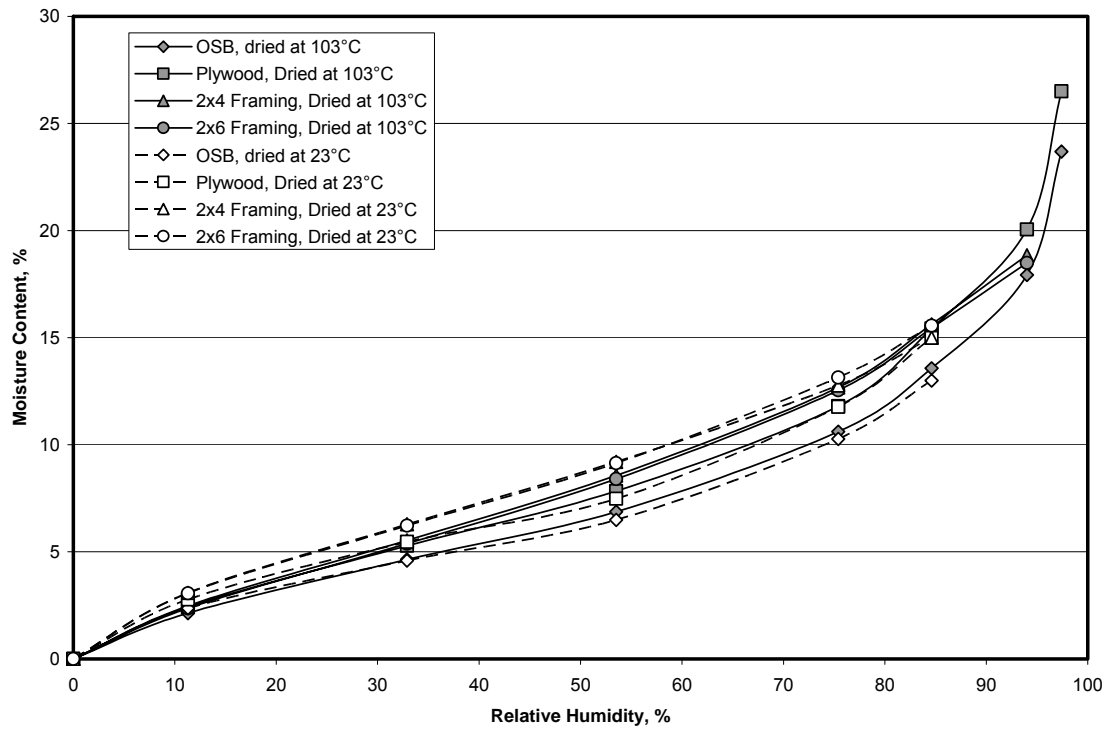


Figure 19: Sorption Isotherms as a function of the Average Relative Humidity (%)

## Liquid Diffusivity

In Figures [20] to [26] the liquid absorptivity values were used to calculate the liquid diffusivity as a function of moisture content (kg/kg). The results show both the suction and redistribution curves.

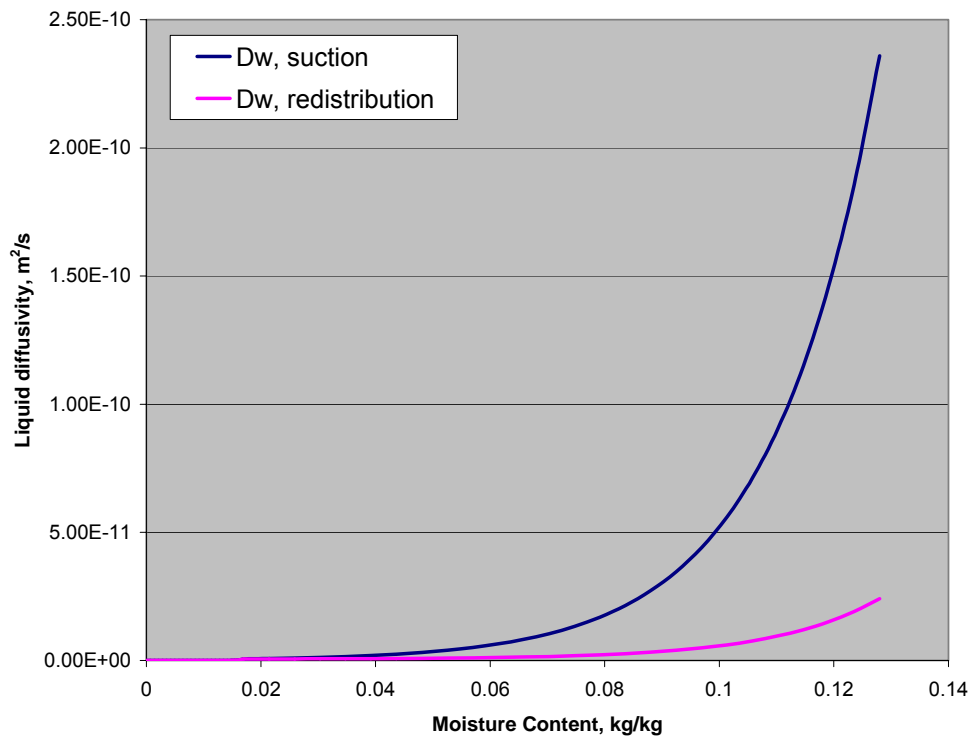


Figure 20: Stucco Liquid Diffusivity as a function of moisture content

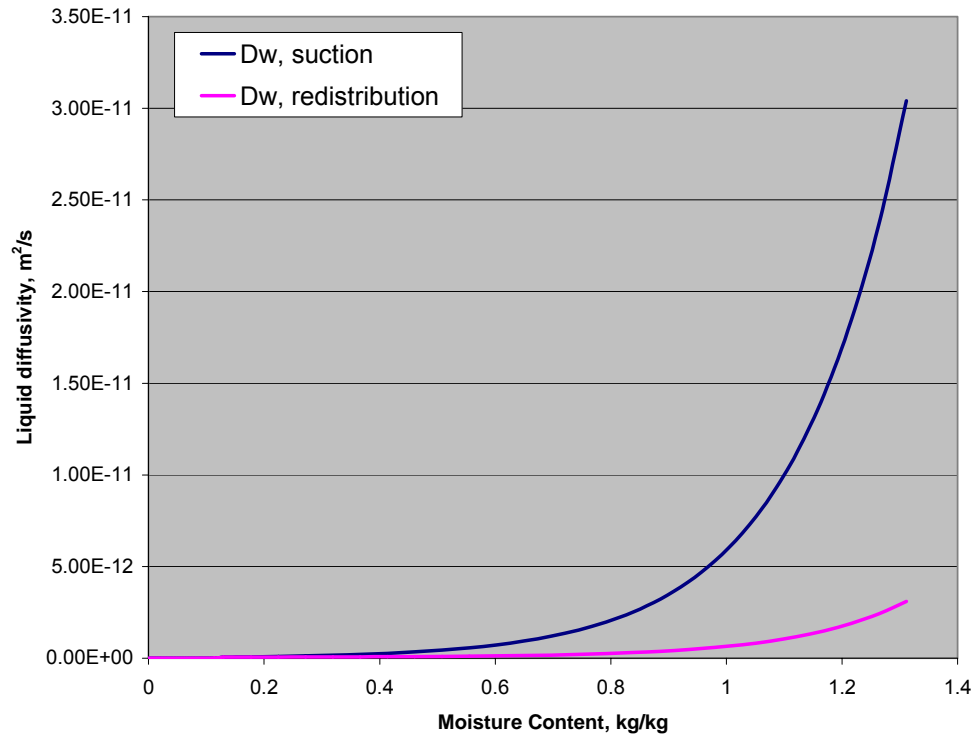


Figure 21: OSB Liquid Diffusivity as a function of moisture content

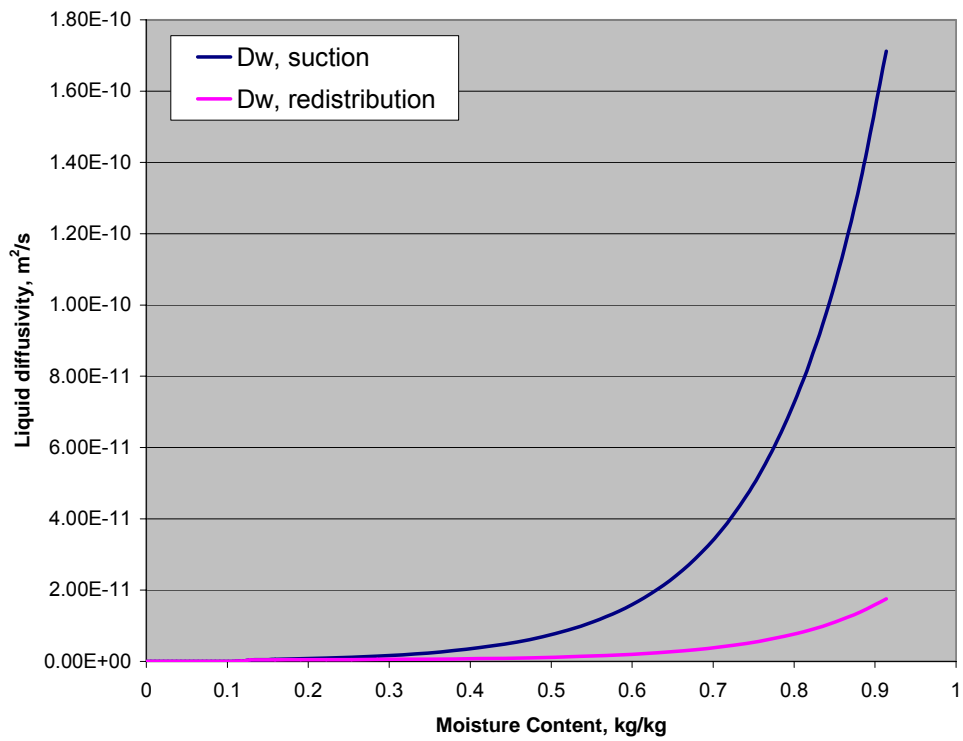


Figure 22: Plywood Liquid Diffusivity as a function of moisture content

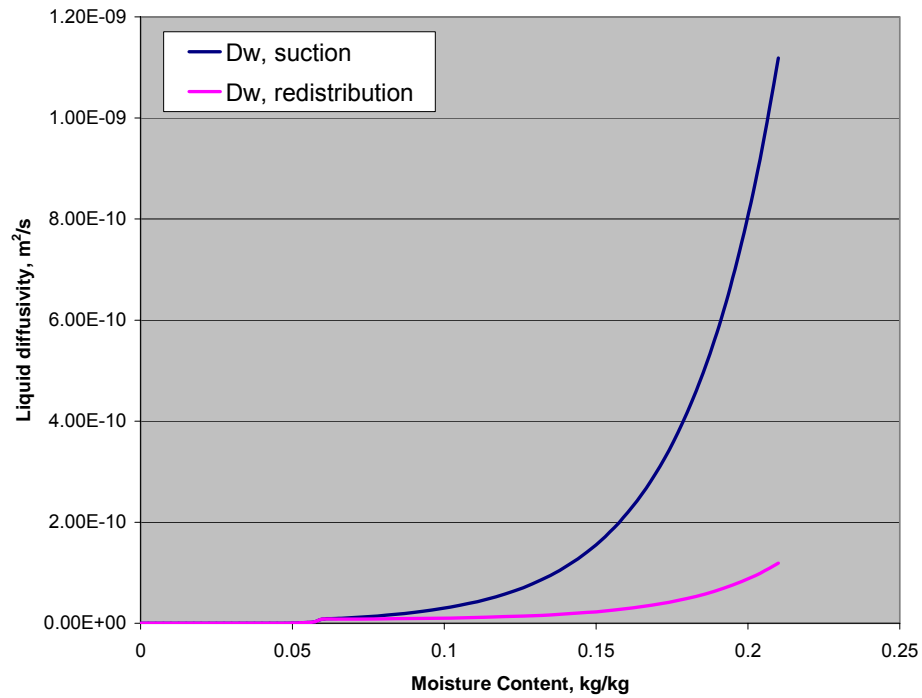


Figure 23: Exterior Cementitious Board (Paint Down) Liquid Diffusivity as a function of moisture content

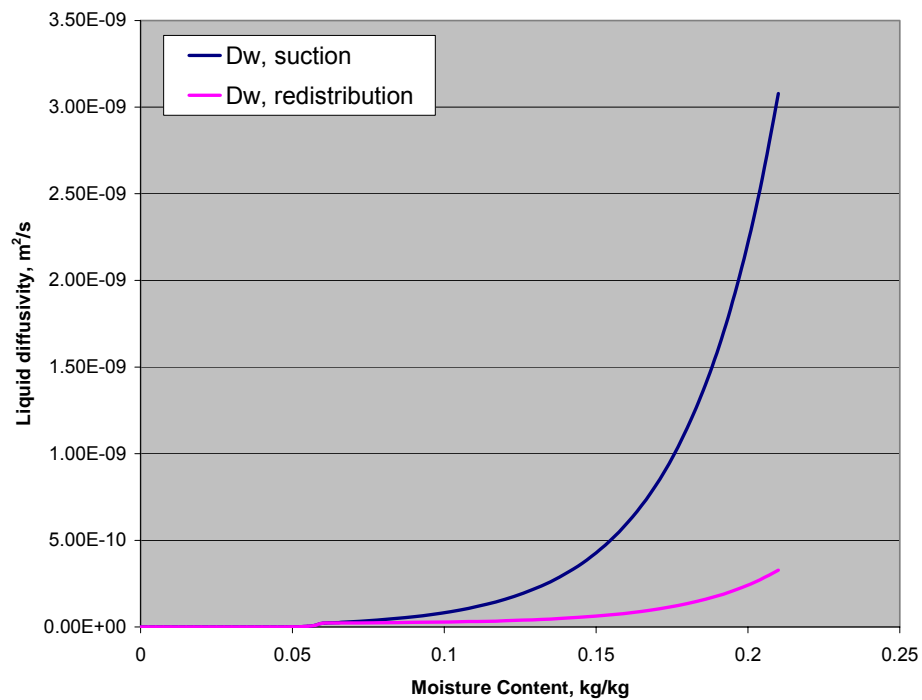


Figure 24: Exterior Cementitious Board (Paint Up) Liquid Diffusivity as a function of moisture content

## Conclusions

Materials were collected by WSU during the construction phase of the wall systems and sent to ORNL to perform a hygrothermal material property characterization. These materials were then conditioned to the various hygrothermal loads and the hygric capacities, and the transport coefficients in both the hygroscopic and capillary regimes were measured. The available results and the methodology employed during the characterization have also been presented. In this activity, ORNL has characterized additional properties (and in a more elaborate approach) than required by the DOE DE-FC26-02NT41498 contract. Some of the properties especially the cementitious board, stucco and the wooden material experience very long times to establish equilibrium moisture conditions.

Some of the results presented in this report are not currently available in the open literature. It is expected that these will be delivered to the WUFI-ORNL software version 5. Inclusion of these material properties will permit users a wider range of hygrothermal analysis capabilities.

Without the hygrothermal material property characterization, ORNL could not explain the strange behavior of Stucco Wall7 (no vapor retarder) case as discussed in the final DOE DE-FC26-02NT41498 report. In that wall, the painted gypsum was assumed to impart a vapor permeance of approximately 3 to 8 perms. These measured water vapor permeance properties when adjusted to Kirchhoff potential exhibited values between 12 and 67 perms. This explains the large interior loading to the sheathing board. Before these measurements, it was presumed that air leakage was present and had distorted the results.

The ORNL measured material properties were found to be critical for the hygrothermal modeling analysis and NET wall field hygrothermal performance characterization.

## **TASK 2: Advanced Hygrothermal Modeling**

In this task, the wall performances were analyzed by using WUFI/MOISTURE-EXPERT to characterize the drying and wetting performance of walls when various moisture and thermal loads are applied. Wall performances were analyzed in terms of vapor, air, and liquid diffusion control. Moisture transport through the wall and the various materials and sub-systems were analyzed to provide accurate feedback on climate specific designs. A part of this activity was to validate the model to various “new” features that could be introduced in the WUFI-ORNL designer family of software. One of these features was to introduce the exterior cladding ventilation/venting capability into the WUFI software. A number of the walls placed in the Puyallup test facility included the use the intentionally designed ventilation systems. In addition, at the same period, an ASHRAE awarded project was in place to further supplement the field result from Puyallup with data from a colder climate, Waterloo, Canada (similar to higher elevation mountainous locations in the Northwest Pacific regions). Some laboratory tests (Penn State) were also performed to further validate the ventilation performance of the MOISTURE-EXPERT model.

In this task 2, scientific information is provided about the model, the validation work performed on the WUFI 3.3, WUFI 4.0 version and Moisture-Expert and the latest upgrades to WUFI 4.0 that resulted in WUFI 4.1 with sources and sinks as well as cladding ventilation capabilities.

Data generated from Tasks 1 and 2 have lead to model enhancements followed by creation and analysis of improved building envelopes. This part of the research project was ambitious: its overall objective was to study the moisture engineering performance of a number of walls placed in field conditions (Puyallup, WA). Stucco cladding and the exterior membrane to the exterior sheathing are two important constituent layers in these multi-layer residential wall assemblies. Much of the work has relevance to a large number of building enclosures for wood-frame house construction.

This particular report deals with the use of modeling to predict the hygrothermal drying performance of a number of wall systems in various ventilation schemes, insulation levels and wall cladding scenarios. The primary objective of this report was to test and demonstrate the ability of the ORNL advanced hygrothermal model (MOISTURE-EXPERT) to predict complex hygrothermal processes that involve; wetting (water injection),

redistribution and drying. The physical processes present are: liquid sources, storage, liquid transport, vapor transport, evaporation, and air flow transport. During the same period, ASHRAE funded a research project on *“Development of design strategies for rainscreen and sheathing membrane performance in wood frame walls”* (ASHRAE 1091-TRP). Several laboratory controlled wall experiments were designed to develop these complex heat, air and mass transport behavior by the PENN State and these wall experiments were then used to compare the MOISTURE-EXPERT model predictions.

Results are reported for two different phases of the work. The hygrothermal model benchmark results for a series of experimental wall drying wall tests for different ventilation flow rates are presented first followed by a parametric analysis capturing a wider range of ventilation rates and conditions. An additional objective beyond the original scope of this project was to demonstrate the ability of the advanced model to predict complex hygrothermal transport behavior. This demonstrated validation provides a higher level of confidence with the use of the ORNL advanced hygrothermal model for use in design and forensic analysis. It is important to understand that there was no intention to validate the hygrothermal models using test data, but rather develop a better understanding of the fundamental performance of the field data using hygrothermal models. A totally different approach would have been undertaken to conduct field validation of the features of the hygrothermal models.

The objective of any numerical modeling is obviously to represent reality, but this is difficult because one cannot easily model the physical enclosure exactly (each crack, twist, and imperfection). Our knowledge of needed material properties is always incomplete and the properties are variable, and our ability to model every hygrothermal mechanics is somewhat limited. Circumstance, money, and time oblige us to do the following:

- be as complex and comprehensive as possible when accuracy is required,
- be as complex and comprehensive as needed when relative accuracy is sufficient.

We believe that the benchmark results presented in this report clearly show that we have met the validation objectives as stated in the original proposal. This also allowed us to provide the interpretation of the field results.

## **Purpose of Benchmark Activity**

The purpose of this activity of this research project was:

- To develop and implement a unique systems engineering approach for the design of wood frame building assemblies that are energy efficient and moisture tolerant. Oak Ridge National Laboratory (ORNL) efforts were to be augmented with efforts by the Washington State University (WSU) Energy Program to provide manufacturers and building designers with information on material properties and wall system descriptions that provide energy efficient and moisture tolerant performance.
- To develop the sensor instrumentation layout for wall system by using advanced hygrothermal analysis.
- to examine the function of a number of oriented strand board sheathing products and their impact on the hygrothermal performance of wall systems.
- To conduct research, to optimize and provide moisture control strategies for each sub-element of the envelope. To investigate the effect of the exterior facade, ventilation cavity, sheathing paper, sheathing substrate, studs, insulation system, interior vapor control strategy, and interior sheathing elements.
- To evaluate further and identify performance characteristics of wetting and ventilation drying for exactly the same boundary and initial conditions.
- To parametrically evaluate the effect of convective flow for various air cavity flow rates.

The analysis sought scientific evidence to support or refute widely held beliefs regarding hygrothermal performance of the role of ventilation effectiveness and the drying performance of simulated stucco walls.

### ***Value of ORNL-WSU- Industry Research Activities***

This research project complements ongoing activities in the ORNL BTC's Building Thermal Envelope Systems and Materials (BTESM) Program. It supports the Department of Energy's (DOE's) stated goal of developing long-term hygrothermal modeling capabilities and guidelines for moisture management strategies in wall systems. The understanding of how to construct thermally efficient and moisture tolerant residential building enclosures is already the main focus of the Moisture Technology Program at BTC (led by Karagiozis). The ORNL collaboration with WSU and Industry Partners supplied the needed three level competencies required in this project, that are experimental (laboratory and field) and analytical modeling.

## ***Project Information***

### **Wall Sensor Location**

To accomplish these objectives, an initial series of simulations were performed to analyze the experimental sensor layout for the proposed field walls at the Puyallup test facility. Dr. Karagiozis from ORNL performed the simulations on vented and ventilated stucco wall cavities. The experimental layout for each sensor was further refined by conducting a series of simulations using 2-D heat, air and moisture transport modeling (MOISTURE-EXPERT). The temperature, moisture content and relative humidities were developed for a 2-D cross section of the proposed wall systems. From the multi-year hygrothermal modeling analysis, the thermal and moisture gradients were analyzed and the instrumentation location was developed based on the transient simulation.

While increasing the number of sensors installed in the wall test section would be beneficial, the fiscal realities required ORNL to establish the bare minimum the instrumentation location was developed based on the transient simulation.

### **Sensor Location in the Test Walls**

The exact sensor locations are listed below, and they are illustrated in Figures 25 to 26.

Further details for Figures 25, 26 and 27 can be found in the Report on the field investigation by Murray and Tishy [2007].

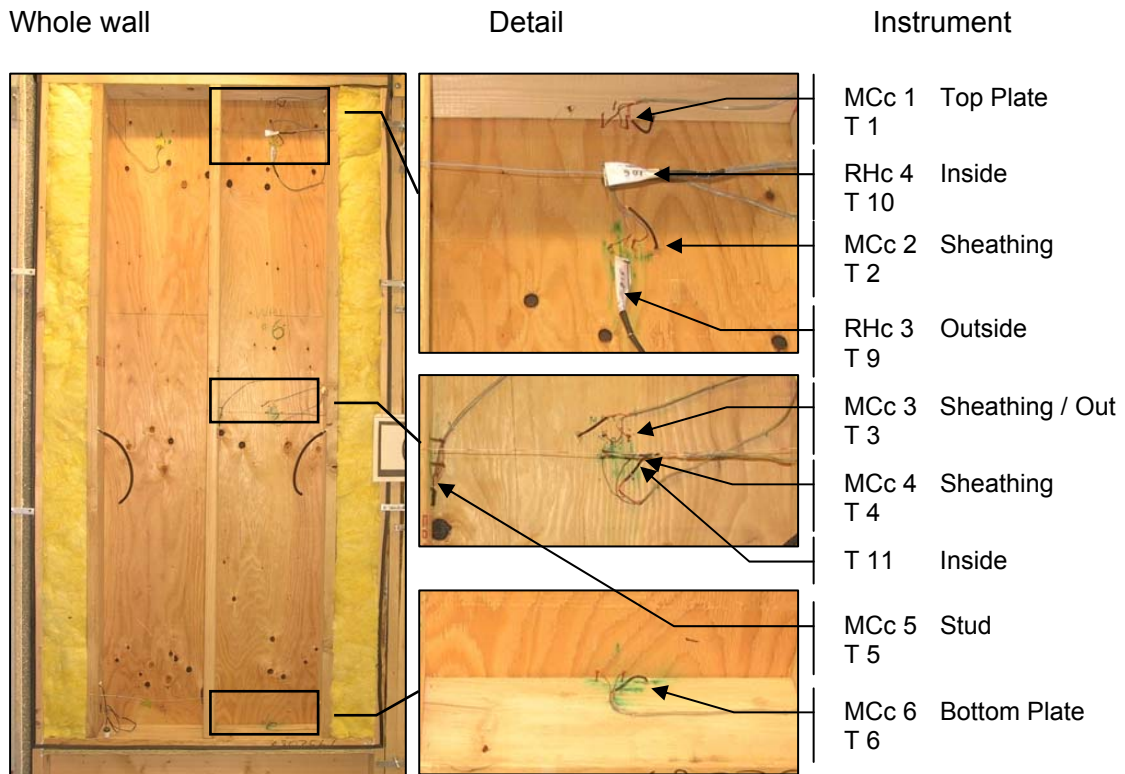


Figure 25: Wall Sensor Placement (Right Cavity)

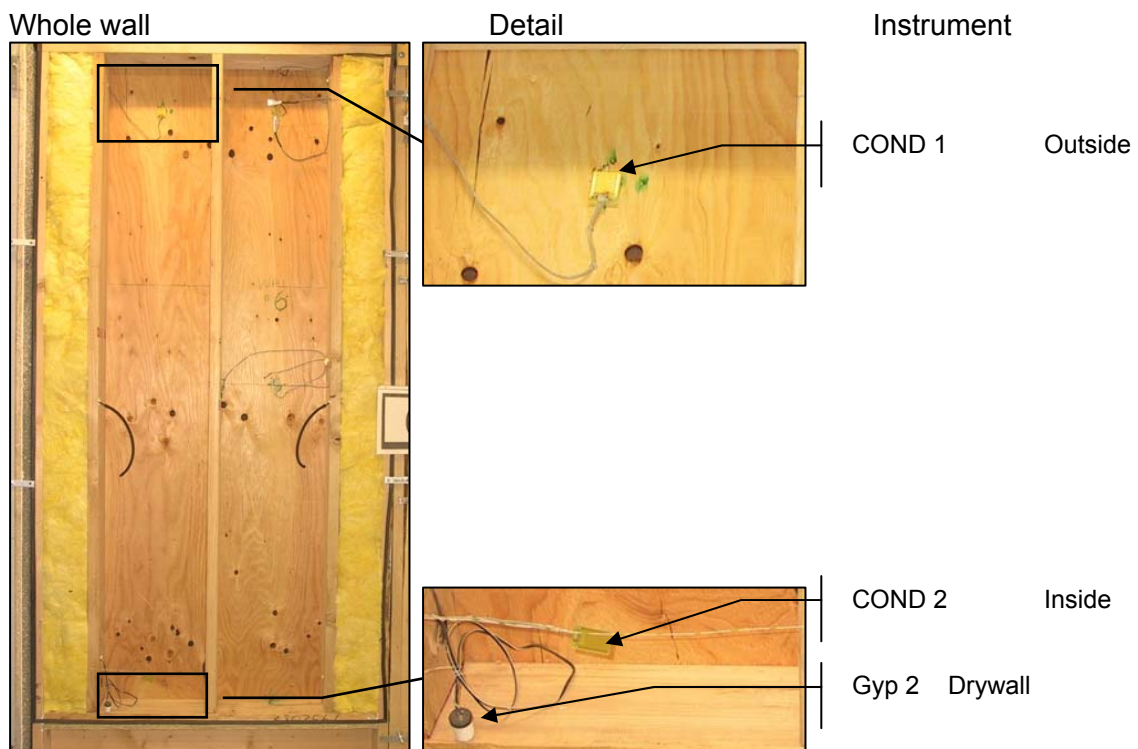


Figure 26 Wall Sensor Placement (Left Cavity)

## Exterior Cladding

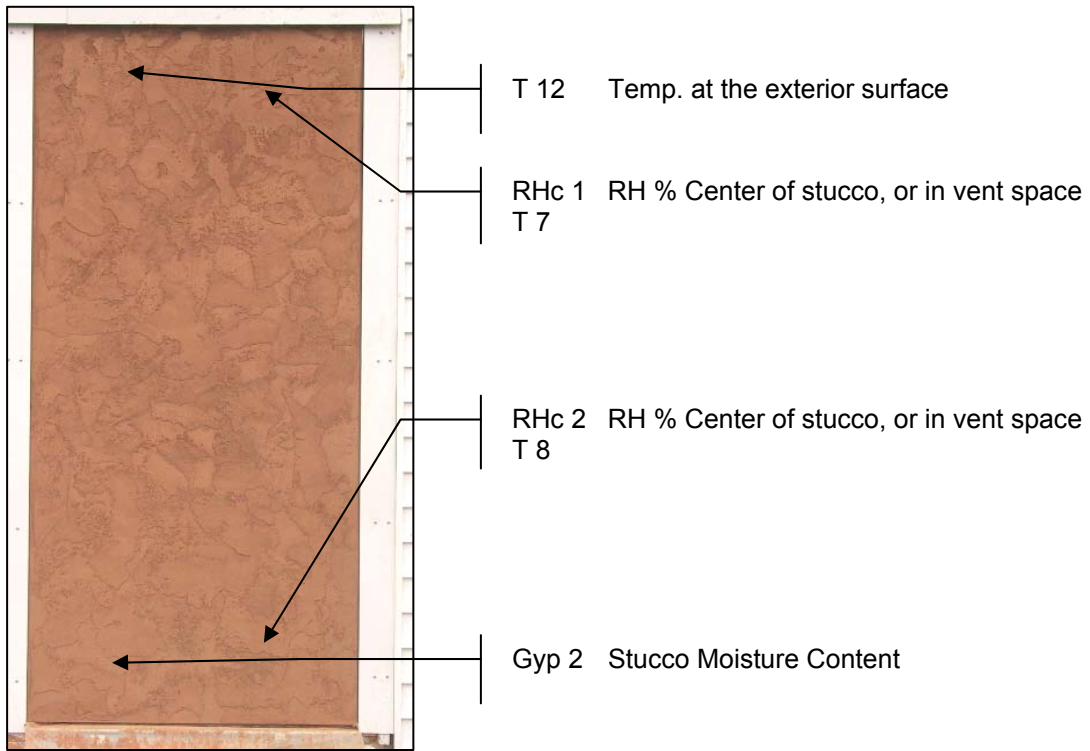


Figure 27: Wall Sensor Placement (Left Cavity)

## **MOISTURE-EXPERT – Advanced Hygrothermal Simulation Model**

The MOISTURE-EXPERT model developed by Dr. Karagiozis [2001, 2004, 2006] at the Oak Ridge National Laboratory is one of the most comprehensive research hygrothermal models as described in a recent ASTM manual on Moisture Analysis and Condensation Prediction by Heinz Treschel [2001] and the ASHRAE 1091-RainScreen and cladding ventilation project. Essentially, four sets of inputs are required to set-up the model for hygrothermal analysis, as depicted in Figure 28. Requirements include; the exterior hygrothermal loads, interior hygrothermal loads, material properties and building envelope systems and sub-system characteristics. It is important to recognize that depending on the effort taken to accommodate the exactness of the prescription of these loads and material and system performances of materials, a corresponding level of prediction performance results. For example, if the dependencies of the material properties on variables such as temperature, moisture content or relative humidity and at times density are properly accounted for, then more accurate predictions will result from the advanced hygrothermal model MOISTURE-EXPERT. Similarly, as the particular system and sub-system information is provided to the model, for example, cavity ventilation sub-system characteristics then correspondingly more accurate predictions will result. Both influences, the level of effort in implementing the accuracy of the material property inputs and including specific information on the sub-system performance such a ventilation flow, will be demonstrated in this report.

The governing equations implemented in MOISTURE-EXPERT are given below. The moisture transport potentials used in the model are relative humidity ( $\phi$ ) and vapor pressure ( $P_v$ ); for energy transfer, temperature is the driving force.

MOISTURE-EXPERT, Karagiozis (1999, 2001, 2002) is a software program that allows 2-D calculations of the transient hygrothermal behavior of multi-layer building components and is customized for climatic conditions in North America. The uniqueness of the model is the inclusion of temperature dependent sorption isotherm, and capability to handle wind-driven rain. Two systems of transport equations have been employed, one based on vapor pressure and capillary pressure and the other based on vapor pressure and relative humidity. This model is a research model, and has capabilities to model complete buildings, by including each wall assembly, roof and basement and coupling with an indoor air quality model.

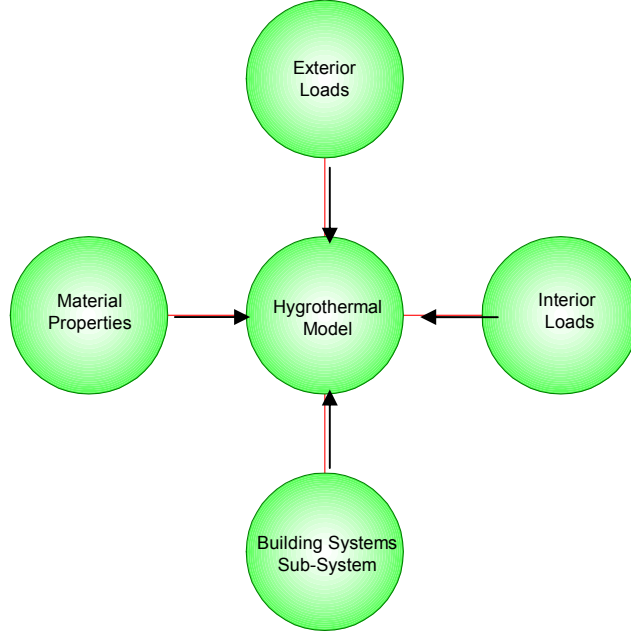


Fig. 28. Inputs required in 1-D and 2-D hygrothermal simulations.

## ***Equations of State:***

### ***Moisture balance***

$$\frac{\partial w}{\partial \phi} \cdot \frac{\partial \phi}{\partial t} = \nabla \cdot (D_{\phi} \nabla \phi + \delta_p \nabla (\phi p_{sat})) - u \rho_v \quad (1)$$

### ***Energy balance***

$$\frac{\partial H}{\partial T} \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + h_v \nabla \cdot (\delta_p \nabla (\phi p_{sat})) - \rho_a u c_p \nabla T + S \quad (2)$$

### ***Air Flow***

$$\frac{\partial (\rho u)}{\partial t} = -\nabla \cdot (\rho u \cdot u) - \nabla P - \eta \nabla^2 u + F \quad (3)$$

where:

$\phi$  is the relative humidity,  $t$  time,  $T$  temperature,  $c$  specific heat,  $w$  moisture content,  $p_{\text{sat}}$  saturation vapor pressure,  $\lambda$  thermal conductivity,  $H$  total enthalpy,  $D_\phi$  liquid conduction coefficient,  $\delta_p$  vapor permeability,  $h_v$  latent heat of phase change,  $c_p$  specific heat of fluid,  $\rho_a$  density of fluid, where  $u$  is the velocity vector (m/s),  $P$  is pressure (Pa),  $\eta$  is the dynamic viscosity (s Pa) and  $F$  is the body force per unit volume (N/m<sup>3</sup>),  $\rho_v$  vapor density and  $S$  volumetric heat source or sink

**Boundary Conditions:** Indoor and outdoor air temperature on any time interval, relative humidity; direct and diffuse solar radiation; precipitation, wind speed and direction, pressure differences or prescribed mass flows (opt.: clear sky radiation, driving rain).

#### **Limitations:**

The model is not user friendly, as a graphical user interface does not exist and the model is exclusively a research tool. Hysteresis of the moisture retention curve is not taken into account. The model is computationally slow, as it precisely conserves heat and mass in each control volume.

### **Recent MOISTURE-EXPERT Validation**

#### **Laboratory Validation**

In the 2005 ASHRAE Research Project TRP-1091 study set out to accomplish three tasks:

- Develop experimental data for ASHRAE TRP-1091 benchmarking of ORNL's hygrothermal model MOISTURE-EXPERT.
- Develop performance data on convective airflow to the drying of wall systems at representative flow rates, especially at relatively low flow rates.
- Provide insight on the drying rate and the ventilation flow rate.

These tests were intentionally developed to reduce the number of intentional variables to three, namely the convective airflow rate, environment temperature, and relative humidity. A laboratory wall assembly of non-typical configuration, was designed with imbedded controls to inject water into the wall and to measure the drying performance. As this experiment did not provide tight control of the exterior environmental and initial conditions, the experimental

results can not lend themselves to generalization (extrapolations), in their existing form. The different fluctuating temperatures and relative humidities were not identical for each of the different air cavity ventilation rate. These wall tests are best suited for the benchmarking and validation activity of the hygrothermal MOISTURE-EXPERT model as identical conditions are not required. Only accurate measurements of all environmental loads and transient behavior of the walls is needed for model benchmarking and that was achieved by the Penn State team.

This experimental project was an extension of two larger projects directed at convective drying in wall systems. Thermal gradients did exist across the assembly, but were small. Water was injected and was uniformly spread throughout the interior surface of the sheathing board. This wetting approach was done by injecting a precise dosage of water and was repeated for all tests. The wall assembly had dimensions of 1.2 x 2.4 m (4' x 8'). Only a portion of this was wetting, accounting for approximately 78 % of the wall.

The experimental process involved injecting a predetermined quantity of water into the wall, and then the walls were monitored in terms of total weight, relative humidity distributions, temperatures, moisture contents in the sheathing board and air cavity ventilation flow rate. Three initial sets were delivered to ORNL, and results will be reported on those.

A detailed description of the assembly and the testing of the walls is reported by Burnett et al [2004]. The reader is referred to this work for much more in-depth-experimental reporting. Below, only a brief outline of the tests will be presented.

## **EXPERIMENTAL SETUP AND PROCEDURE**

### **Experimental program development**

The benchmark experimental program at the Penn State University involved 5 tests. One test was conducted for zero induced airflow -- a datum test. Four wall panels were tested at flow rates that were measured; 1.6 L/s (0.056 ft<sup>3</sup>/s), 0.8 L/s (0.02825 ft<sup>3</sup>/s), 0.4 L/s (0.01412 ft<sup>3</sup>/s) and 0.2 L/s (0.00706 ft<sup>3</sup>/s). Three were used for the model benchmark activity, the zero air flow, 1.6 L/s and 0.4 L/s, as these were performed first. Table 6 relates these three flow rates to air change rates and average velocities for a 50 mm cavity depth ( ≈ 2 inch). The flow rates selected for this study result in velocities that are at the lower end of the range of measured values at the University of Waterloo. These small flow rates were

selected to show that the contribution of ventilation air flow to drying is apparent at even very low flow rates.

**Table 6 – Test flow rates, average velocities & air change rates Burnett et al [2004]**

Flow rate (Lps)	Average locity (m/s)	Air change rate (ACH)
No Flow	0.000	---
0.2	0.003	4.8
0.4	0.007	9.7
0.8	0.013	19.4
1.6	0.026	38.8

Efforts were concentrated by the experimental team to develop an accurate measurement of the weight change of the panel systems, and this was achieved by developing an innovative measurement apparatus.

### **Simulated Wall panel Assembly**

The basic test wall panel, shown in Figure 29, was designed and built to idealize the outer portions of a typical wall system (i.e. those components that form and interact with the air space or chamber). The simulated test panel consists of 7 layered components, and:

- A five-sided OSB box, lined with foil-faced polyisocyanurate. Joints are carefully taped to form an insulated, airtight, vapor tight container for the test panel
- The wetting system, consisting of sheets of distribution paper,
- 12.5 mm (0.5 inch) of Homasote fiber sheathing
- Tyvek housewrap
- A 50mm (2 inch) deep air space
- The Plexiglas cladding with 1100 mm (43.3 inch) wide × 19 mm (0.75 inch) high vent slots located 25 mm (1 inch) from the top and bottom of the panel
- The top and bottom inlets

Accurate measurement of the weight change of the test wall panel during the wetting and drying process is one of the keys to this experiment. A counterbalance weighing system was developed to measure with an accuracy of 5 grams (0.01102 lb) or less. As shown in Figure 30, the system consists of a load cell, counterbalance weights, and a steel arm. Most of the panel weight is counterbalanced by the suspended weights while only a small portion is carried by the load cell. Because of friction and panel movement, calibration of the

counterbalance system was required at the start of each test. The calibration equation was then used to convert the measured weight change of the panel to the actual weight change.

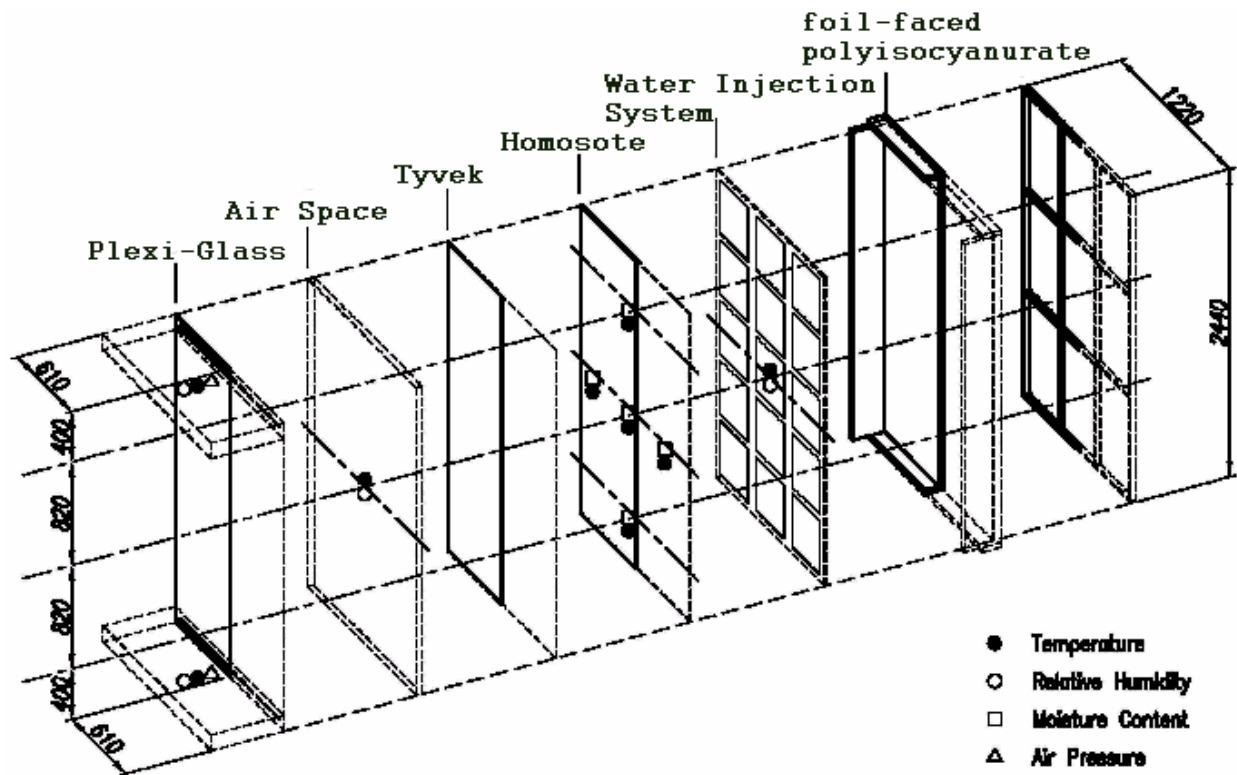


Figure 29: Experimental Configuration, Burnett et al [2004]

## Wetting Approach

The Homasote sheathing board was wetted by injecting 1350g (2.976 lb) of water through the wetting tubes. Three quantities of water were supplied to the wall. The three doses were 450 g (0.9921 lb) each and were injected at a 4 hour time interval.

## Ventilating air supply system

Two air pressure manifolds, were designed and constructed by Penn State, Burnett et al, [2004] to provide a consistent flow to the panel at the top and bottom vents. A calibrated orifice plate was installed at the upstream side of the bottom vent to measure the ventilation airflow rate. Figure 31 shows the test wall panel assembly with the counterbalance system and the ventilation air supply system in place.

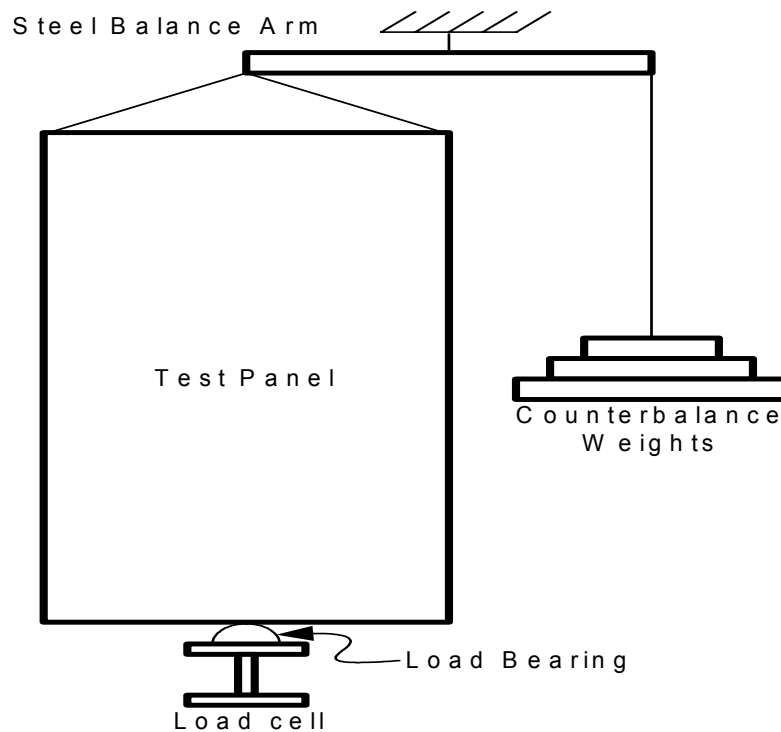


Figure 30. Counterbalance System Burnett et al [2005]

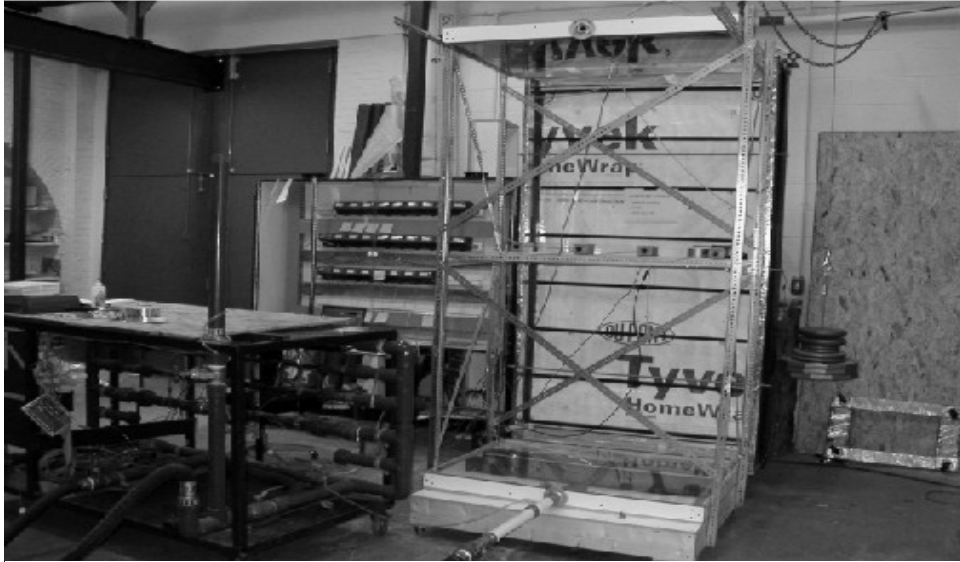


Figure 31. Airflow manifolds connected to test panel on counterbalance system

## Experimental procedure

Each test was initiated by injecting the first 450 g (0.9921 lb) of the 1350 g (2.976 lb) water to wet the Homasote sheathing. The weight change of the panel, along with other physical measurements, were monitored and saved using the data acquisition system. The data was then provided to ORNL for model benchmarking.

### *Understanding the Experiment (wetting/drying relationship)*

As previously discussed, 3 of the 5 tests were sent to ORNL for model benchmarking. These cases were for the zero induced ventilation case, the 1.6 L/s (0.056 ft<sup>3</sup>/s) induced ventilation case and the 0.8 L/s (0.02825 ft<sup>3</sup>/s) ventilation case. Experimental data supplied included the weight change of the assembly as a function of time (5 minute interval). The data files included drying data from the total weight gained due the water injection period. When the ambient relative humidity was higher than the surface conditions of the test assembly, moisture ingress was also recorded. This additional accumulation process further complicated the analysis and increased the benchmark challenge. Later in the series of tests, this additional influx of moisture was diminished by painting the assembly with a vapor tight finish.

In most model benchmark activities, the initial conditions and boundary conditions are usually maintained constant, or varied in a systematic manner. The of lack of ability to control the room temperature and humidity of the laboratory, the boundary and initial

conditions floated and were not repeatable from one test to the other. Brief and sudden increases in the relative humidity of the laboratory were experienced during rainy periods and were found to influence the slope of the drying curves.

An additional challenge to the hygrothermal model was the process of water injection needed to be appropriately accommodated. To the best of our knowledge, such a benchmark modeling case has not been reported in literature before. The transport phenomena in the benchmark cases provide closure to heat and mass transfer model. Vapor transport, convection air transport, heat transport, liquid transport, evaporation and condensation all are simultaneously occurring the test wall. The premise for this benchmark activity is that if agreement was found between this experiment and the model, then a very high level of confidence would exist in using the model for ventilation/wetting and drying configurations investigated in these tests. This would then validate the hygrothermal model.

A great effort was required by the experimental team to develop these five sets of experimental tests. Effort was directed at measuring the weight of the wall to high accuracy, and to accurately measuring the air flow, and moisture content. The water ingress and distribution system was also designed and tested several times to provide a uniform wetting mechanism for the water injection. This allowed the Homasote to start with a nearly uniform moisture content, the entire area of the sheathing interacts with the air space as the water is removed from the system and the panel dries.

### ***Initial Conditions***

No special pre-treatment was made to the material used in the tests. All the tests were conducted in an enclosed building. Before the wetting (water injection) was initiated, the moisture content at all five locations (top-center, middle-left, middle-center, middle-right and the bottom-center) measured in the Homasote was within the range of 11 to 13%. At time equal zero, three 450g (0.9921 lb) doses of water were injected into the wall. However, the wetting system only covers 78% of the area of the sheathing. Taking into account the reduced area of contact and the fact that the transducers are located within the contact area, the measured moisture content increase could add 11% to the initial 11 to 13%.

### ***Boundary Conditions***

Figure 32, shows the ambient temperature in the building as well as the temperature evolution in the test wall that had 0.8 L/s (0.02825 ft<sup>3</sup>/s). It is evident that during the test

period a considerable temperature variation existed, and transient daily temperatures of up to 1.5 °C (2.7 °F) were present. The maximum variation between the lowest and highest room temperature was slightly over 5 °C (9 °F) during the test period. Variations in relative humidity were also present over the testing period, and these are plotted out for case 9 in Figure 33. A variation of approximately 15% room relative humidity between the lowest and highest values occurred during the 8 days of testing.

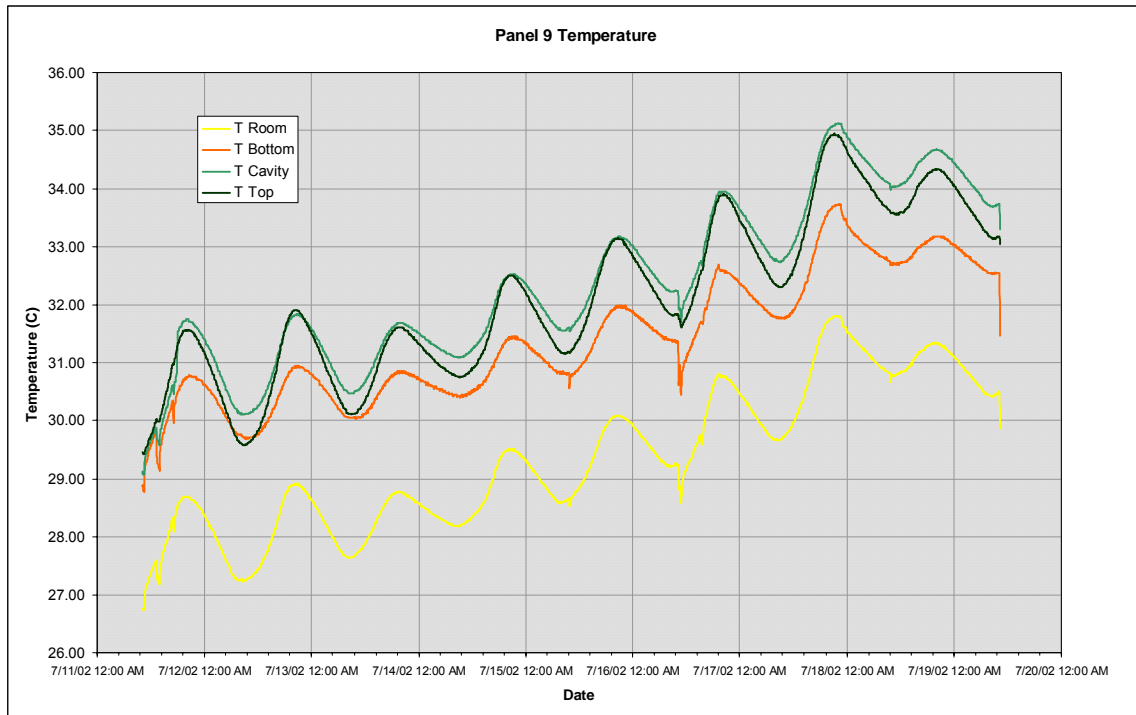


Figure 32: Temperature Distributions (0.8 L/s) (Boundary Conditions & Results)

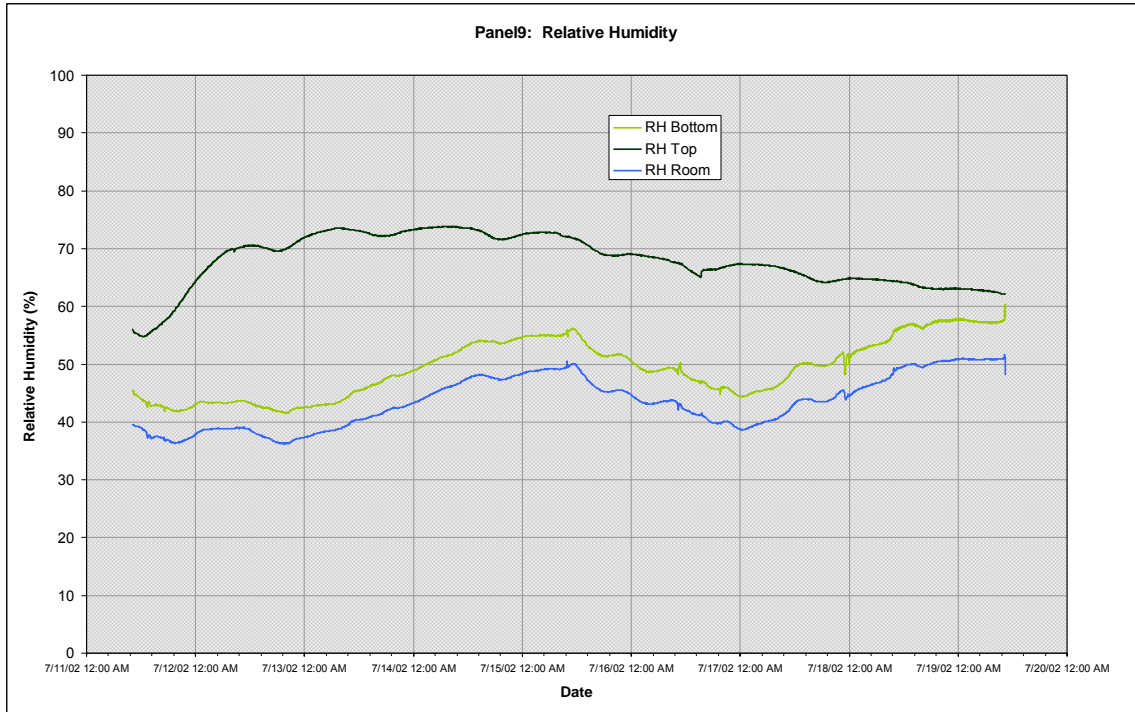


Figure 33: RH Distributions (0.8 L/s) (Boundary Conditions & Results)

### Simulation Details

In Figure 34 the grid distribution is given for the test walls as shown in Figure 1. Four different grid size distributions were initially used in the analysis. These were 18 x 13, 35 x 25, 70 x 50 and 140 x 100. The purpose of parametric was to obtain a minimum grid size distribution that provided numerical free error (grid size dependency) within a tolerance of  $\pm 0.01\%$  of the dependent variable. The 35 x 25 grid size was found to satisfy this criteria, and was used in the analysis of the test walls. The simulations were performed for a time step of 1 hour.

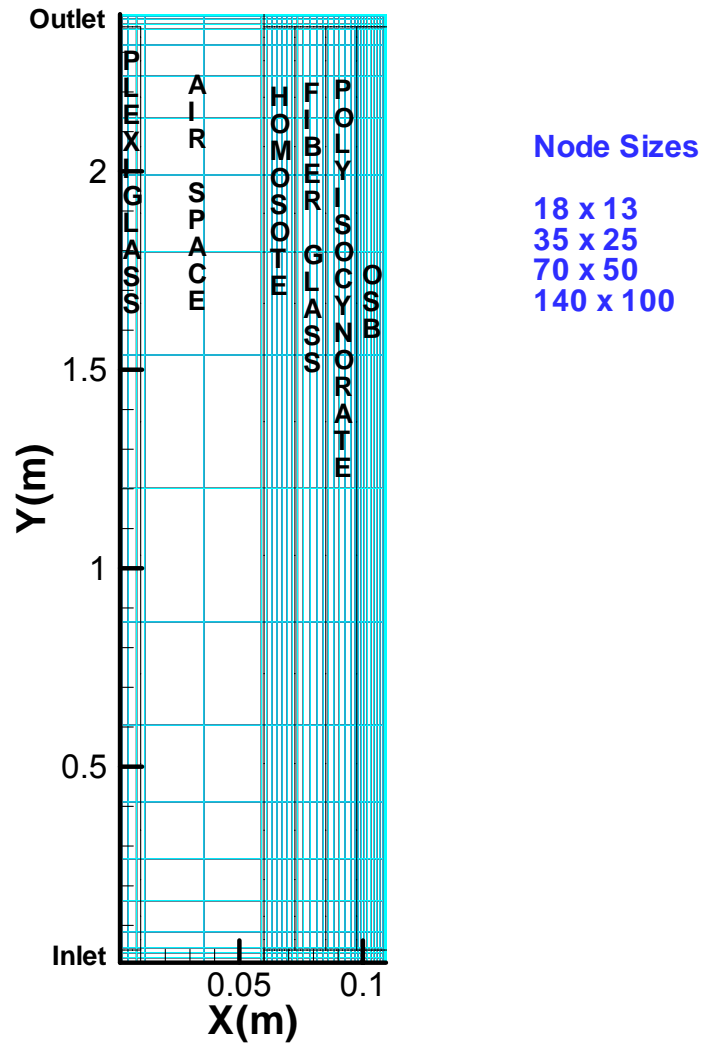


Figure 34: Grid Distribution Analysis for 2-D hygrothermal simulations.

Figure 35 plots out the measured and simulated weight gains using ORNL material properties. The results show remarkable agreement. This excellent agreement is evidence of the importance of correctly including the transport mechanisms as well as material and sub-system performance characteristics of the simulated model. The differences between experimental and numerical simulation are very small, approximately less than 5% for the majority of the time. While the uncertainty in the weight measurement is of the order of  $\pm 5$  gr, (0.011 lb) the total uncertainty in the experiment taking into account the uncertainties in all interior and exterior loads could be estimated to be of the order of  $\pm 1$  to 12.5%. Higher uncertainties are certainly present during the drier conditions/periods in the wall (end of the experiment). The agreement, is though remarkable in that the model was able to correctly follow the fluctuating excitations from the interior environment very closely. This agreement clearly depicts the importance of having better than representative material properties when benchmarking hygrothermal models.

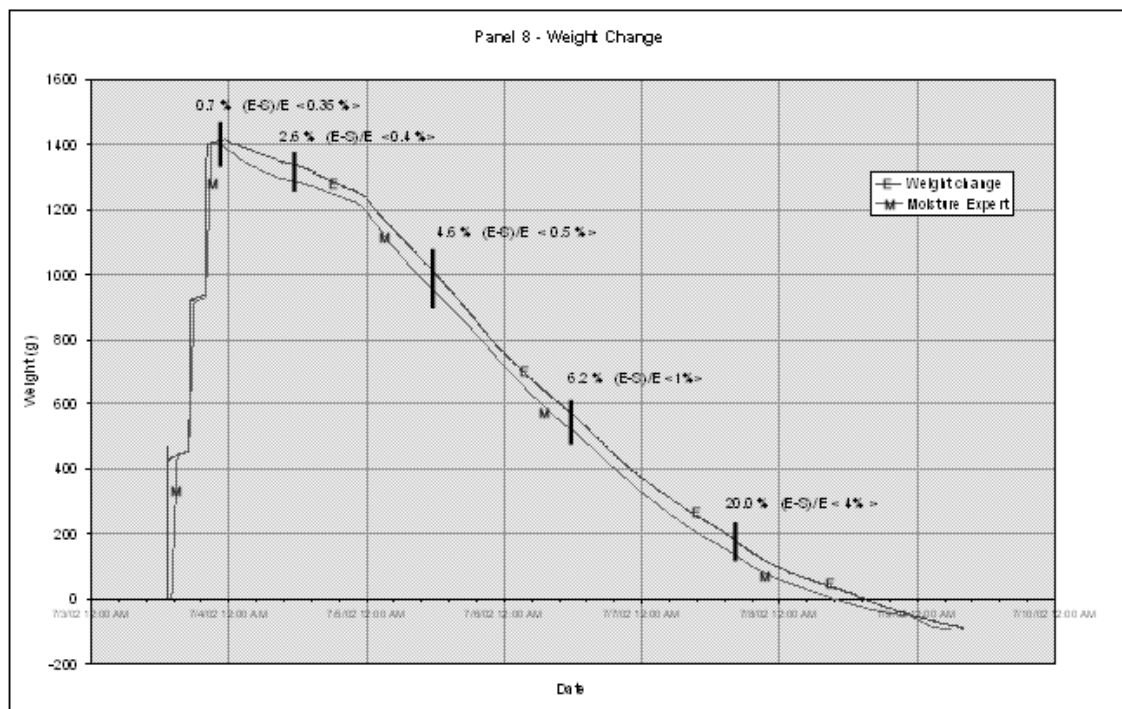


Figure 35: Comparison between model simulation results using ORNL Hygrothermal Data

### ***Simulation of the Zero Air Flow Case***

Being the first of the wall benchmark cases performed, this case became the testing ground for all the other tests with ventilation air flow. This particular wall case had a 4 inch air cavity and both the top and bottom inlet regions were open to the ambient. During the test the room unit heater was located at the top of the building and had a direct influence on the experimental loads (temperature, relative humidity and pressures) that the wall felt. Since no protection was provided to the inlet and outlets cavity openings of the test wall (no special encasement), it was difficult to calculate or assign air flow conditions. The operation of this mechanical unit heater affected not only the local temperature and relative humidities observed in the room, but developed pressure distributions and air flow patterns in the rooms. To investigate the results and understand better the laboratory conditions, some additional parametric investigations were performed. One case was performed with no induced flow (not realistic as flow would be developed from the room unit heater) and then two cases that assumed a constant air flow value. These two constant air flow values were selected as similar values that have been measured and observed in the past in the Beghut at the University of Waterloo (Straube, Thesis 1997).

In Figure 36, results are shown for the case without induced air flow. Air flow was allowed to develop due to an air density gradient produced because of evaporative heat flow temperature redistributions and density gradients present due to vapor pressure gradients, but was mechanically induced. The assembly was allowed to be open. The maximum difference between the experimental data and simulation results was 17.6%, but for the majority of the time, this difference was less than 6%. Very good agreement was observed for the both the beginning and end of the test. The maximum difference was found during the third day of the experiment. In this experiment, substantial temperature gradients were observed in the room and the wall assembly. An overall observation is that the simulation predictions were consistently lower than the experiments.

In Figure 37, results are shown for two prescribed constant flow rates of 0.1 (0.3281 ft/s) and 0.05 m/s (0.1640 ft/s). The agreement between the experimental results and the simulations become excellent. Closer agreement is found with the lower flow at 0.05 m/s (0.16402 ft/s). With this cavity's ventilation rate the maximum difference observed is 6% well within the experimental uncertainty of the drying and wetting test.

In summary, the three simulation cases show very good agreement with the experimental data. This benchmark case was particularly challenging for the model as the driving forces for drying (forced convection) was that of natural convection. The ORNL Moisture-Expert model has shown that it has been able to capture both the trend as well as the closeness with actual experimental values.

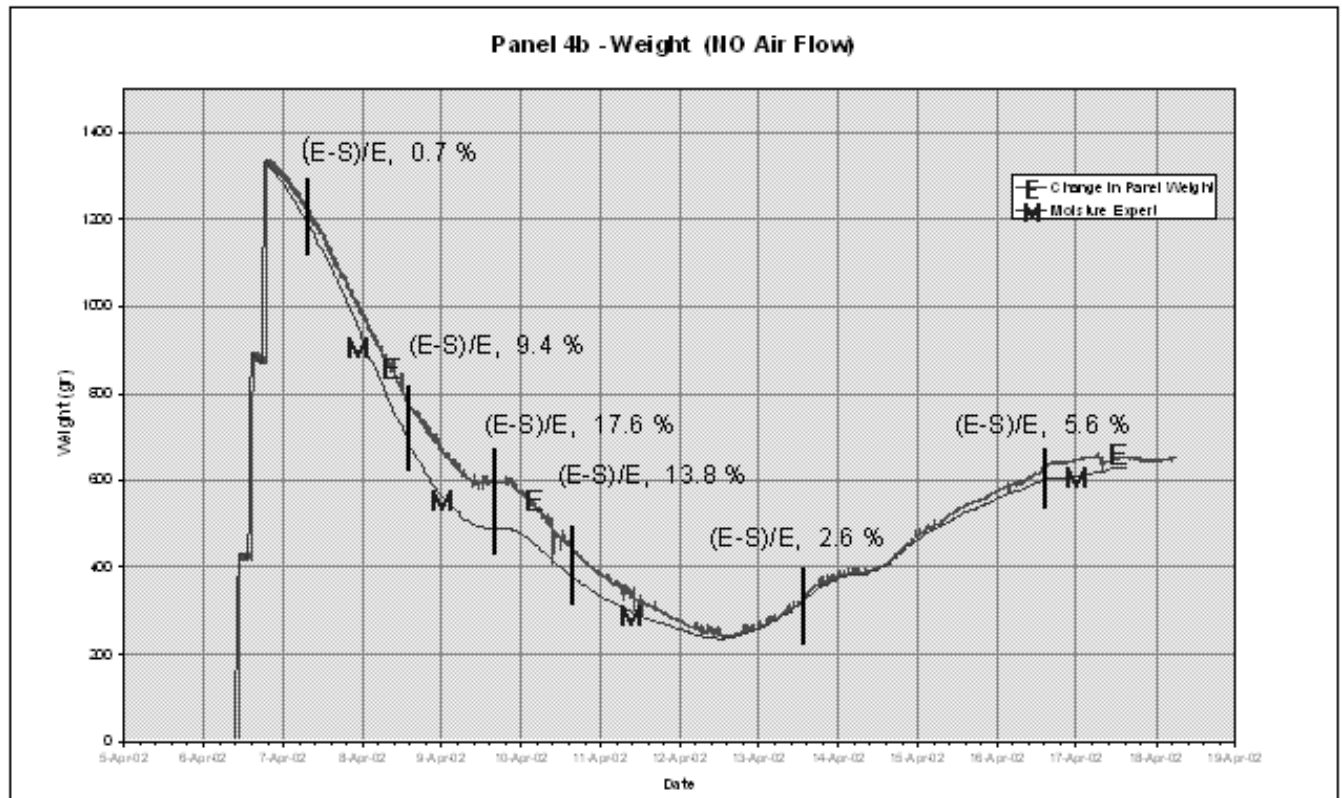


Figure 36: Comparison between model simulation results and experimental Data (No Flow Case)

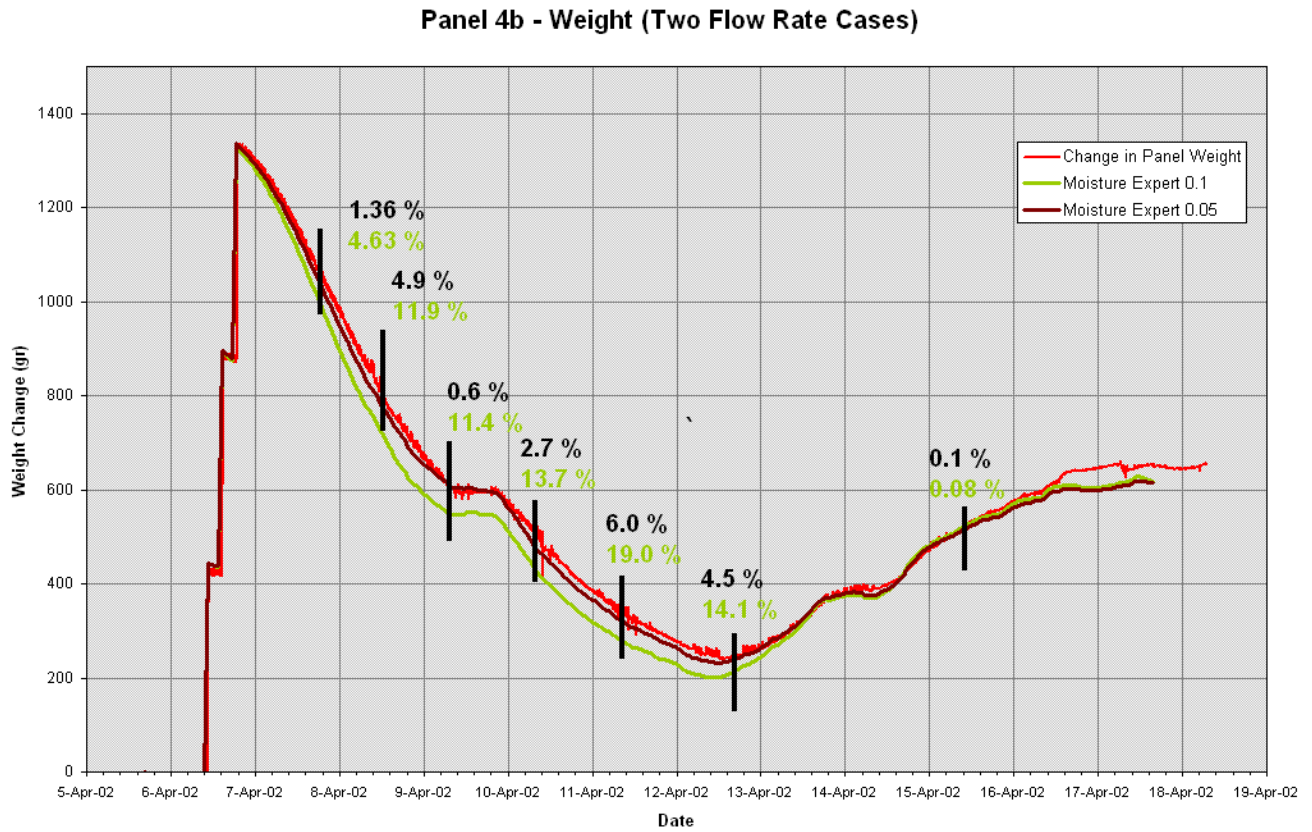


Figure 37: Comparison between model simulation results and experimental Data

### ***Simulation of the 1.6 lps (0.056 ft<sup>3</sup>/s) Case***

In this particular wall wetting and drying test, the air cavity was 2 inches and at the bottom of the test wall, an air flow of 1.6 Lps (0.056 ft<sup>3</sup>/s) was maintained at the bottom inlet region of the air cavity. In these tests, the pressure influence of the room unit heater was negligible as the inlet and outlet region were protected. In Figure 38 the transient weight of the wall assembly is shown for the experiment and the simulation. Good agreement is found between the laboratory results those simulated by MOISTURE-EXPERT. The simulation results lie within the total experimental uncertainty for more than 95% of the test period. The agreement in many ways is remarkable, as three modes of mass transfer are very well predicted, a) water injection and storage, b) initial redistribution and c) and convection air drying.

Figure 39, displays the relative humidity as a function of time for several locations in the air cavity and in the room. Results are also displayed for the calculated relative humidity at

the top location of the ventilation cavity, Figure 40. The agreement between the measured and calculated relative humidity results at the top location of the ventilation cavity is very good. It is important to observe that the experimental results are given on a 5 minute basis, while the simulated results every 1 hour. A maximum difference in RH of 2.5% was found. Figure 40 displays a snap shot of the spatial relative humidity distribution and temperature distribution at 5 days after the initial wetting period. Warmer room air is heating the bottom of the test wall allowing evaporation to occur and slightly wetter conditions are observed at the top of the Homasote. In summary, excellent agreement is found when comparing the MOISTURE-EXPERT simulation results with Penn State experiment data at a cavity ventilation rate of 1.6 Lps ( $0.056 \text{ ft}^3/\text{s}$ ).

### **Simulation of the 0.8 lps ( $0.02825 \text{ ft}^3/\text{s}$ ) Case**

The same wall configuration is used in this benchmark test as in the 1.6 Lps test, but the air cavity ventilation is halved. In this case 0.8 liters of air per second is passed through the 2 inch cavity. In Figure 41 the transient weight of the wall assembly is shown for both the experiment and the simulation. Good agreement is found between the laboratory result (0.8 Lps) and those simulated by MOISTURE-EXPERT. The close agreement is present until the end of the experiment, where the measured weight changes are small. At the end of the experiment, the deviation is larger indicating the particular sensitivity of the modeling test to the inputted thermal and moisture boundary conditions. This difference could be present as the room boundary conditions were taken at the inlet region of the experiment. In this benchmark test a large ( $4 \text{ }^\circ\text{C}$ ) temperature difference between the initial start temperature and the ending temperature of the room occurred. Room boundary conditions (T & RH) for this test was taken from the inlet T and RH as substantial differences between these and the instrumented wall existed.

In summary, again with this benchmark experiment, good agreement was found between model simulation and experiment. Agreement in the weight difference was within 5% for the majority of the test.

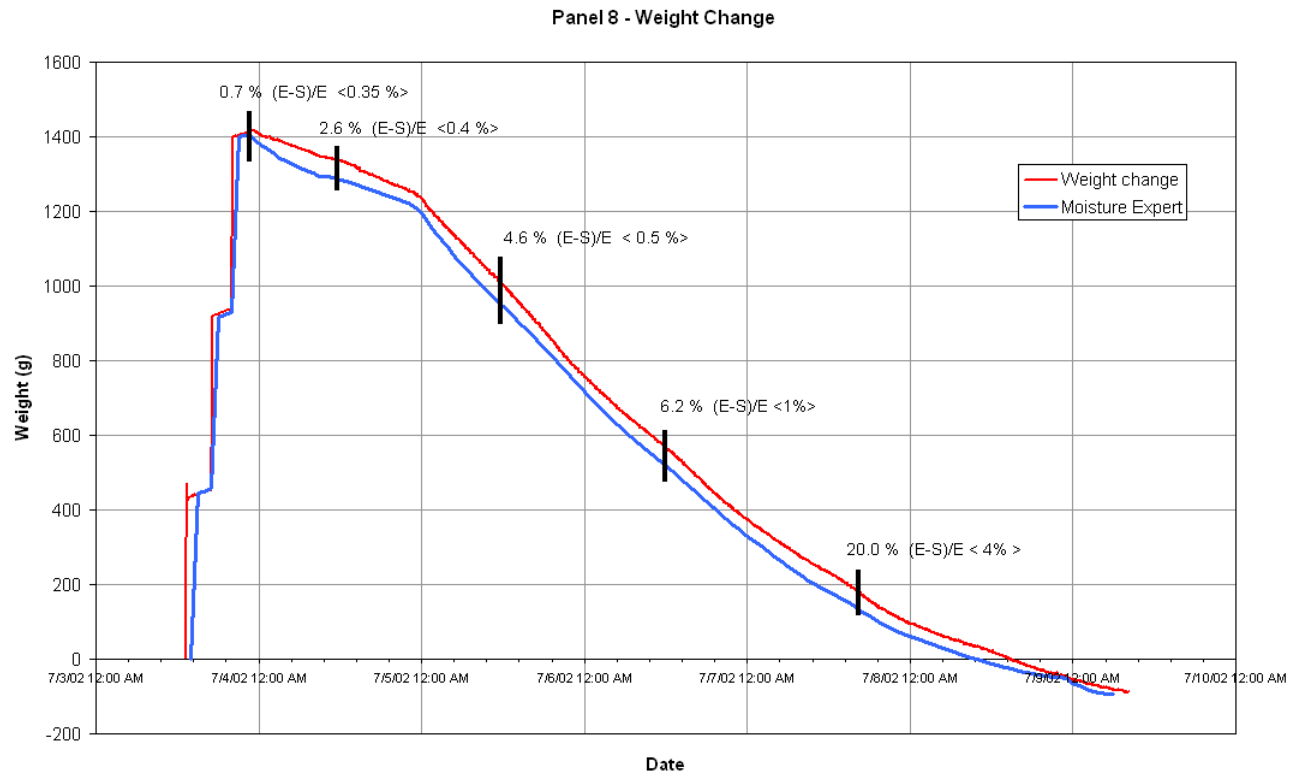


Figure 38: Comparison between model simulation results and experimental Data (1.6 Lps)

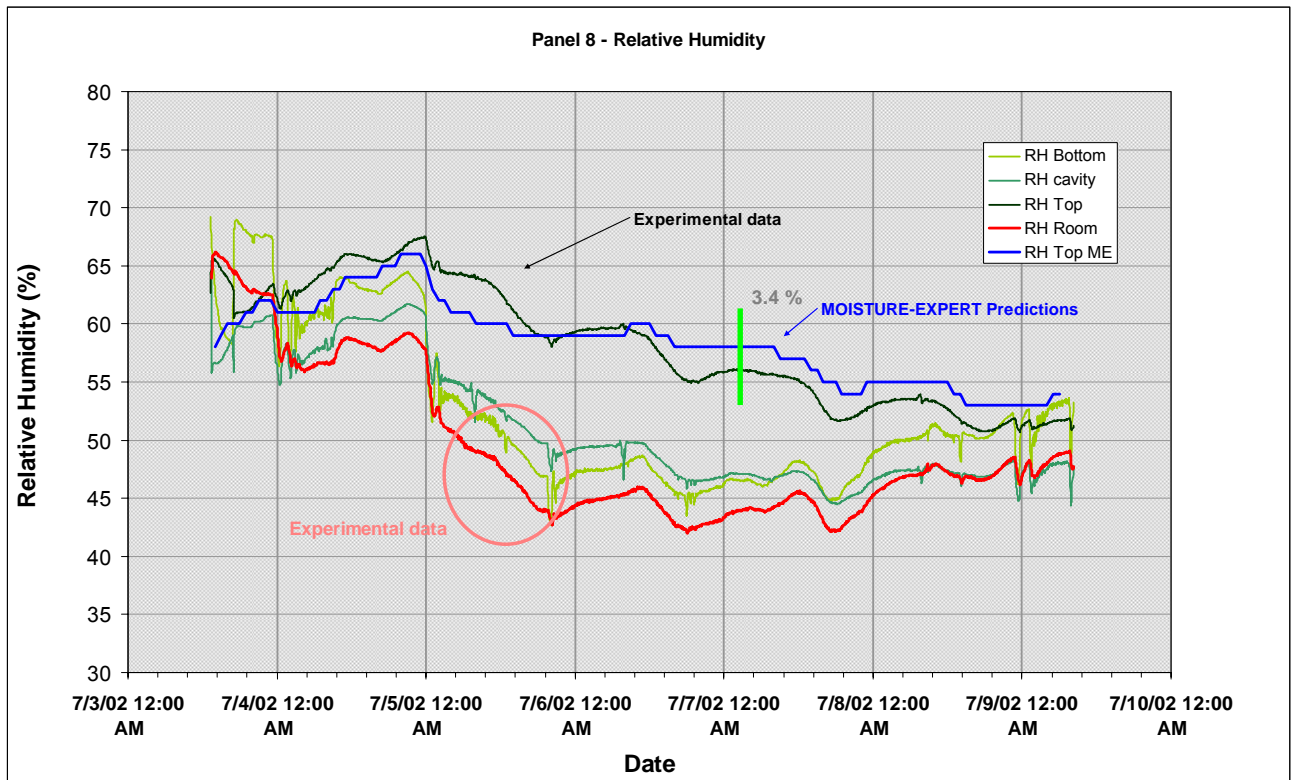


Figure 39: Comparison between model simulation results and experimental Data (1.6 Lps)

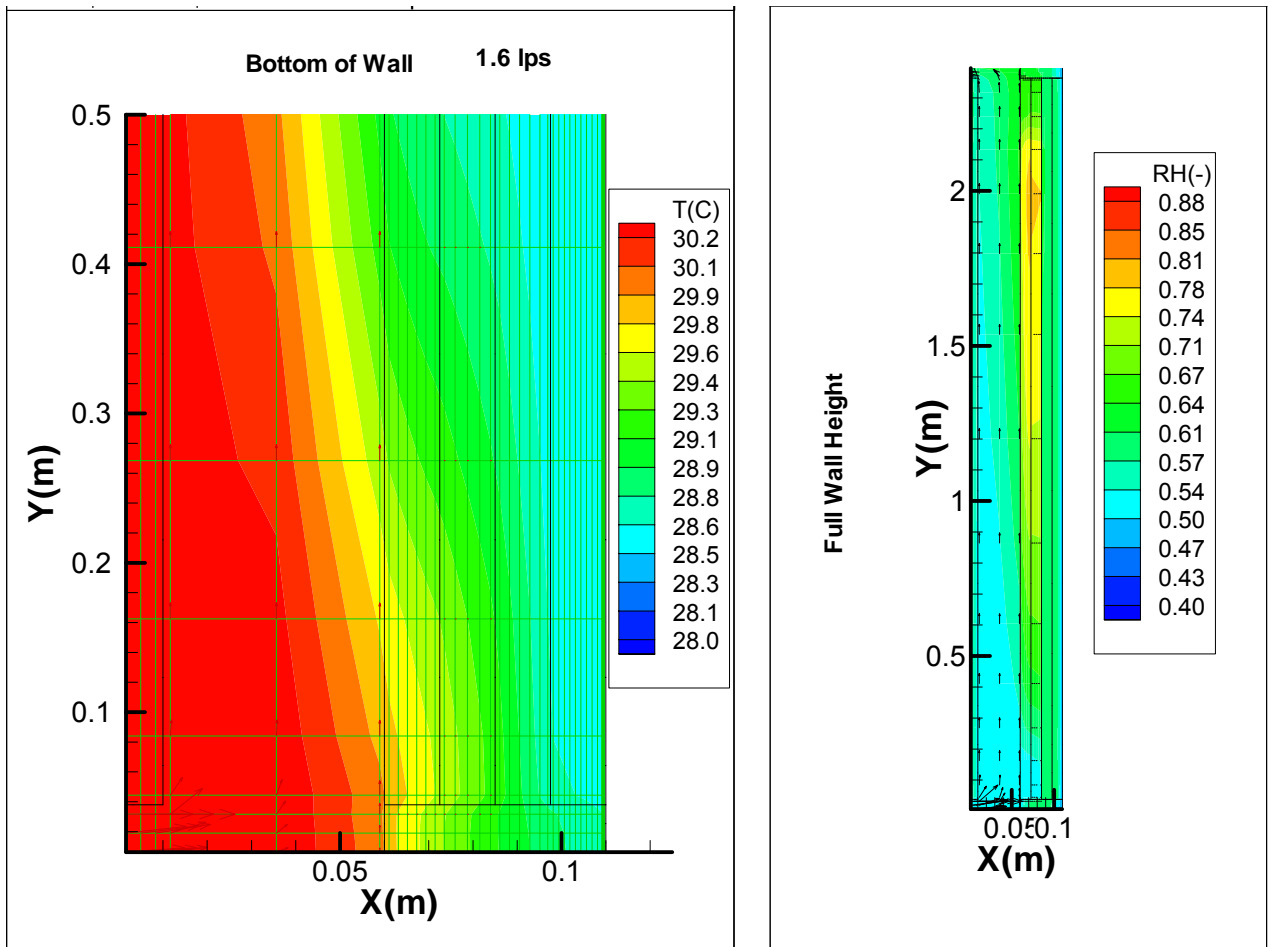


Figure 40: Spatial Temperature and RH Distribution at 1.6 Lps at time=5 days hr

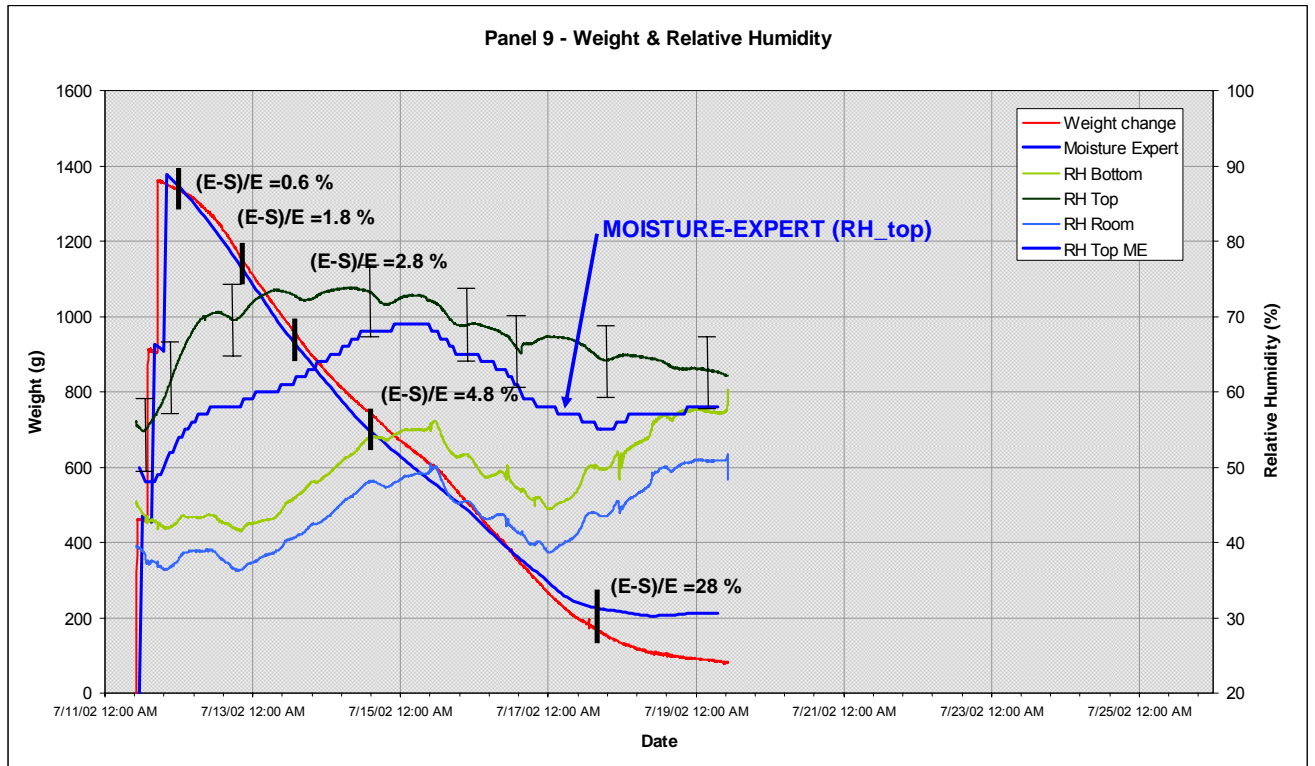


Figure 41: Comparison between model simulation results and experimental Data (0.8 Lps)

### **Laboratory Experimental Validation Summary:**

Three benchmark experimental cases were compared to model predictions and very good agreement was found. All the wetting and drying trends were correctly predicted in the simulations. The criticality of using measured material properties rather than generic data was also demonstrated. The model has been validated for the benchmark cases as the weight loss due to ventilation drying was accurately predicted.

As boundary conditions were allowed to float, representing possible fluctuations present in real interior loads, the MOISTURE-EXPERT model demonstrated its robustness to capture all critical elements of the benchmark test. These were:

- a) The moisture storage because of the water injection (and time history)
- b) The redistribution of water in the Homasote
- c) The moisture transport (vapor and liquid)
- d) The convective drying as a function of air flow

Results from this benchmark test demonstrates the capability of the hygrothermal model to capture these phenomena very well, providing the WSU-ORNL team with a high level of confidence to proceed to the next two validation tests and subsequent design guideline generation activities required by the research project.

The objective of any numerical modeling is obviously to represent reality, but this is difficult because we cannot easily model the physical enclosure (each crack, twist, and imperfection). Our knowledge of needed material properties is incomplete and the properties are variable, and our ability to model the hygrothermal mechanics is somewhat limited. Circumstance, money, and time oblige us to do the following:

- be as complex and comprehensive as possible when accuracy is required
- be as complex and comprehensive as needed when relative accuracy is sufficient.

We believe that the benchmark results presented in this report clearly show that we have met the objectives as stated in the original proposal.

## **Field Data Analysis**

In Table 7 the first year wall matrix is laid out. It is the intention of this section of the report to discuss the hygrothermal analysis performed for the first year data. For the second and third year wall matrix, the hygrothermal model MOISTURE-EXPERT was used to further validate the measured results and extend the fundamental understanding of the transient heat and moisture transport.

### **Limitations of the experimental work**

In the field investigation a number of sensors were employed. The accuracy of these sensors depended on the type of measurement performed. Higher resolution capacitance sensors could have been employed to measure the relative humidity to less than  $\pm 3\%$  at the higher end of the relative humidity scale. The Sereda and gypsum sensors were only used to recognize incidents of wind driven rain and thus did not provide quantitative values as needed in the validation activities of the model. More discussion on the locations of these sensors are presented in the final report by Tishy and Murray (2006).

For all the moisture content measurements, moisture pins were employed. The moisture pins sensors are not particularly accurate sensors as they depend on a number of critical parameters:

- 1) They provide volumetric average values
- 2) The accuracy is dependent on the localized density. In many wooden materials, density variations are very large (OSB, Plywood) rendering the results very inaccurate
- 3) The water gradients can short-circuit the reading
- 4) An angular dependency of the probe exists
- 5) Polarity effects that can degrade accuracy of the pin measurement
- 6) The single ended measurements provide an additional challenge to the accuracy as even small ground fluctuations can have sporadic results that require extensive filtering of the raw data
- 7) Calibration curves for the measurements did not exist
- 8) Drifting of the sensor (same can occur with the RH sensor)

As the measurement accuracy degrades substantially at both low moisture contents (below 10%) and high moisture contents (above 20 %), the uncertainty in the in-between region has been documented in the past as higher than  $\pm 4$  % moisture content. The moisture pin is essentially a sensor that is not that accurate. However, no other sensors exists that can measure moisture contents in a cost effective fashion. Gravimetric analysis would have been the only feasible approach, but that was not implemented due to the lack of WSU students (as initially envisioned) in this project.

Another deficiency for the validation activity was the uncertainty of the wind direction in the 1<sup>st</sup> year results. The wind directions uncorrected show wrong wind-driven rain loads. Indeed, as rain gauges were not installed until after the 1<sup>st</sup> year, the only way one can interpret the results is by using a comparative analysis of the resulting performances of the walls systems.

An important issue that is often not discussed in field data analysis is that the exterior wall loading is significantly different at the ends of the test facility and those at the middle of the test facility. In the modeling analysis, one can adjust these loads but this not possible with field measurements

### **Limitations of the interior environment**

In Figure 42 the interior temperature and relative humidity is plotted out for the two sections of the Puyallup test facility. The plots show averaged monthly results. Even though these results were averaged, important differences were found. Up to 1.5 °C (2.7 F) and 7% relative humidity averaged monthly differences were found between the two rooms. These differences make the wall comparisons between the two rooms difficult especially in those walls that had a small vapor resistance at the interior gypsum sheathing.

### **Analysis of the results**

In Figures 43 to 54, the first year results are processed and are depicted in terms of the average monthly moisture content. All six sensors are plotted out. The results clearly show that all walls perform satisfactory with the exception of Wall 7. Wall 7 did not have a vapor retarder and the only interior vapor resistance of the wall was provided by the gypsum. Upon the completion of the water vapor permeance testing at ORNL, it was

discovered that the paint did not provide the 1-perm rating as presumed by the Polyvinyl acetate primer and latex paint. Indeed it provided a larger much vapor permeance at the high relative humidity region by a factor of 100. In walls 5, and 6 the plywood sheathing showed higher levels of moisture in the sheathing board, which could be attributed to the correction factors due to the wood species or adjusted temperature correction.

In Figures 55 to 60, the averaged monthly relative humidity is displayed for walls 1 to 12. The first obvious results is that for the unvented cladding, different amounts of wind-driven rain exist for each wall. This is evident when examining Figures 55 and 56, where the sensor has been imbedded into the stucco layer. The relative humidity sensor indicates the level of water present due to exterior surface condensation and wind-driven rain. In sensor location 3 (at the interface between the fiberglass insulation and sheathing board), high levels were found in Wall 2 (Unvented, Membrain vapor retarder) and Wall 7 (no vapor retarder). Wall 2 only exhibits high levels of relative humidity during the fall and winter periods, and very dry conditions during the summer period. At location 4, Figure 58, the driest walls were: Wall 8, Wall 4, Wall 2 and Wall 7. Wall 8 and Wall 2 were installed with the climatically tuned MemBrain vapor retarder while Wall 4 was ventilated and Wall8 had additional sheathing insulation.

Figures 61 to 64 show the average monthly relative humidity of at the four locations from October 2003 till September 2004. As our sensing accuracy is higher using the RH sensors, results show the importance of ventilation and interior vapor resistance. Figures 3 and 4 are of particular importance as they provide information on the hygric performance of in the insulation cavity. It is evident that at the interface between the fiberglass insulation and the exterior sheathing board, more than 7 out of 12 walls had average monthly relative humidities exceeding 80% for more than 3 months. Inward vapor pressure drives can be seen in Figure 64, where during the summer months 3 out of the 12 walls show average relative humidities exceeding 80% for a period of 3 months.

**Table 7: Test wall matrix 2003-2004 (Test Cycle 1)**

**WSU Natural Exposure Test Facility**

Wall	Window	Ext Finish	Siding	Ext. Venting	WRB	Sheathing	Ext Insulation	Cavity Insulation	Frame	Vapor Retarder	Int Board	Int Paint	lo
w1		Cement	Stucco 7/8"	Unvented	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	
w2		Cement	Stucco 7/8"	Unvented	2x 60 min	OSB		R-21	2X6	MemBrain	Drywall	Latex	
w3		Cement	Stucco 7/8"	Vented	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	
w4		Cement	Stucco 7/8"	Ventilated	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	
w5		Cement	Stucco 7/8"	Unvented	2x 60 min	Plywood		R-11	2X4	Kraft	Drywall	Oil	
w6		Cement	Stucco 7/8"	Unvented	2x 60 min	Plywood		R-21	2X6	Poly	Drywall	Latex	
w7		Cement	Stucco 7/8"	Unvented	2x 60 min	OSB		R-21	2X6	None	Drywall	Latex	
W8		Cement	Stucco 7/8"	Unvented	2x 60 min	OSB	Foam - 1"	R-13	2X4	MemBrain	Drywall	Latex	
W9		Latex	lap	Unvented	2x 60 min	Plywood		R-21	2X6	Poly	Drywall	Latex	
w10		Latex	lap	Vented	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	
w11		Latex	lap	Ventilated	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	
w12		Latex	lap	Unvented	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	

OSB	7/16"	Aspen
Plywood	15/32"	4 Ply Doug Fir
Unvented		Siding direct applied over sheathing and weather resistive barrier
Vented	3/4"	Cavity behind exterior sheathing open at the bottom of the panel only
Ventilated	3/4"	Cavity behind exterior sheathing open at the top and bottom of the panel
WRB		Weather Resistive Barrier
2x 60 min		2 layer 60 minute building paper.
MemBrain <sup>o</sup>		CertainTeed smart vapor retarder
Drywall	1/2"	Standard drywall taped and finished

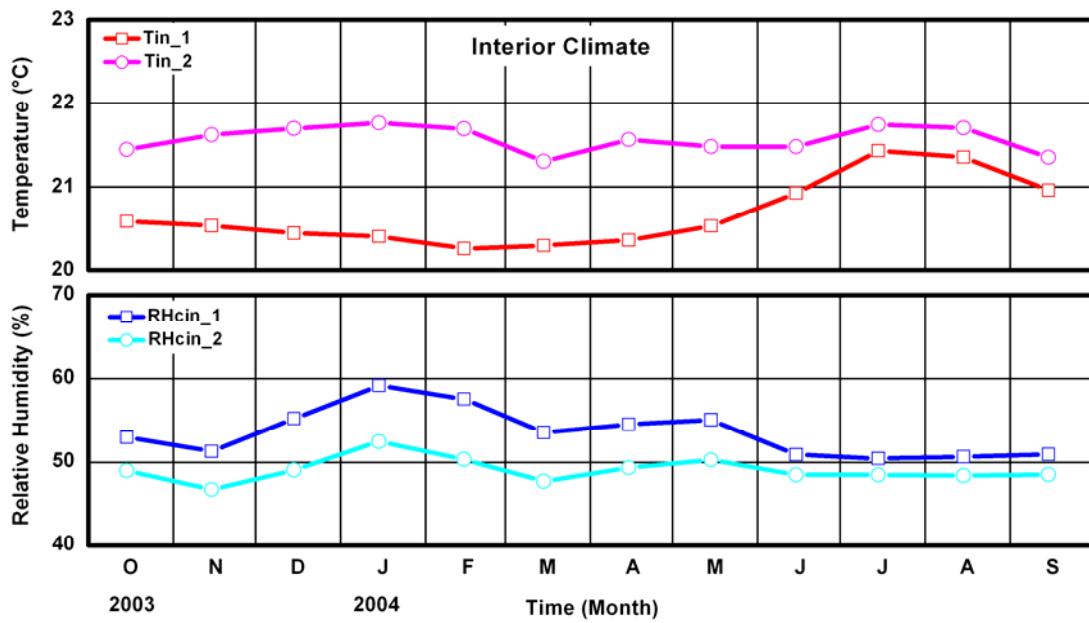


Figure. 42. Monthly Averaged Indoor Temperature and Relative Humidities

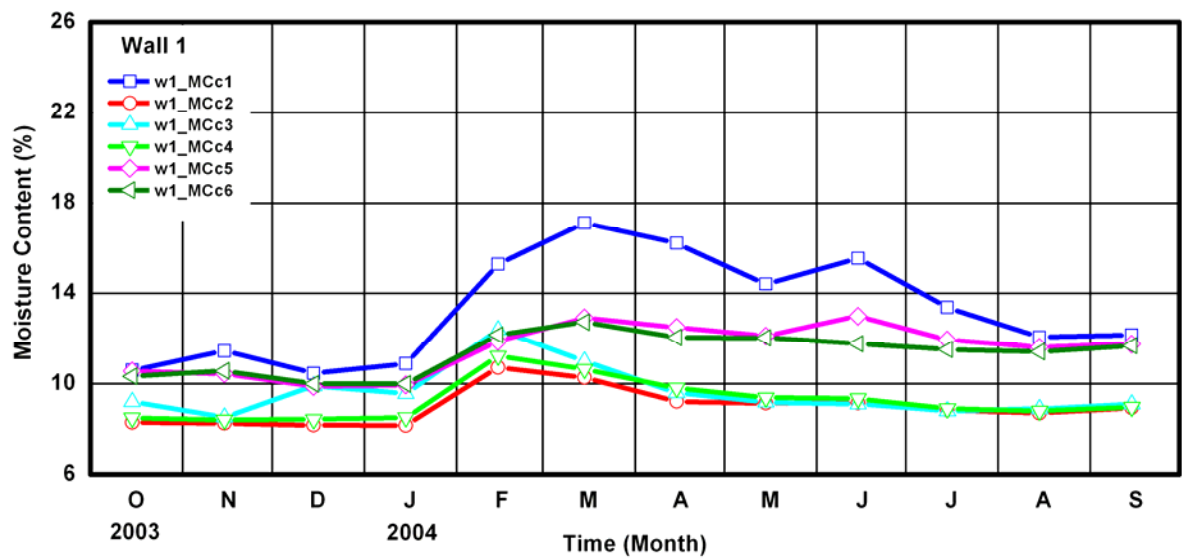


Figure 43: Wall 1: Monthly Averaged Moisture contents as a function of time for Test Cycle 1

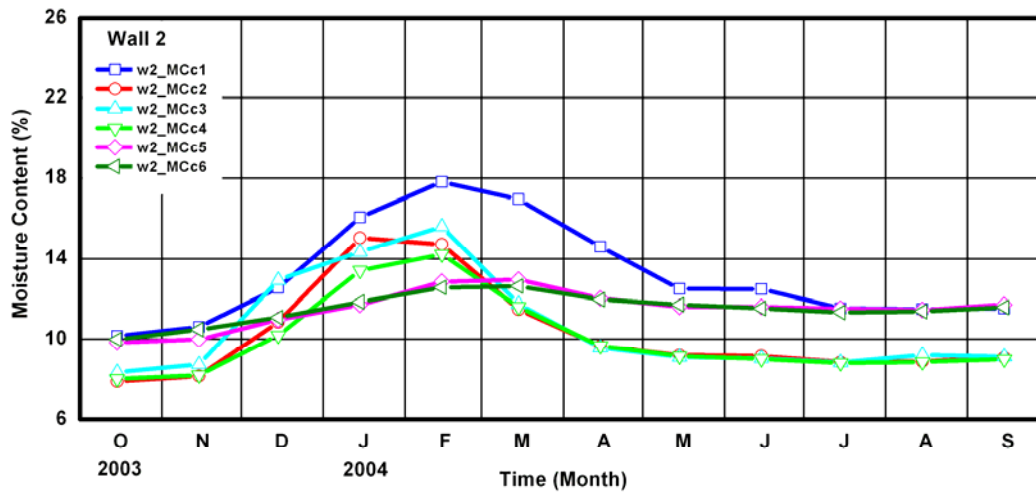


Fig. 44. Wall 2: Monthly Averaged Moisture contents as a function of time for Test Cycle 1

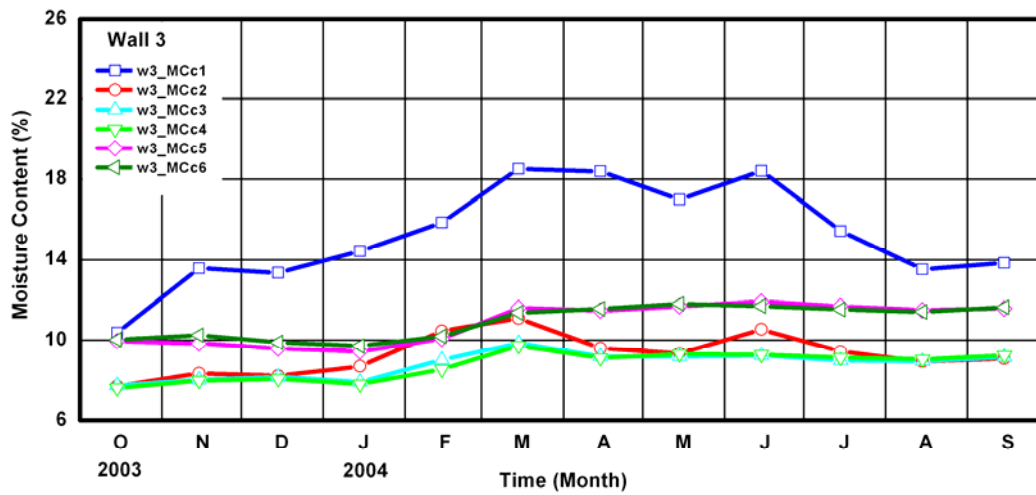


Fig. 45. Wall 3: Monthly Averaged Moisture contents as a function of time for Test Cycle 1

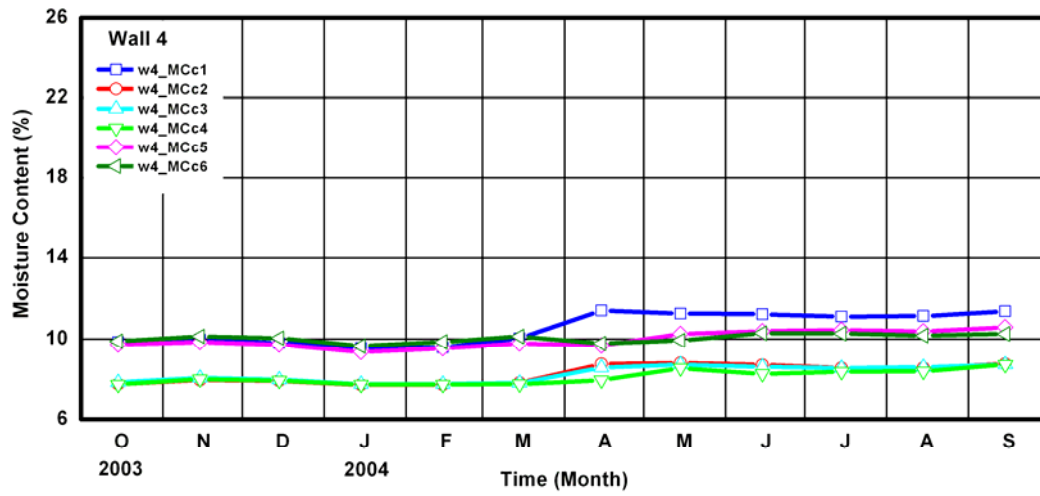


Fig. 46. Wall 4: Monthly Averaged Moisture contents as a function of time for Test Cycle 1

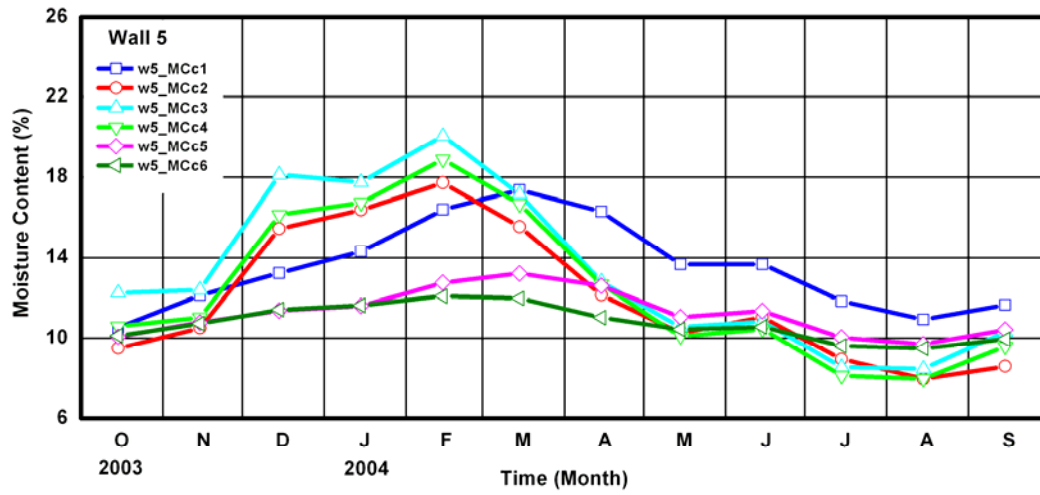


Fig. 47. Wall 5: Monthly Averaged Moisture contents as a function of time for Test Cycle 1

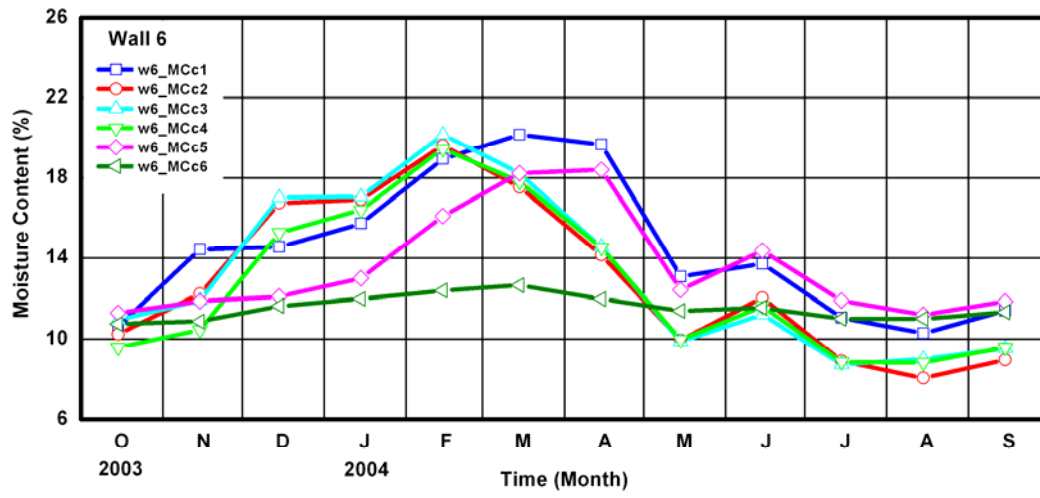


Fig. 48. Wall 6: Monthly Averaged Moisture contents as a function of time for Test Cycle 1

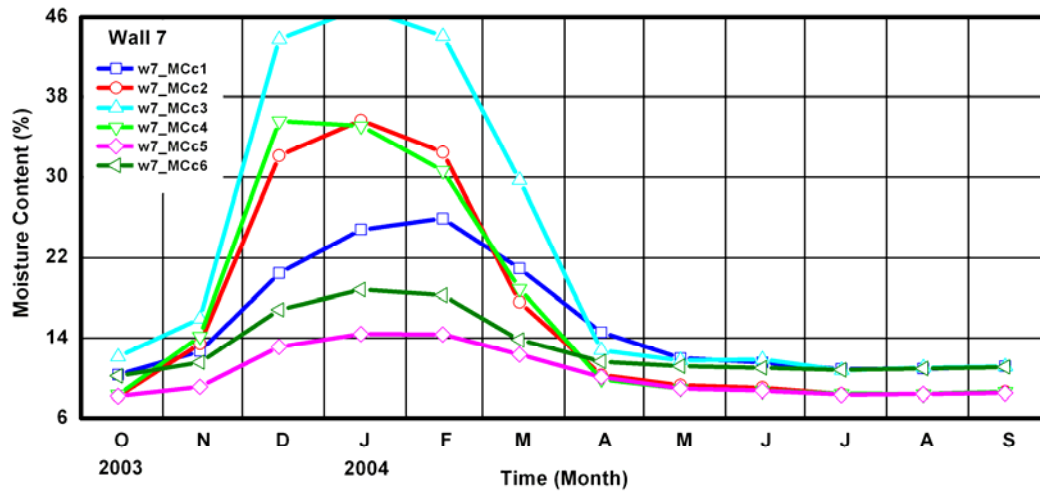


Fig. 49. Wall 7: Monthly Averaged Moisture contents as a function of time for Test Cycle 1

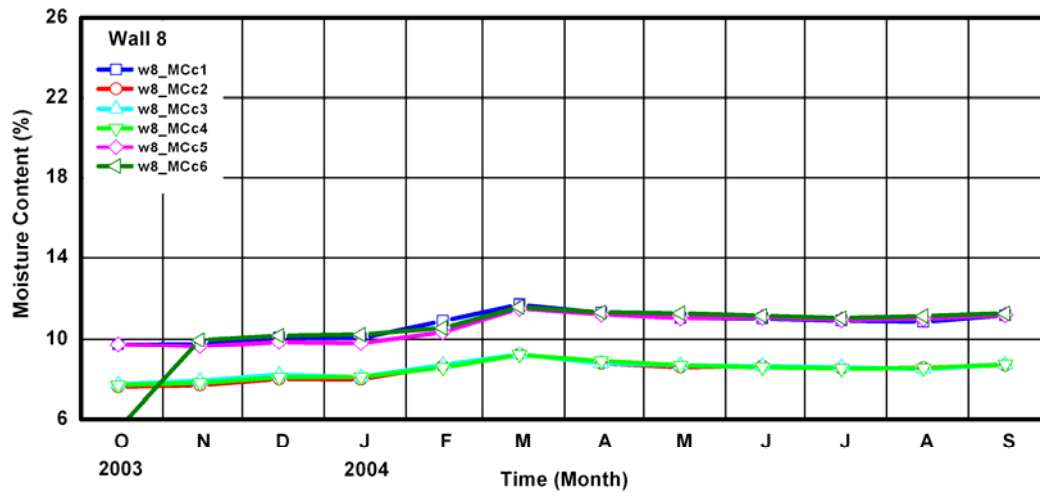


Fig. 50. Wall 8: Monthly Averaged Moisture contents as a function of time for Test Cycle 1

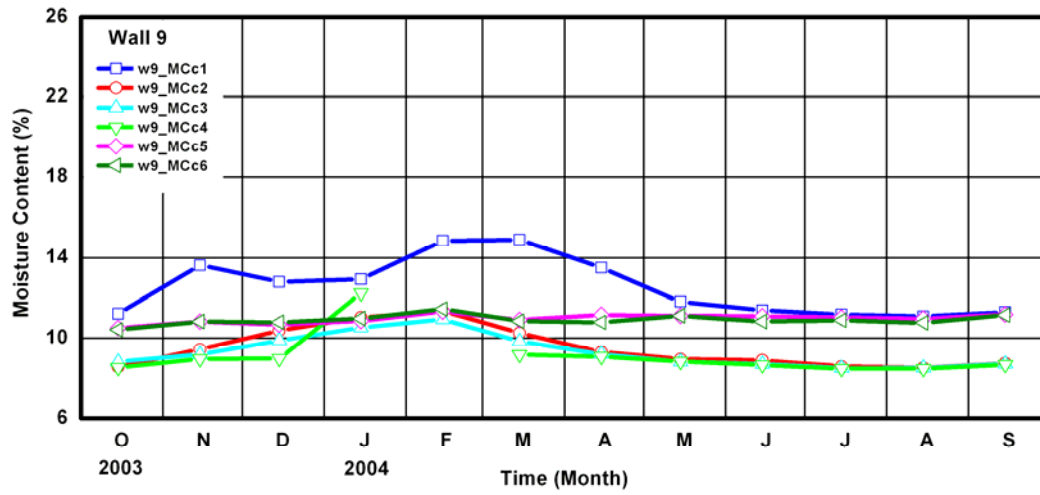


Fig. 51. Wall 9: Monthly Averaged Moisture contents as a function of time for Test Cycle 1

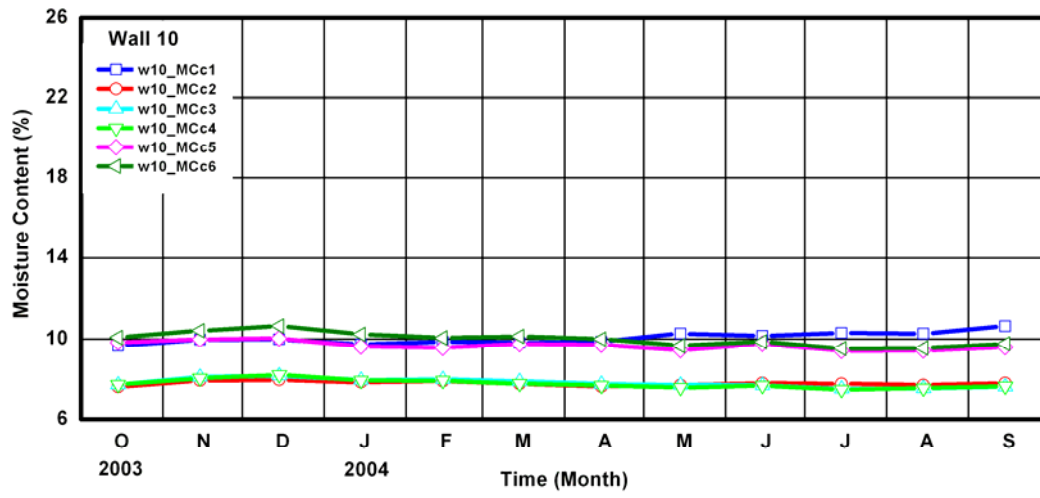


Fig. 52. Wall 10: Monthly Averaged Moisture contents as a function of time for Test Cycle 1

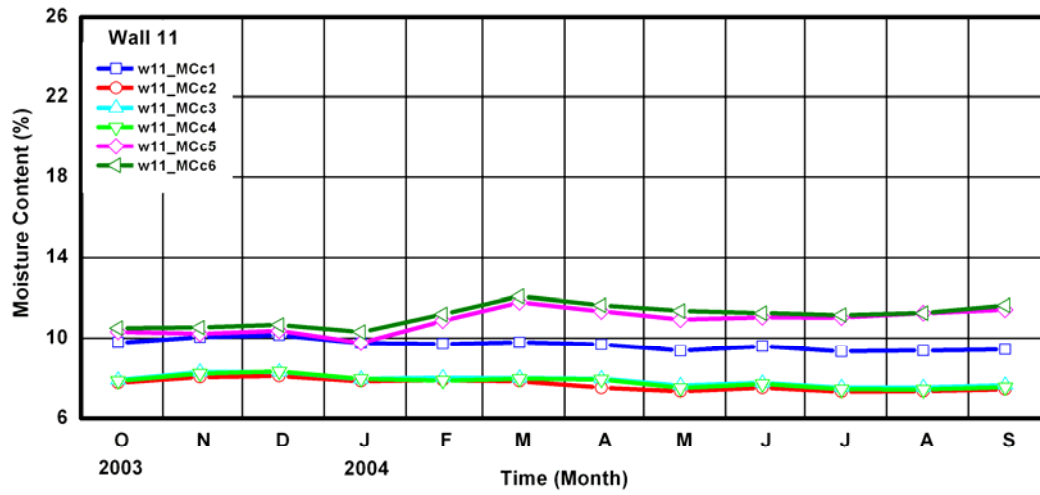


Fig. 53. Wall 11: Monthly Averaged Moisture contents as a function of time for Test Cycle 1

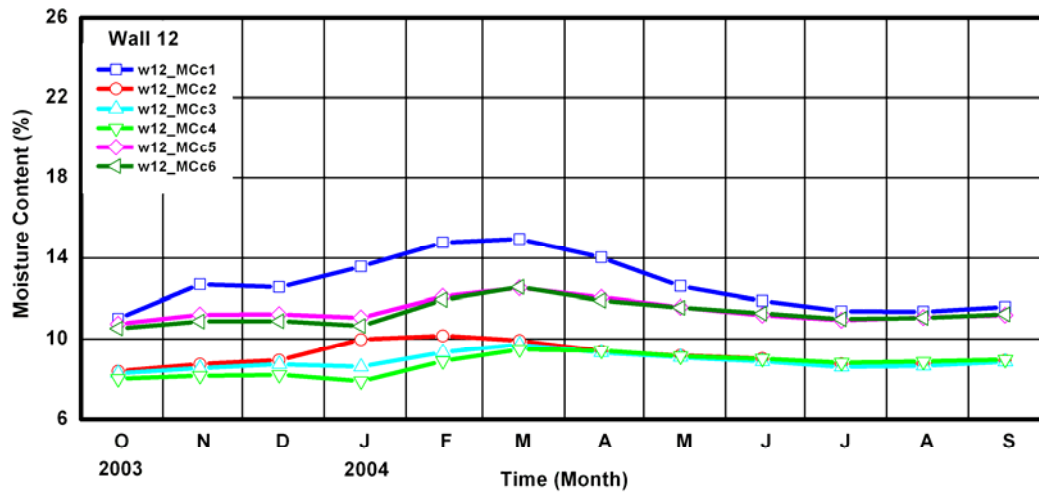


Fig. 54. Wall 12: Monthly Averaged Moisture contents as a function of time for Test Cycle 1

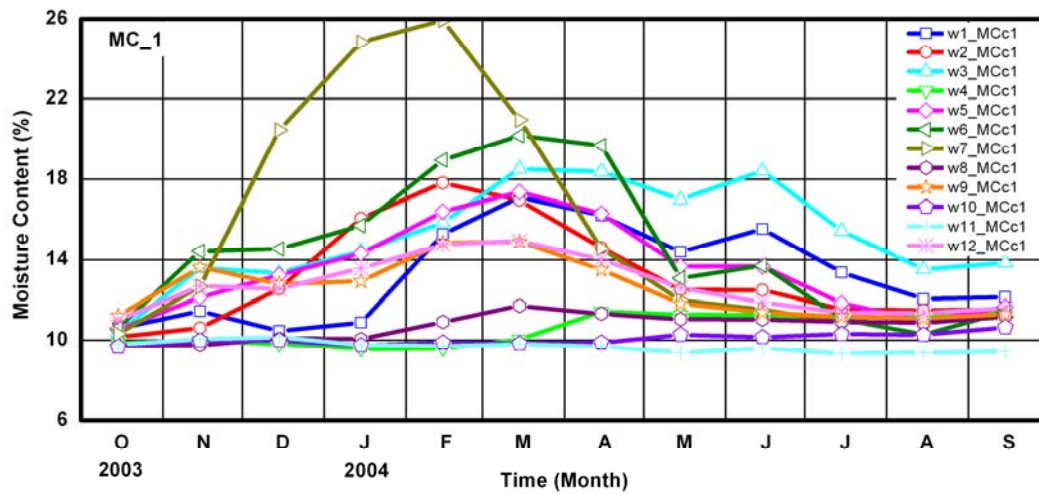


Fig. 55. Moisture Content Sensor 1 for all wall sections

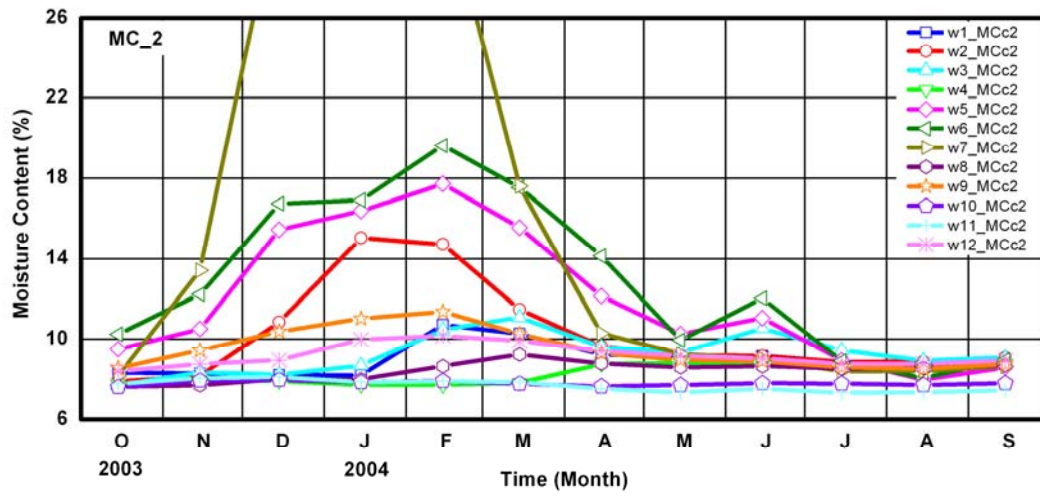


Fig. 56. Moisture Content Sensor 2 for all 12 wall sections

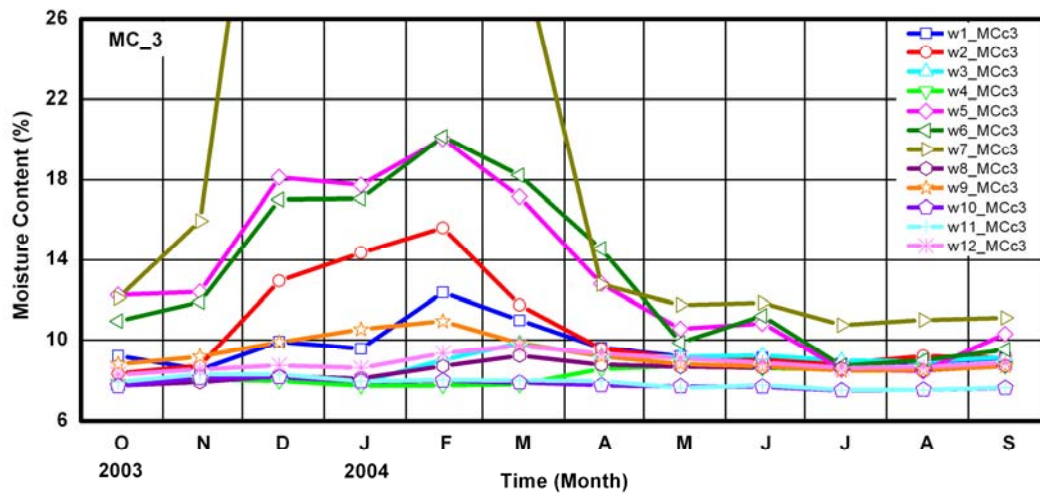


Fig. 57. Moisture Content Sensor 3 for all 12 wall sections

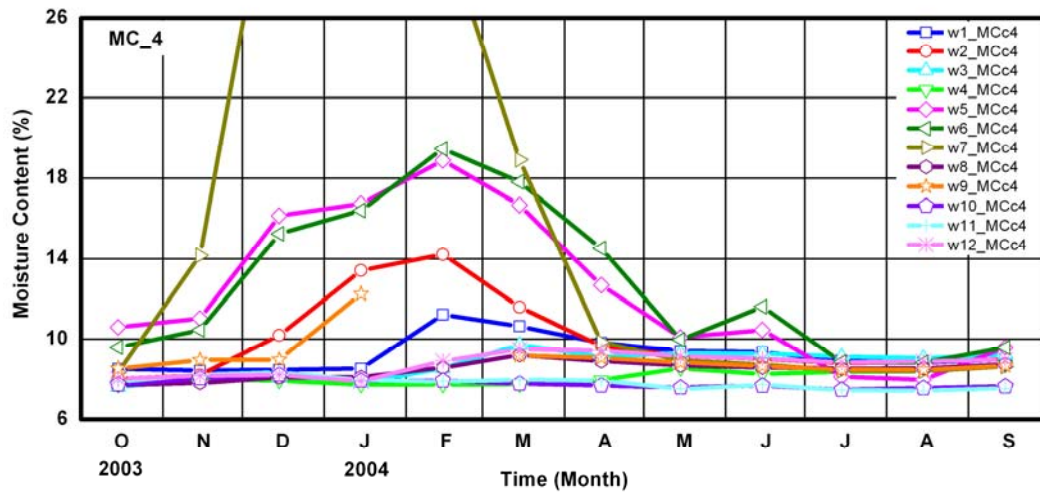


Fig. 58. Moisture Content Sensor 4 for all 12 wall sections

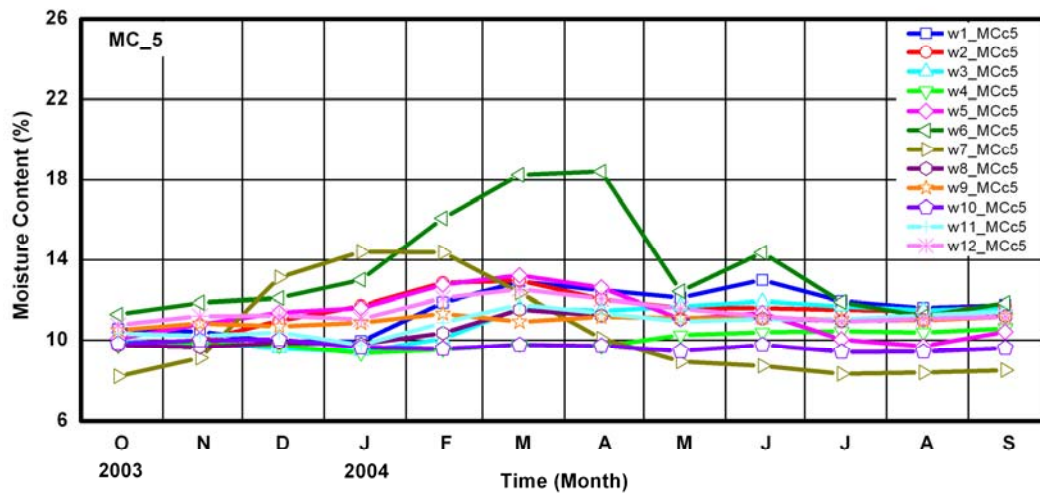


Fig. 59. Moisture Content Sensor 5 for all 12 wall sections

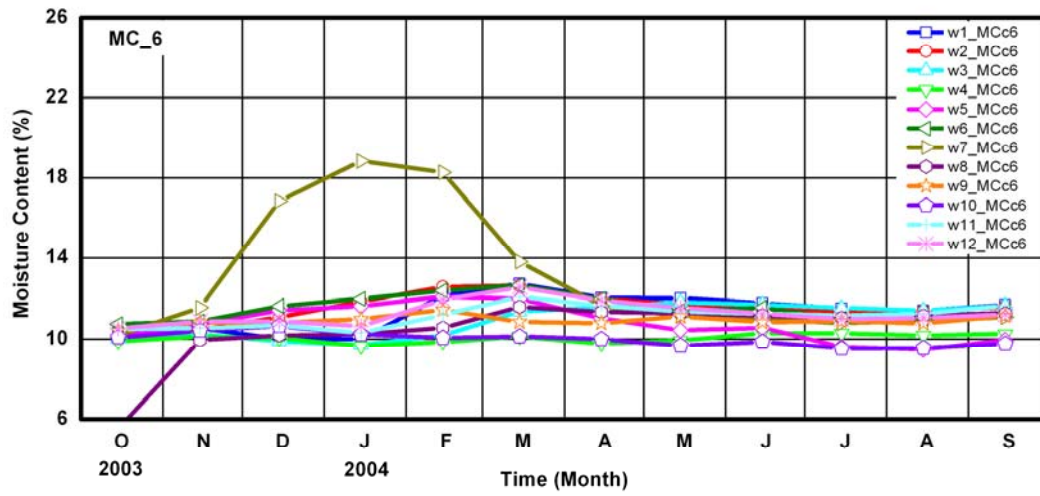


Fig. 60. Moisture Content Sensor 6 for all 12 wall sections

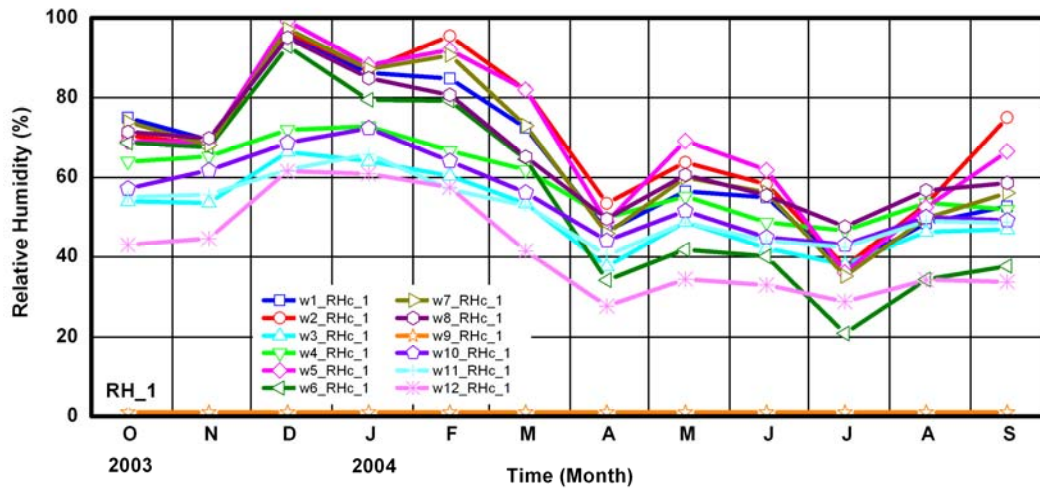


Fig. 61. RH1 in 12 Walls ( Monthly Averaged Relative Humidity as a function of time for Test Cycle 1)

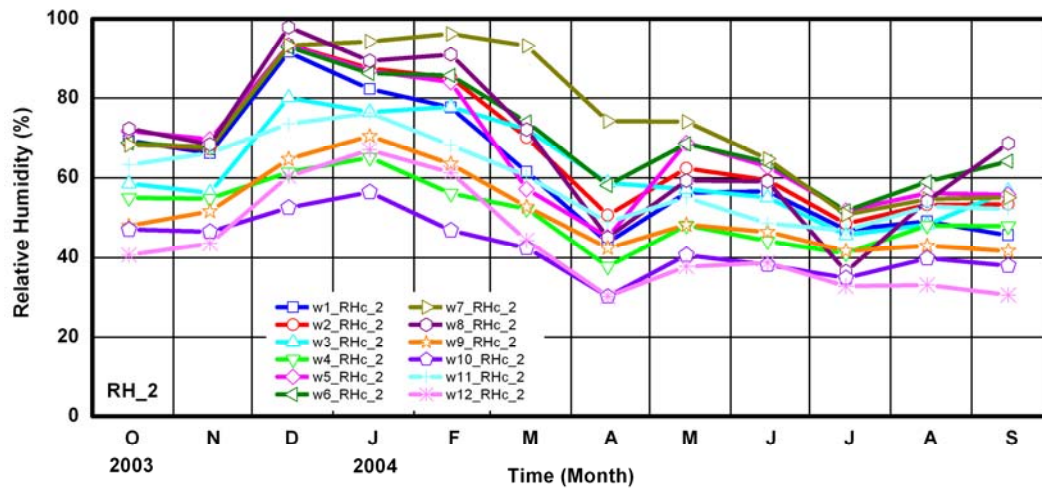


Fig. 62. RH2 in 12 Walls ( Monthly Averaged Relative Humidity as a function of time for Test Cycle 1)

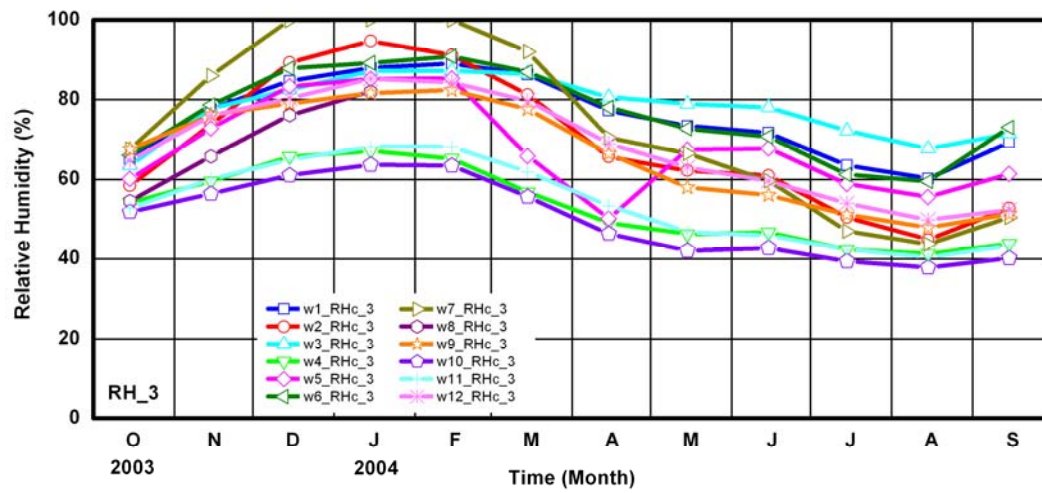


Fig. 63. RH3 in 12 Walls ( Monthly Averaged Relative Humidity as a function of time for Test Cycle 1)

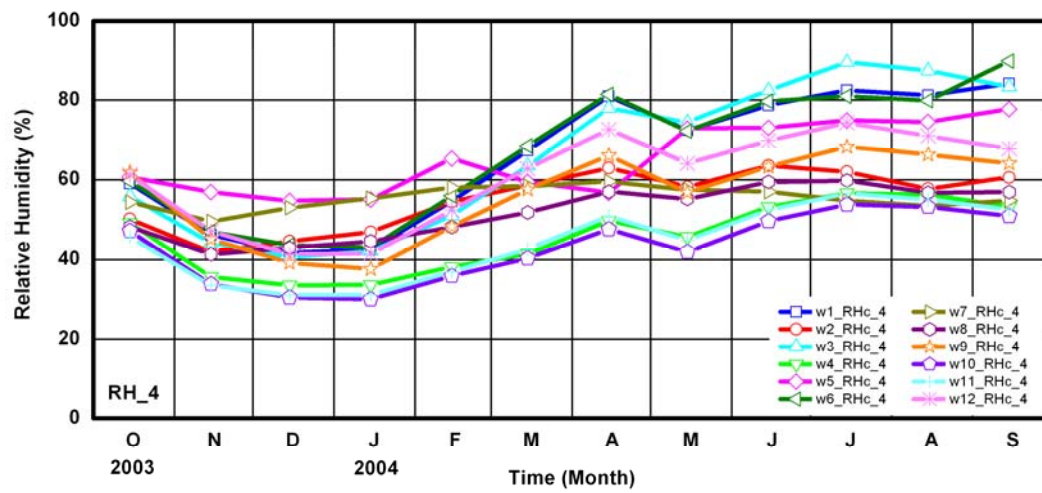


Fig. 64. RH<sub>4</sub> in Walls 12 ( Monthly Averaged Relative Humidity as a function of time for Test Cycle 1)

## Location of the Puyallup Facility

In Figures 65 through 67 depict the specific location of the Puyallup test facility. It is evident that a wetting patterns exhibited elsewhere in the greater vicinity of Tacoma will be remarkably different than those present in Puyallup. Indeed the localized geographic conditions with a number of distinct corridors make the exposure conditions not representative of the area location. For this reason extrapolating data or using specific wind direction data from adjacent weather station would be inappropriate for use at the WSU facility due to the localized wind corridor flows.

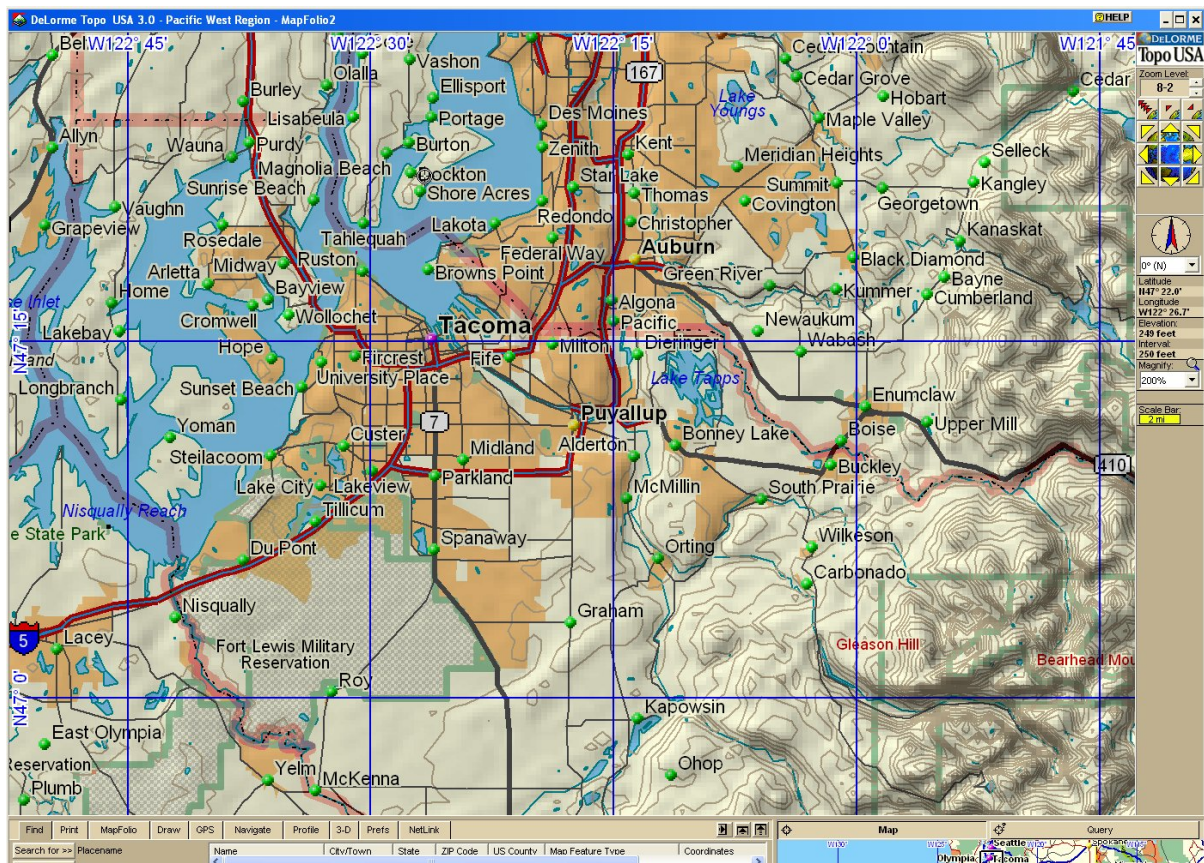


Figure 65: WSU-Puyallup Geographic Location

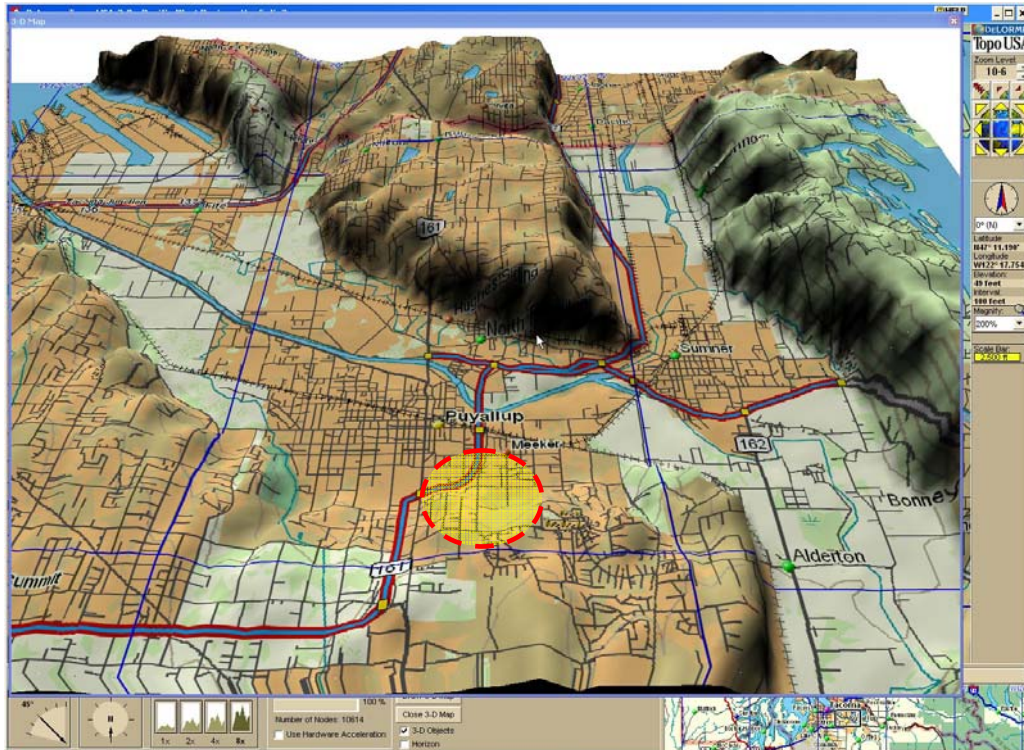


Figure 66: Corridors for Wind Driven Rain Directions

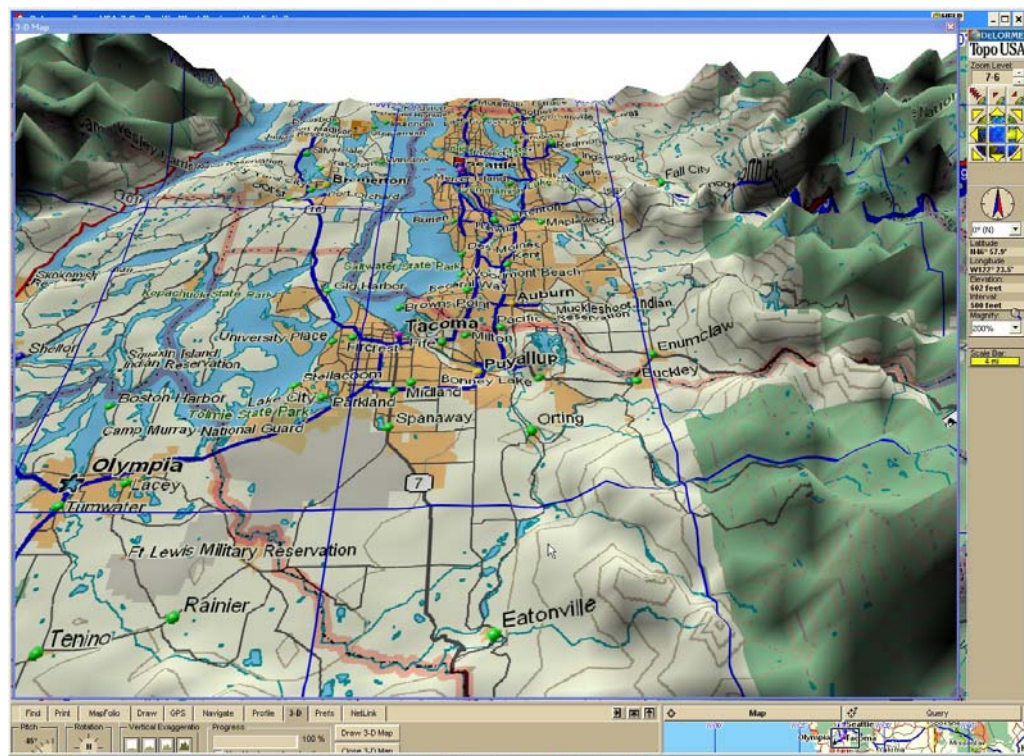


Figure 67: Greater View Region

## **Modeling Analysis for the 2<sup>nd</sup> and 3<sup>rd</sup> Testing Period (MOISTURE-EXPERT)**

### **Description of Approach**

In this part of the report an intensive hygrothermal modeling analysis was performed on the 2<sup>nd</sup> and 3<sup>rd</sup> year results. As explained previously, a full validation analysis could not be performed using the existing experimental data due to the lack of information on the surface rain loads (not measured) verifiable wind speed and directions, hourly air cavity ventilation measurements, wall section air leakage, stucco crack analysis and stucco water penetration characteristics. The missing information is the exterior environmental load based and additional wall system and sub-system characterization.

A smaller scale benchmarking exercise was performed to analyze and provide additional insight on the measured data. Not all the walls were included in this analysis as similarity was present in these. Wherever possible, validation was conducted using localized time periods when events such as rain loads could be quantifiable.

### **Simulation layout**

In the hygrothermal analysis, hourly measured indoor and exterior conditions were employed. The heat and mass transfer coefficients were varied on an hourly basis and were dependent on the exterior and interior environmental conditions. The simulations were performed using one hour time steps. The start conditions (initial conditions) were approximated using the actual field data. The conditions simulated were those from Phase II and Phase III of the field testing experimental plan.

Water penetration was also introduced as per the schedule supplied by Mr. Murray (WSU). Some uncertainty was present in terms of the wetting distribution of the cloth during the water injection, indeed it has been documented that drainage occurred in many of the water penetration periods increasing the uncertainty of the simulations. In the simulations during the water penetration periods, the wetting capacity of the cloth did not include drainage.

During the testing period within Phase II and Phase III any interruptions such the opening of the walls (taking off the gypsum sheathing) and allowing these to dry out were not adjusted in the simulations. Agreement is not expected to occur during and after this period.

## Material Property Analysis

In Figures 68 through 72 the processed material properties that were included in the hygrothermal analysis are shown for the water vapor permeance, thermal conductivity, liquid diffusivity, sorption-suction isotherm. At the time of the simulation, the missing material property still undergoing testing (April 2007) was the suction isotherm for the stucco and cementitious boards. Those properties were approximated from the capillary water content.

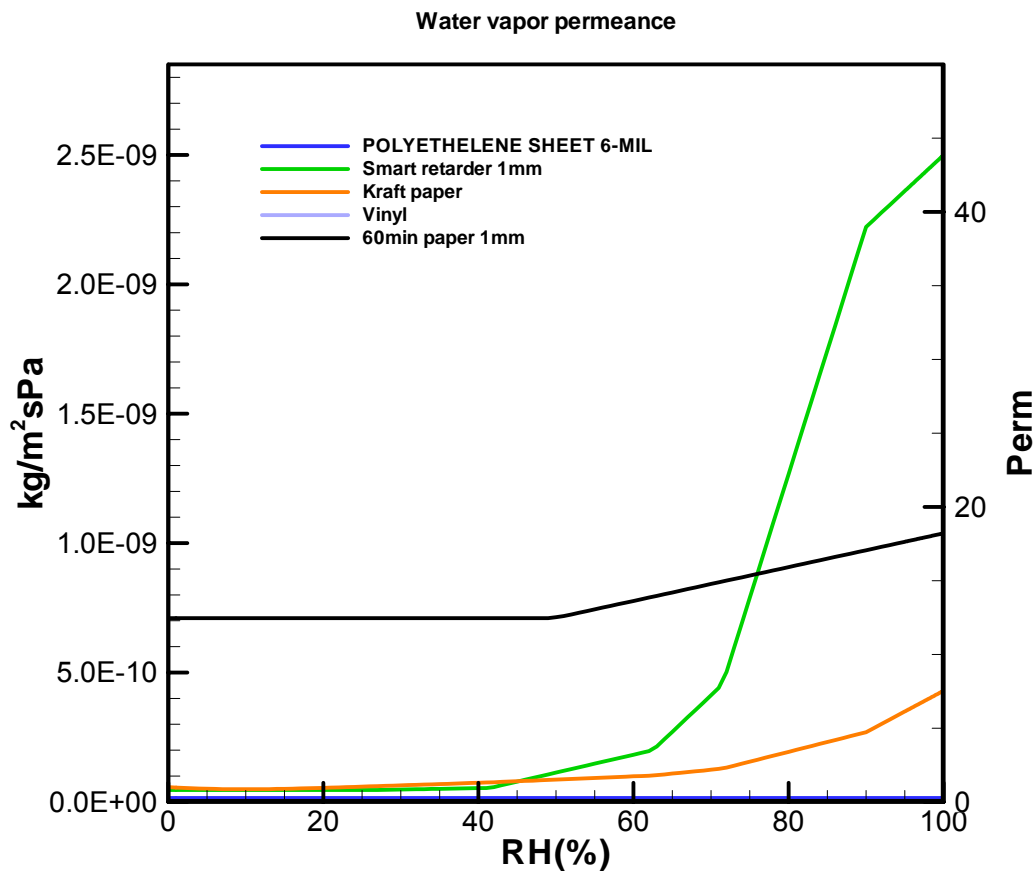


Figure 68: Water vapor permeance of thin material layers used in simulations.

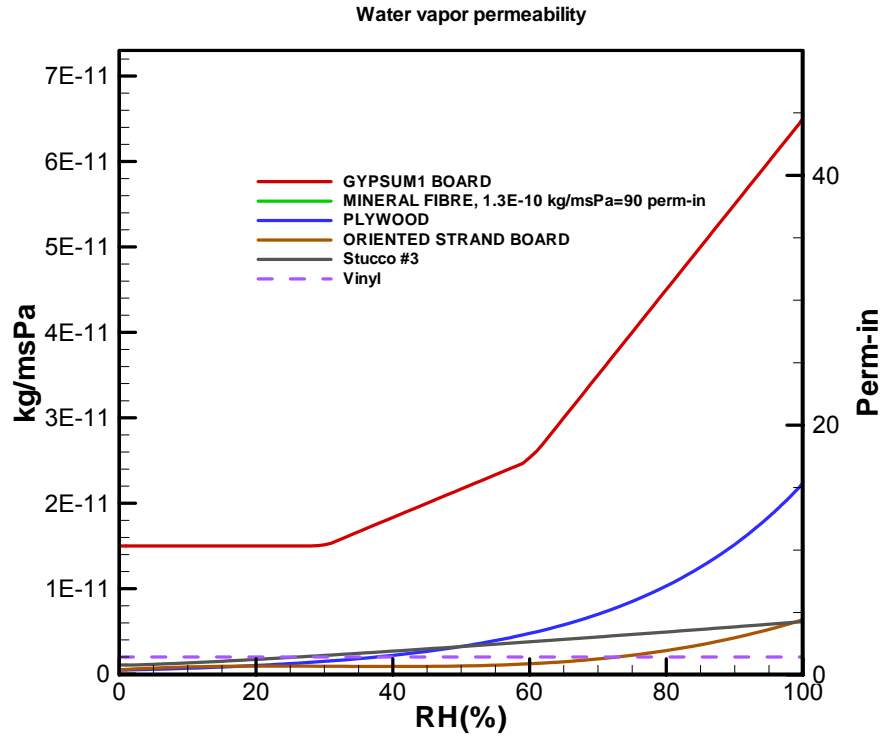


Figure 69: Water vapor permeability of materials used in the simulations.

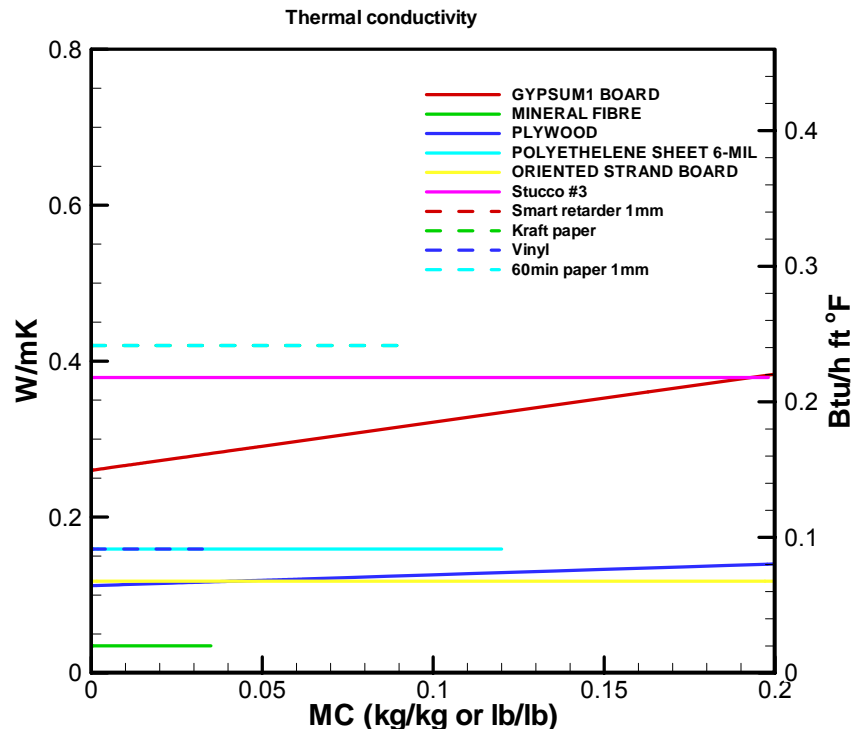


Figure 70: Thermal conductivity of materials used in the simulations.

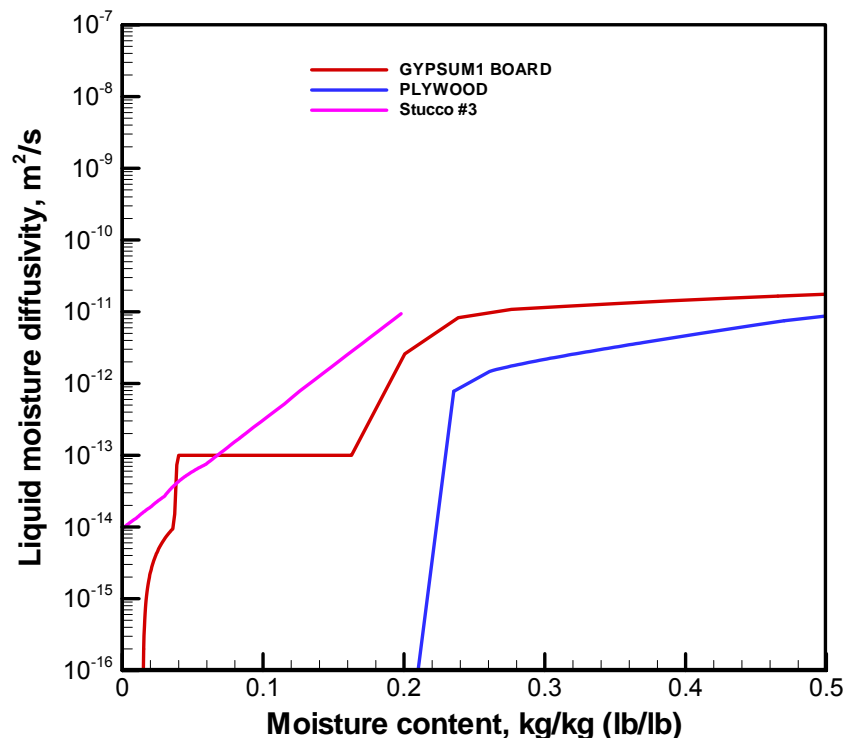


Figure 71: Liquid moisture diffusivity of materials used in the simulations. Liquid diffusivity is not shown for materials that have negligible liquid transport.

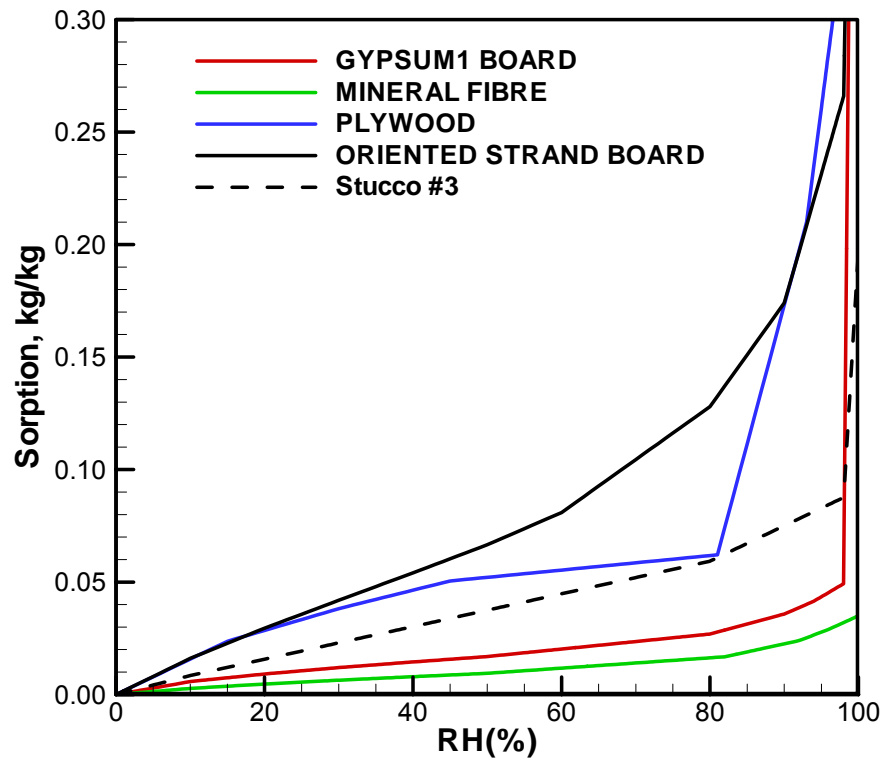


Figure 72: Sorption isotherms of materials used in simulations.

## Wall Systems

In Table 8, the wall matrix for test cycle II and III are shown. The following walls were used for the analysis:

North Facing walls:

- Wall 3
- Wall 4
- Wall 5
- Wall 7

South Facing walls:

- Wall 1
- Wall 2
- Wall 3
- Wall 6
- Wall 7
- Wall 8

In Figures 73 to 82 the measured relative humidity of sensor 3 and 4 is plotted out against model predictions. The raw measured data are shown along with the 168 hourly moving average experimental and modeling results. The agreement was found to range between excellent and good. Agreement between the model predictions and the measurements were found for the cold side of the insulated cavity for the majority of the wall systems facing either north or south. Excellent agreement was found on the warm side of the insulated cavity. In Figures 73 to 82 the comparison is only truly valid for the start time of the simulation around 310 days till 132 days. After this date the walls were opened up, and forensically examined and documented. During this period the interior air of the test facility was intentionally dried down for a few weeks. In the modeling exercise, the simulations were continued without that special condition included. That is why the comparison after day 132 is not appropriate. However, from the trends exhibited, the agreement would be expected to continue.

The results also seem to correctly model each wetting occurrence as the relative humidity modeling results close to the warm side of the insulation showed good agreement with the measurements.

Table 8

Test wall matrix 2004-2006 (Test Cycle 2 and 3)													
WSU Natural Exposure Test Facility													
Wall	Window	Ext Finish	Siding	Ext. Venting	WRB	Sheathing	Ext Insulation	Cavity Insulation	Frame	Vapor Retarder	Int Board	Int Paint	Cycle 1 Name
S1		Cement	Stucco 7/8"		2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	w1
S2		Cement	Stucco 7/8"		2x 60 min	OSB		R-21	2X6	MemBrain	Drywall	Latex	w2
S3		Cement	Stucco 7/8"	Vented	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	w3
S4		Cement	Stucco 7/8"	Ventilated	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	w4
S5		Cement	Stucco 7/8"		2x 60 min	Plywood		R-11	2X4	Kraft	Drywall	Oil	w5
S6		Cement	Stucco 7/8"		2x 60 min	Plywood		R-21	2X6	Poly	Drywall	Latex	w6
S7		Cement	Stucco 7/8"		2x 60 min	OSB		R-21	2X6	None	Drywall	Latex	w7
S8		Cement	Vinyl		1x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	
S9	mech.fla	Cement	Stucco 7/8"		2x 60 min	Plywood		R-21	2X6	Poly	Drywall	Latex	
S10	peal+stick	Cement	Stucco 7/8"		2x 60 min	Plywood		R-21	2X6	Poly	Drywall	Latex	
S11			Stucco 7/8"		1x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	
S12		Latex	lap		2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	
N3		Latex	lap	Ventilated	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	w11
N4		Cement	Stucco 7/8"	Ventilated	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	
N5		Cement	Stucco 7/8"		2x 60 min	OSB	Foam - 1"	R-13	2X4	MemBrain	Drywall	Latex	w8
N6		Cement	Stucco 7/8"		2x 60 min	OSB	Foam+drain	R-13	2X4	MemBrain	Drywall	Latex	
N7		Cement	Stucco 7/8"		2x 60 min	OSB		R-21	2X6	None	Drywall	Latex	
N8		Dryvit	Dryvit		Liquid	Plywood	4" EPS	none	2X4	None	Drywall	Latex	
	OSB	7/16"	Aspen										
	Plywood	15/32"	4 Ply Doug										
	Unvented		Fir										
			Siding direct applied over sheathing and weather resistive barrier.										

Vented	3/4"	Cavity behind exterior sheathing open at the bottom of the panel only
Ventilated	3/4"	Cavity behind exterior sheathing open at the top and bottom of the panel
WRB		Weather Resistive Barrier
2x 60 min		2 layer 60 minute building paper.
MemBrain®		CertainTeed smart vapor retarder
Drywall	1/2"	Standard drywall taped and finished
Foam	1"	Extruded Poly Styrene R-5
Mech. Fla		Vinyl window with mechanically attached flashing system
Peel+ stick		Vinyl window with peel and stick flashing system

## Simulation results for the north facing walls in Seattle, WA

Walls were measured for approximately one year starting in the autumn of 2004. During the testing periods, walls were opened (once), water injected into the cavities and some walls were rebuilt to change the construction. The simulations were not continuous through the whole three year period but instead focused on certain year long periods.

### Year 2

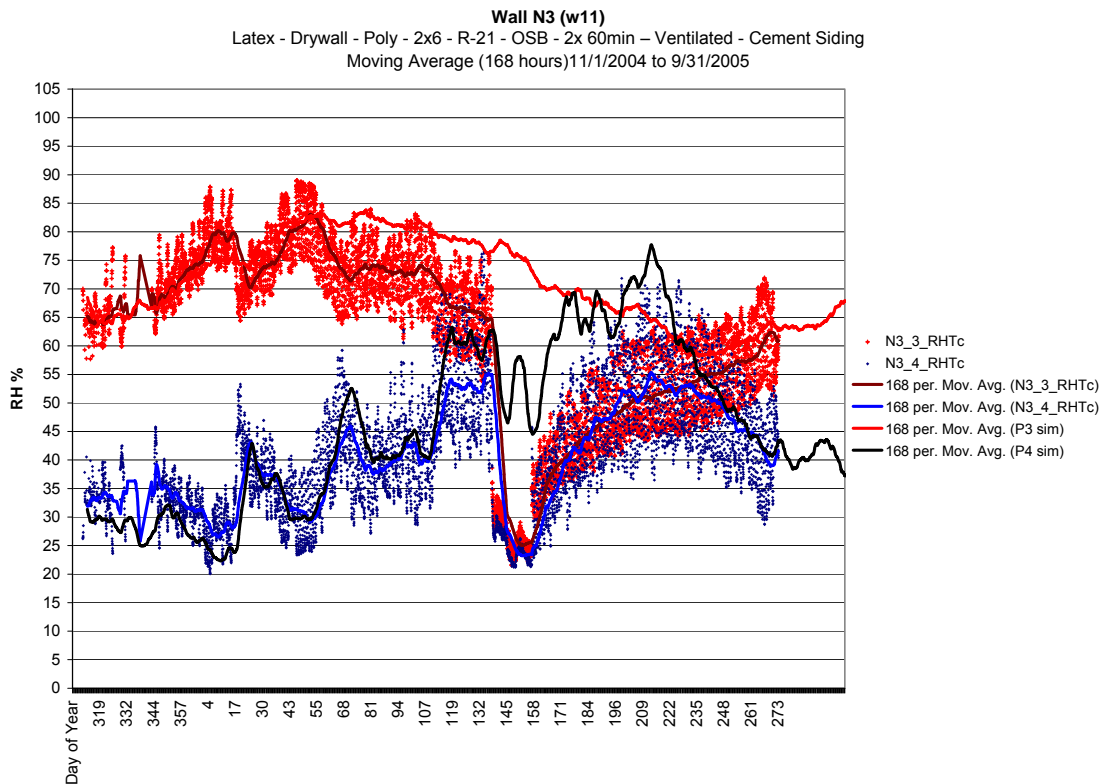


Figure: 73 Relative humidity on cold and warm side of the insulated cavity for wall 3 facing north during November 2004-2005.

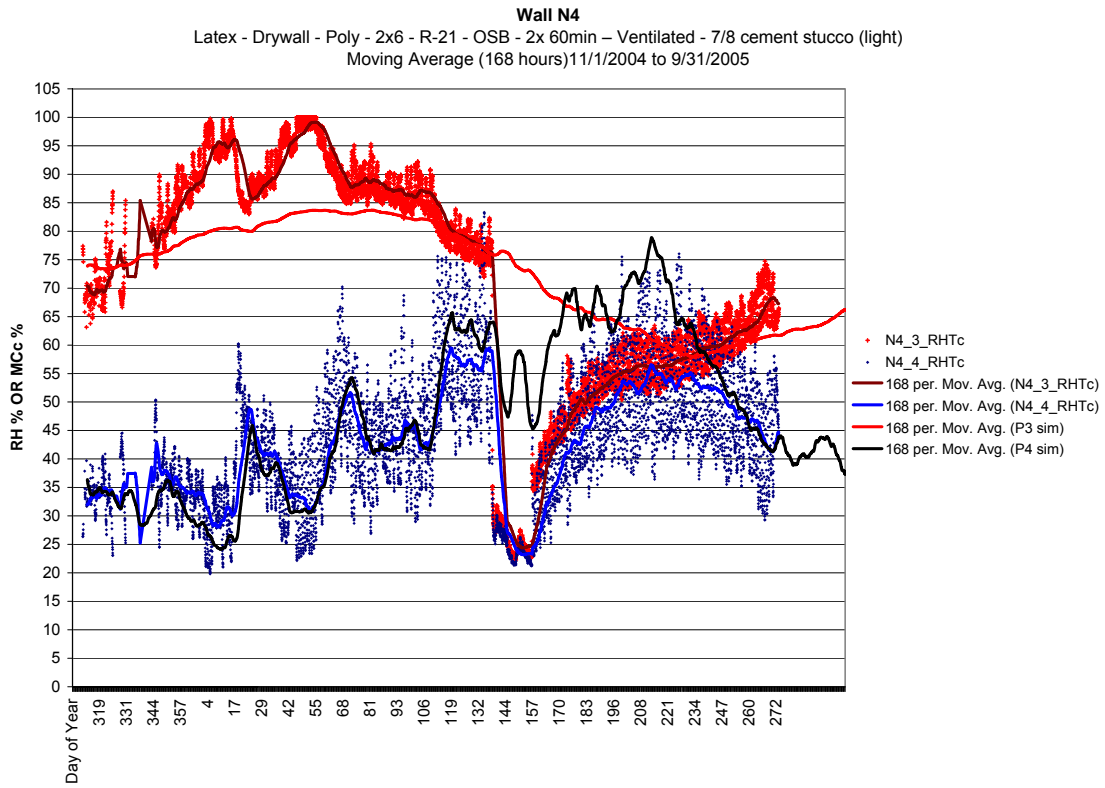


Figure 74: Relative humidity on cold and warm side of the insulated cavity for wall 4 facing north during November 2004-2005.

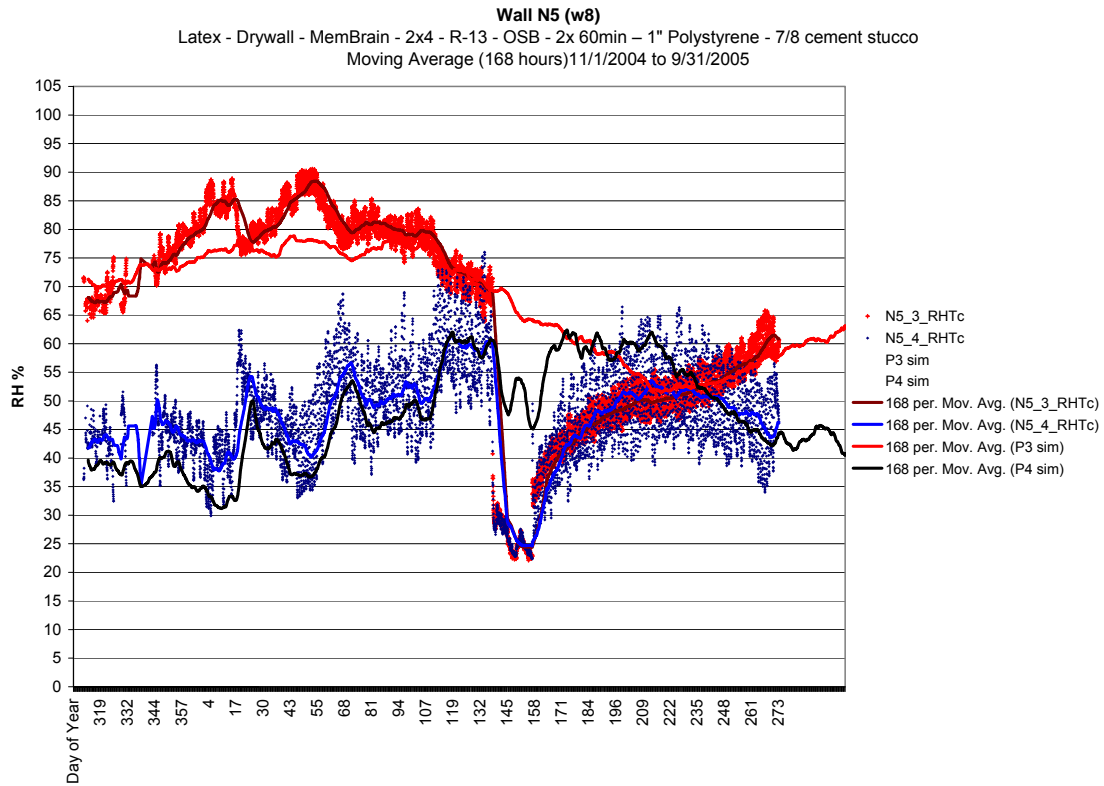


Figure 75: Relative humidity on cold and warm side of the insulated cavity for wall 5 facing north during November 2004-2005.

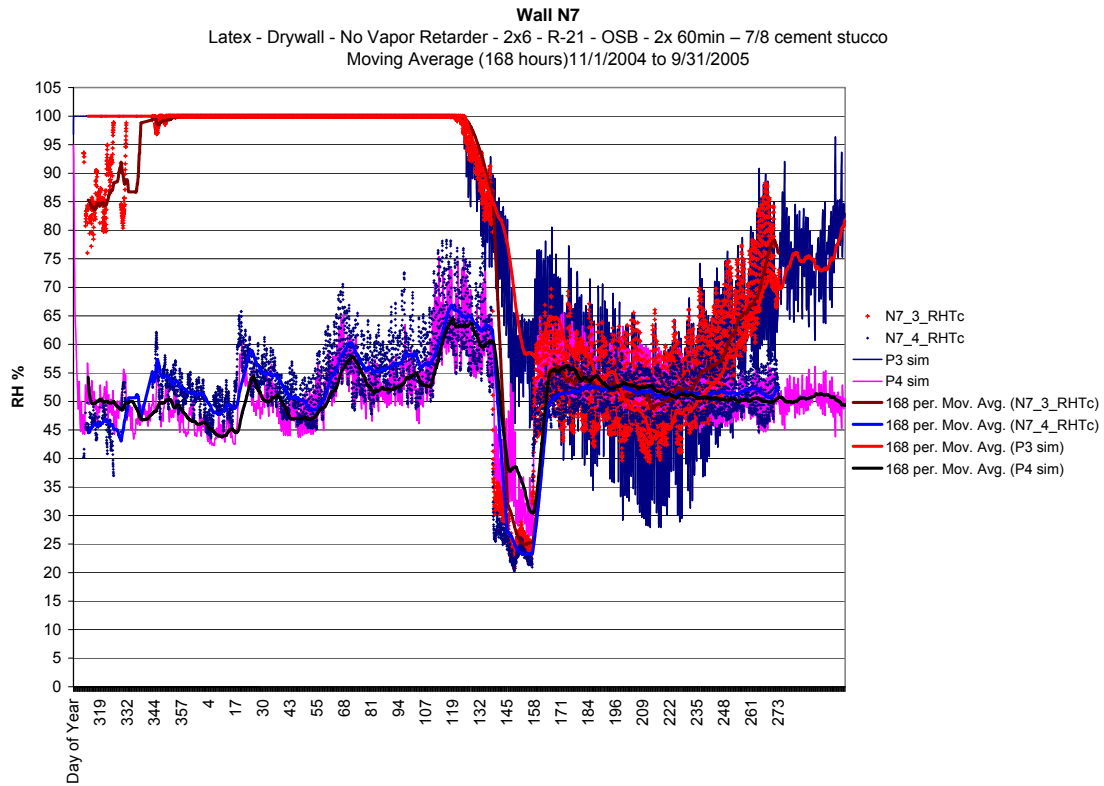


Figure 76: Relative humidity on cold and warm side of the insulated cavity for wall 7 facing north during November 2004-2005. Excellent agreement.

# Simulation results for the south facing walls in Puyallup, WA

Walls were measured for approximately three years starting in the autumn of 2003. During the testing periods, walls were opened (once), water injected into the cavities and some walls were rebuilt to change the construction. The simulations were not continuous through the whole three year period but instead focused on certain year long periods.

## Year 2

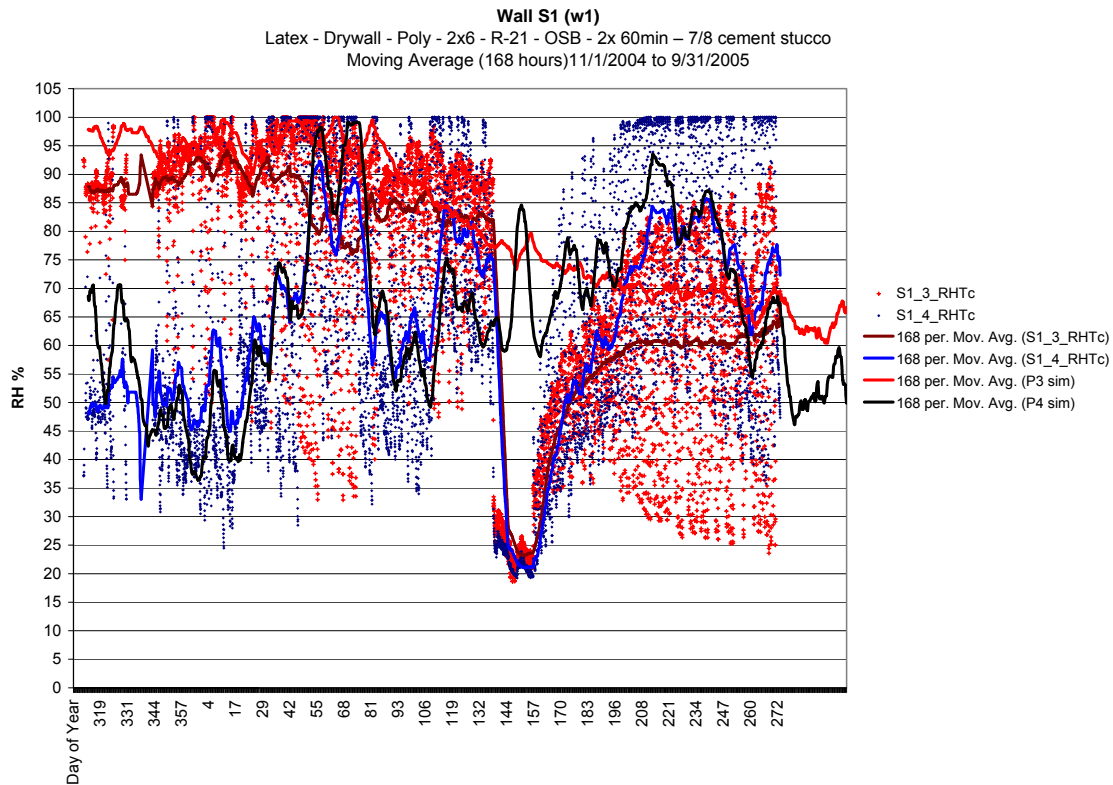


Figure 77: Relative humidity on cold and warm side of the insulated cavity for wall 1 facing south during November 2004-2005.

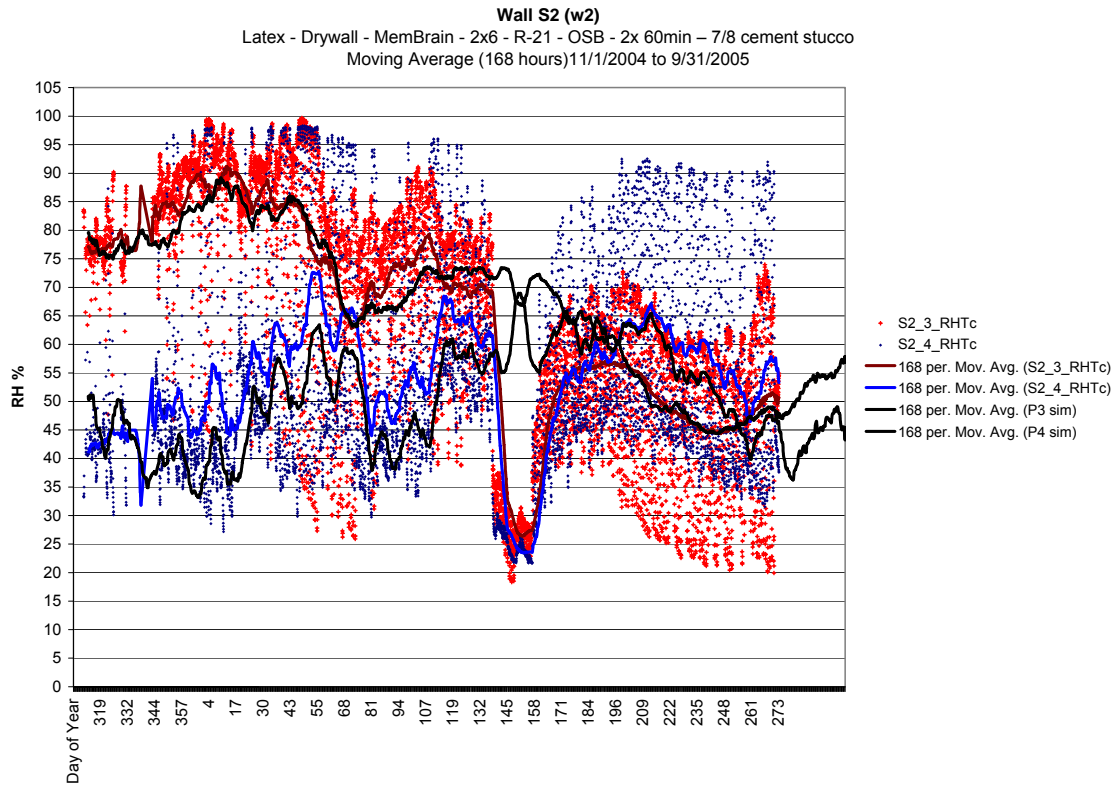


Figure 78: Relative humidity on cold and warm side of the insulated cavity for wall 2 facing south during November 2004-2005.

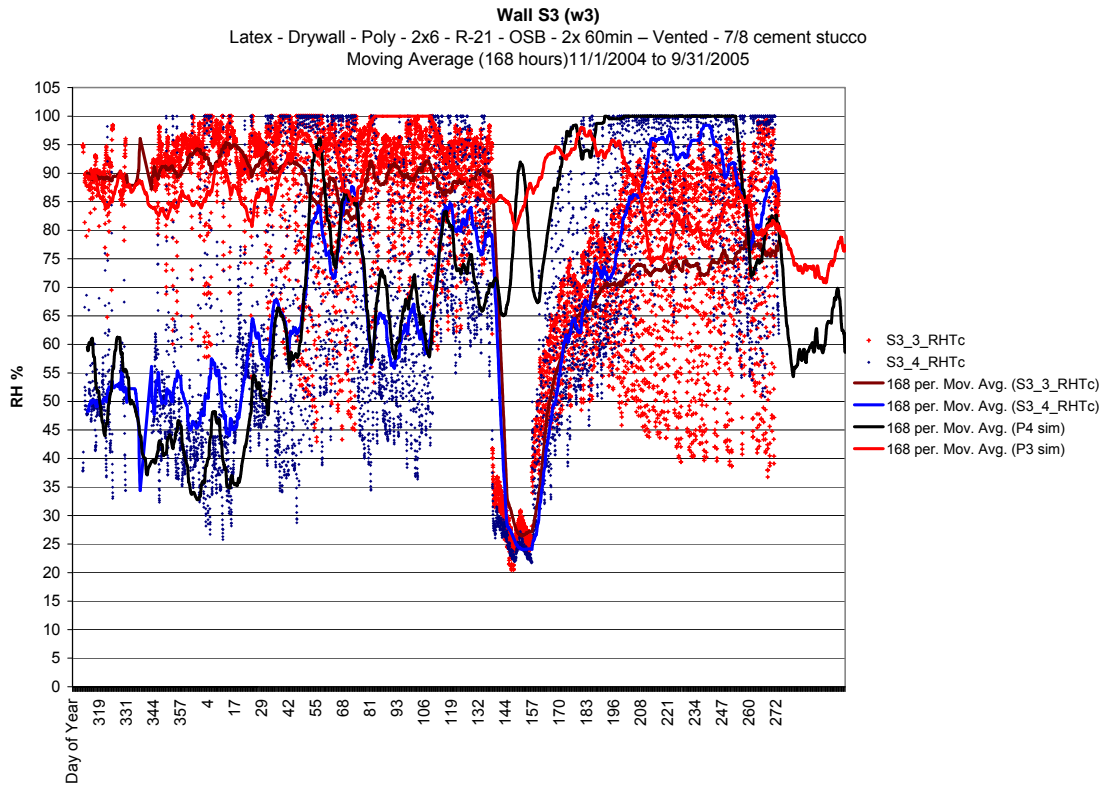


Figure 79: Relative humidity on cold and warm side of the insulated cavity for wall 3 facing south during November 2004-2005.

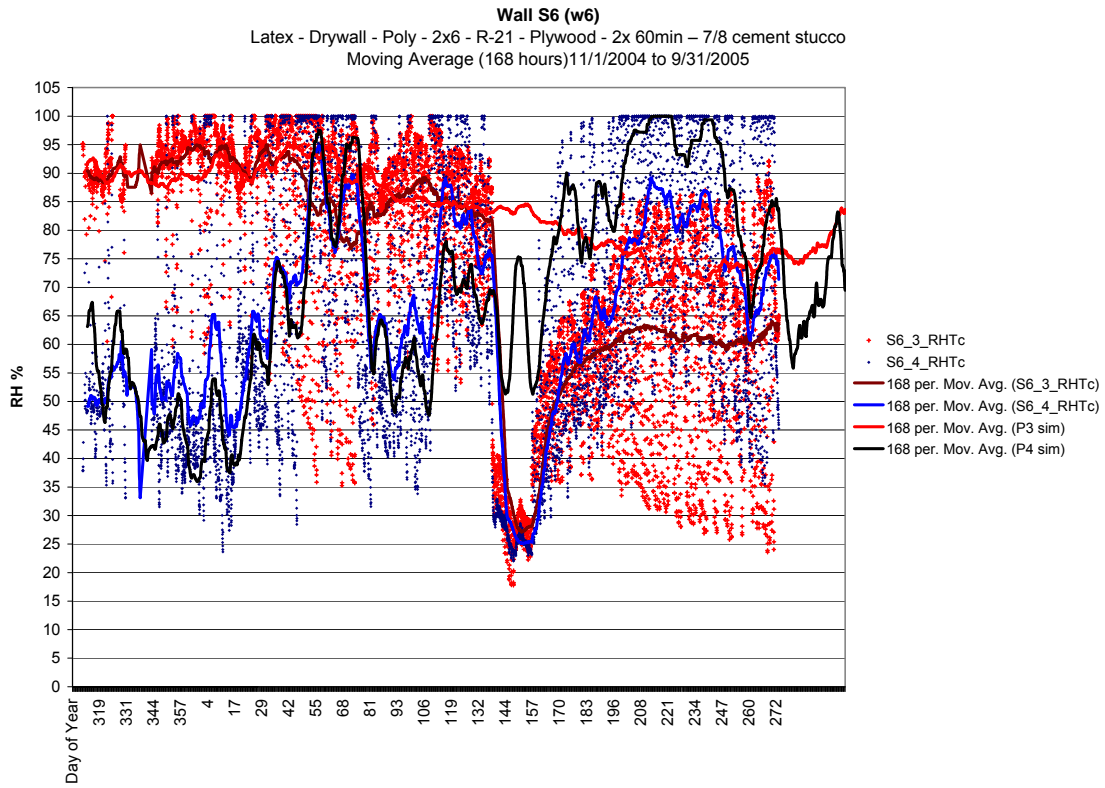


Figure 80. Relative humidity on cold and warm side of the insulated cavity for wall 6 facing south during November 2004-2005.

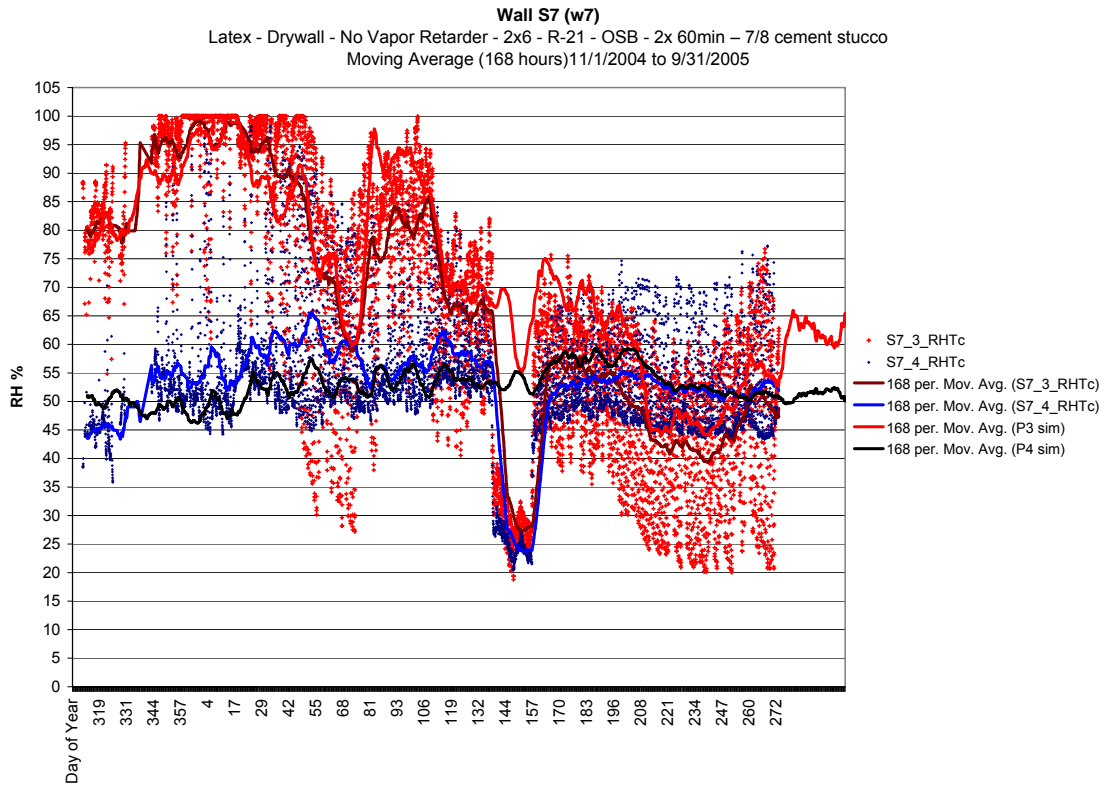


Figure 81: Relative humidity on cold and warm side of the insulated cavity for wall 7 facing south during November 2004-2005.

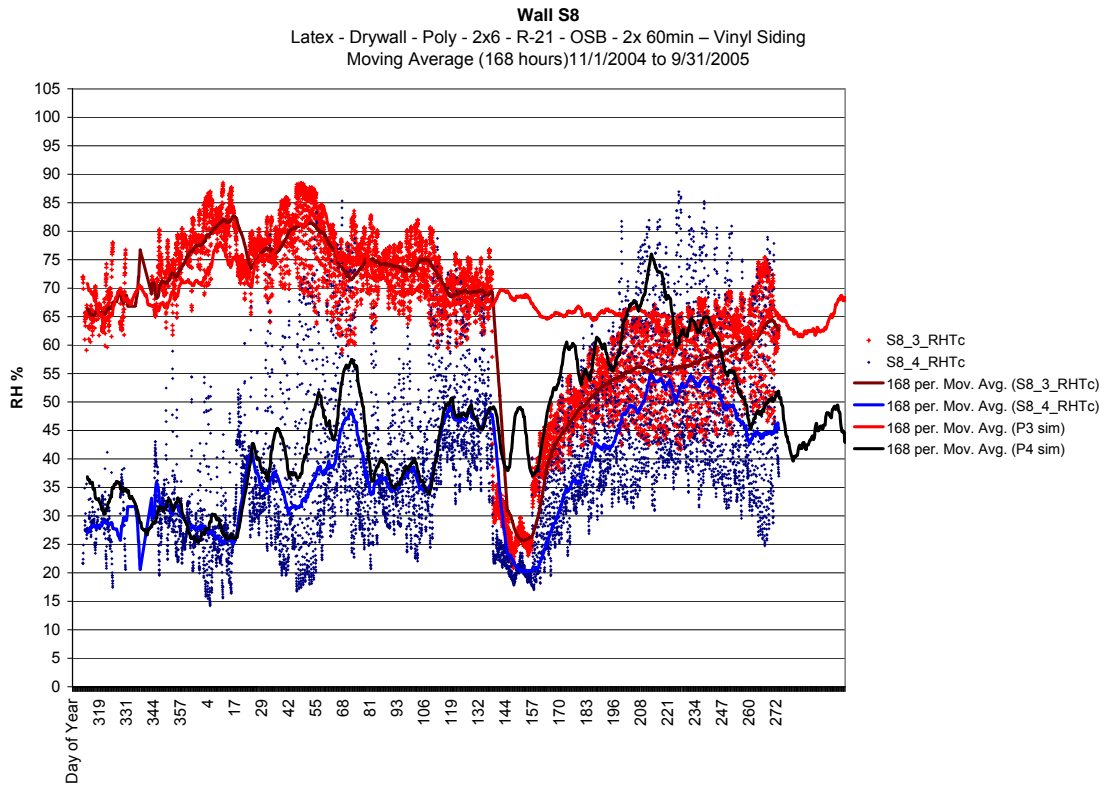


Figure 82: Relative humidity on cold and warm side of the insulated cavity for wall 8 facing south during November 2004-2005.

## **Concluding Remarks**

This part of the report provides details on the material property measurements performed on the WSU-Puyallup test facility wall materials, analysis of the first year results to determine specific trends in the hygrothermal performances of the tested wall structures and finally on the modeling activity to validate the hygrothermal models.

### **Limitations of Work**

The walls were monitored for a multi-year period with the walls installed twice. The exterior wetting loads were deduced to be different based on the location of the wall. A repeat wall would have benefited this study especially if one was placed in the middle of the test facility and the other at the edge. The differences could have been used to determine the rain loading imbalance as a function of the location of the wall. Wind-driven rain patterns on the Puyallup building were substantially different than those found at the NOAA weather station at the Tacoma-Seattle airport, as the geographic characteristics near the test facility created distinct corridors with wind flow. Not all exterior environmental loads were monitored, and reliable data from rain gauges positioned around the test facility would have also provided critical data on the wetting distribution patterns of the exposed walls.

For most of the stucco walls, cracks were present. These cracks allowed substantial water leakage to the backside of the stucco cladding. Depending on the number of cracks, different levels of water wetting occurred. Thus each wall exterior wetting dependent was not only on the location where the wall was placed but also on the exterior crack conditions present. A laboratory analysis of the crack distributions and measurements of the additional water penetration through the stucco could have provided additional insight on the stucco performance. Finally, the dynamic (transient) measurement of the cladding cavity ventilation could have added needed insight on the performance of the wall drying due to ventilation.

In the modeling benchmarking activity, material properties of the stucco suction isotherms were not available during the simulation analysis. The modeling analysis would have benefited with the use of full material characterization. Additionally, if the

dry-out period was included, the additional benchmarking analysis could have been conducted for the period day 150 to 273.

### **Concluding Remarks**

For the walls investigated in this study the amount of cavity insulation does not change the moisture performance of walls significantly.

Ventilation from the air gaps open in the top and bottom of the walls in the field study at Puyallup produced very high drying potentials. These walls are very beneficial for high water loading regions of the Northwest Pacific region. The vented wall systems performed better than the unvented but this difference was not significant for the climate of Puyallup. All classes of cladding performed well if appropriate vapor control is provided. The walls with absorptive cladding such as stucco, cementitious board displayed higher levels of moisture accumulation when compared to vinyl walls (non-absorptive).

Vapor retarders were found to be critical to the performance of walls in Puyallup. The use of MemBrain™ was found to be beneficial during the dry out summer period. The sheathing was found to accumulate a significant amount of moisture when just a vapor open (100 perm PVA primer and Latex paint) paint was used.

The walls also showed a significantly different hygrothermal performance when comparing walls oriented south versus north. Walls oriented north have a lower drying potential than walls oriented south and this is especially true for walls with air cavity ventilation. South oriented walls were able to handle water penetration better than those oriented north. The comparison between osb and plywood found small differences, indicating slightly higher moisture accumulations in the plywood sheathing. However, the moisture content levels were relatively dry. Real performance difference could exist if the comparison was made with walls that had low interior water vapor permeances.

The addition of exterior foam insulation produced walls that outperformed all other wall systems in terms of hygrothermal performance.

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## **LIST OF ACRONYMS AND ABBREVIATIONS**

MC	Wood moisture content
NET	Natural Exposure Test
ORNL	Oak Ridge National Laboratory
OSB	Oriented strand board
RHc	Relative humidity
SIP	Structural insulated panels
T	Temperature
RH	Relative Humidity
US DOE	U.S. Department of Energy
WSU	Washington State University