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

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DISCLAIMER

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**

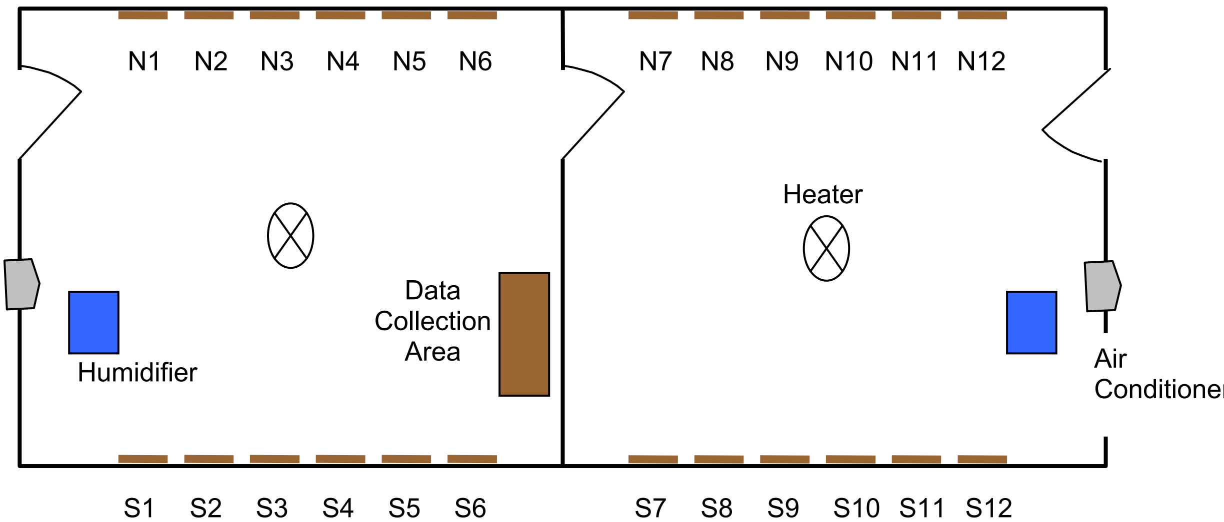


Figure 2 shows the south facing wall of the completed NET with twelve 1.2x2.7 (4x9 foot) test wall assemblies installed for test Cycle 1. Test Cycle 2 and 3 are shown in **Figure 3** and **Figure 4**. Although not all test walls were the same thickness, it was decided to keep the exterior of the building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

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

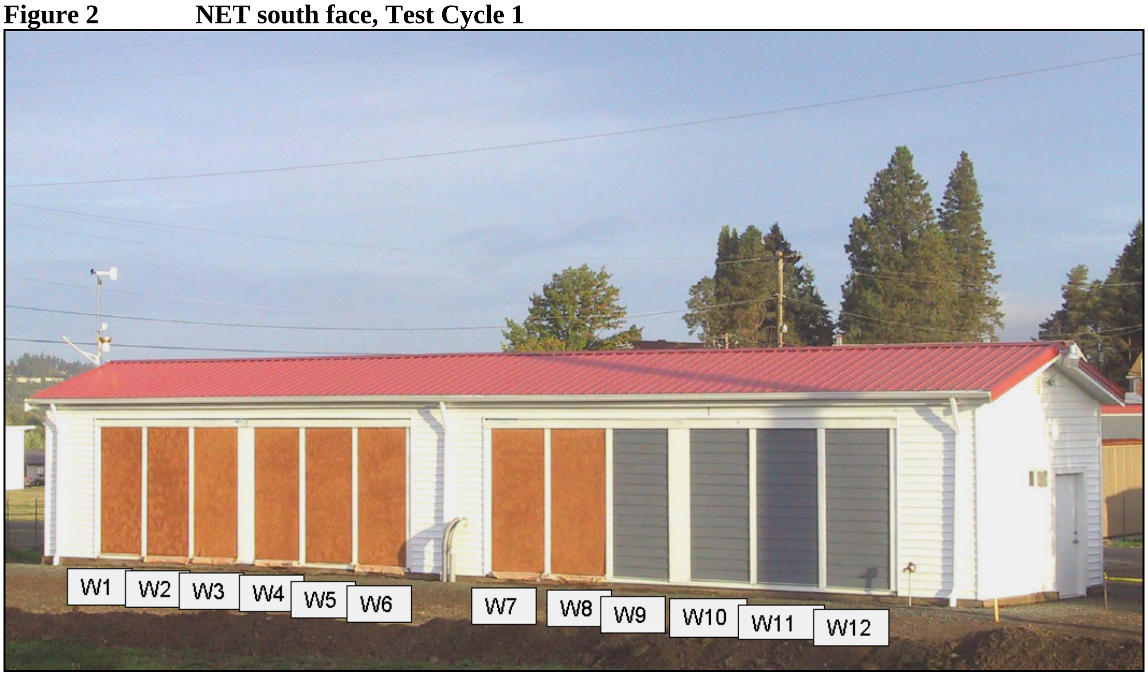


Figure 3 NET south face, Test Cycles 2 and 3

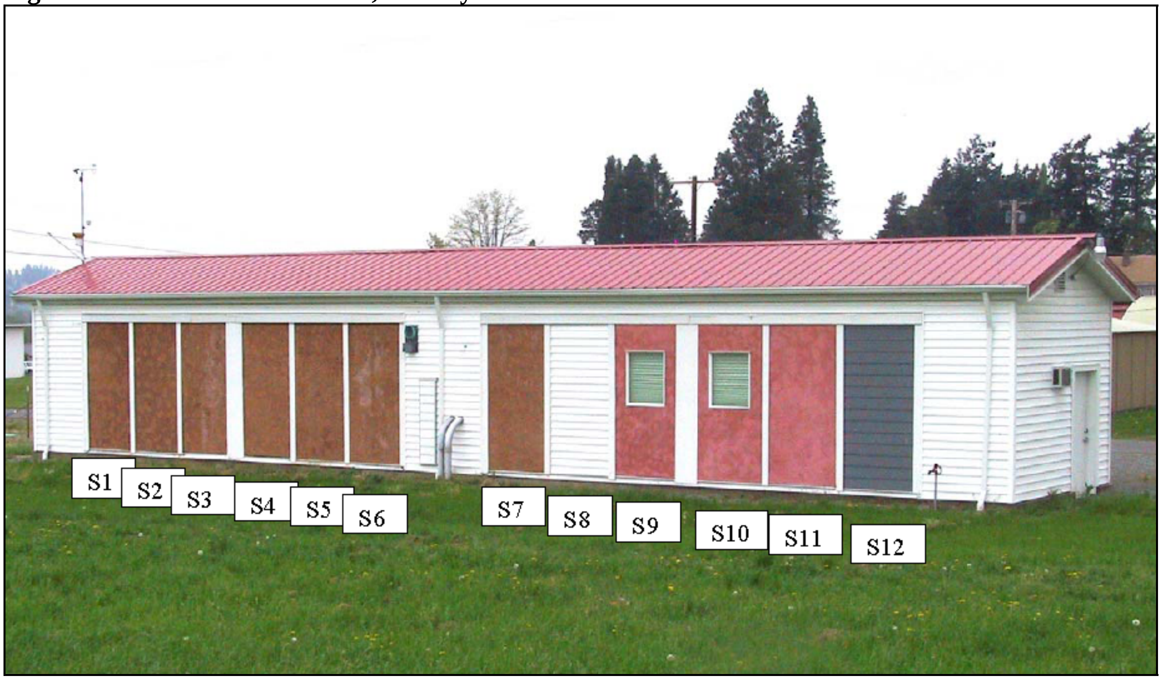
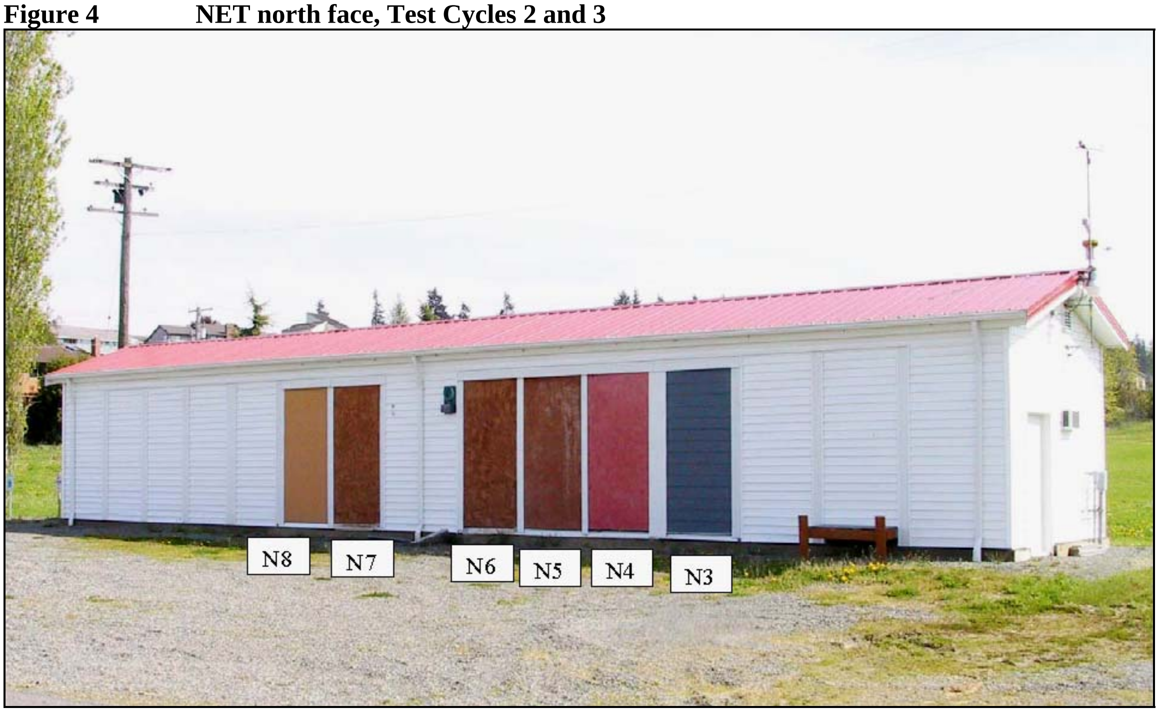


Figure 4 NET north face, Test Cycles 2 and 3



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

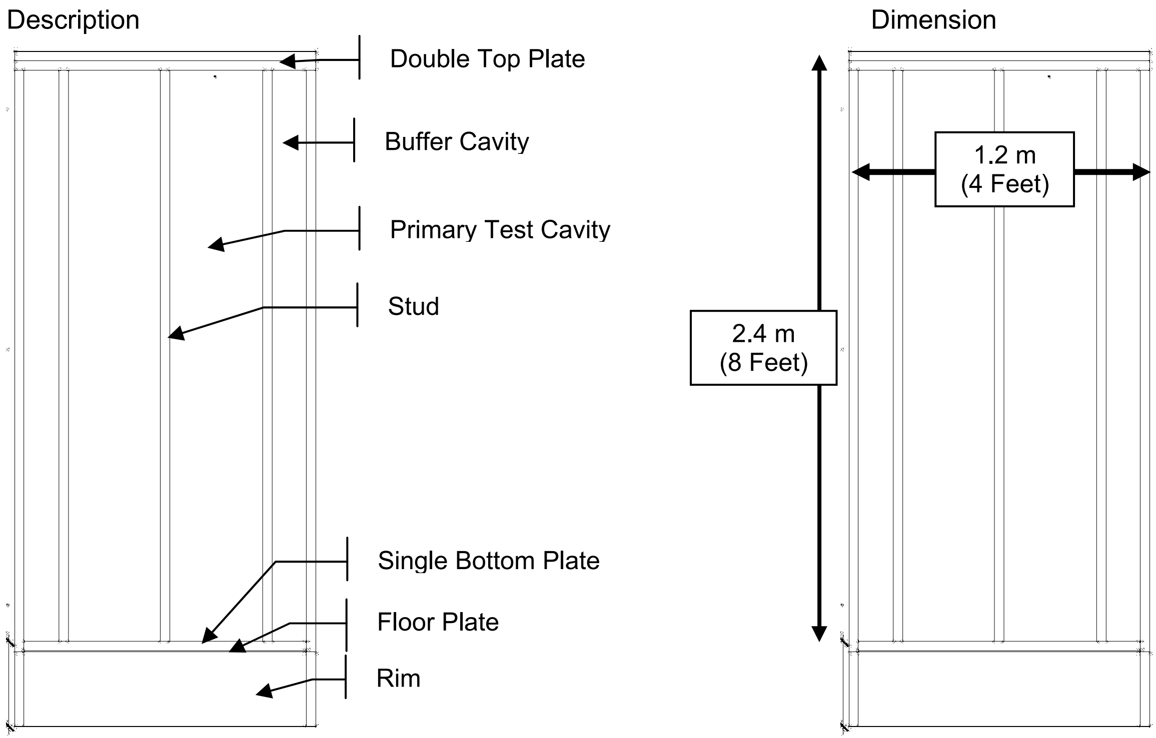


Figure 6 Schematic representation of Test Wall #S1 – unvented stucco system (not to scale)

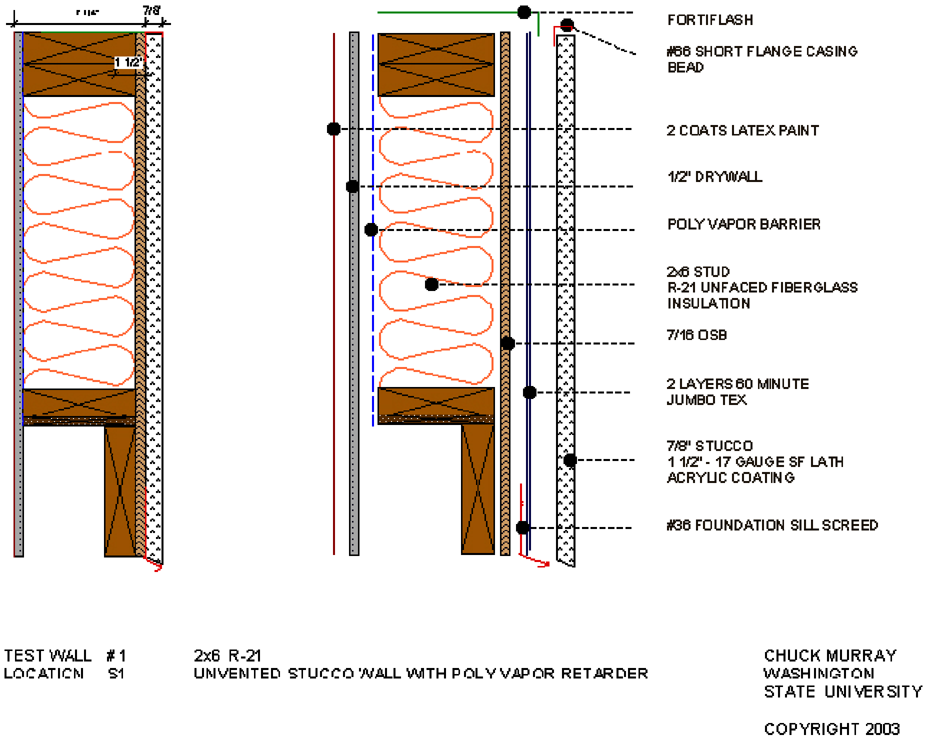


Figure 7 Schematic representation of Test Wall #S4 – ventilated stucco system (not to scale)

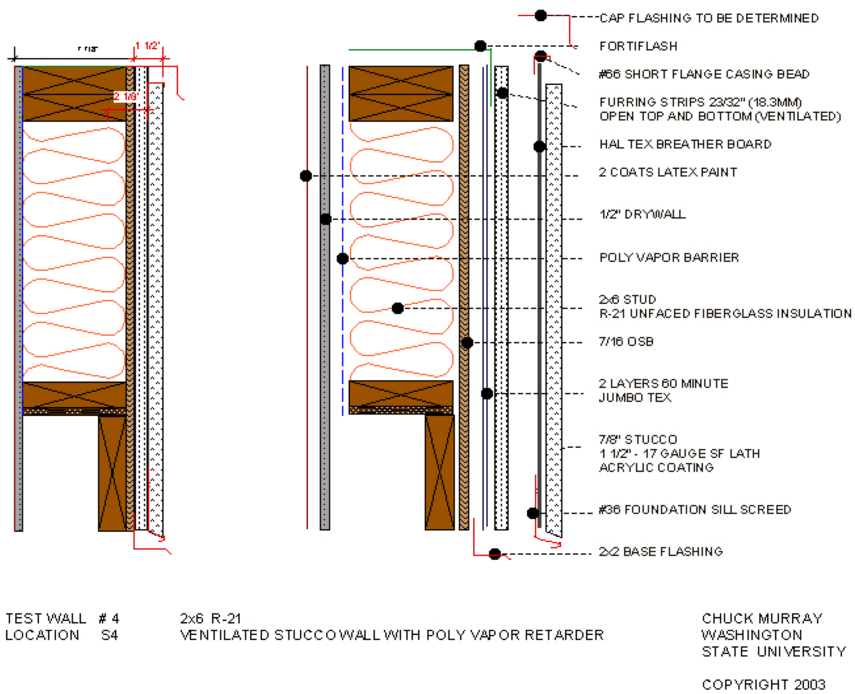
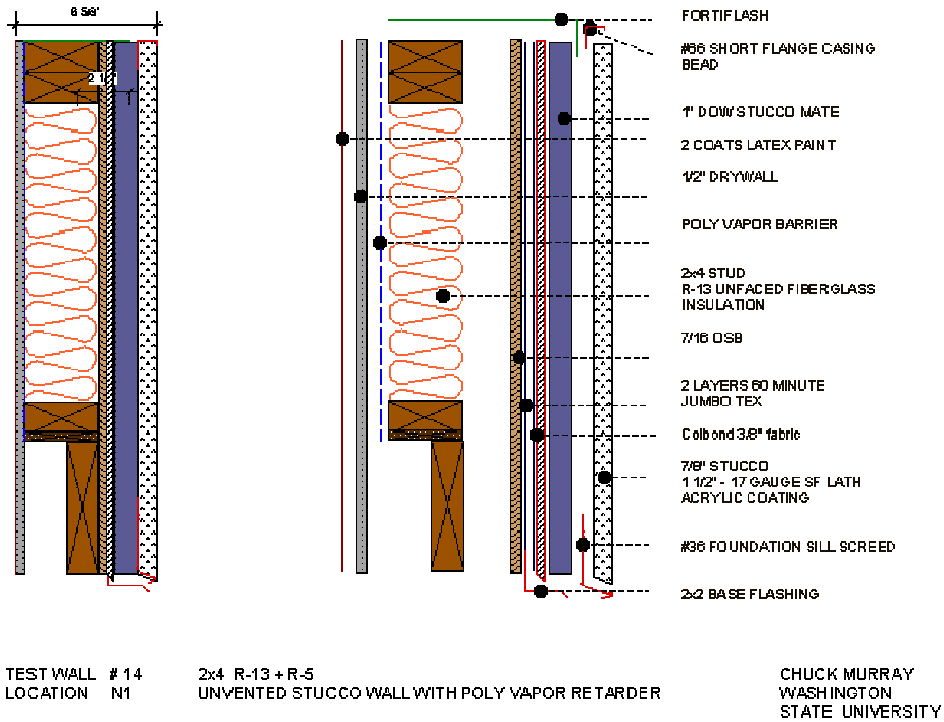


Figure 8 **Schematic representation of Test Wall S6 1" foam clad system (not to scale)**



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

$$v/vo=Ro/R_T+Ro \quad (1)$$

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

$$R_T = Ro * (vo/v)-1 \quad (2)$$

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(RT) then

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

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

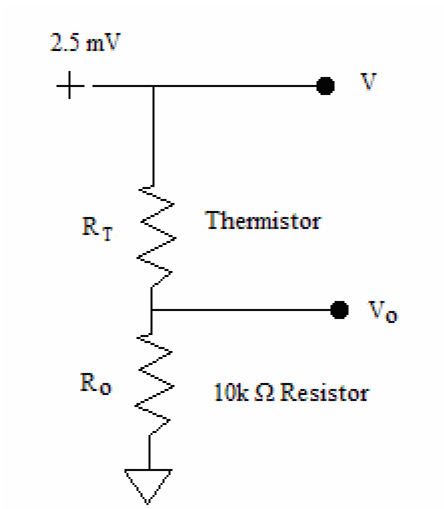


Figure 9 **Three wire half bridge for temperature measurement**

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.

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

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)

RHc = RH/ (1.0546 - 0.00216 * T)   (5)

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

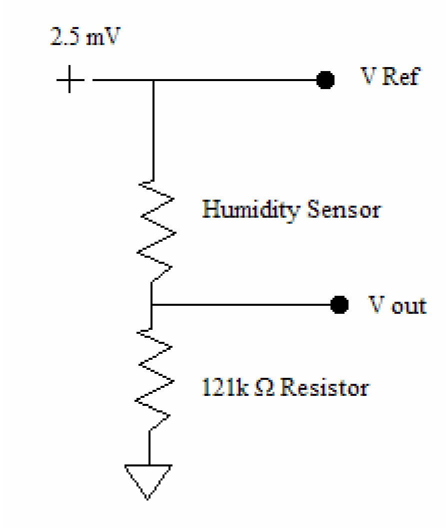


Figure 10 **Three wire half bridge for RH measurement**

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 milivolts. Every 5 minutes three measurements are taken in quick secession 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 <= 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)

$$MCc = ((((10^{(2.99 - 2.113 * Log10(Log10(MC * 1000000)))} + 0.567) - 0.026 * T) + 0.000051 * T^2) / (0.881 * 1.0056^T) - b) / a \qquad (6)$$

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

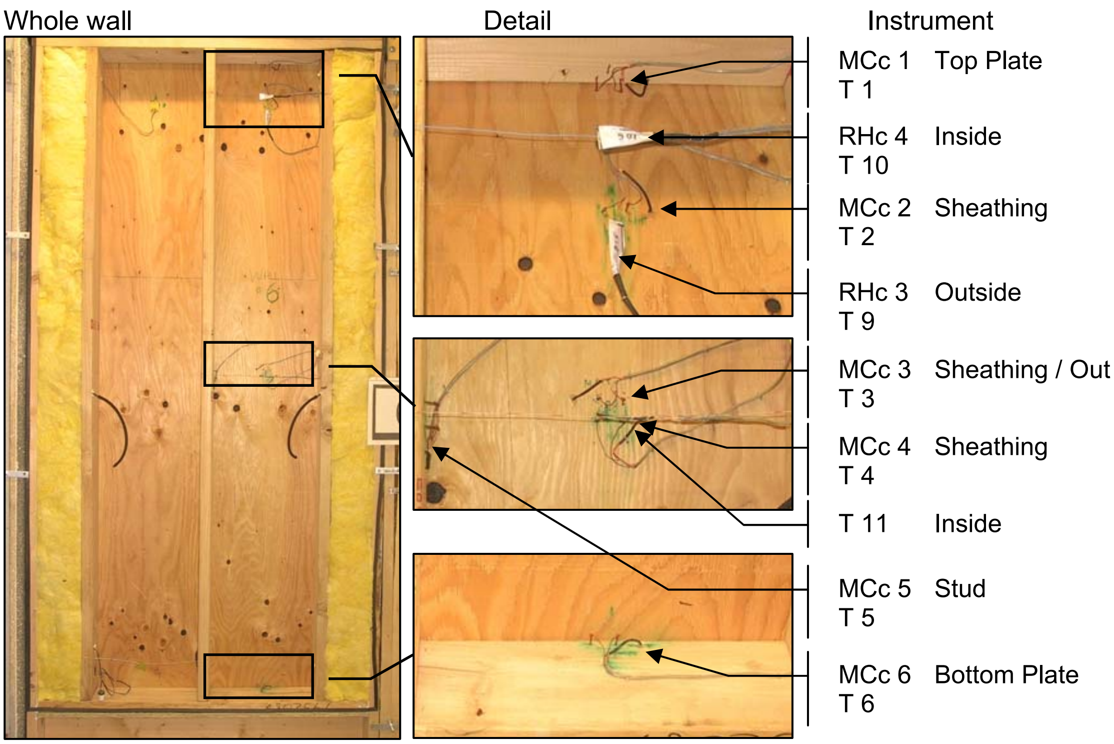


Figure 12 **Instrument location in the left framed cavity**

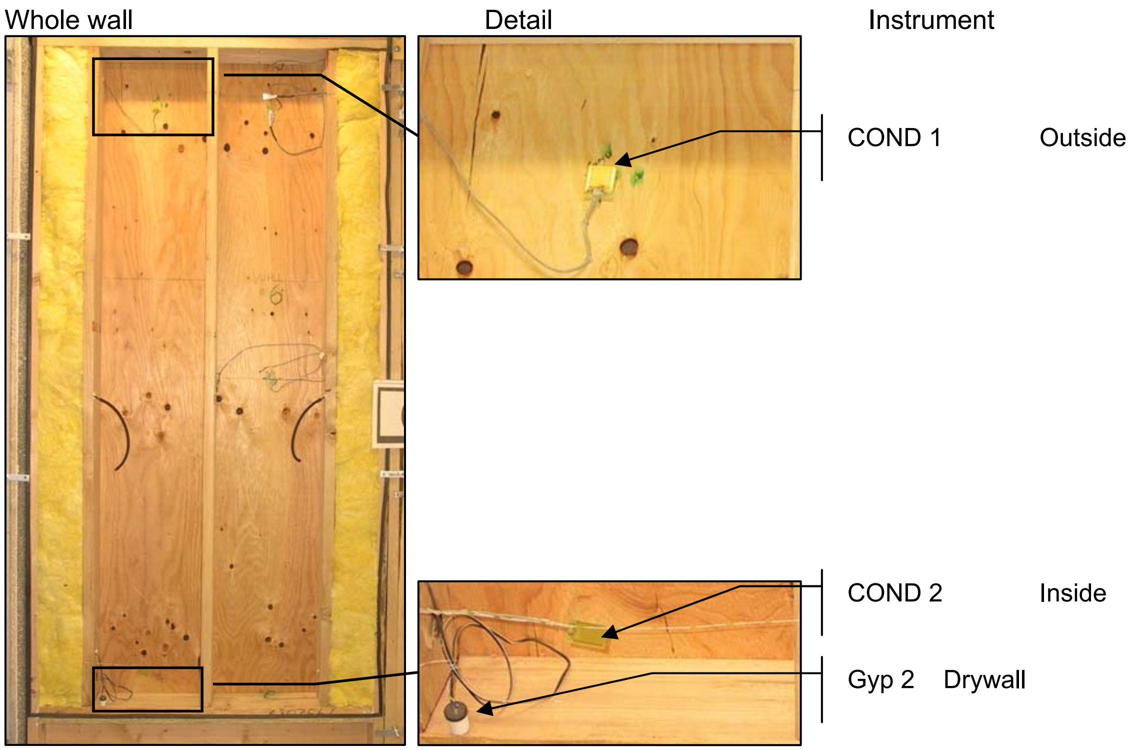
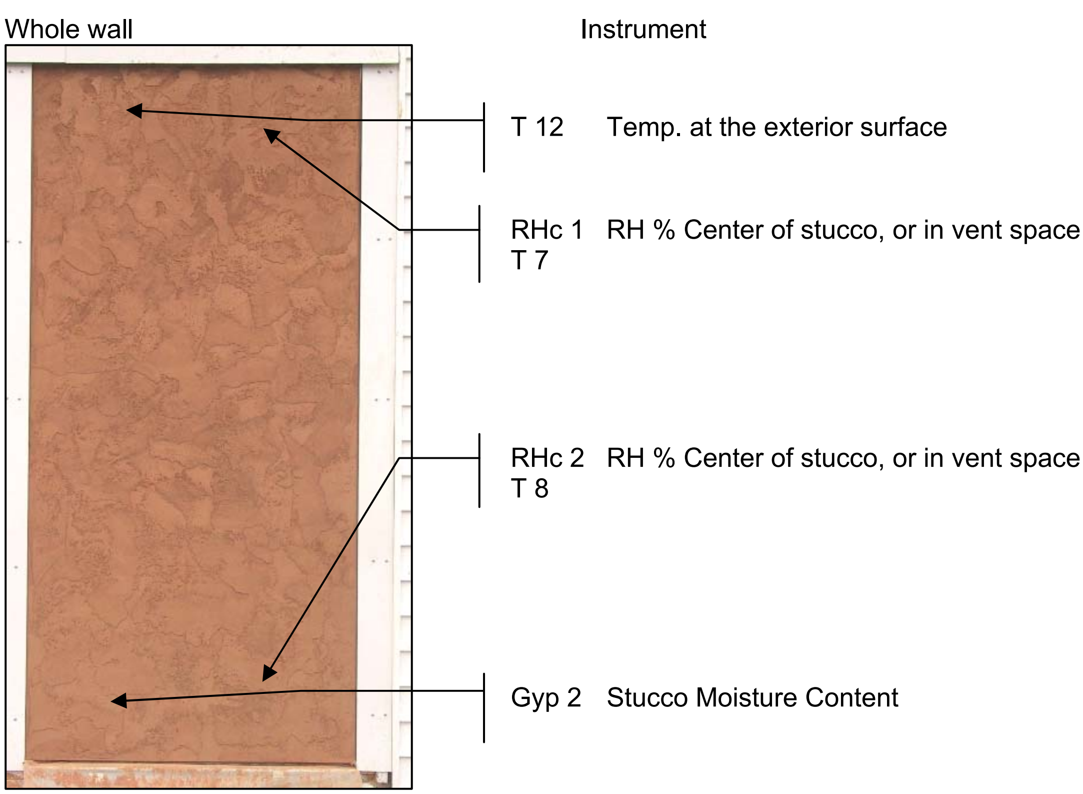


Figure 13 **Instruments located on the exterior**



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
Embeded 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.

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

where

Pi	=	indoor vapor pressure, Pa (in.Hg)
Po,24h	=	24-hour running average outdoor vapor pressure, Pa (in.Hg)
c	=	1.36 105 m2/s2 (10.7 in.Hg·ft3/lb)
$\dot{m}$	=	design moisture generation rate, kg/s (lb/h) (sections 4.3.2.1.1 and 2)
Qventilation	=	design ventilation rate, m3/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.

po,24h = Vapor pressure measured on site during, or from historical climate data

$\dot{m}$ = 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**

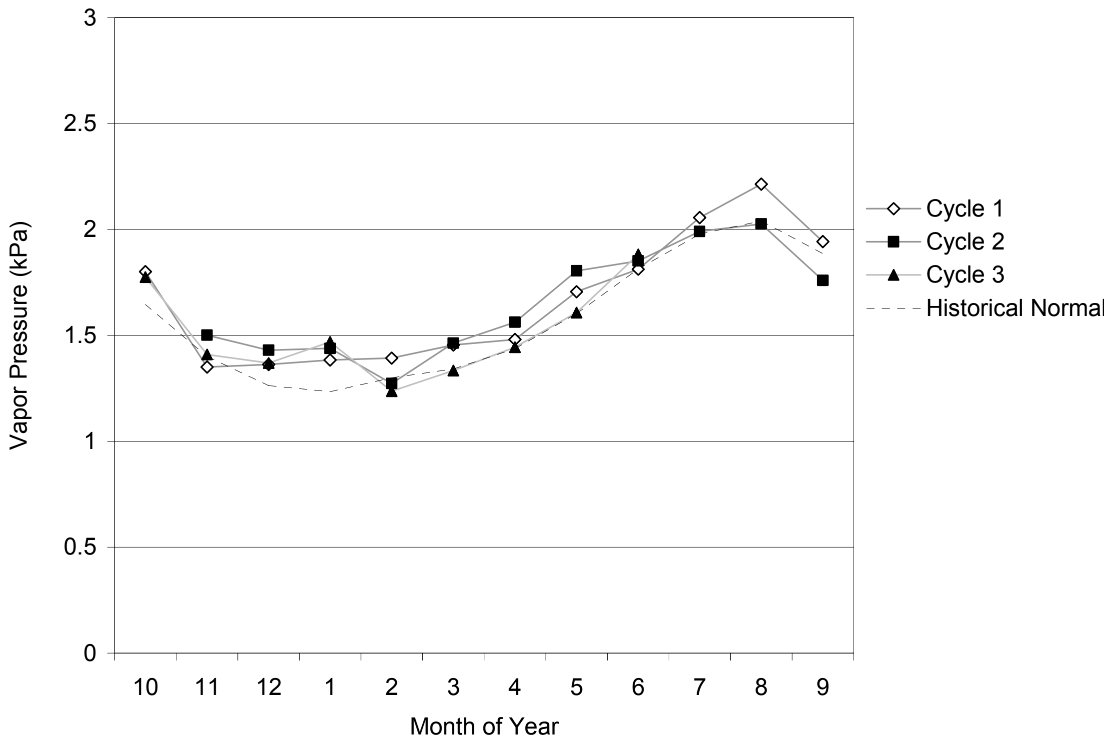
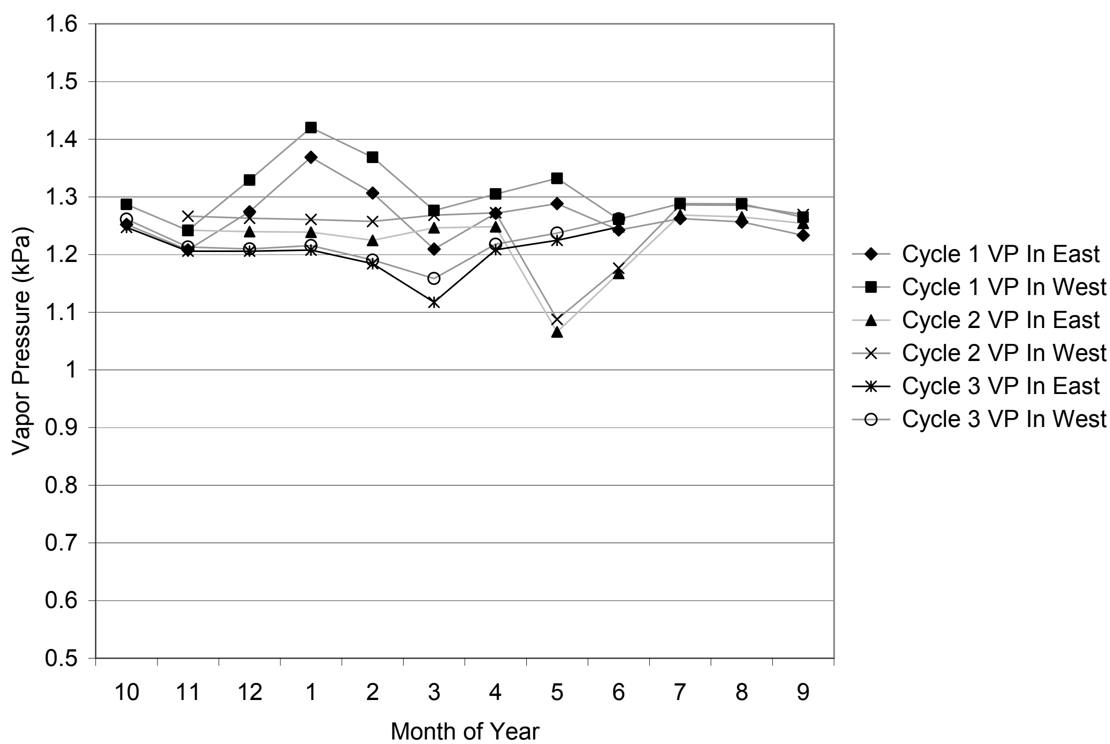


Figure 15 **Recorded interior vapor pressure**



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.
MemBrainÒ		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 from10-14%. 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 (½ 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^2 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 m2 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^2 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^2 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^2 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^2 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
Grey Cement Lap Siding	
Average Solar Reflectance	0.14

Ventilation of Cladding

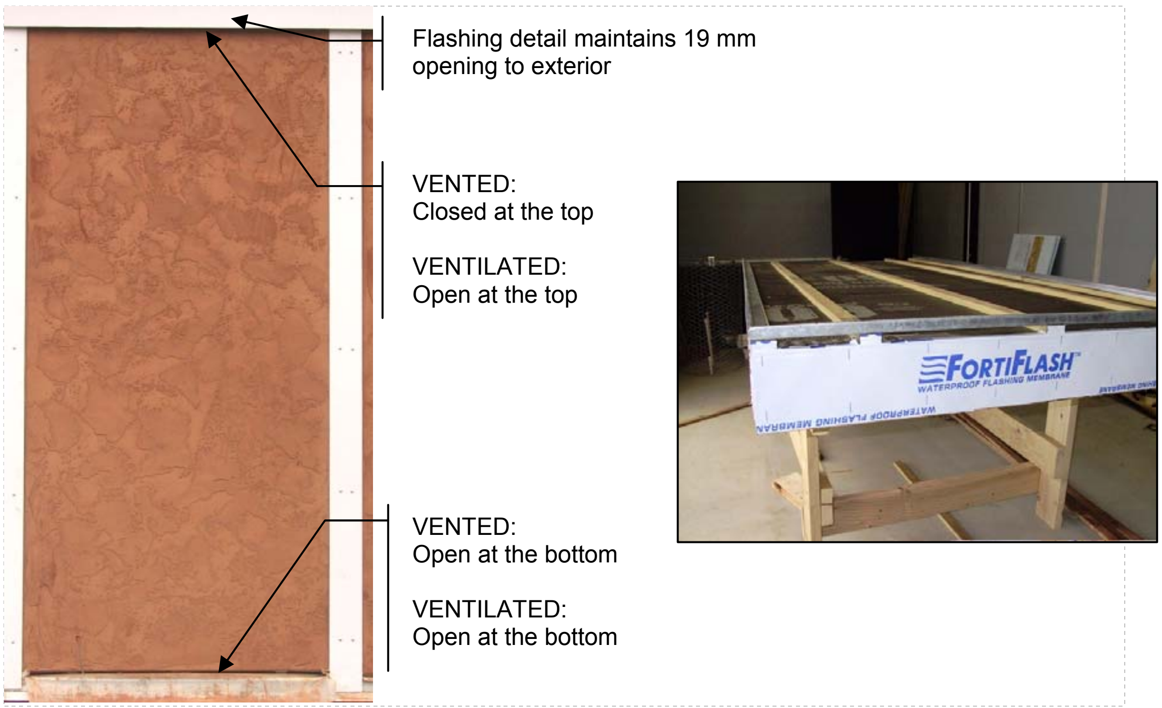
A number of test walls incorporated a 19 mm (¾ inch) space between the exterior cladding and the weather resistive barrier. This space is passively ventilated with outdoor air. Two systems were utilized. One system includes an opening to the exterior at the bottom and is closed at the top of the test 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 (¾ 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 (¾ 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

Mechanical Attachment Self Adhered

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 out performed 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 out perform 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)

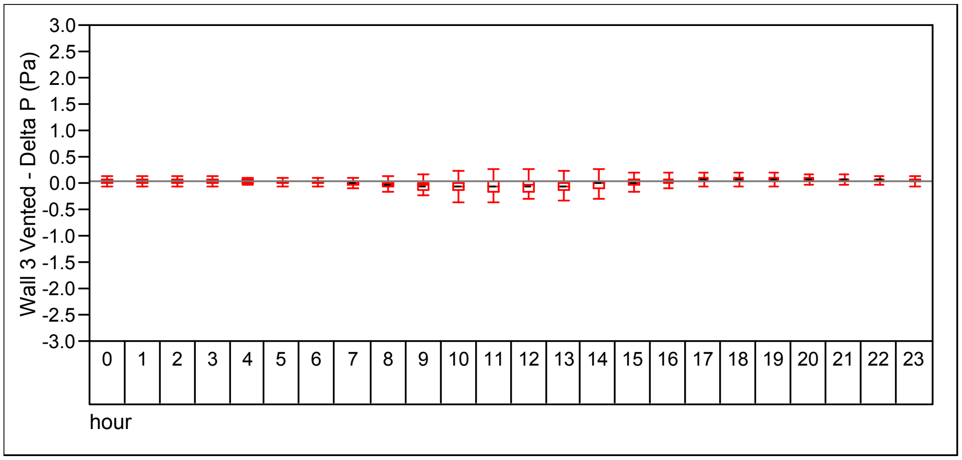
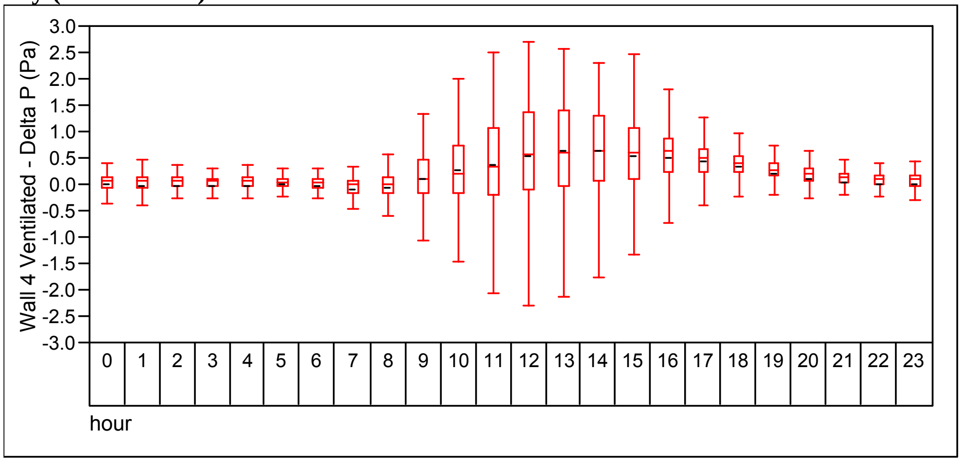


Figure 20 Ventilated stucco cladding: pressure difference in the ventilation cavity by hour of the day (March 2006)



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.

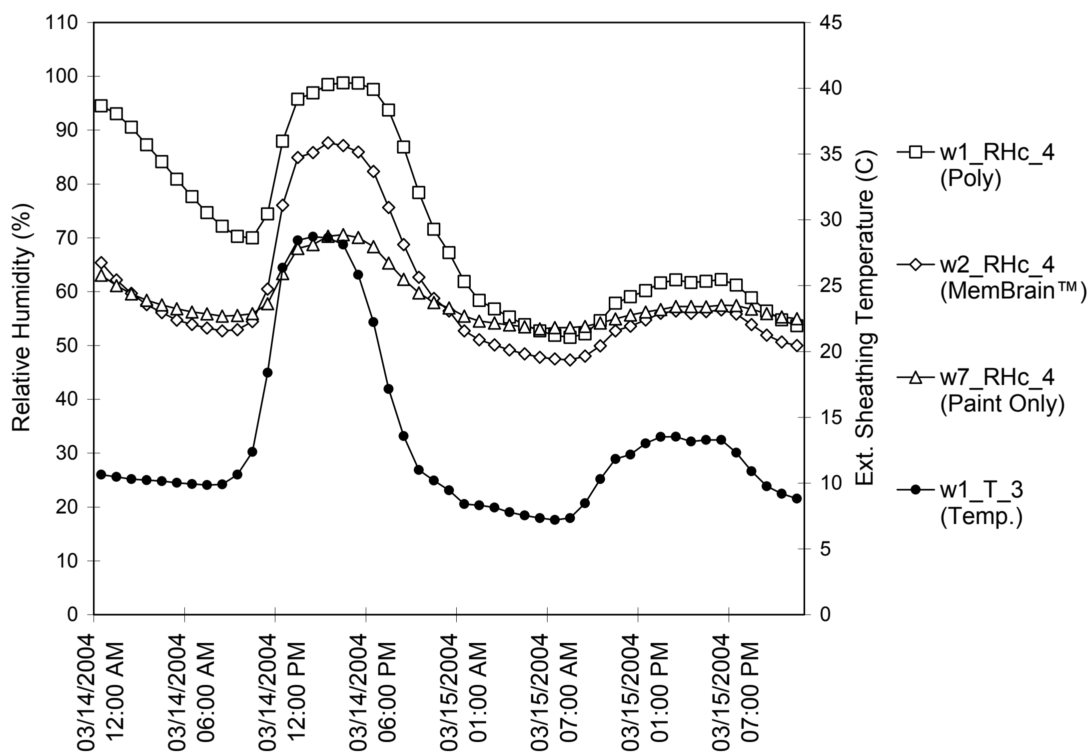
Polyethylene Vapor Retarder

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

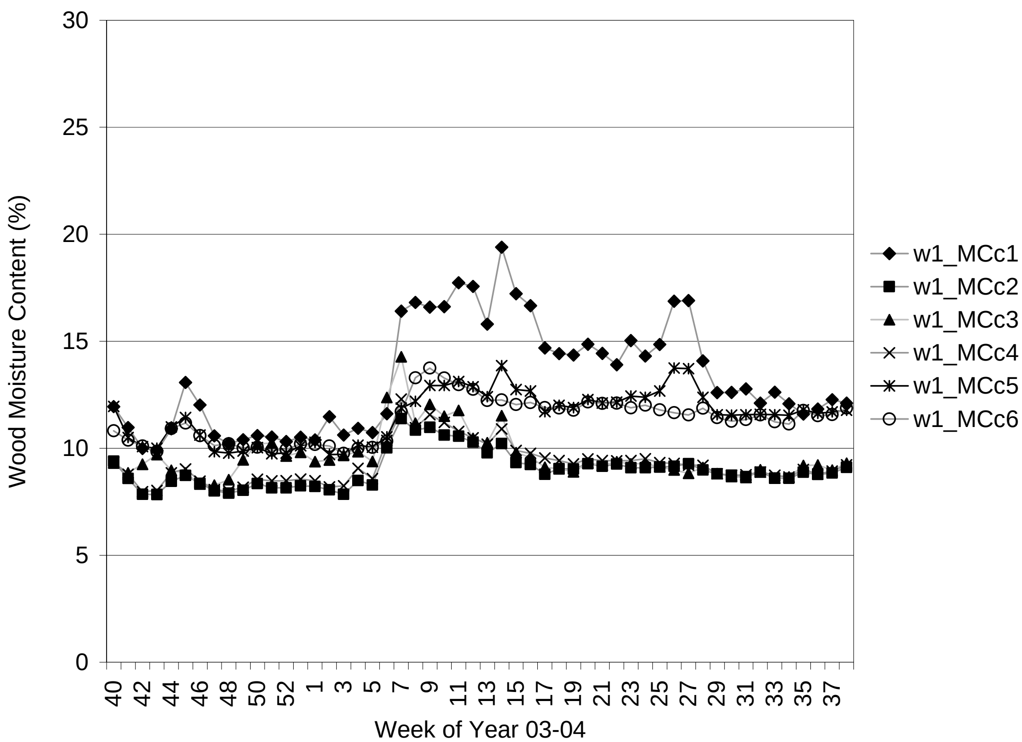


Figure A 1-2 Wall 1 – Cavity Relative Humidity

Figure A 1-3 Wall 1 - Temperature

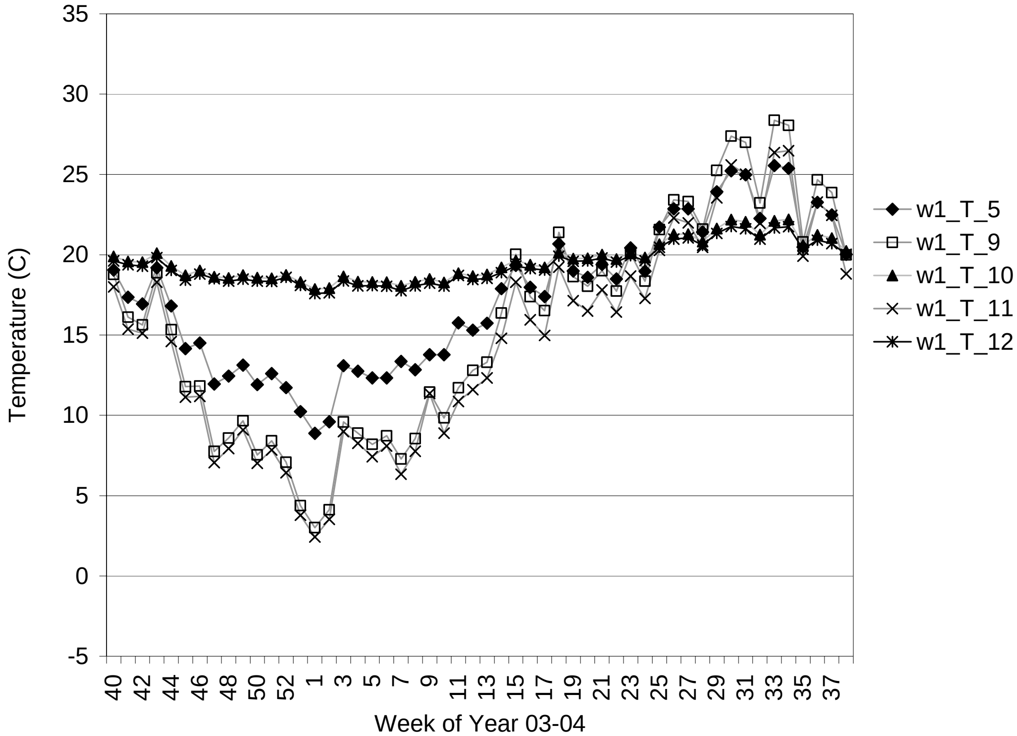


Figure A 1-4 Wall 1 – Vapor Pressure

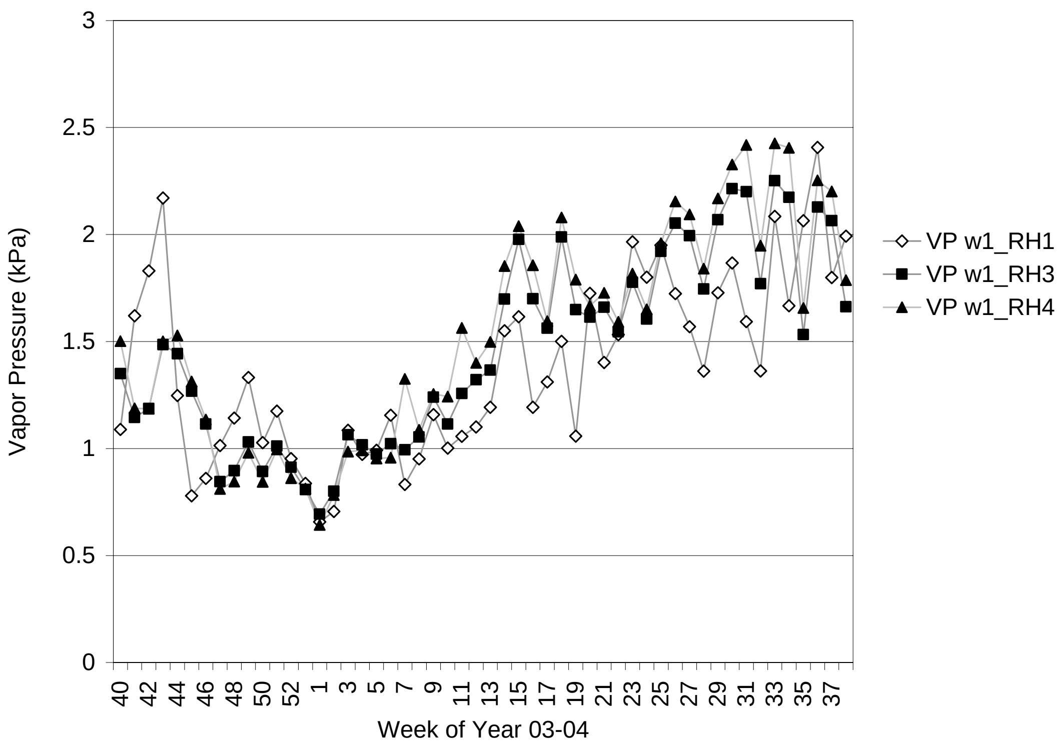


Figure A 2-1 Wall 2 – Wood Moisture Content

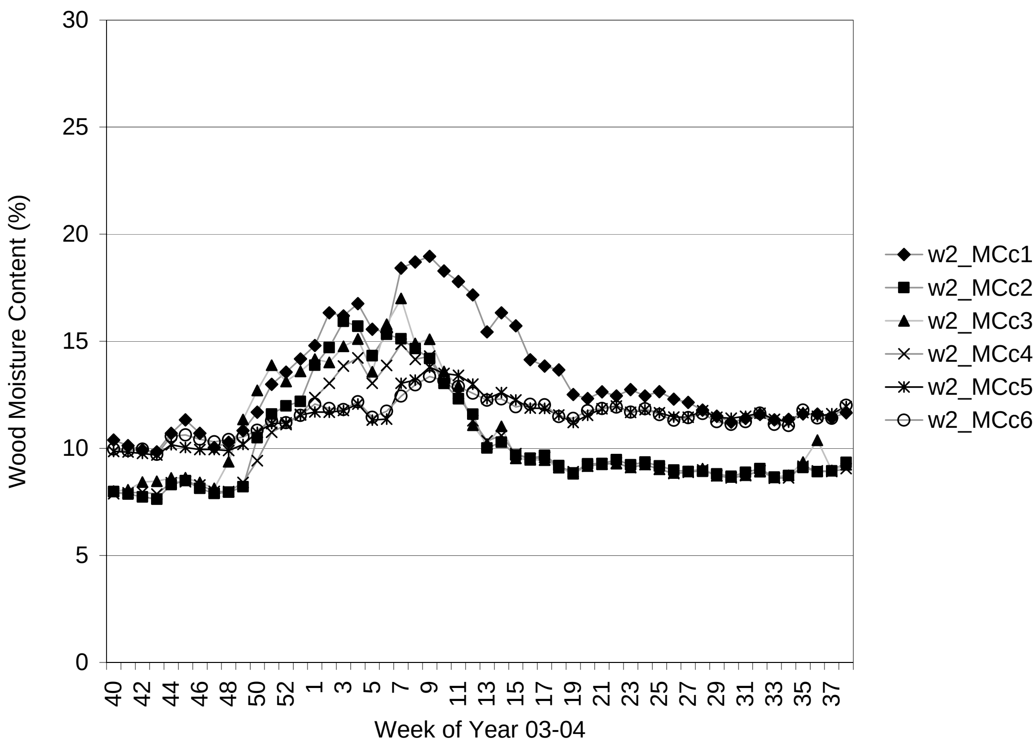


Figure A 2-2 Wall 2 – Cavity Relative Humidity

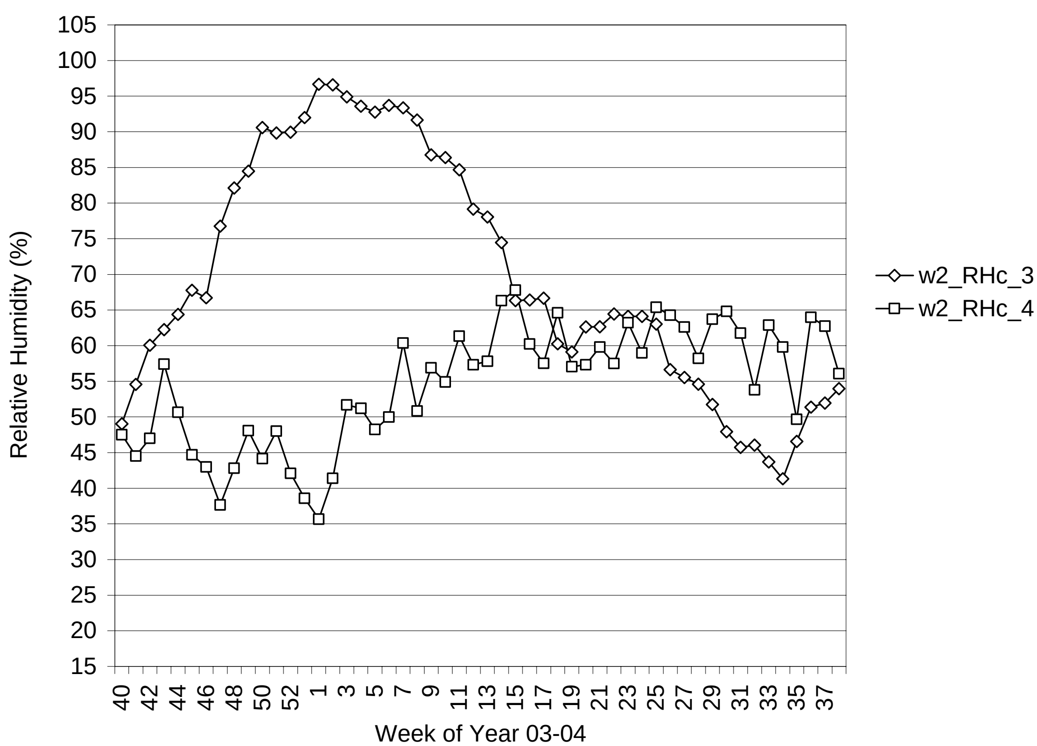


Figure A 2-3 Wall 2 – Temperature

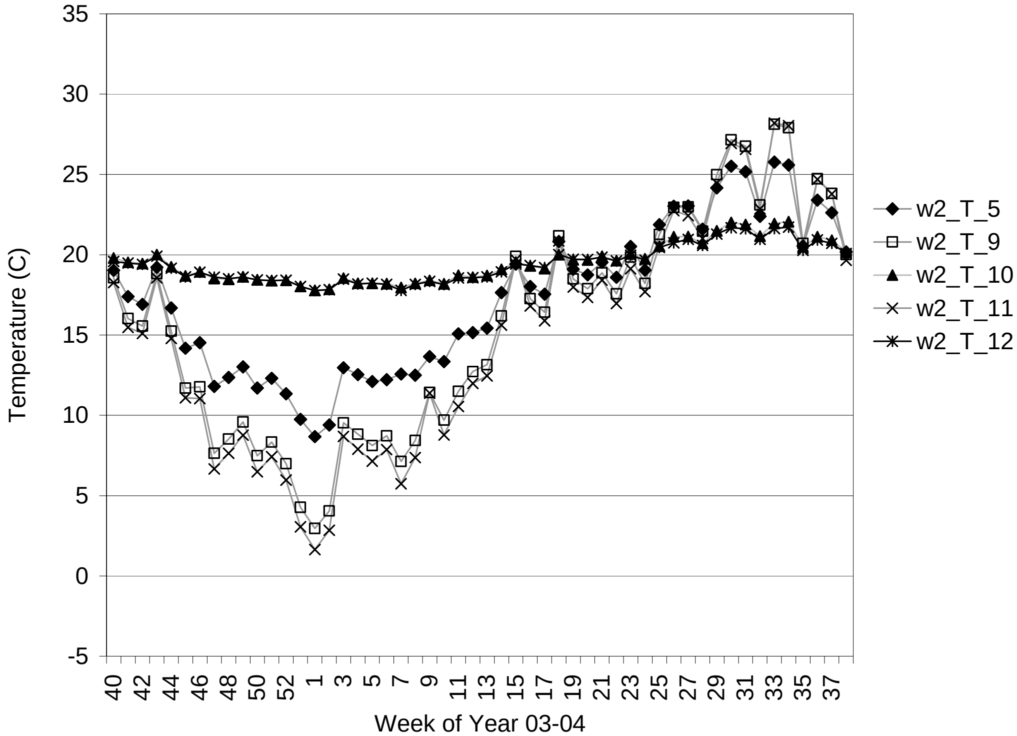


Figure A 2-4 Wall 2 Vapor Pressure

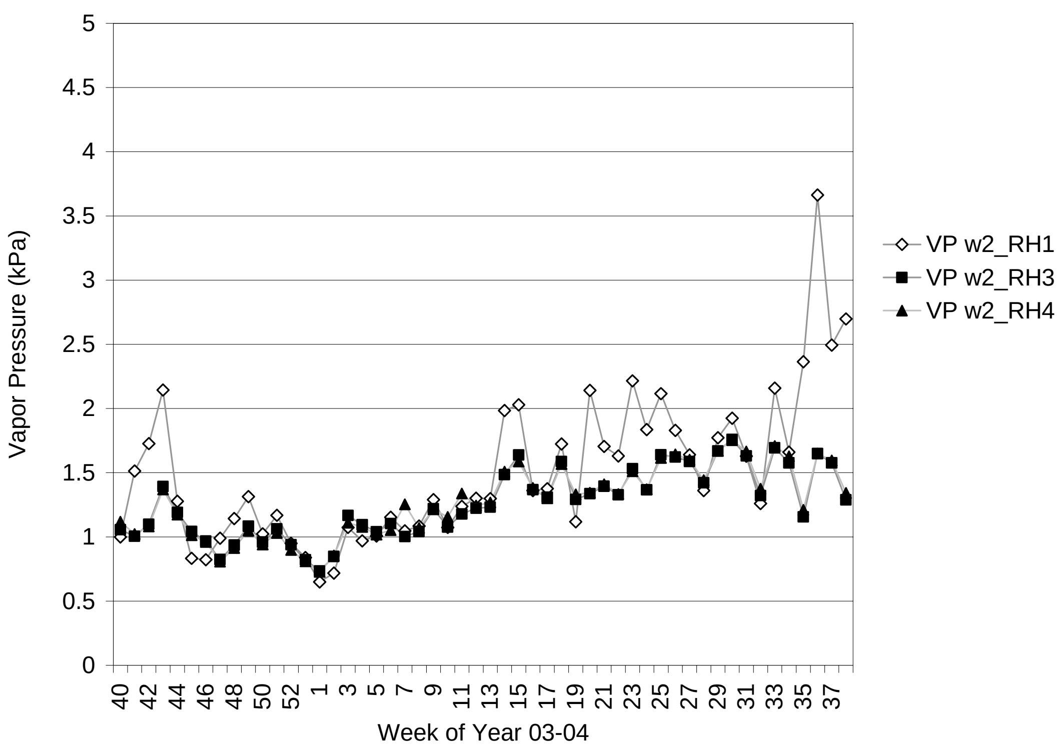


Figure A 3-1 Wall 3 – Wood Moisture Content

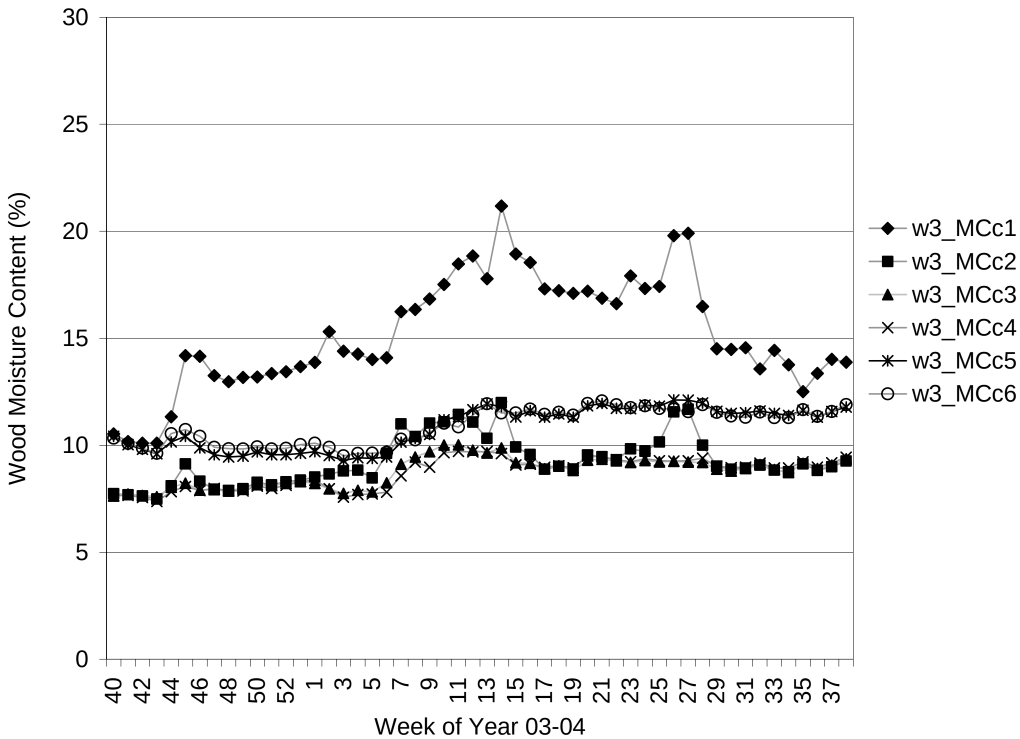


Figure A 3-2 Wall 3 – Cavity Relative Humidity

Figure A 3-3 Wall 3 - Temperature

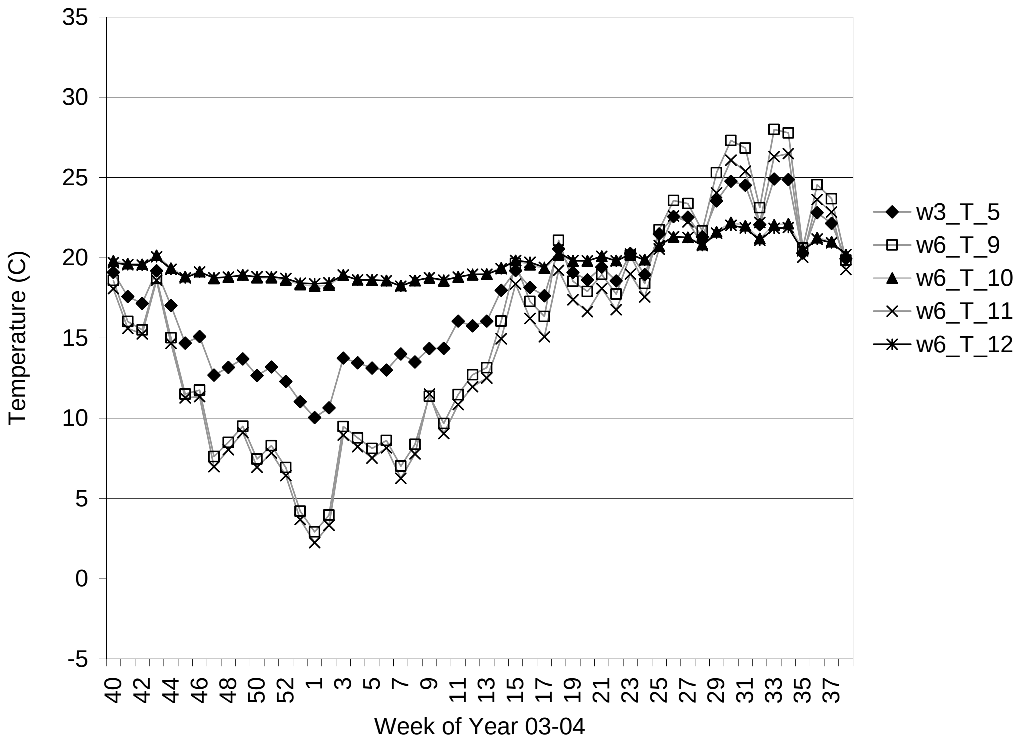


Figure A 3-3 Wall 3 – Vapor Pressure

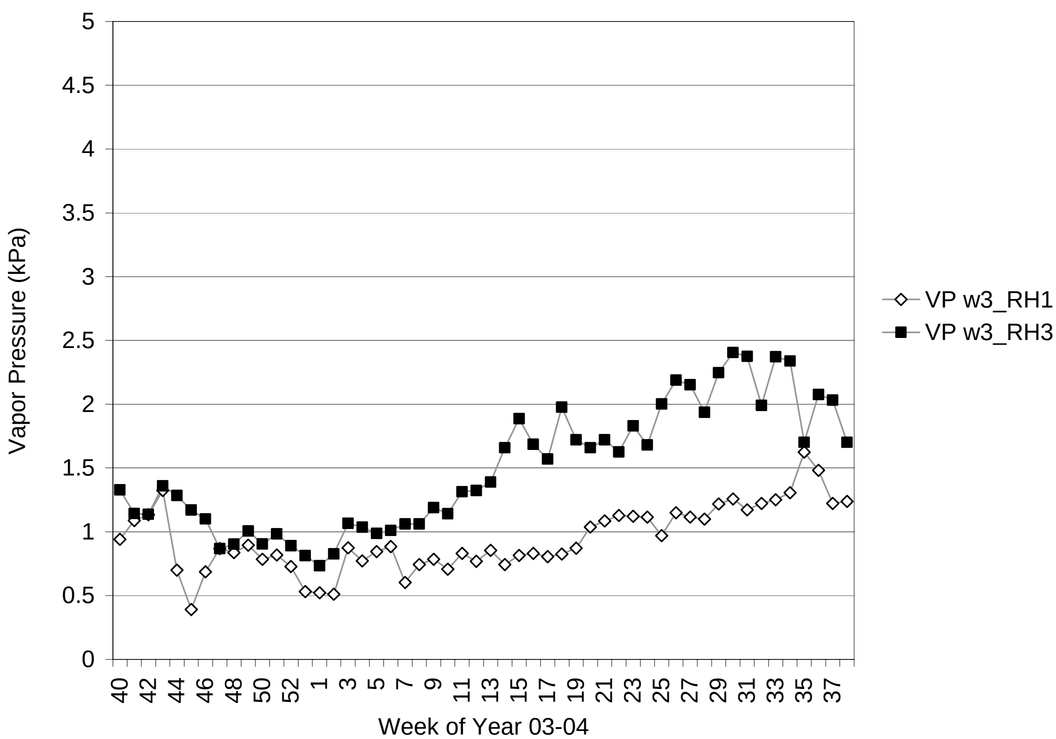


Figure A 4-1 Wall 4 – Wood Moisture Content

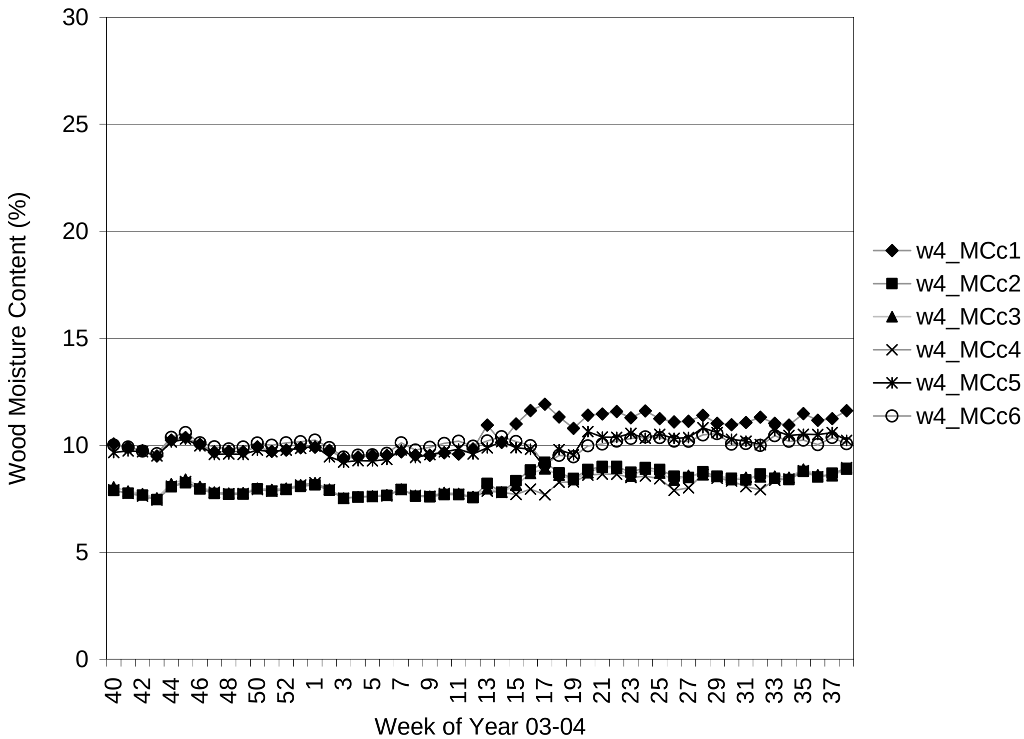


Figure A 4-2 Wall 4 – Cavity Relative Humidity

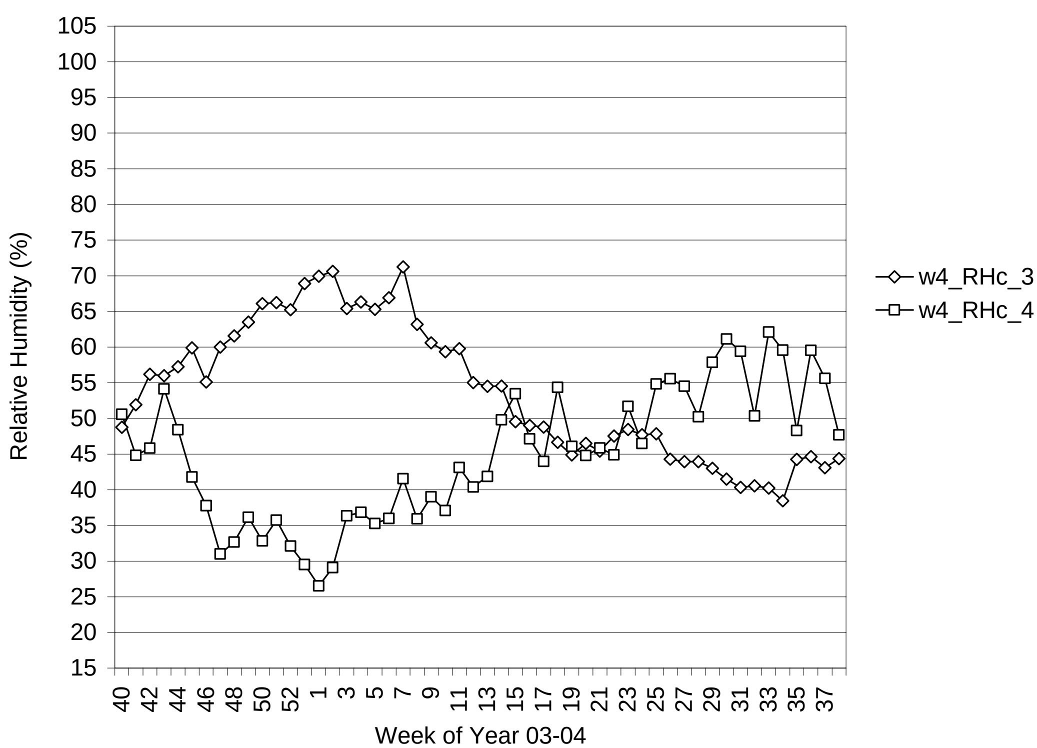


Figure A 4-3 Wall 4 - Temperature

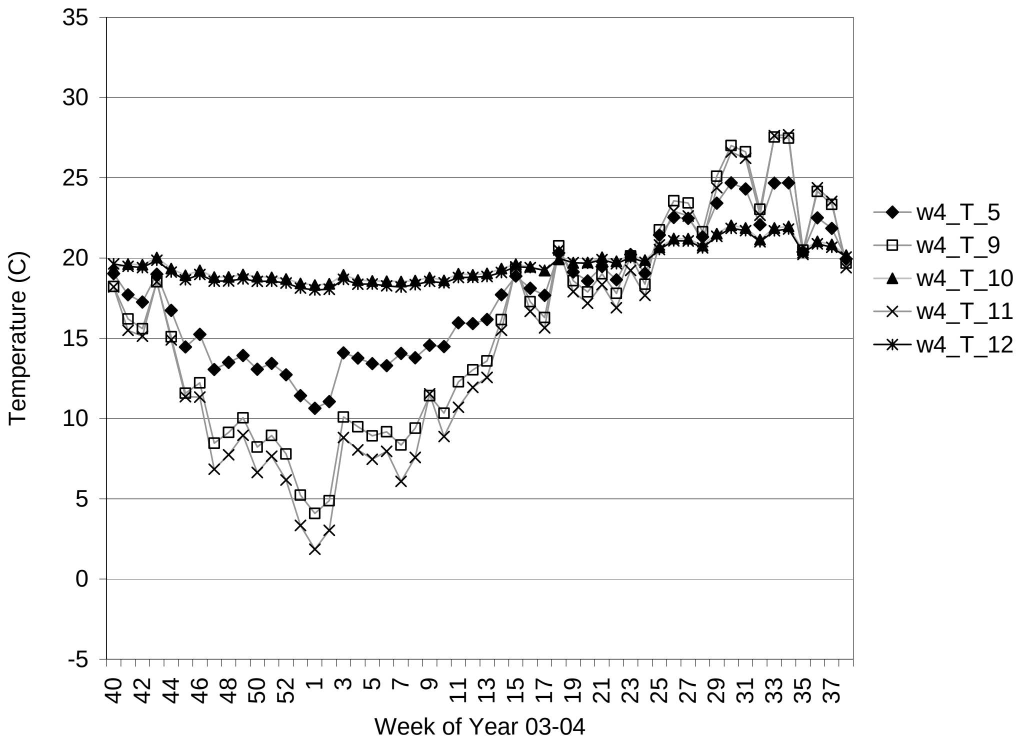


Figure A 4-4 Wall 4 – Vapor Pressure

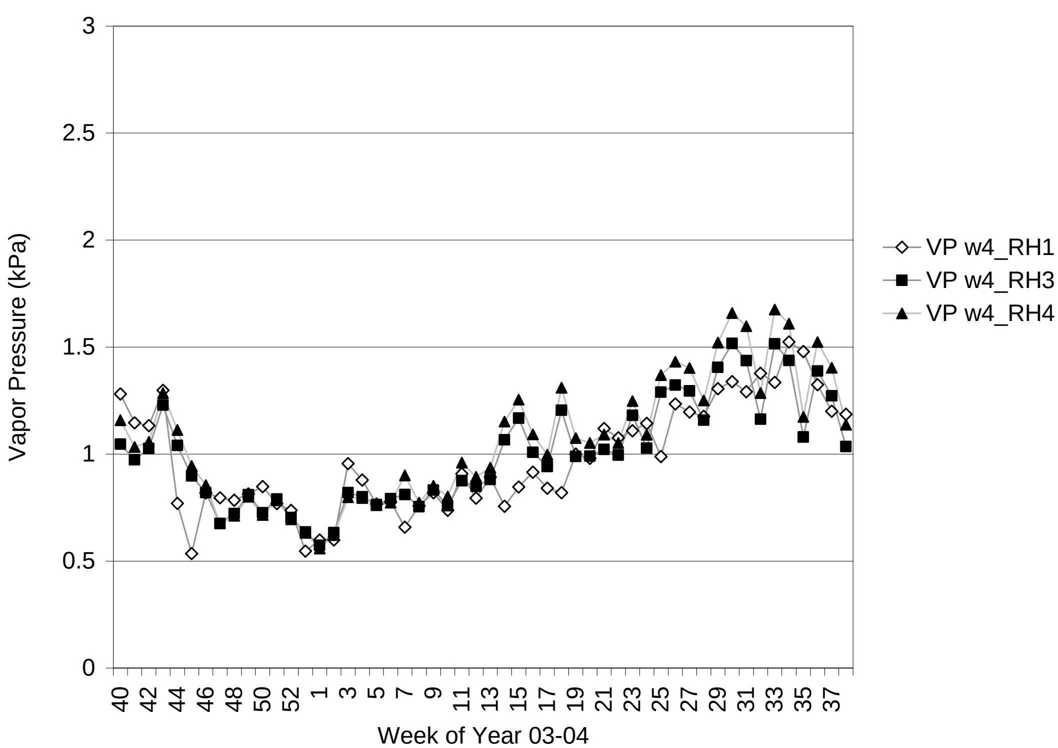


Figure A 5-1 Wall 5 – Wood Moisture Content

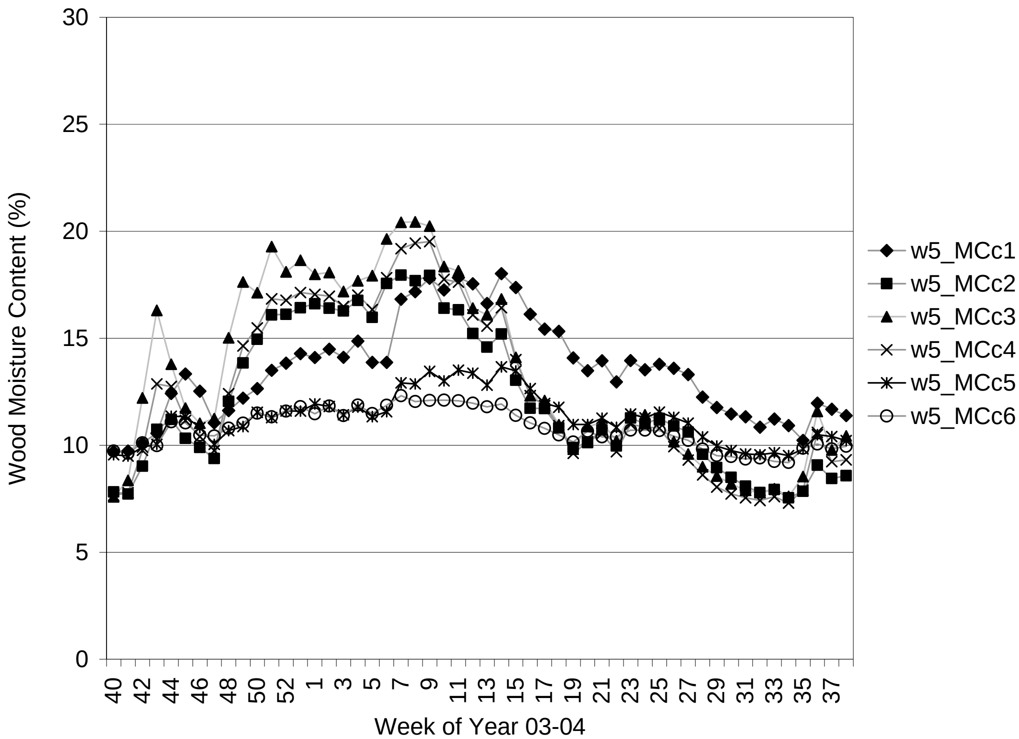


Figure A 5-2 Wall 5 – Cavity Relative Humidity

Figure A 5-3 Wall 5 - Temperature

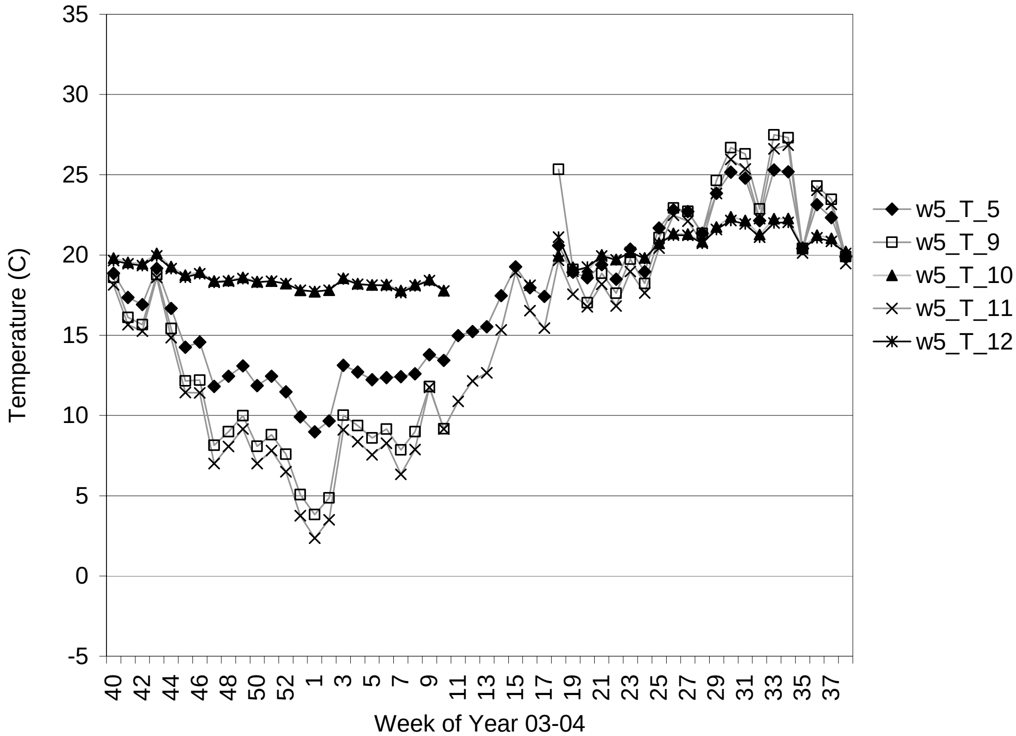


Figure A 5-4 Wall 5 – Vapor Pressure

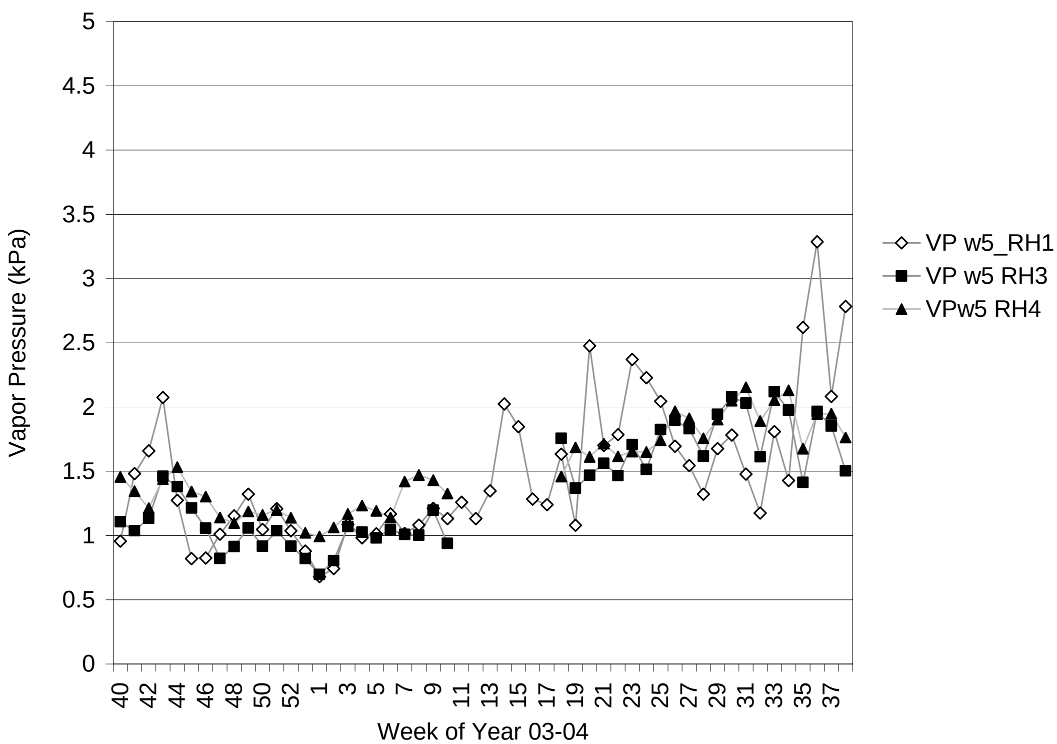


Figure A 6-1 Wall 6 – Wood Moisture Content

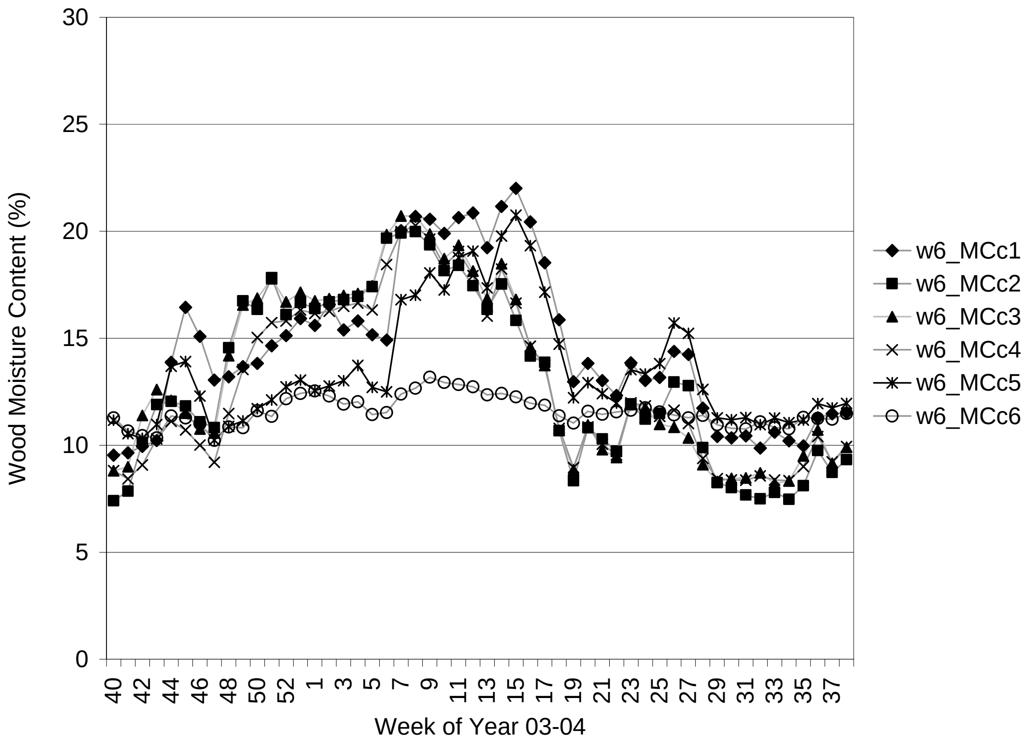


Figure A 6-2 Wall 6 – Cavity Relative Humidity

Figure A 6-3 Wall 6 - Temperature

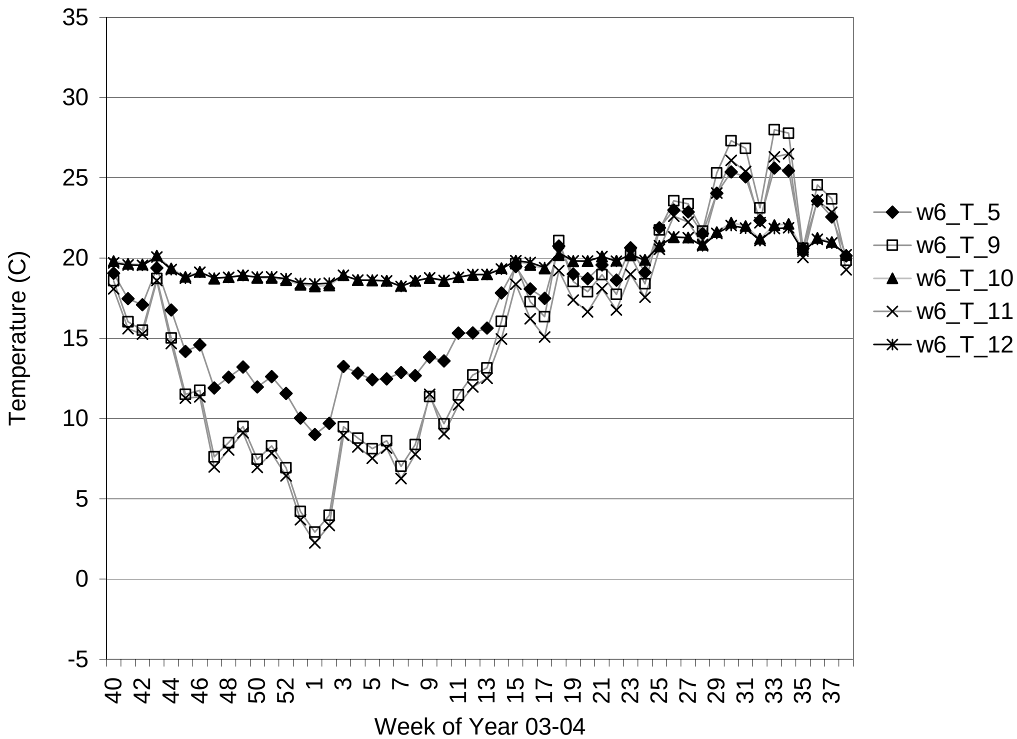


Figure A 6-4 Wall 6 – Vapor Pressure

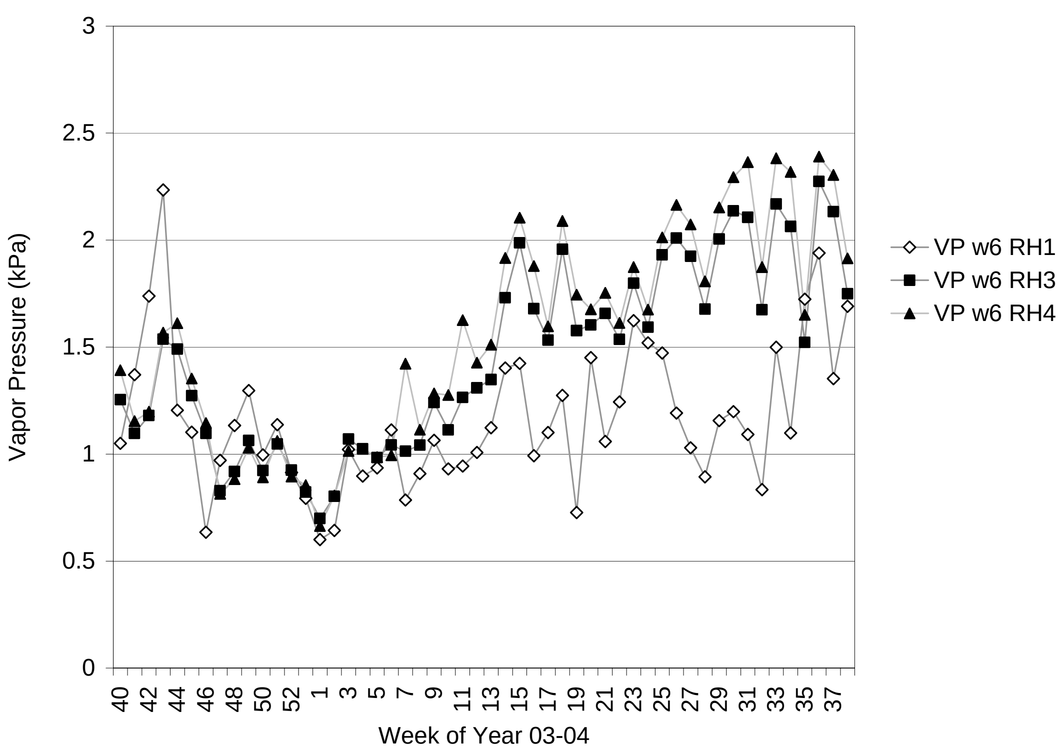


Figure A 7-1 Wall 7 – Wood Moisture Content

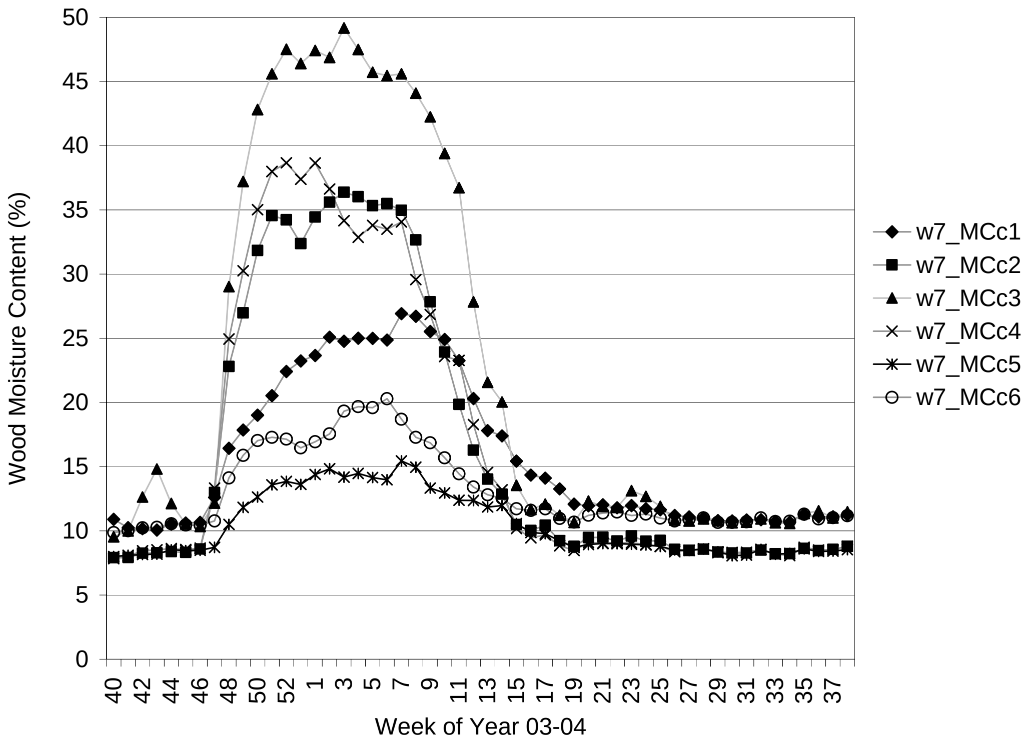


Figure A 7-2 Wall 7 – Cavity Relative Humidity

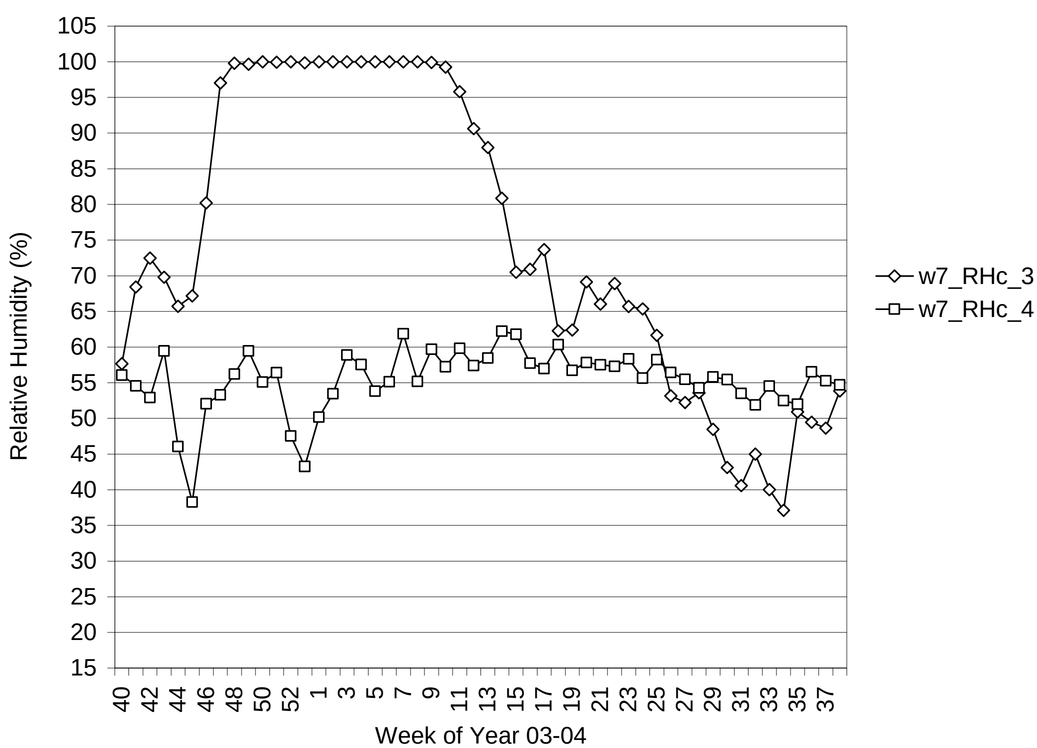


Figure A 7-3 Wall 7 - Temperature

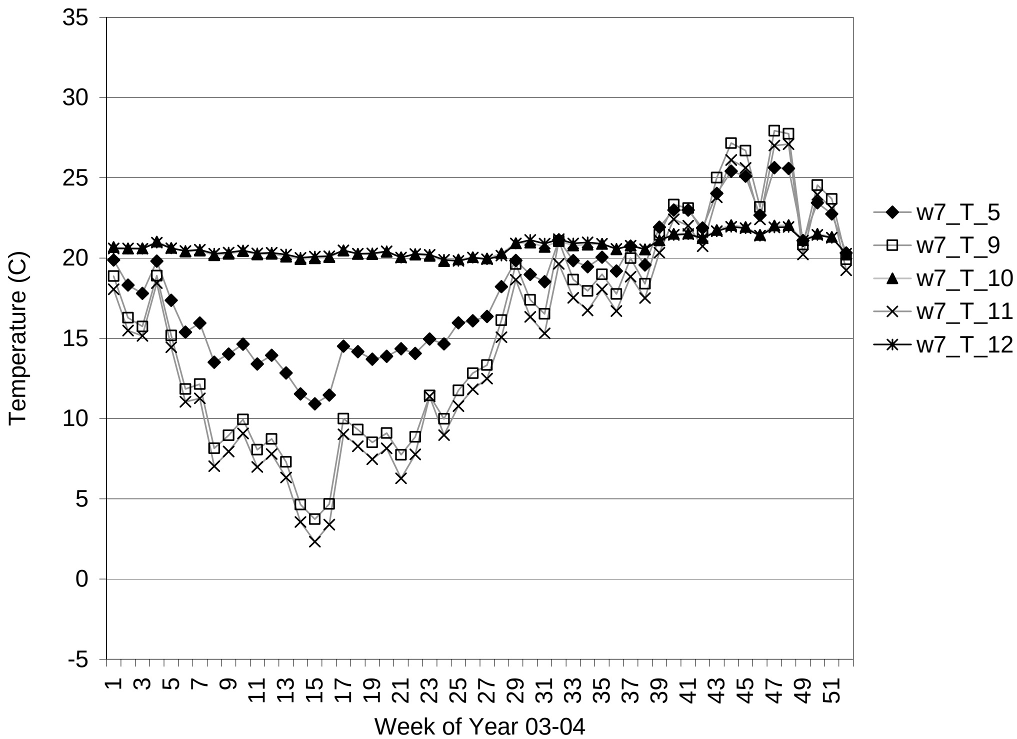


Figure A 7-4 Wall 7 – Vapor Pressure

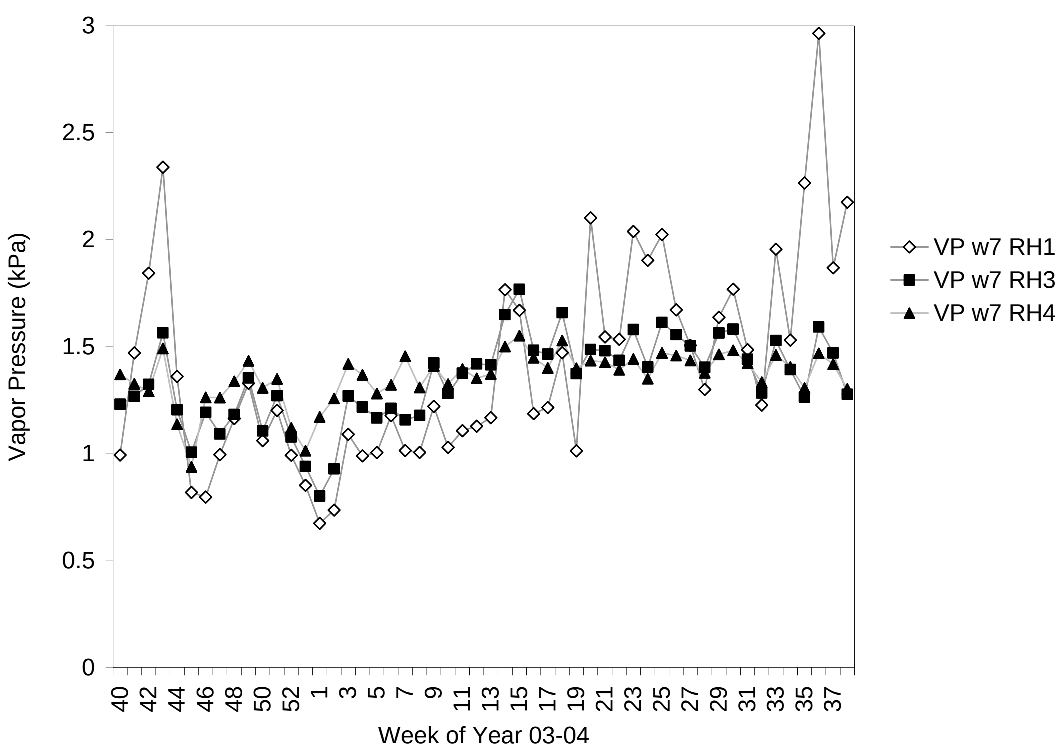


Figure A 8-1 Wall 8 – Wood Moisture Content

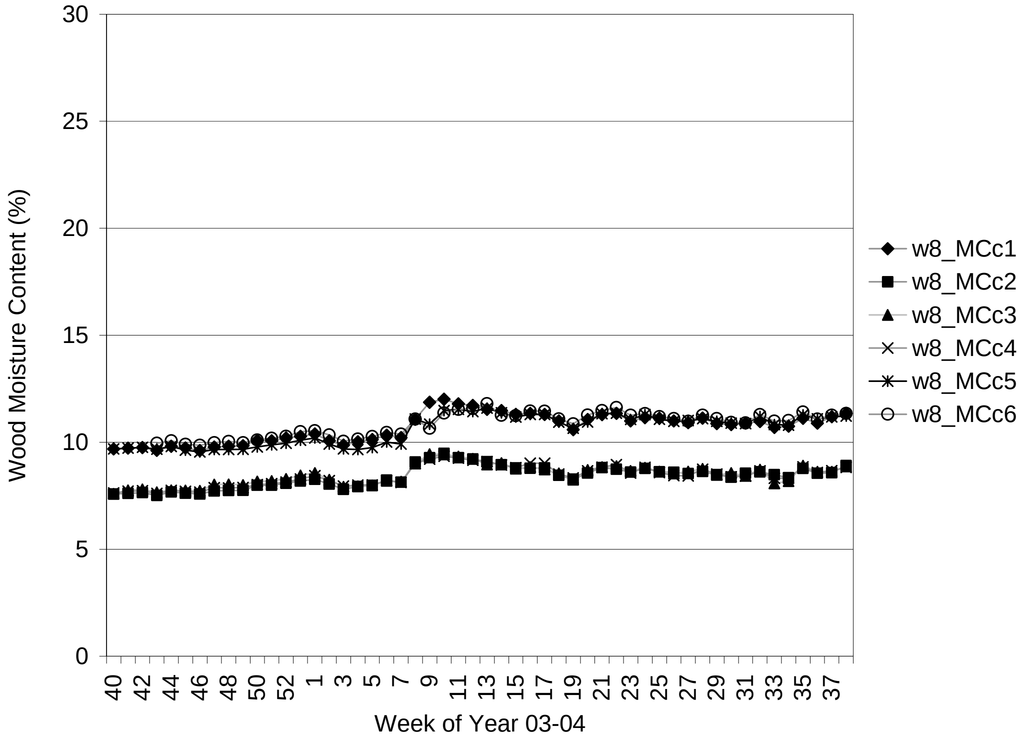


Figure A 8-2 Wall 8 – Cavity Relative Humidity

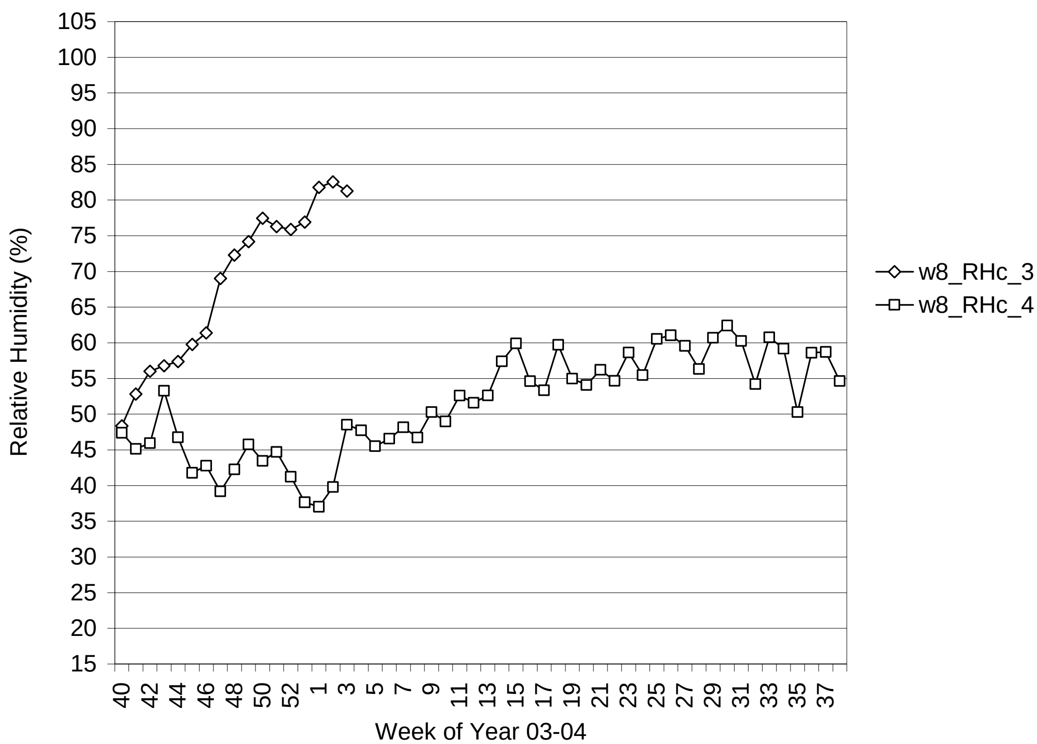


Figure A 8-3 Wall 8 - Temperature

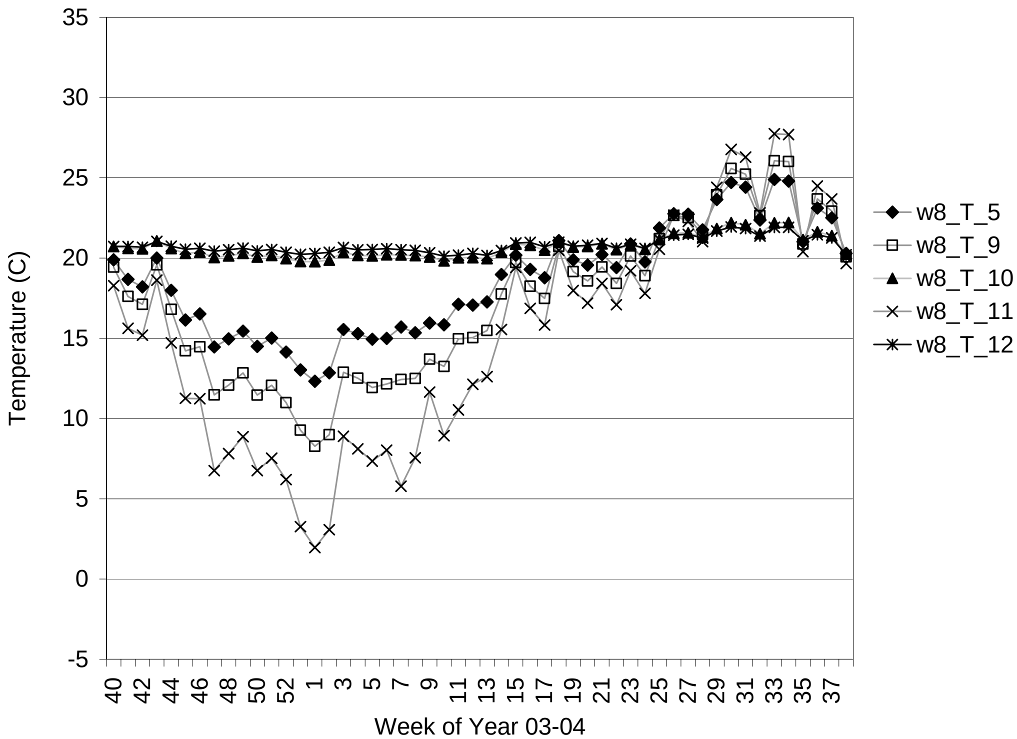


Figure A 8-4 Wall 8 – Vapor Pressure

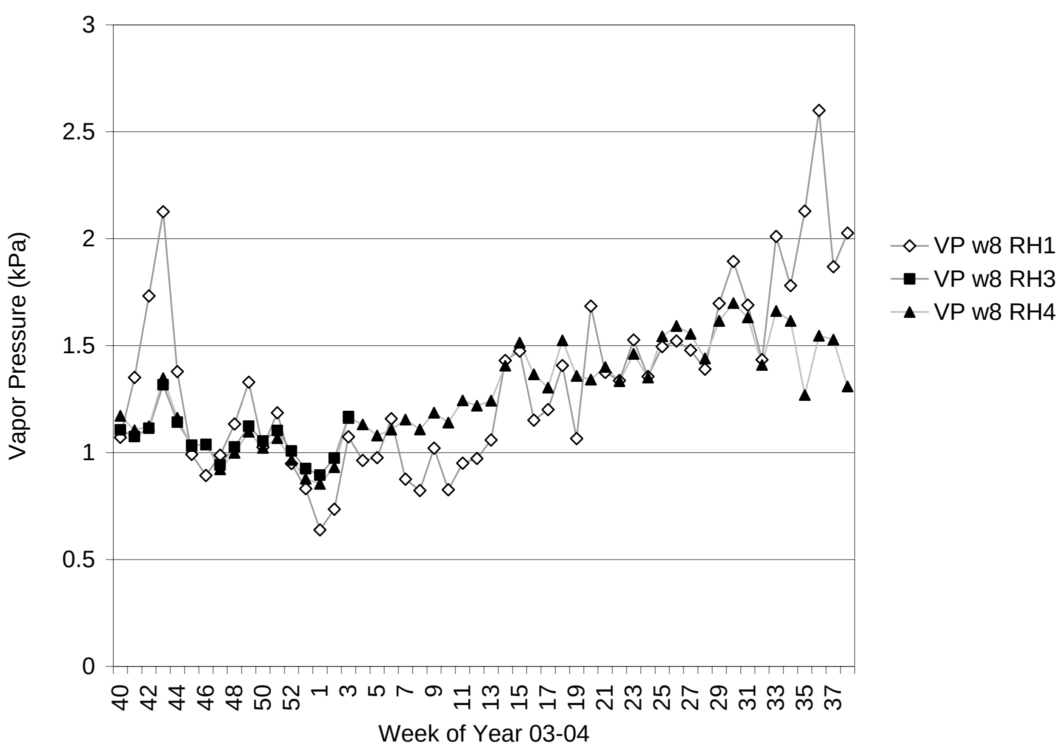


Figure A 9-1 Wall 9 – Wood Moisture Content

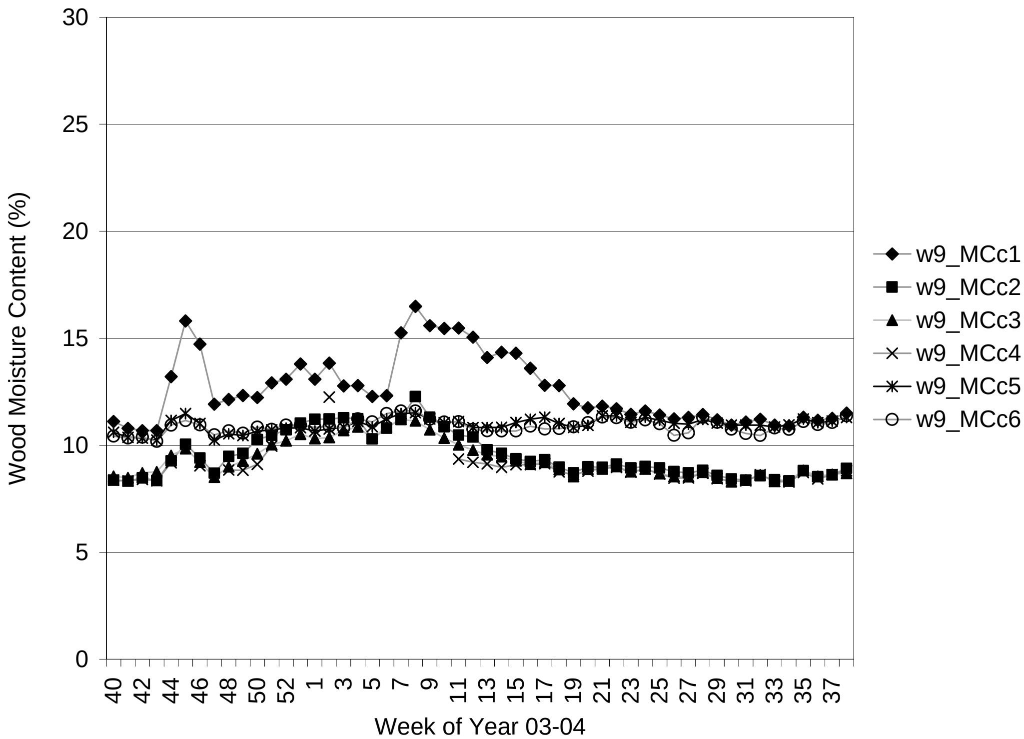


Figure A 9-2 Wall 9 – Cavity Relative Humidity

Figure A 9-3 Wall 9 - Temperature

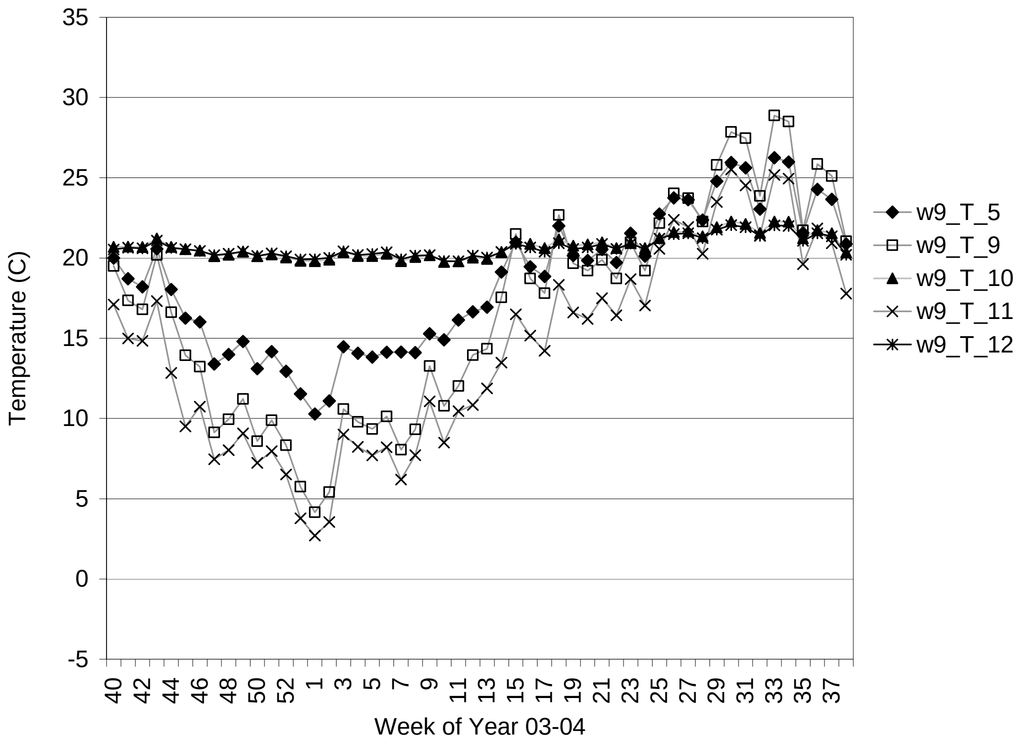


Figure A 9-4 Wall 9 – Vapor Pressure

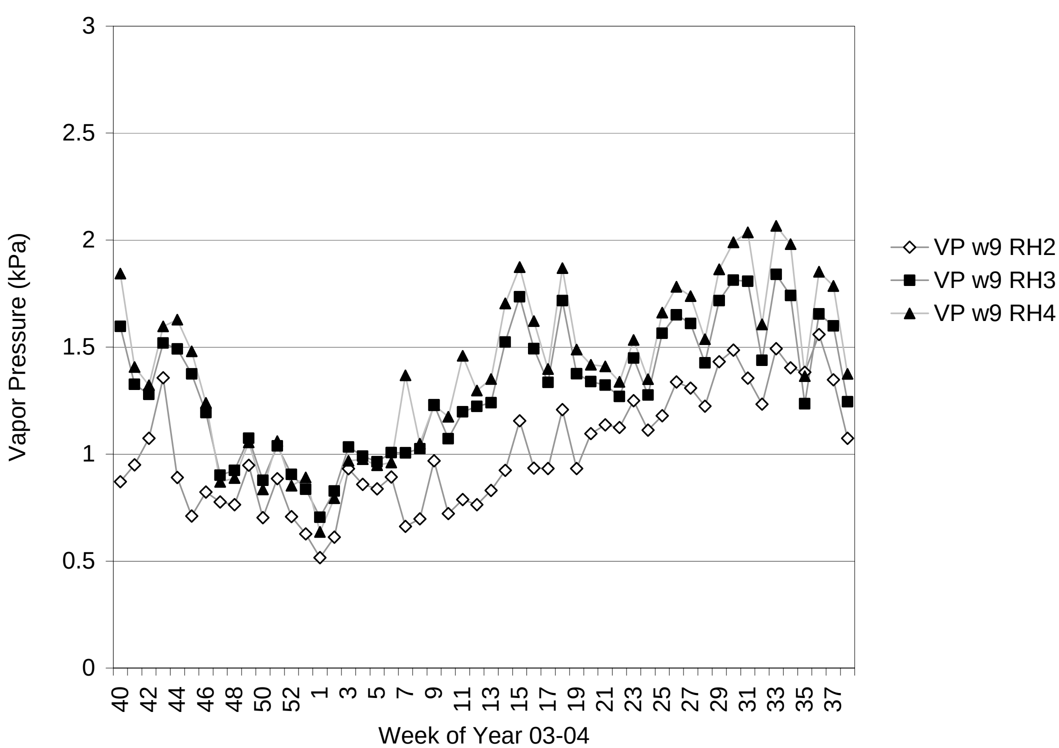


Figure A 10-1 Wall 10 – Wood Moisture Content

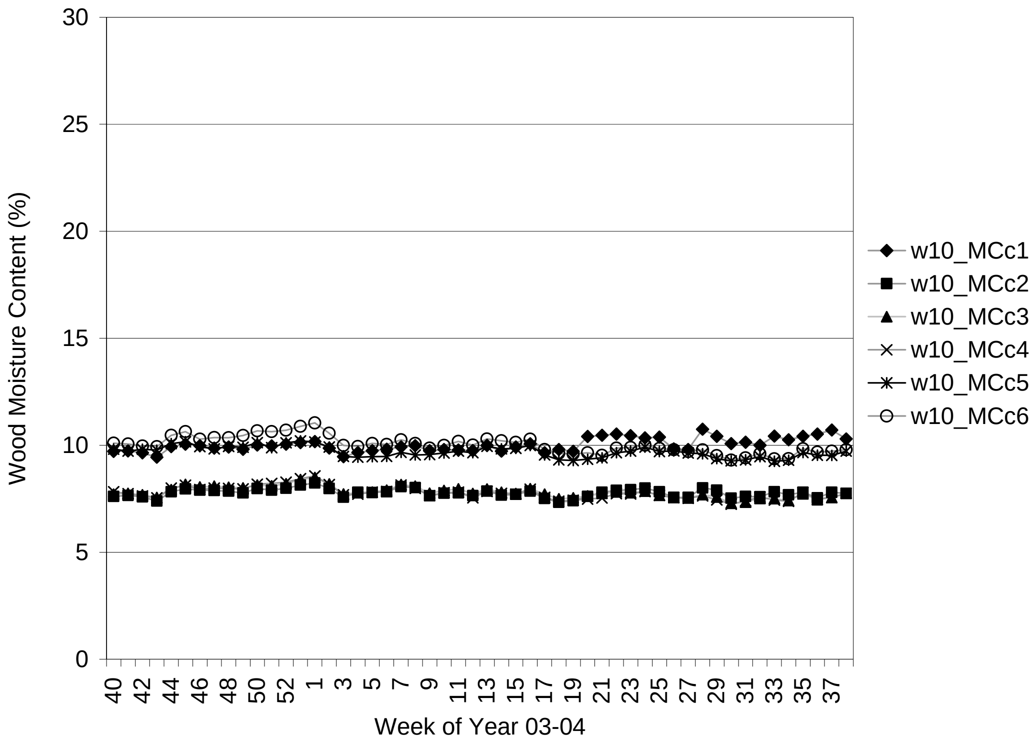


Figure A 10-2 Wall 10 – Cavity Relative Humidity

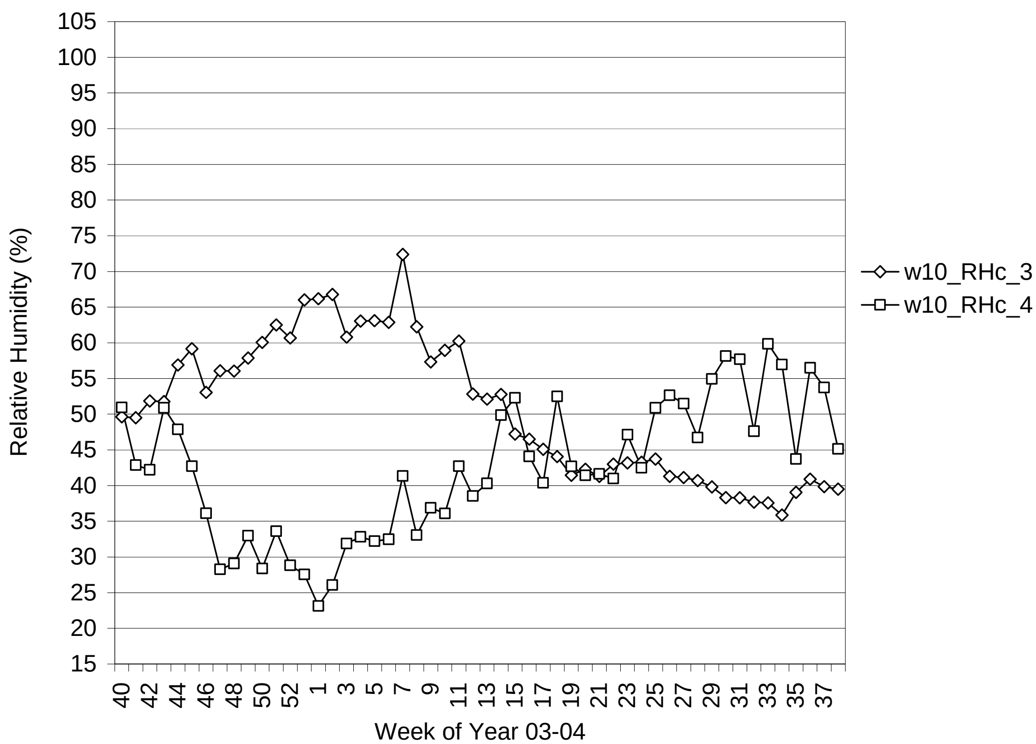


Figure A 10-3 Wall 10 - Temperature

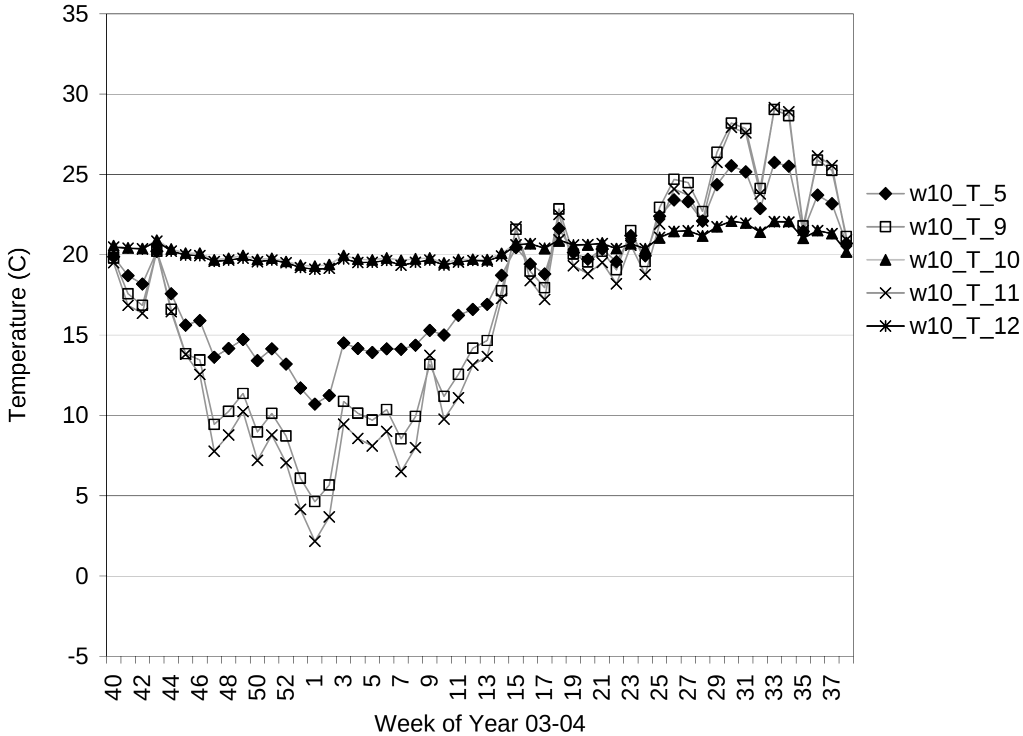


Figure A 10-4 Wall 10 – Vapor Pressure

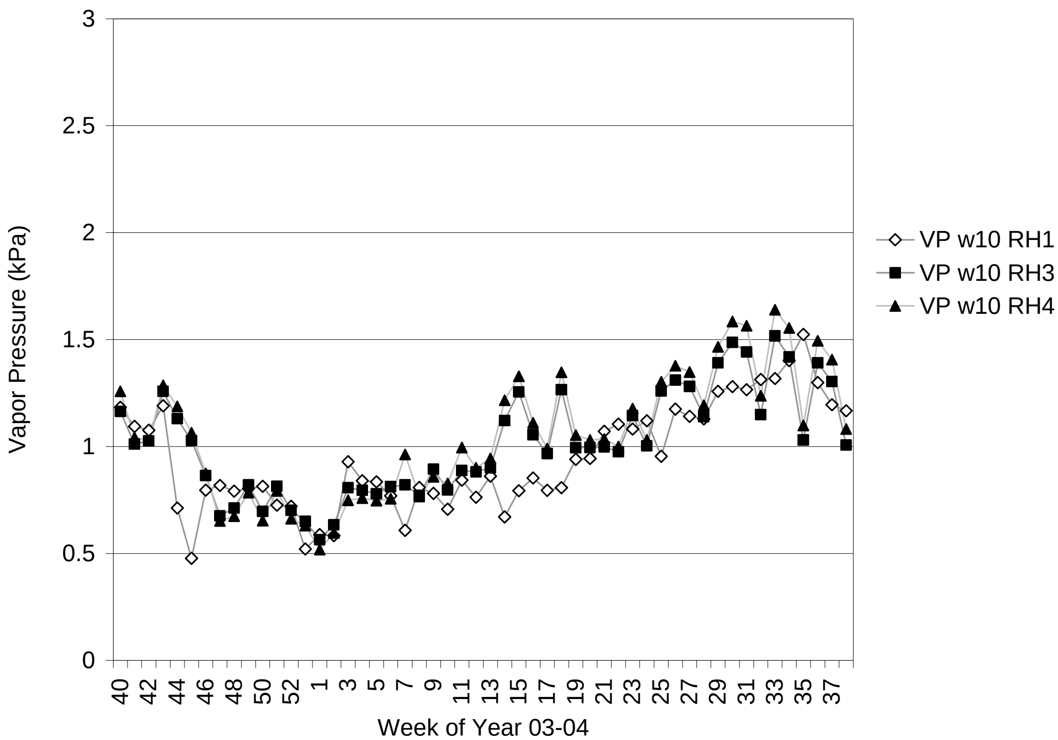


Figure A 11-1 Wall 11 – Wood Moisture Content

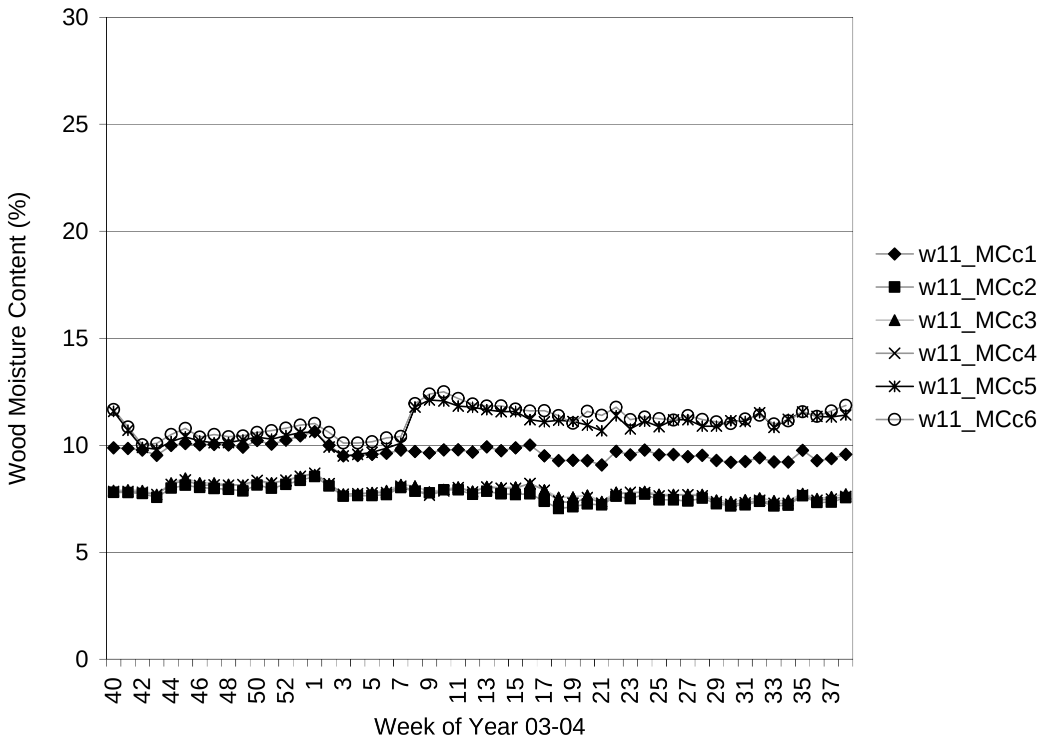


Figure A 11-2 Wall 11 – Cavity Relative Humidity

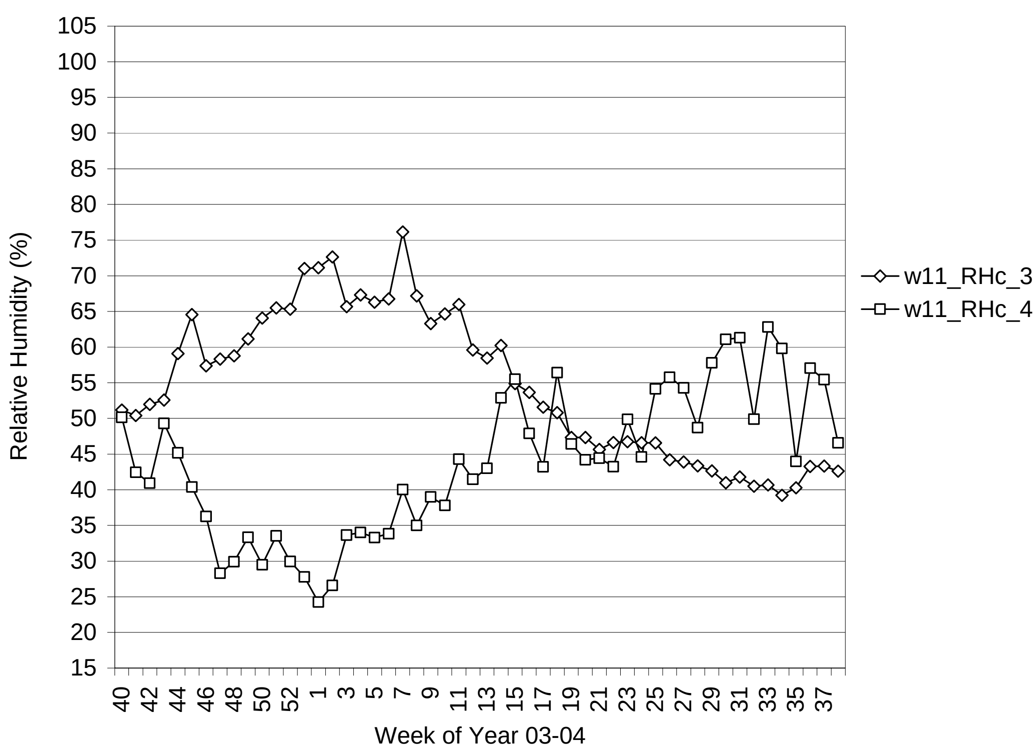


Figure A 11-3 Wall 11 - Temperature

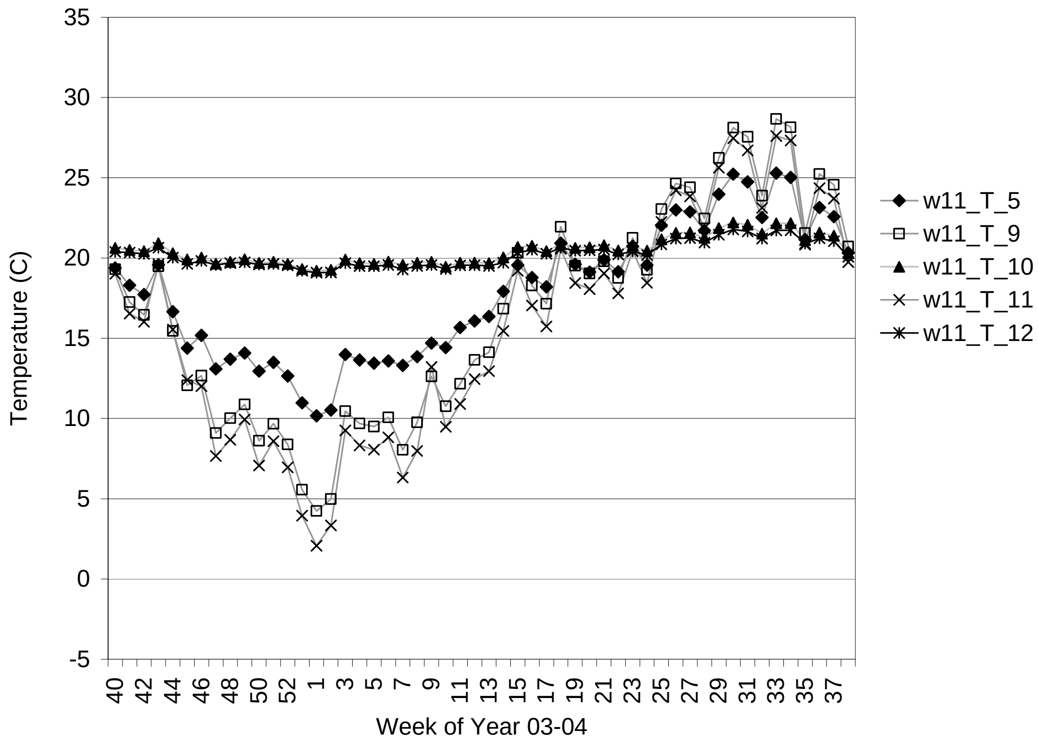


Figure A 11-4 Wall 11 – Vapor Pressure

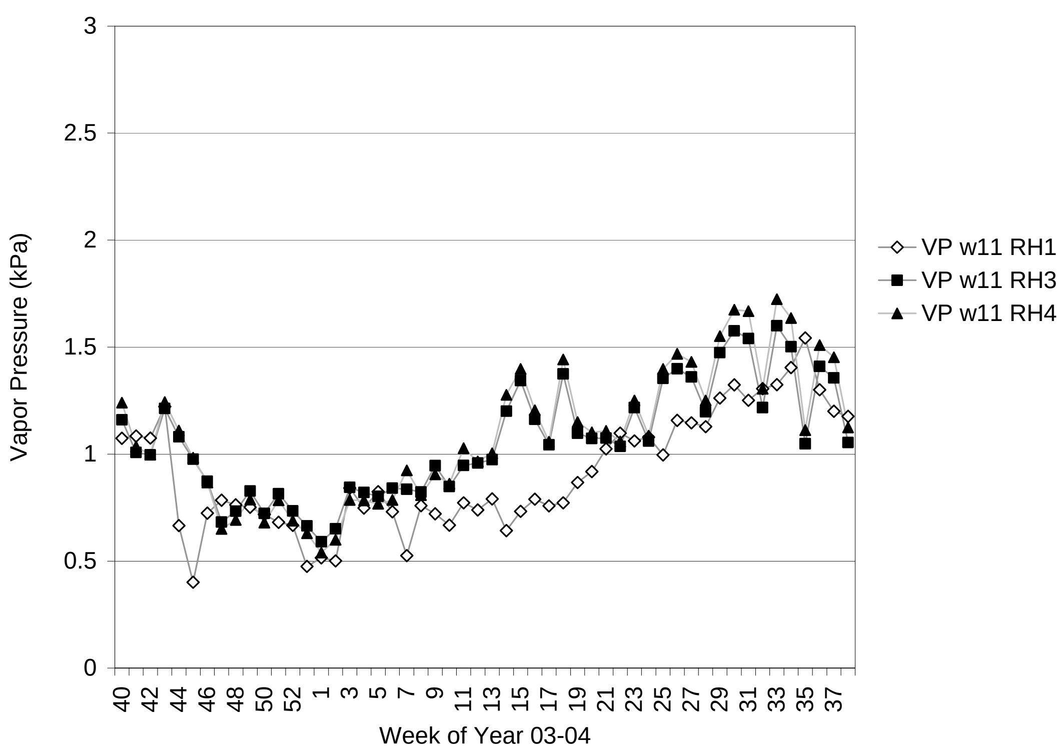


Figure A 12-1 Wall 12 – Wood Moisture Content

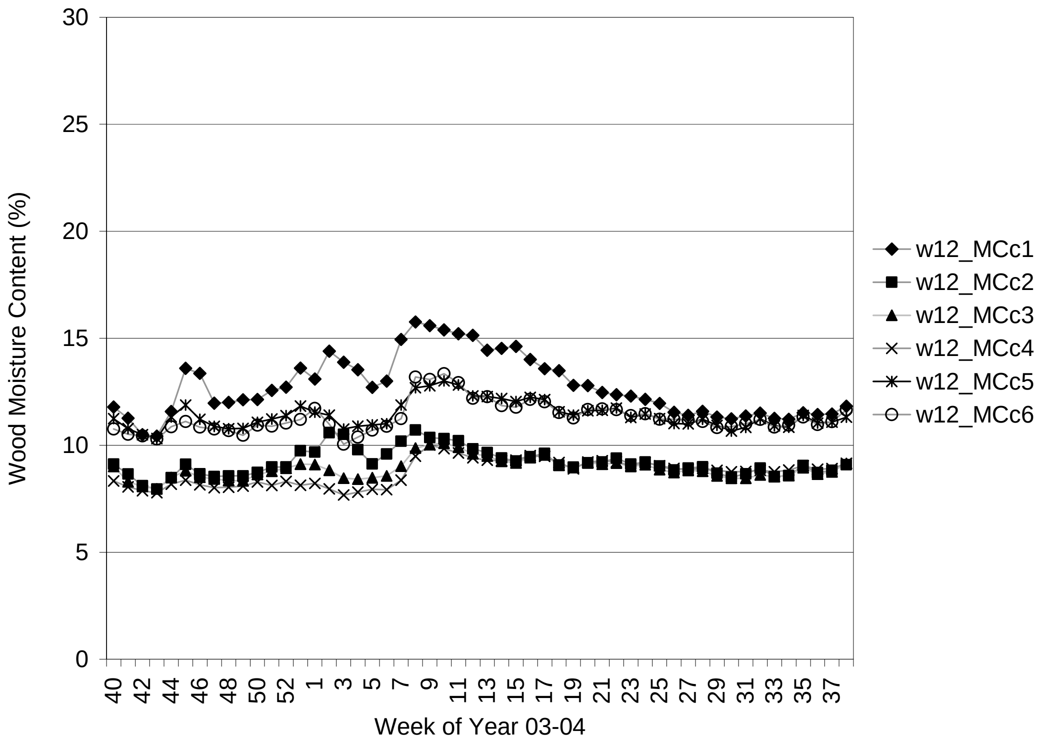


Figure A 12-2 Wall 12 – Cavity Relative Humidity

Figure A 12-3 Wall 12 - Temperature

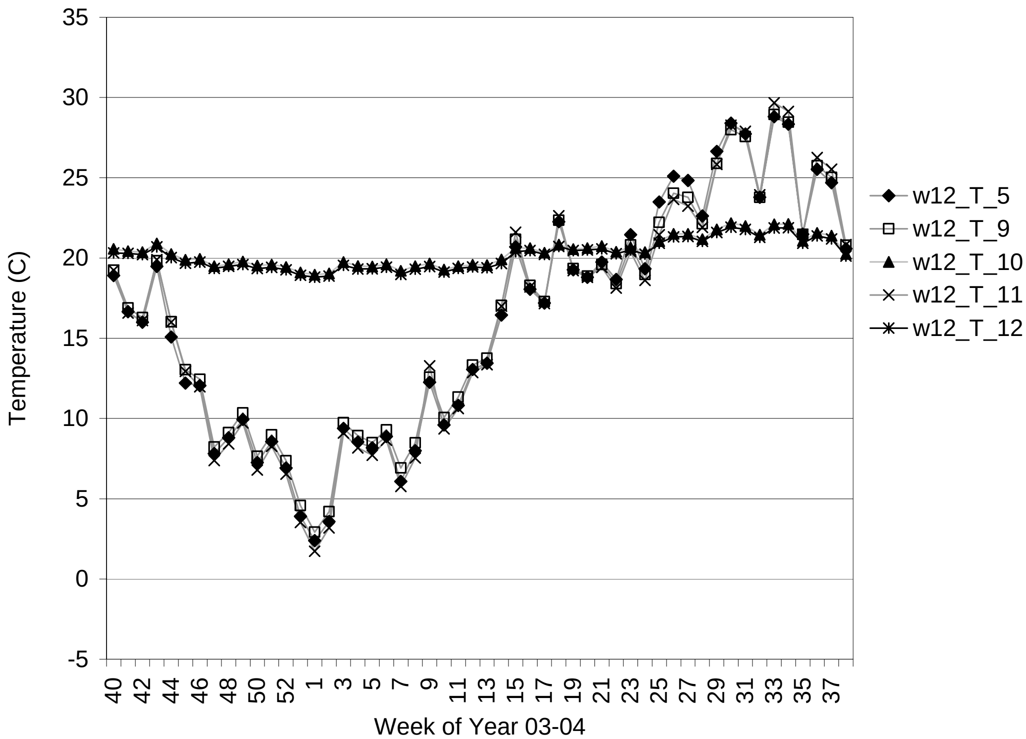


Figure A 12-4 Wall 12 – Vapor Pressure

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

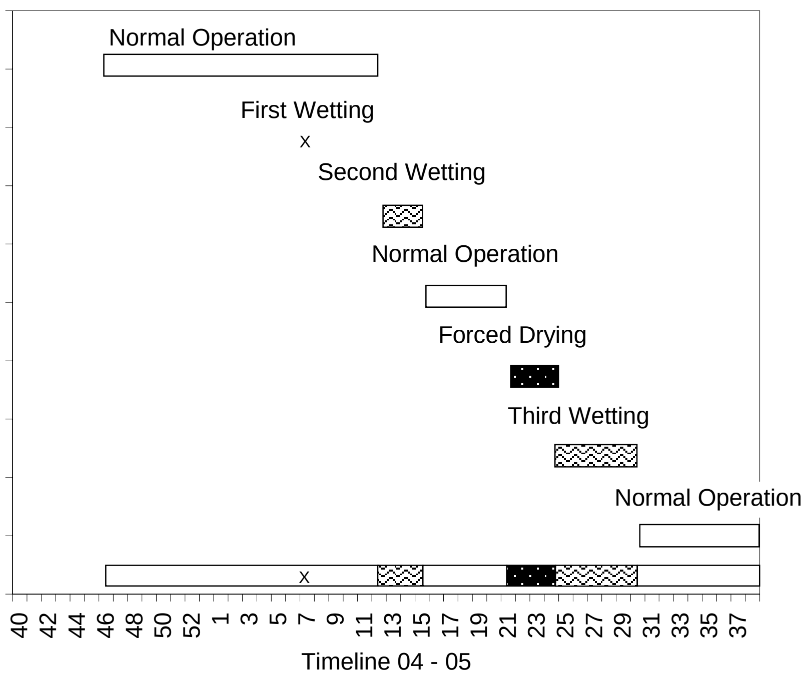


Figure B S1-1 S1 – Wood Moisture Content

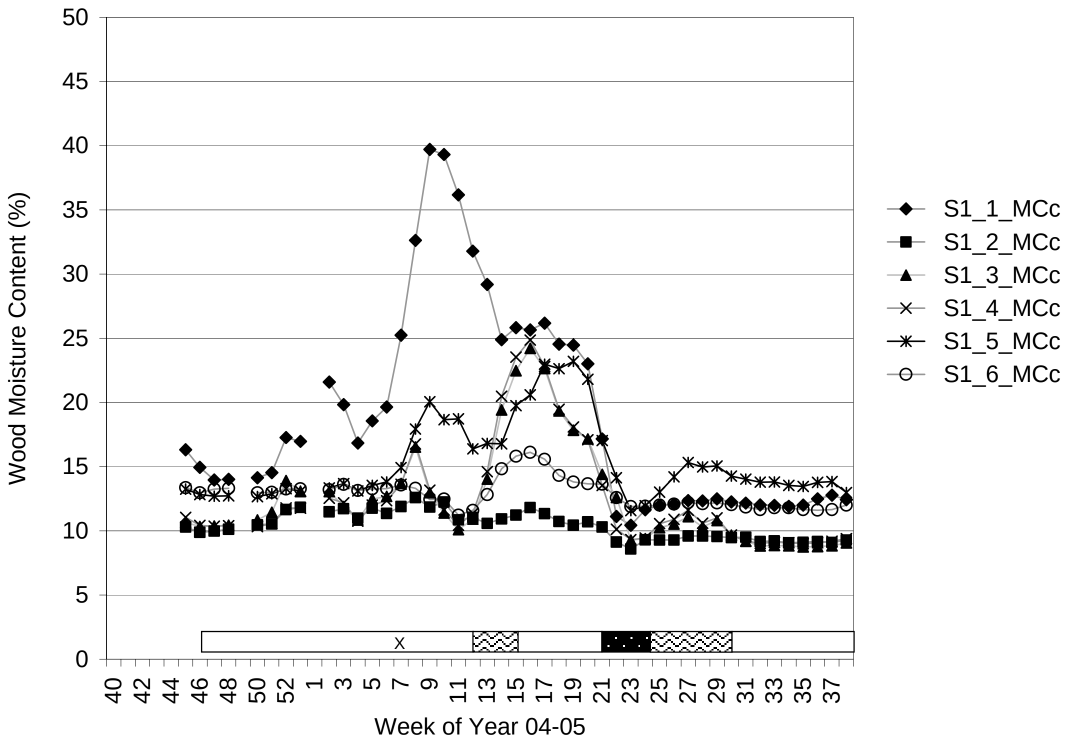


Figure B S1-2 S1 – Cavity Relative Humidity

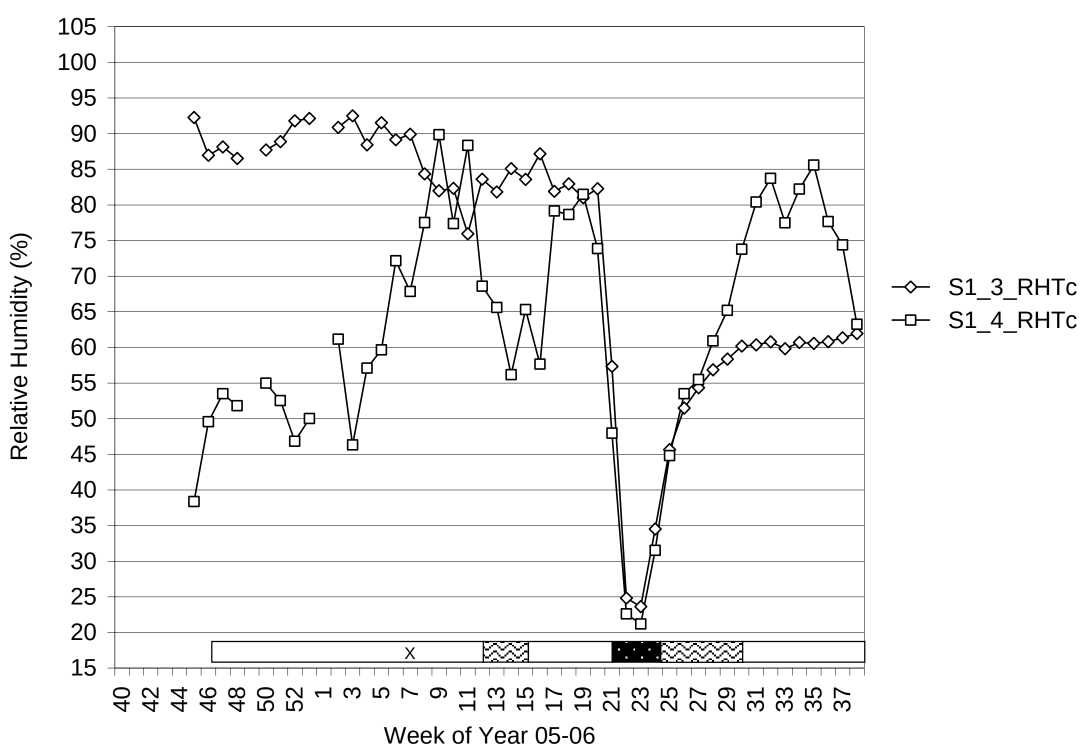


Figure B S1-3 S1 - Temperature

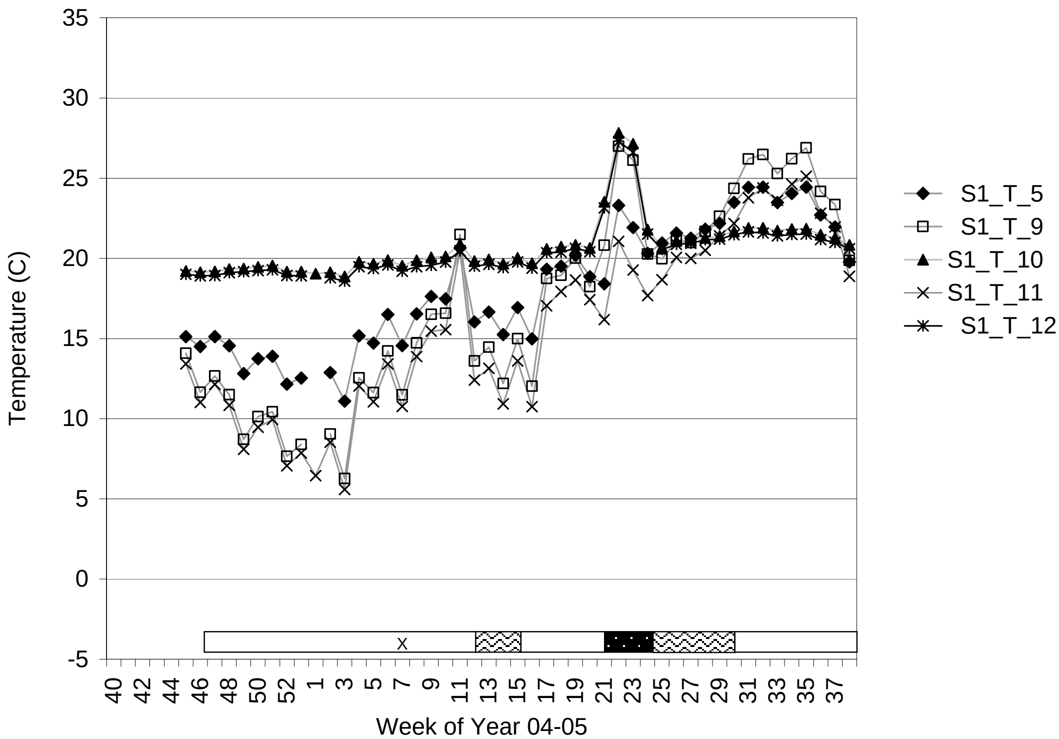


Figure B S1-4 S1 – Vapor Pressure

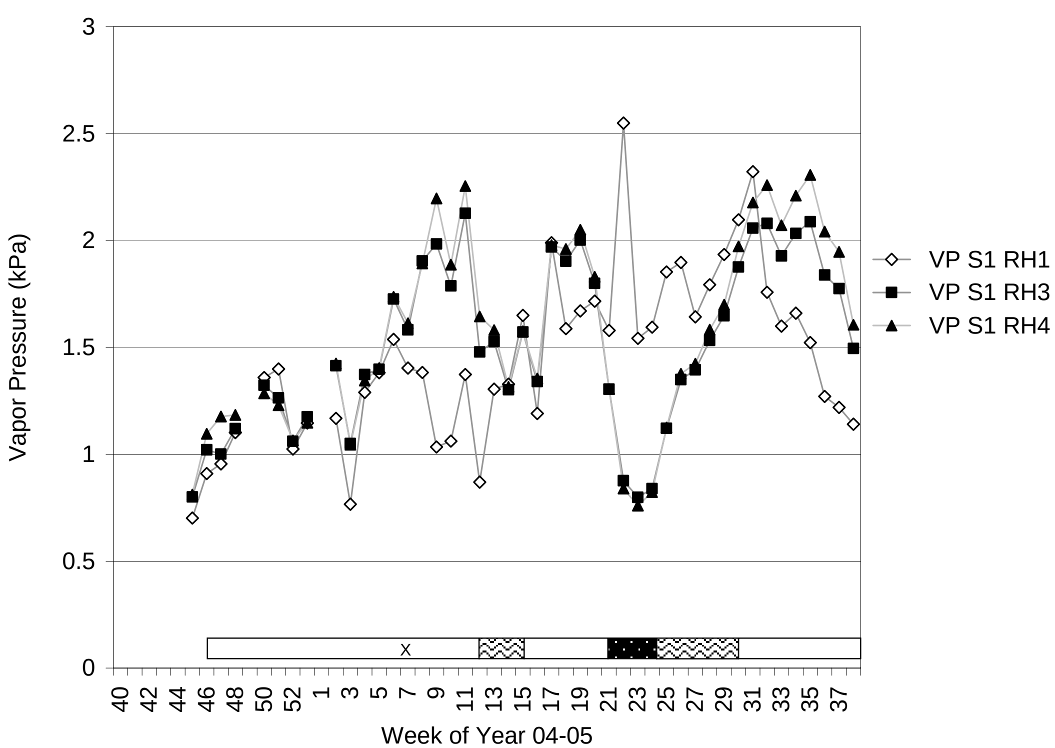


Figure B S2-1 S2– Wood Moisture Content

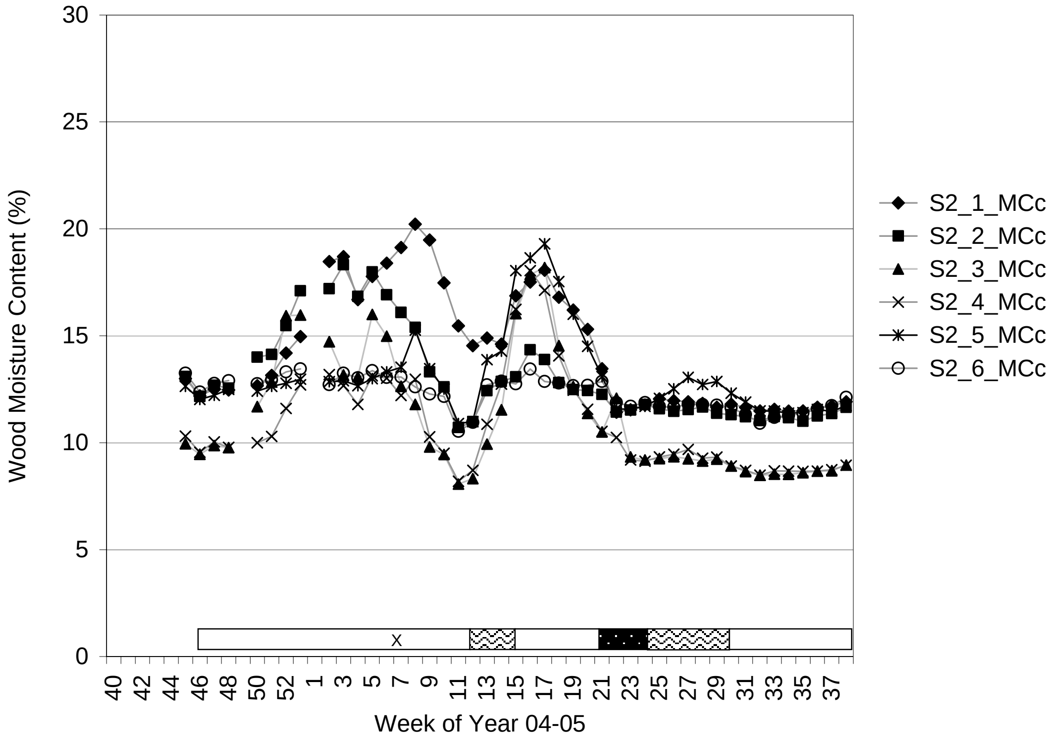


Figure B S2-2 S2– Cavity Relative Humidity

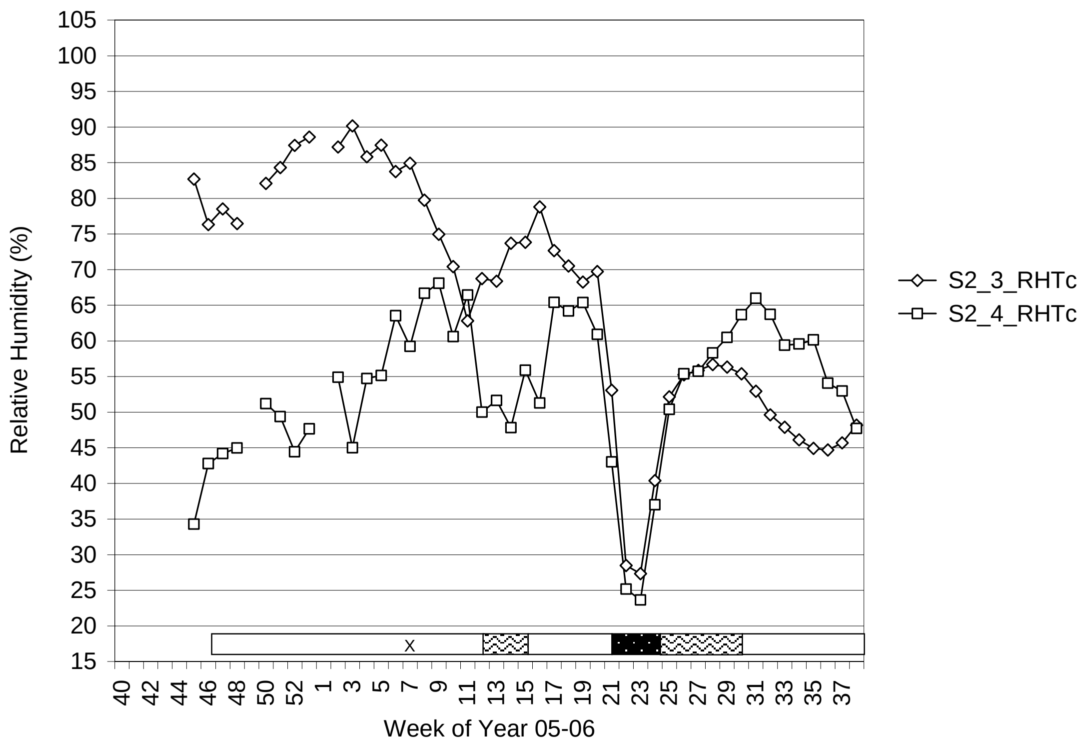


Figure B S2-3 S2- Temperature

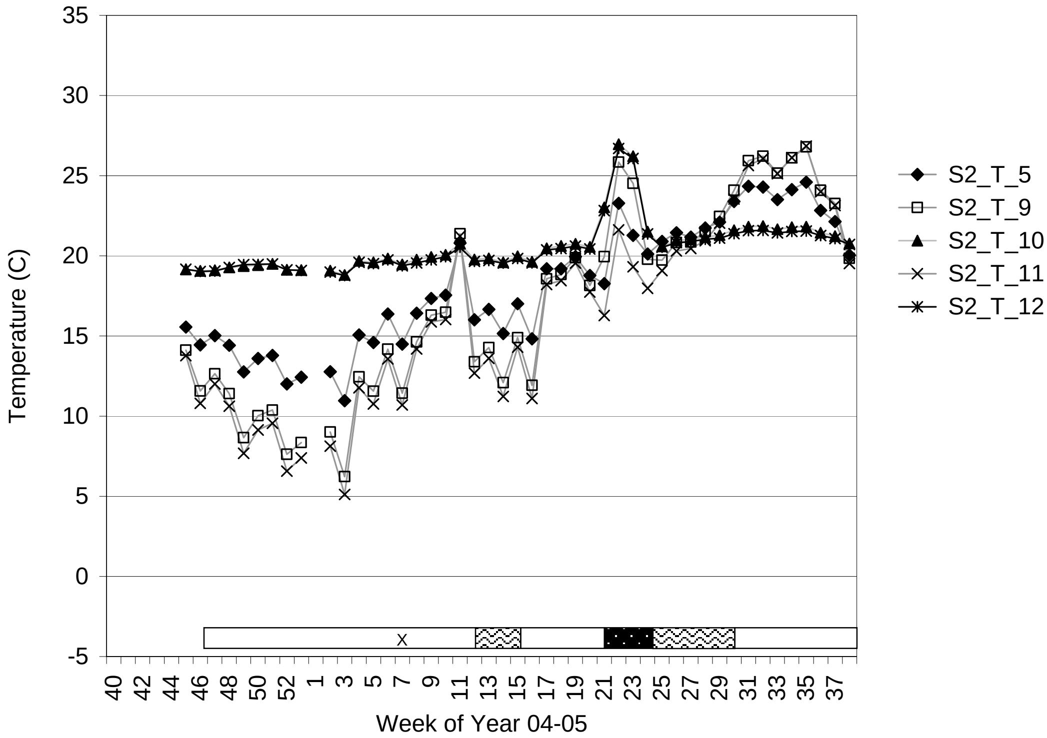


Figure B S2-4 S2 – Vapor Pressure

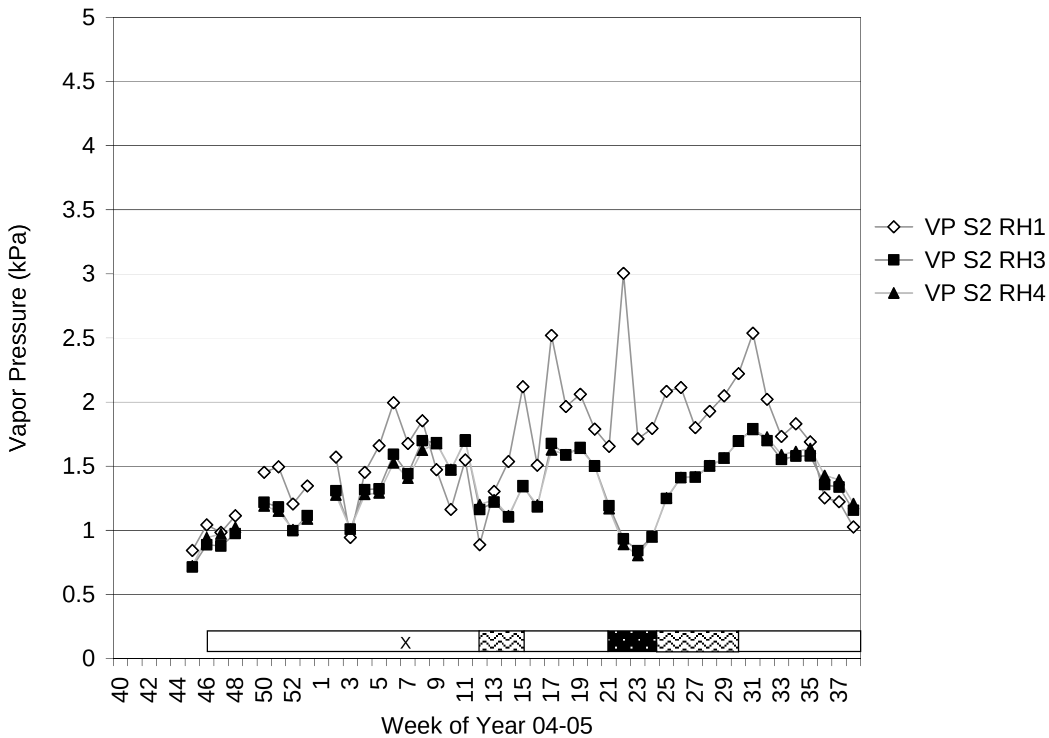


Figure B S3-1 S3 – Wood Moisture Content

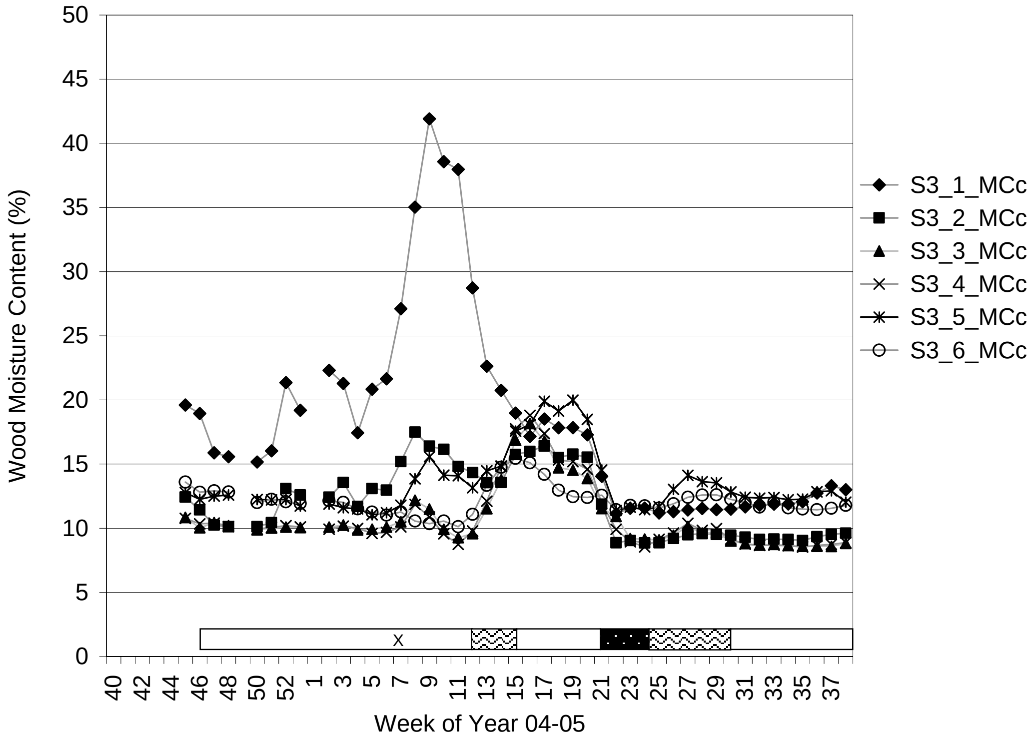


Figure B S3-2 S3 – Cavity Relative Humidity

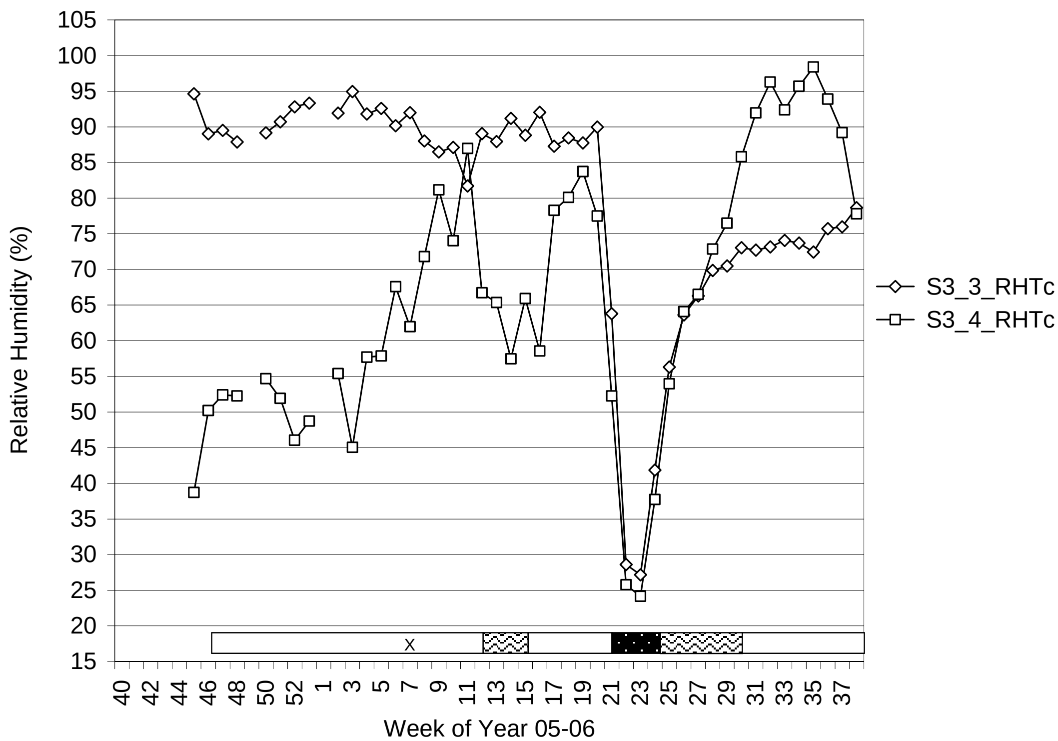


Figure B S3-3 S3 - Temperature

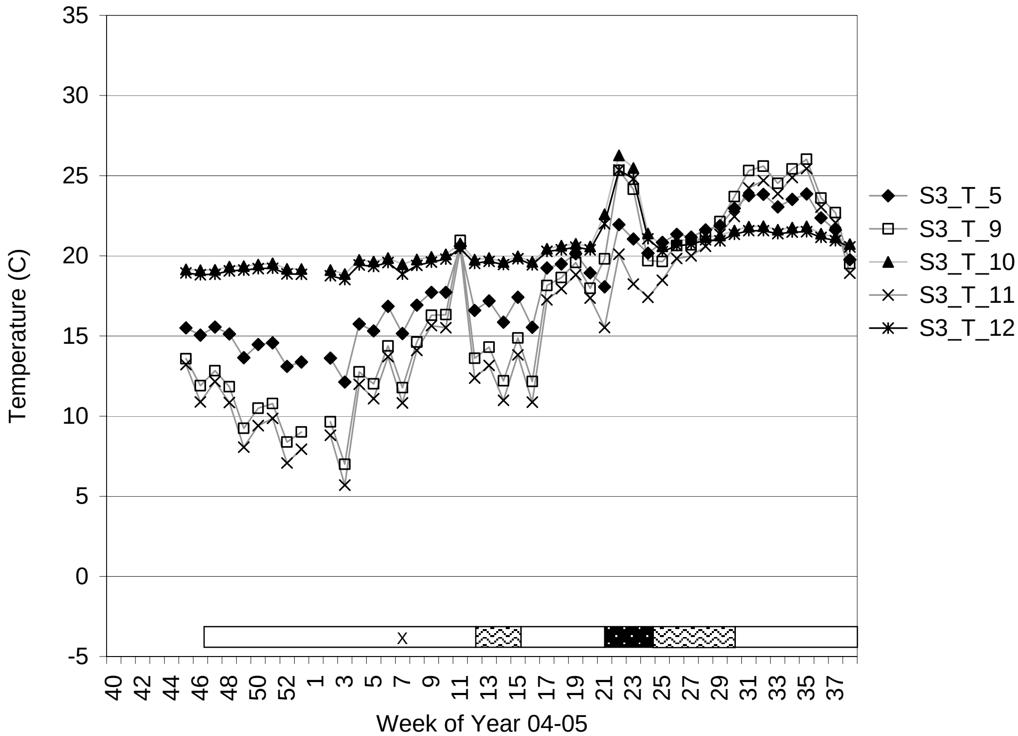


Figure B S3-4 S3 – Vapor Pressure

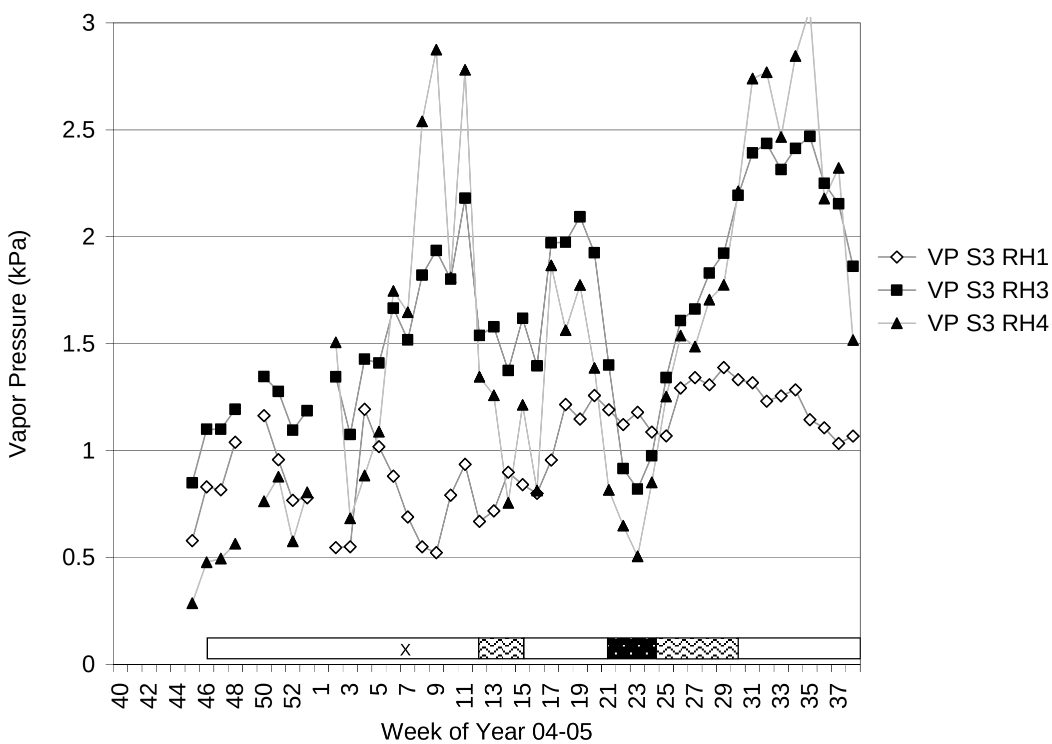


Figure B S4-1 S4 – Wood Moisture Content

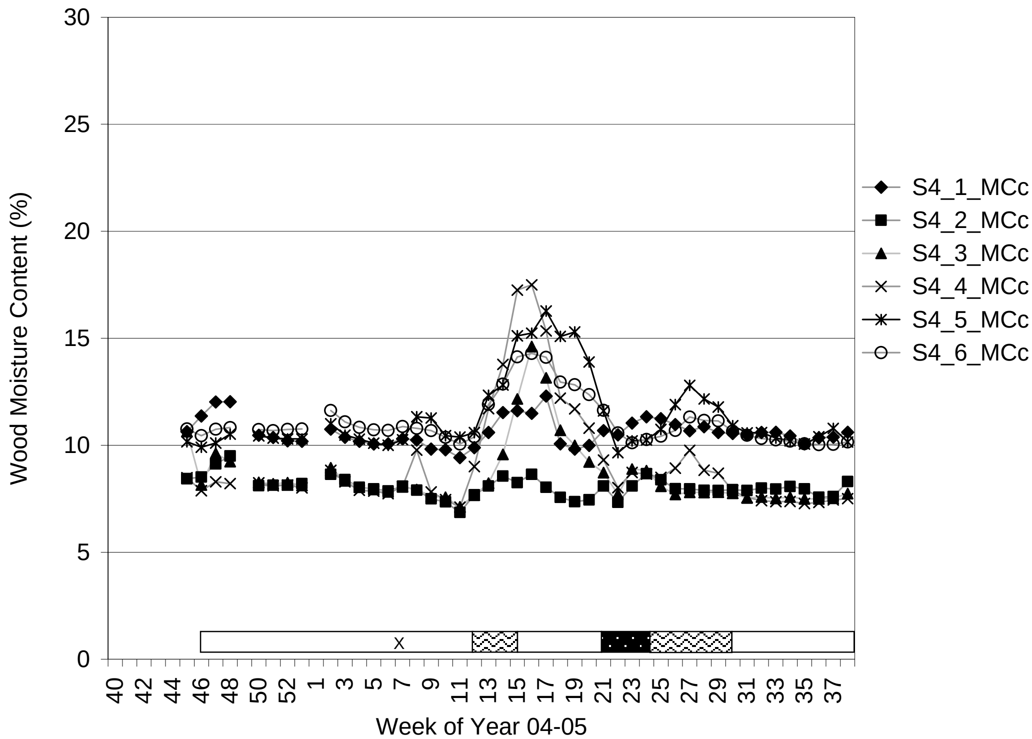
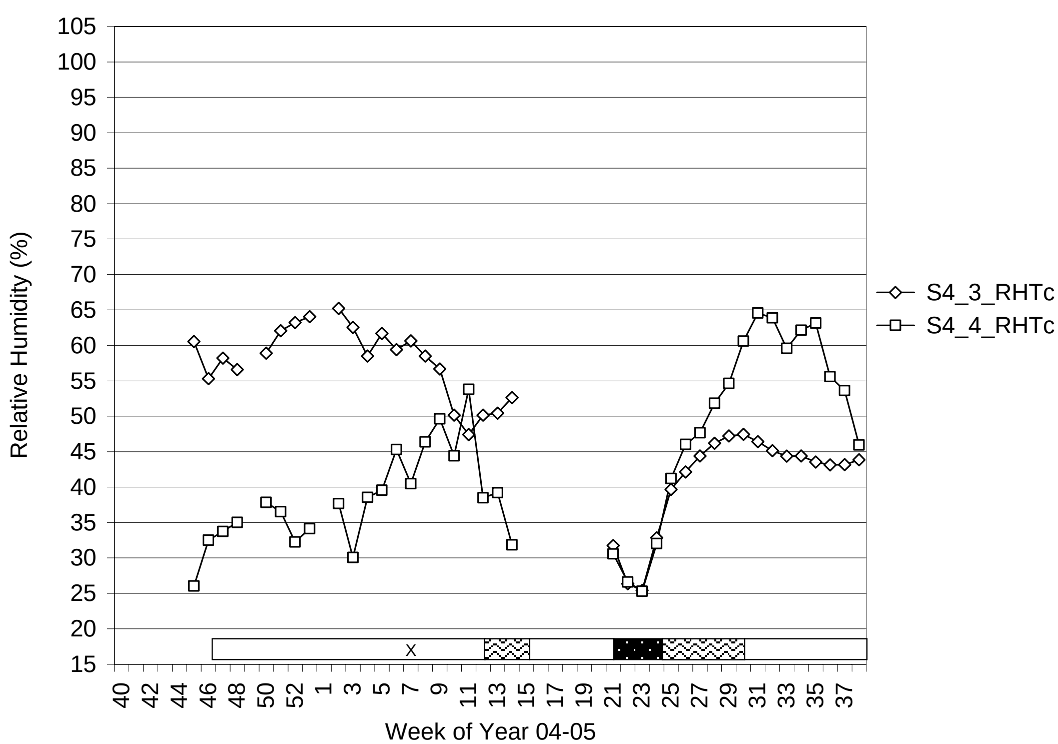


Figure B S4-2 S4 – Cavity Relative Humidity



4

Figure B S4-3 S4- Temperature

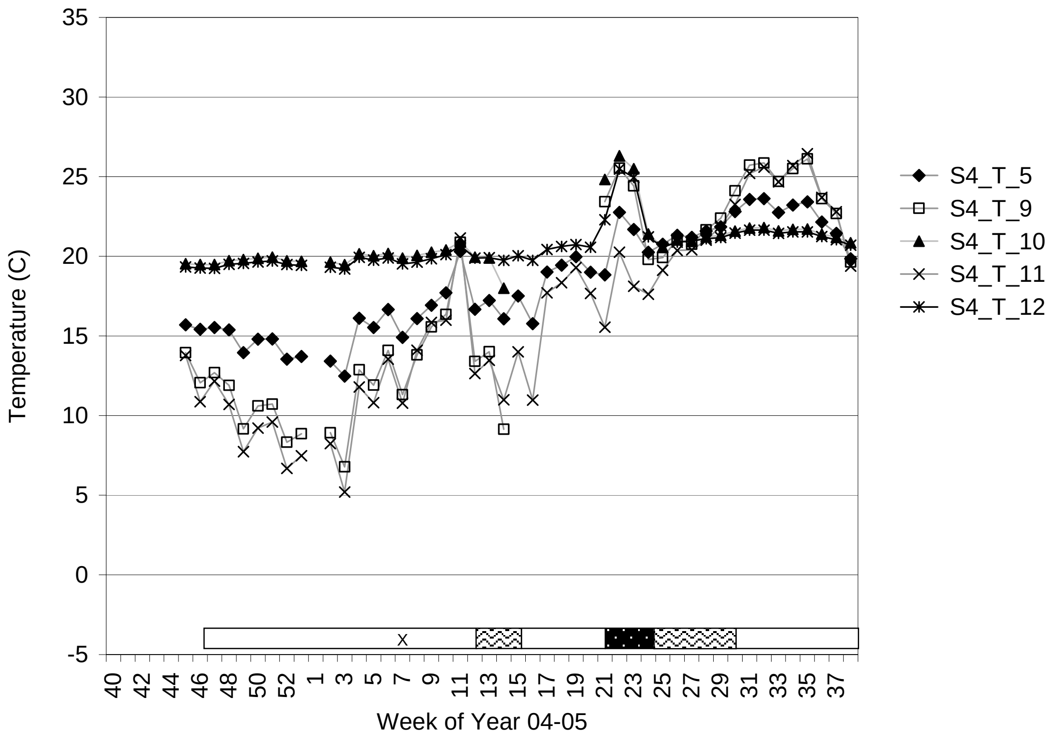


Figure B S4-4 S4 - Vapor Pressure

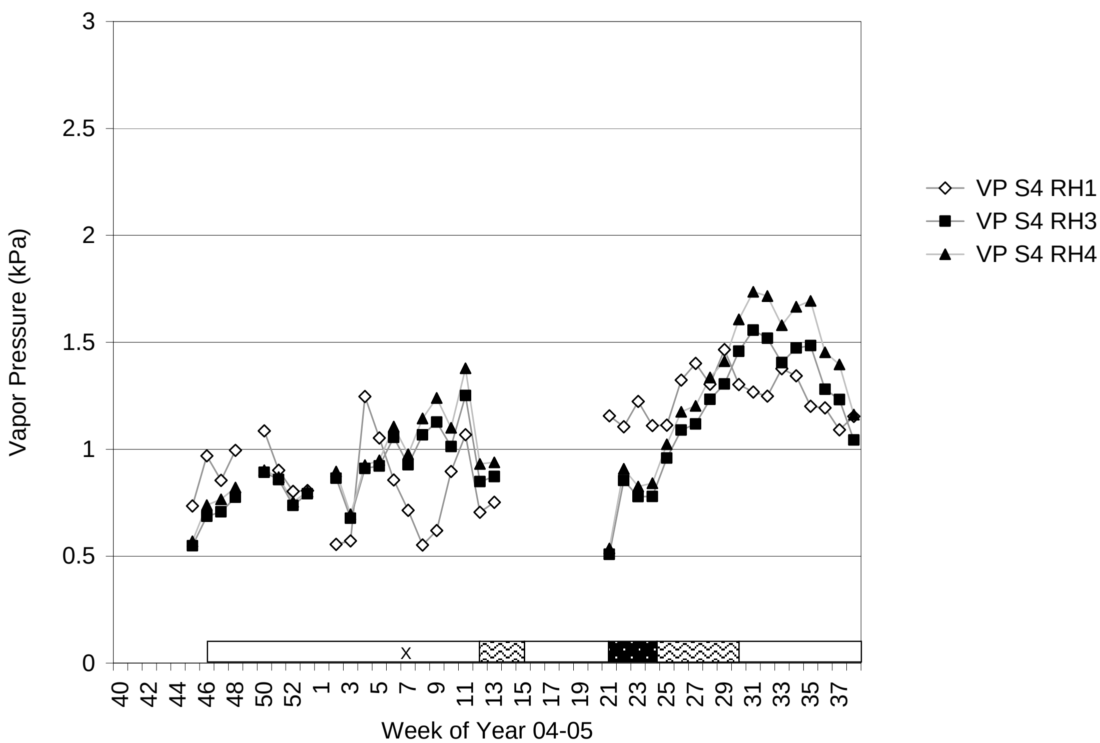


Figure B S5-1 S5 – Wood Moisture Content

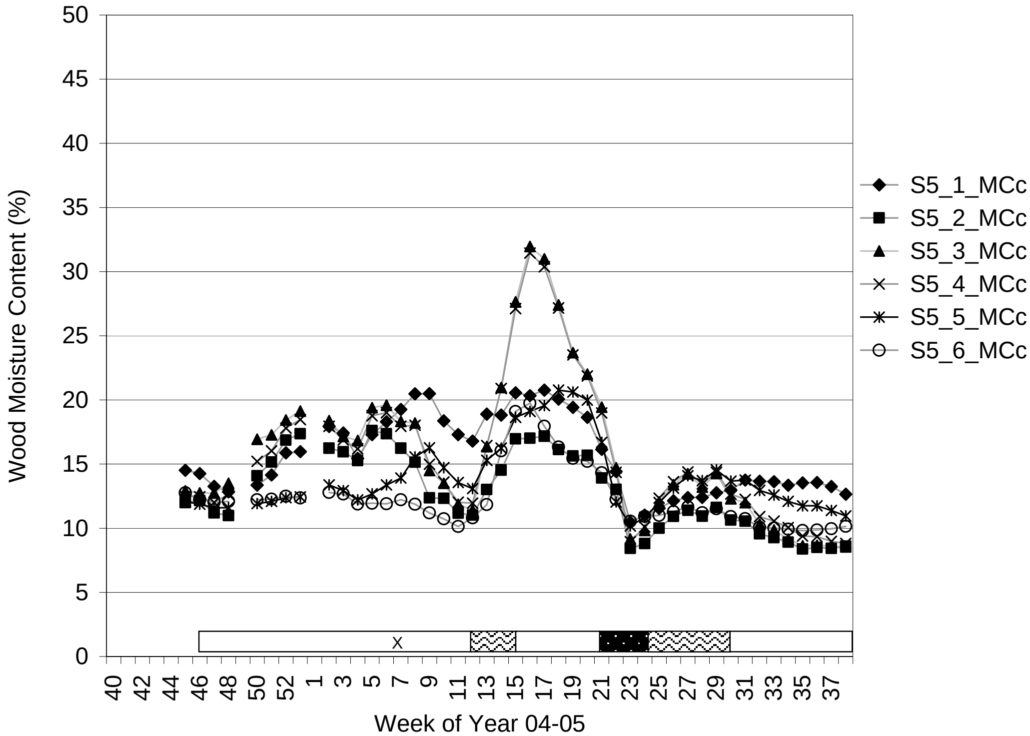


Figure B S5-2 S5 – Cavity Relative Humidity

Figure B S5-3 S5 - Temperature

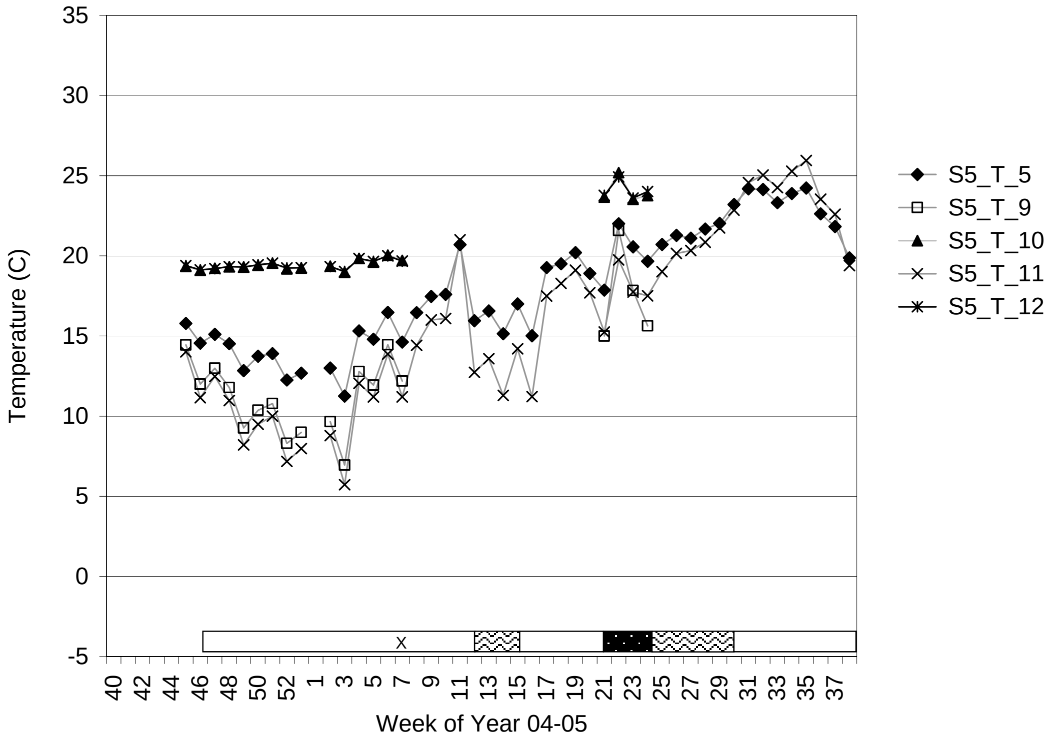


Figure B S5-4 S5 – Vapor Pressure

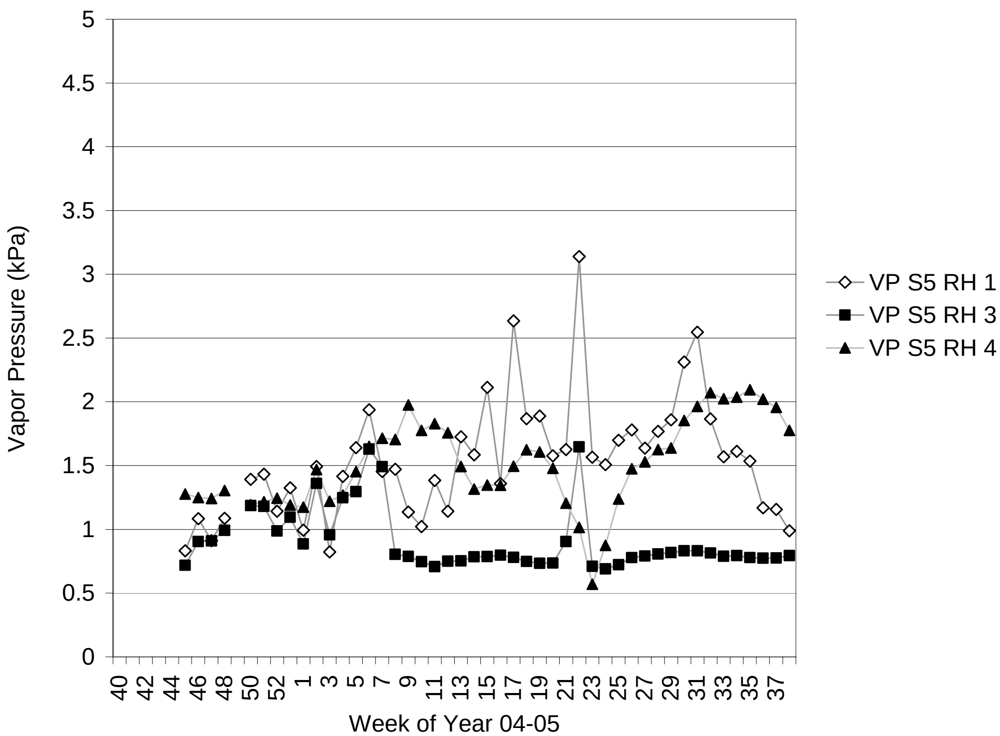


Figure B S6-1 S6 – Wood Moisture Content

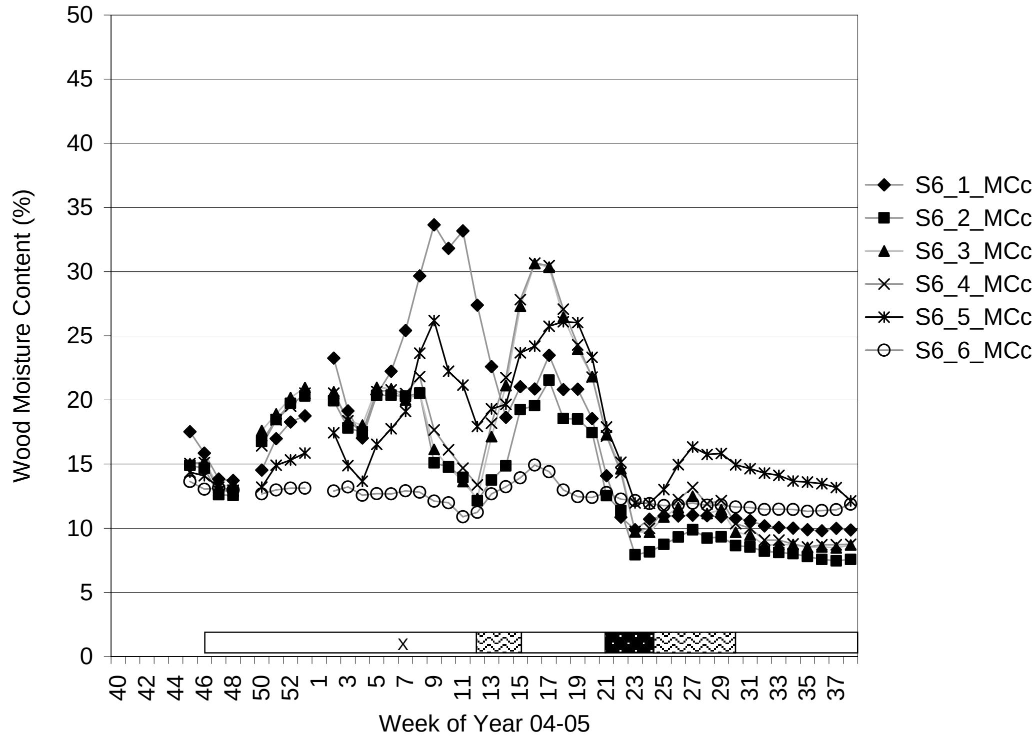


Figure B S6-2 S6 – Cavity Relative Humidity

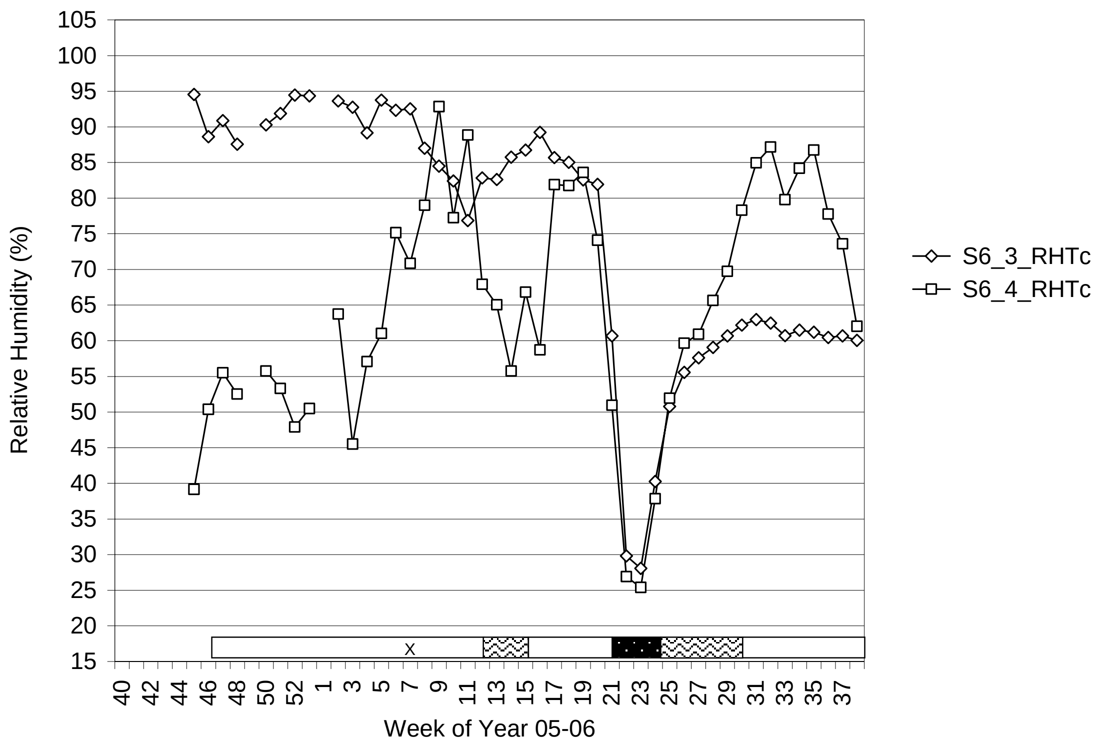


Figure B S6-3 S6 - Temperature

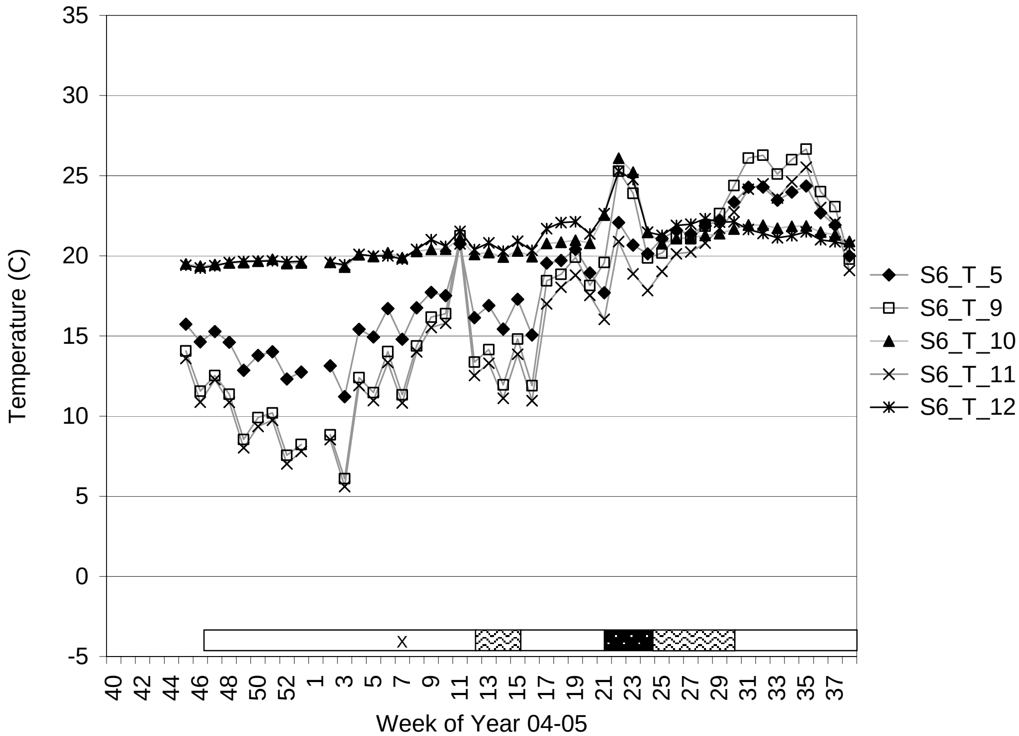


Figure B S6-4 S6 – Vapor Pressure

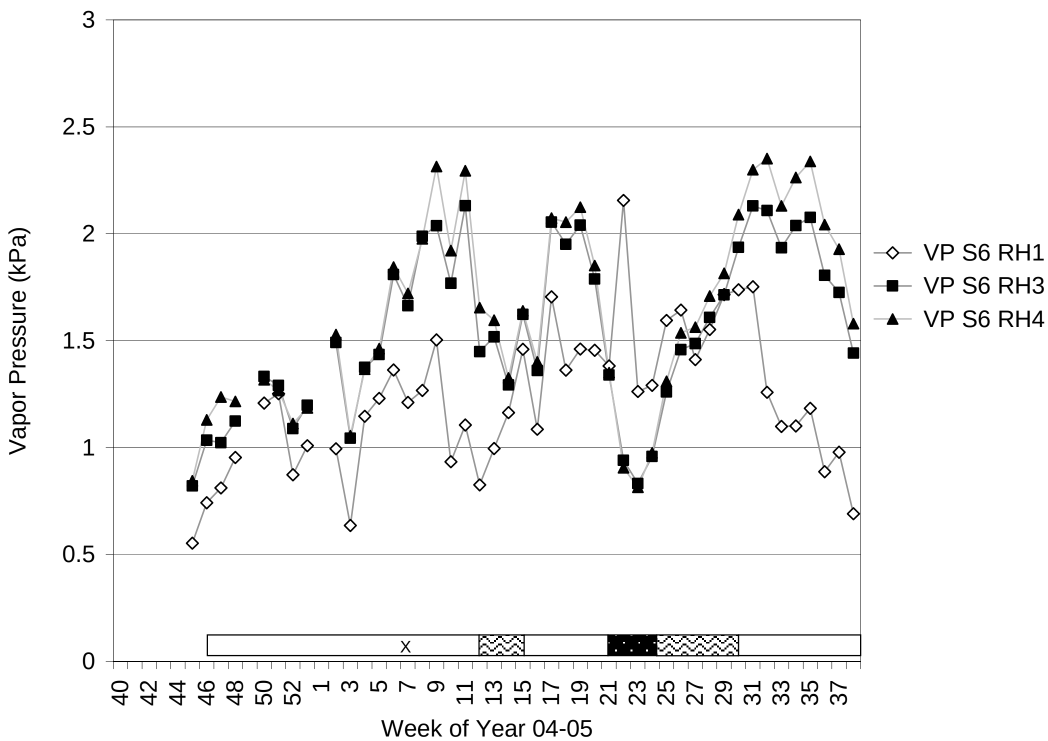


Figure B S7-1 S7 – Wood Moisture Content

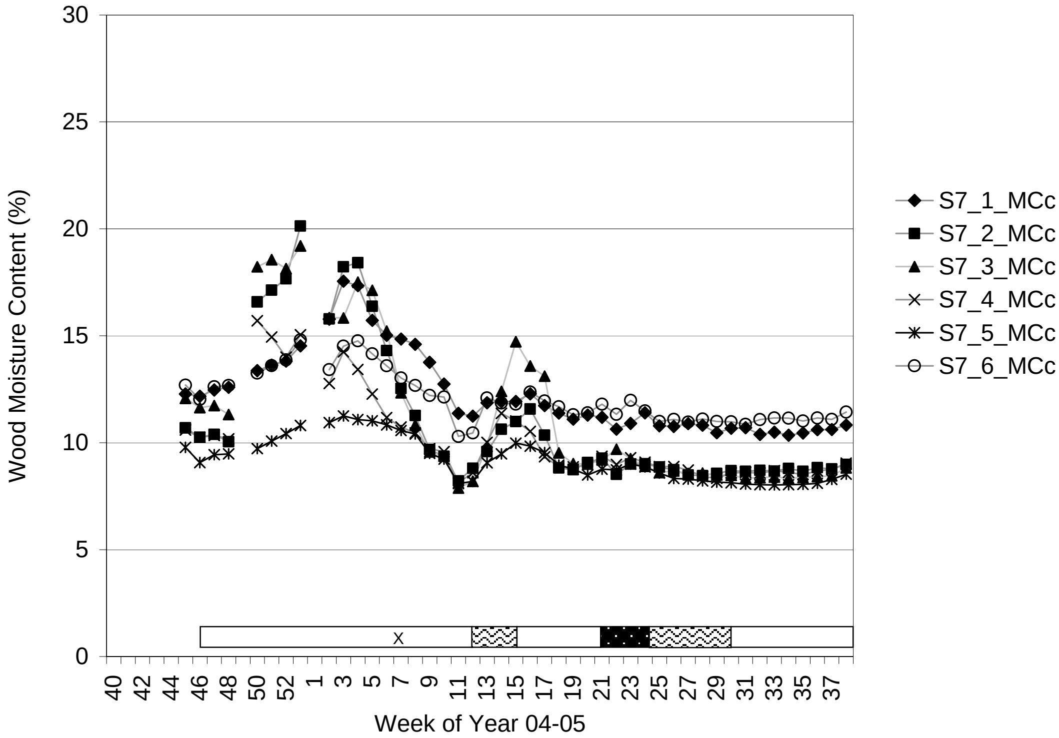


Figure B S7-2 S7 – Cavity Relative Humidity

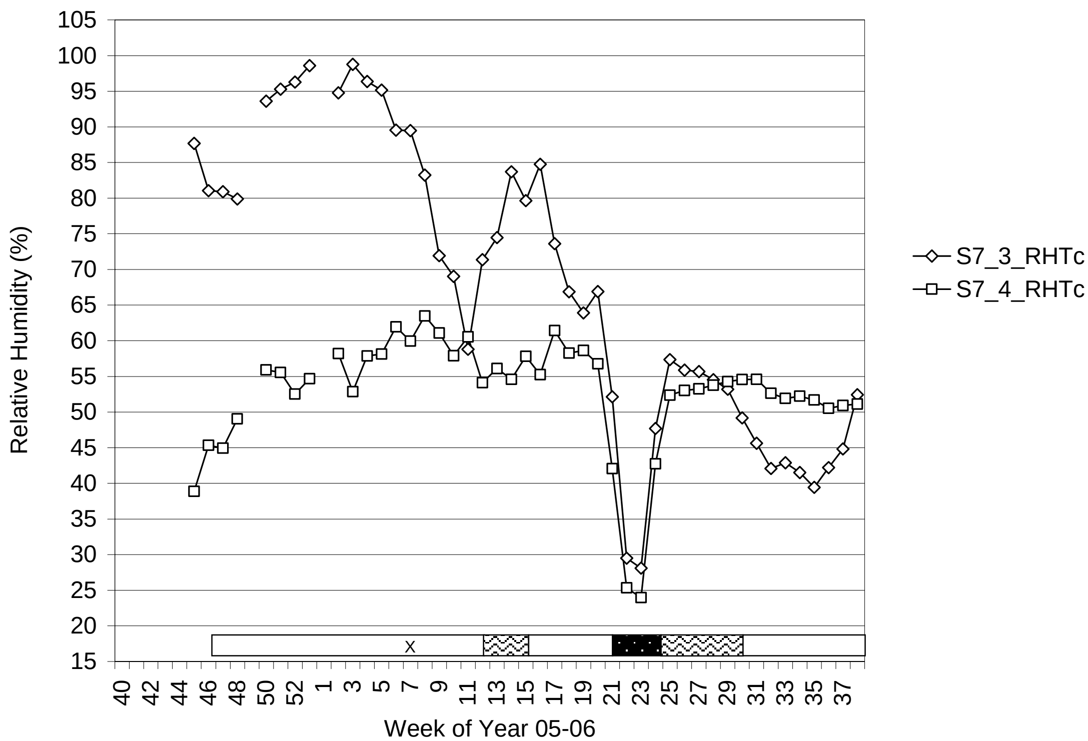


Figure B S7-3 S7 - Temperature

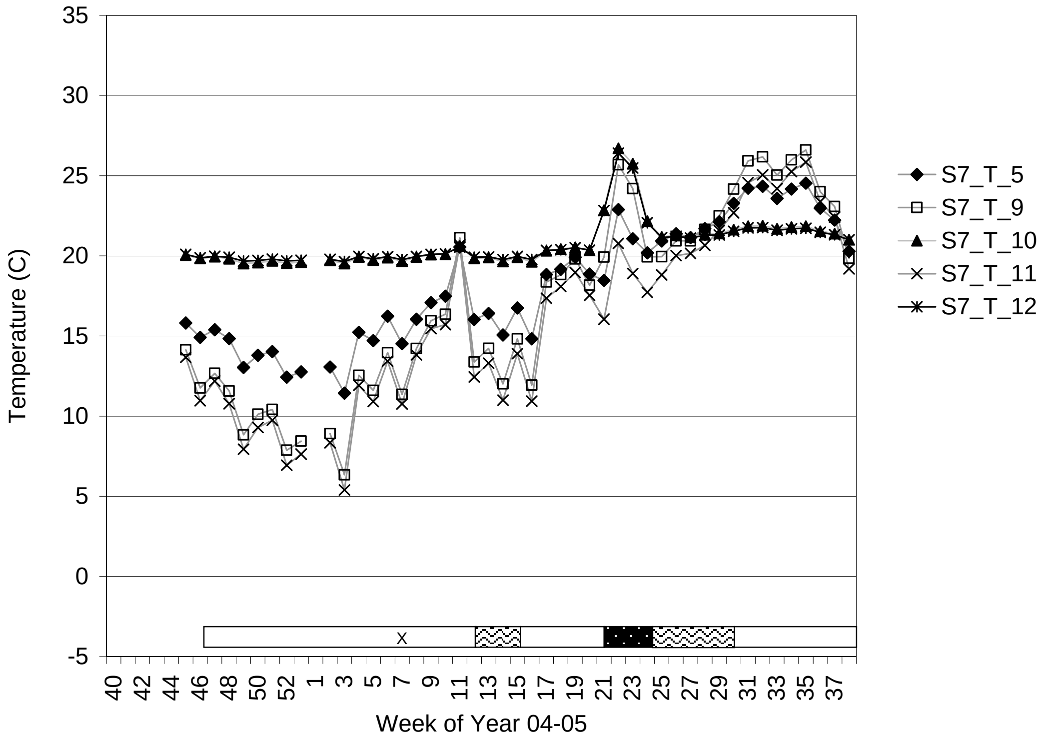


Figure B S7-4 S7 – Vapor Pressure

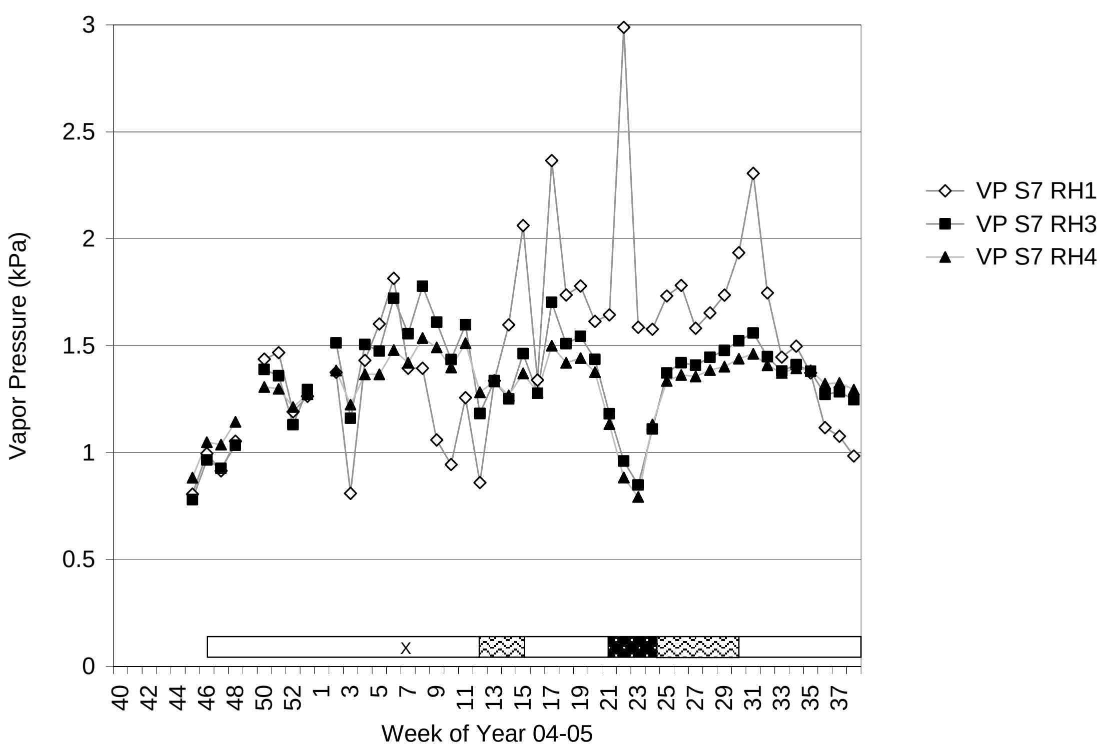


Figure B S8-1 S8 – Wood Moisture Content

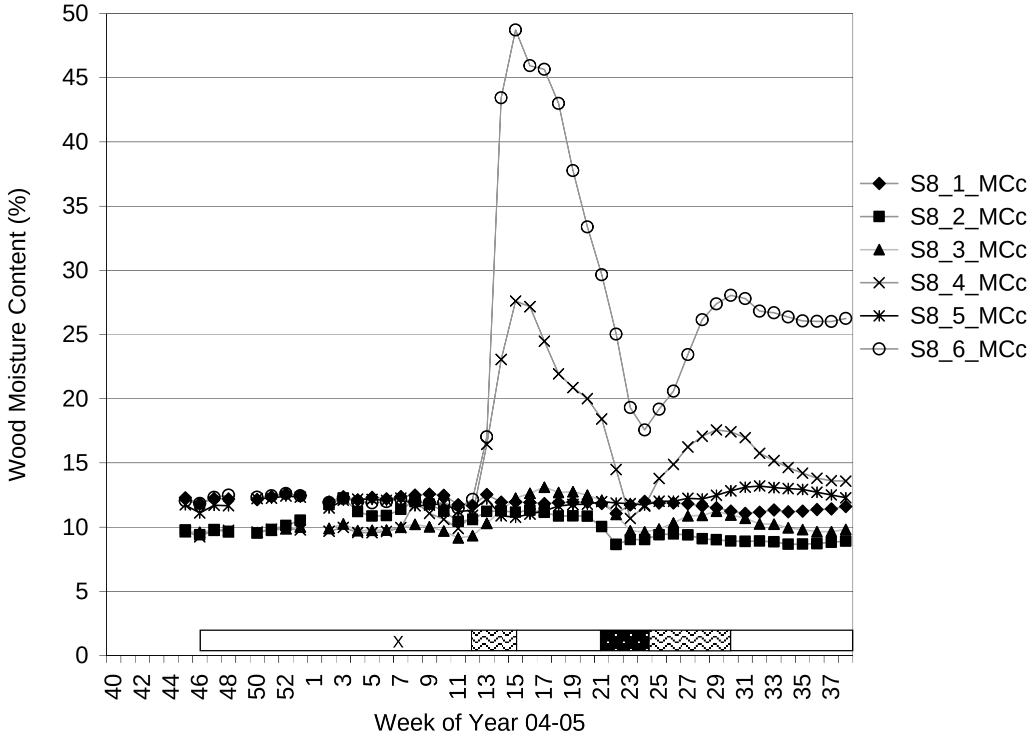


Figure B S8-2 S8 – Cavity Relative Humidity

Figure B S8-3 S8 - Temperature

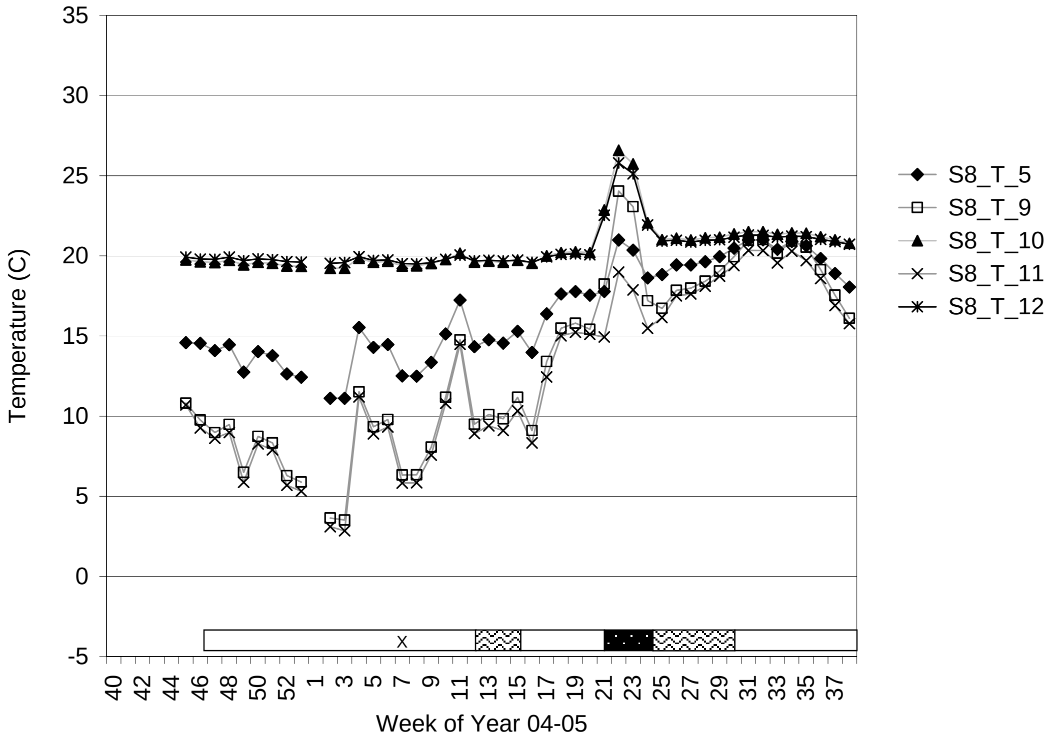


Figure B S8-4 S8 – Vapor Pressure

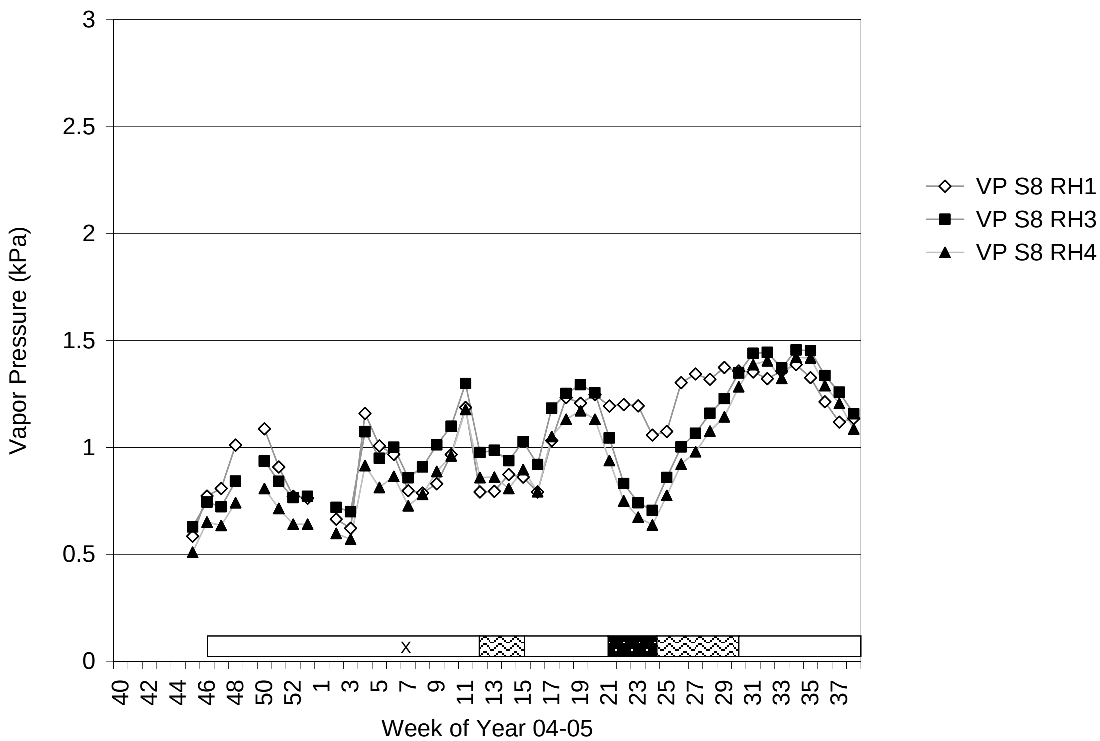


Figure B S8-1 S9 – Wood Moisture Content

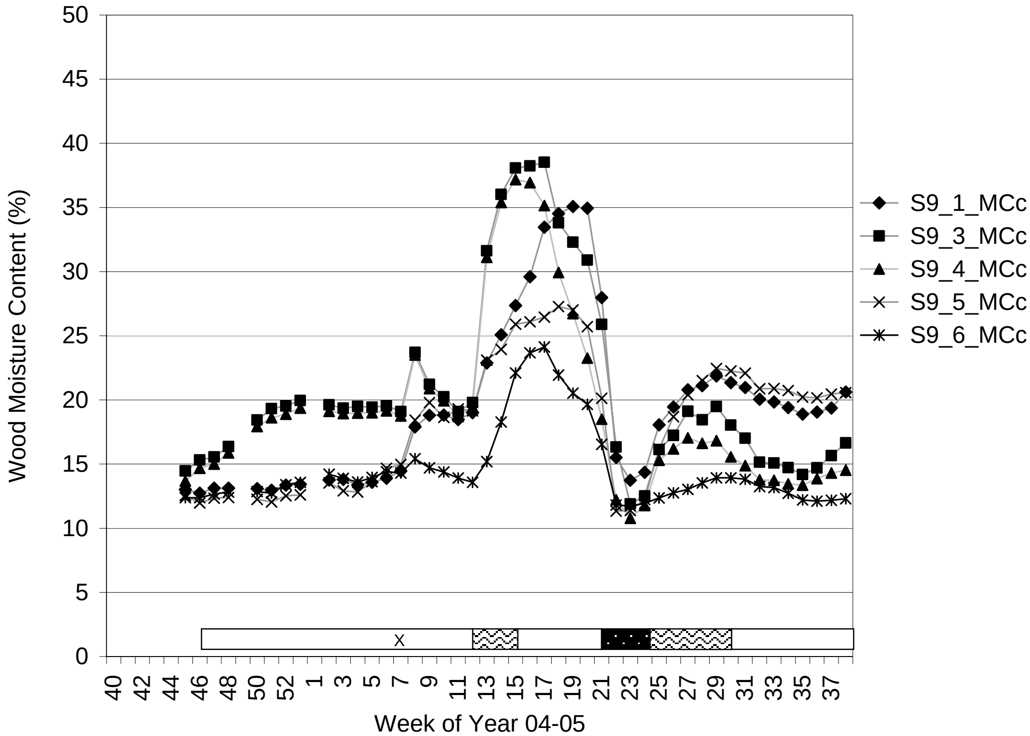


Figure B S9-2 S9 – Cavity Relative Humidity

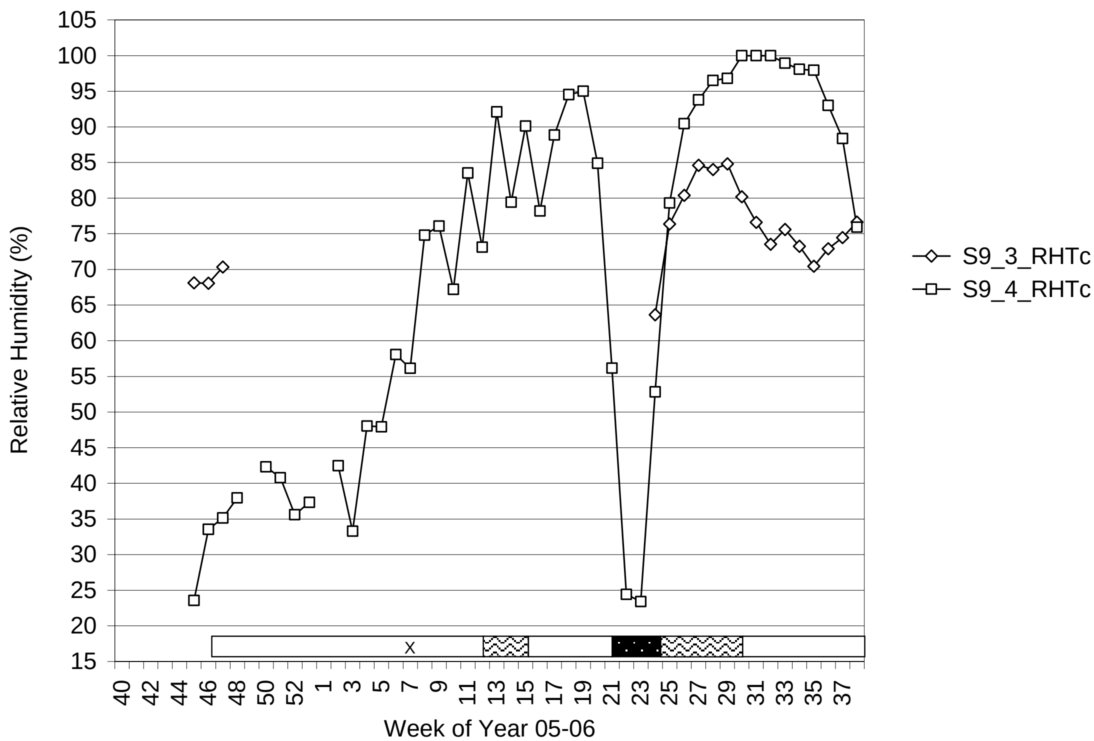


Figure B S9-3 S9 - Temperature

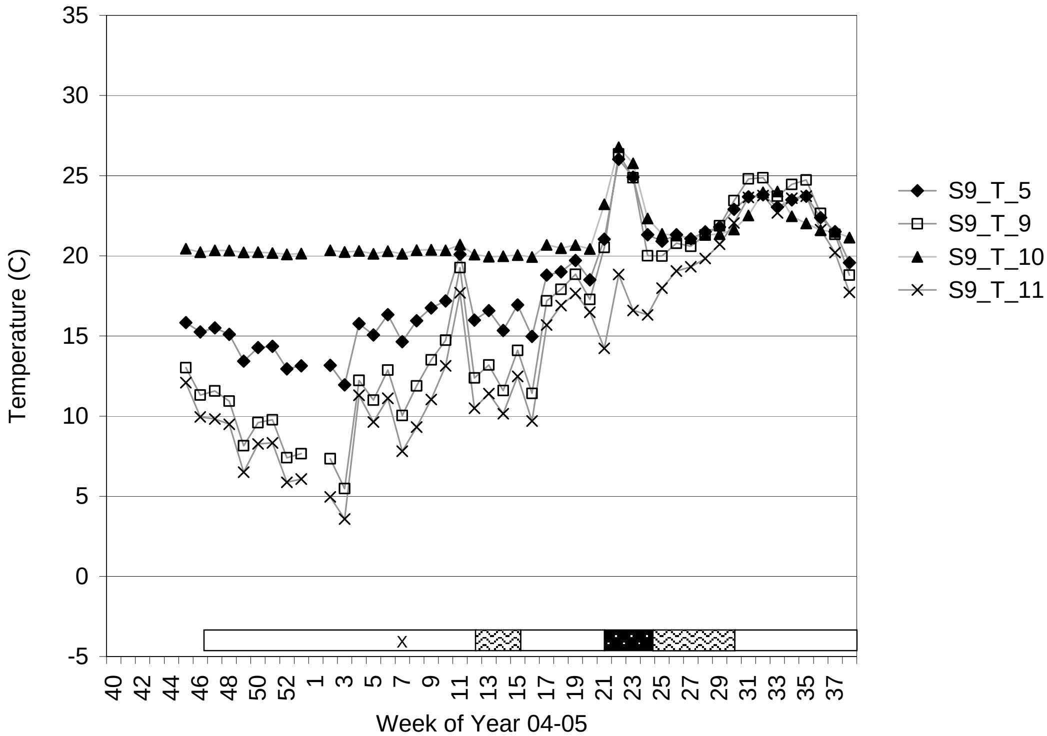


Figure B S9-4 S9 – Vapor Pressure

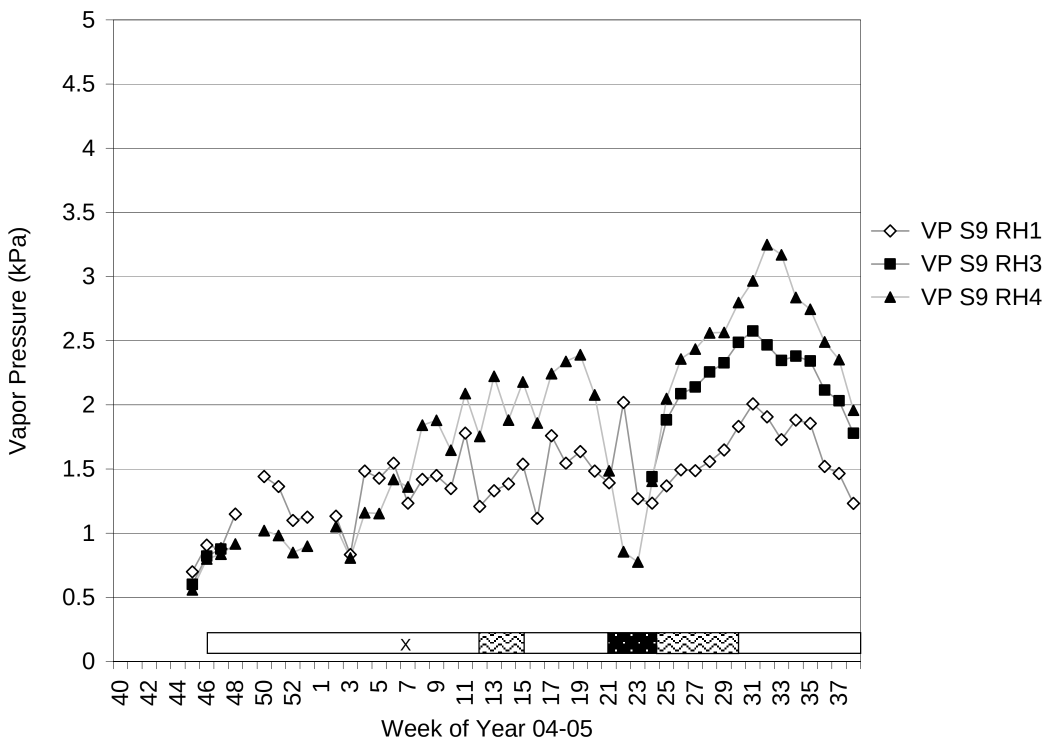


Figure B S9b-1 S9b – Wood Moisture Content

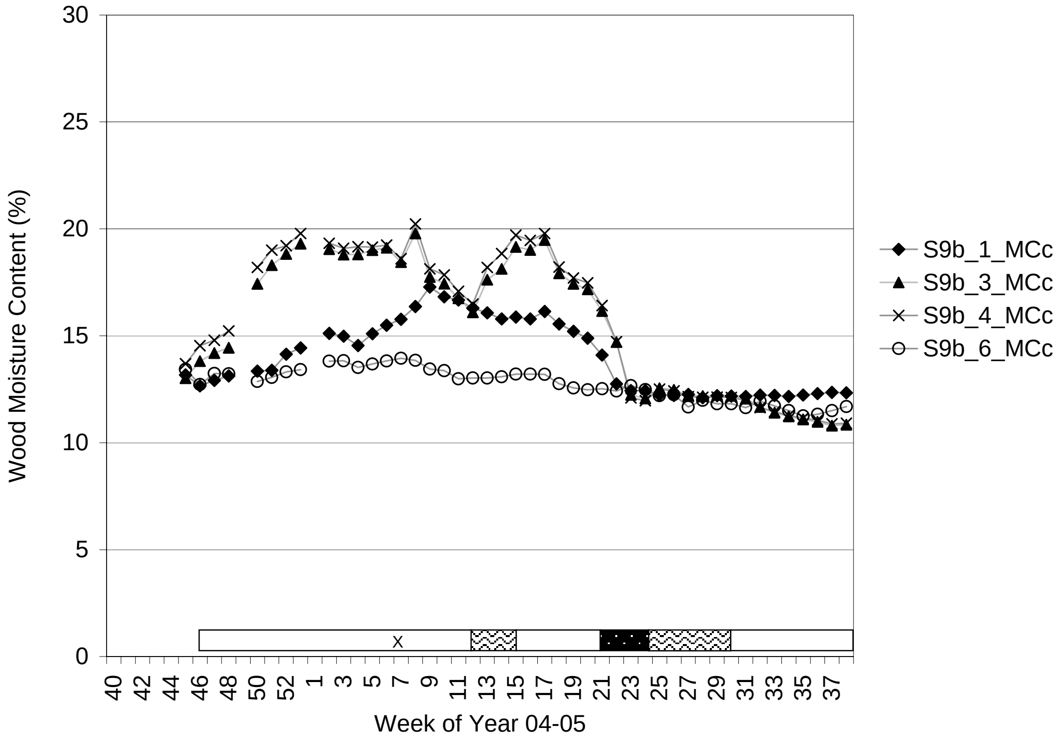


Figure B S9b-2 S9b – Cavity Relative Humidity

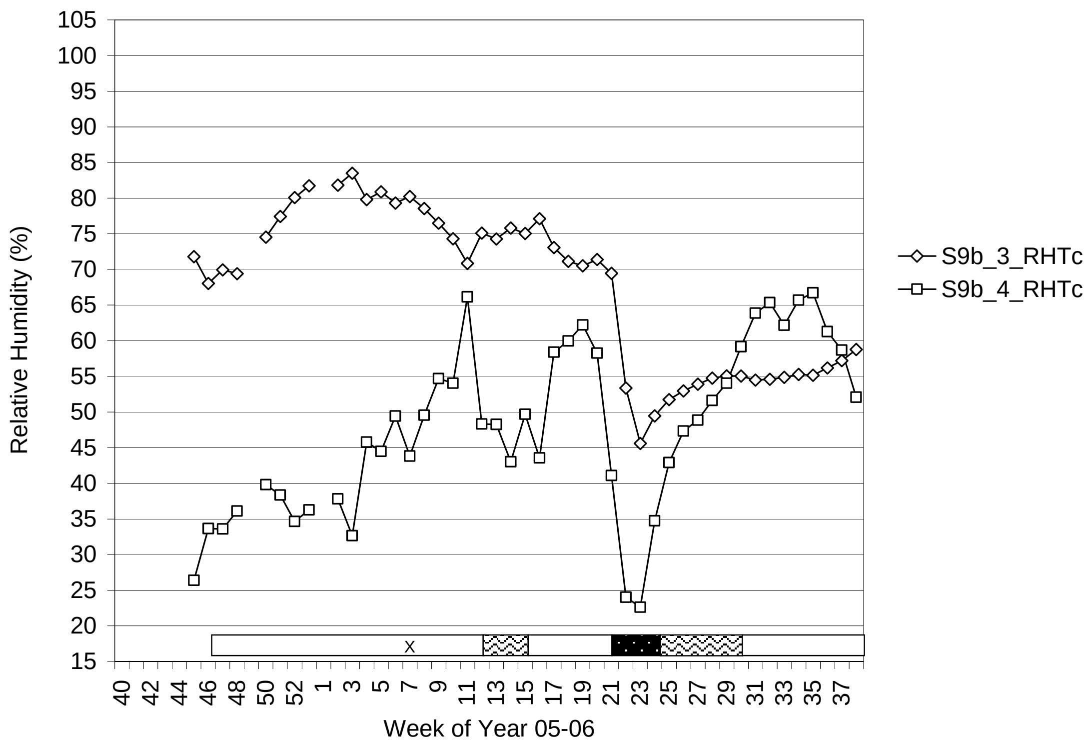


Figure B S9b-3 S9b - Temperature

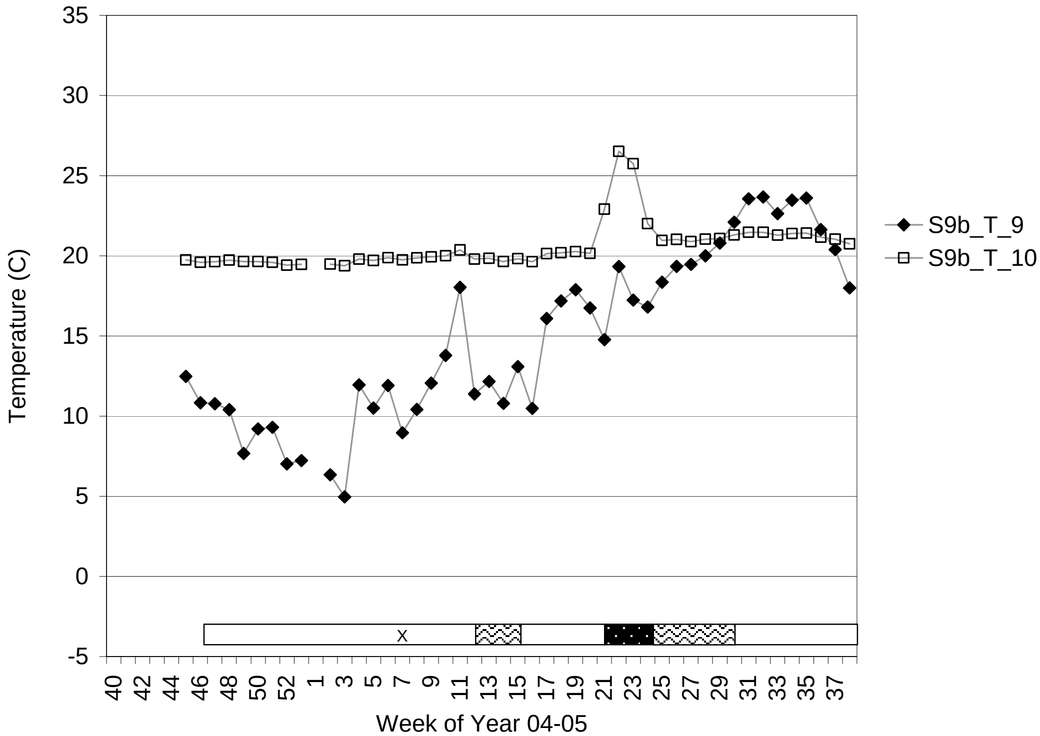


Figure B S9b-4 S9b – Vapor Pressure

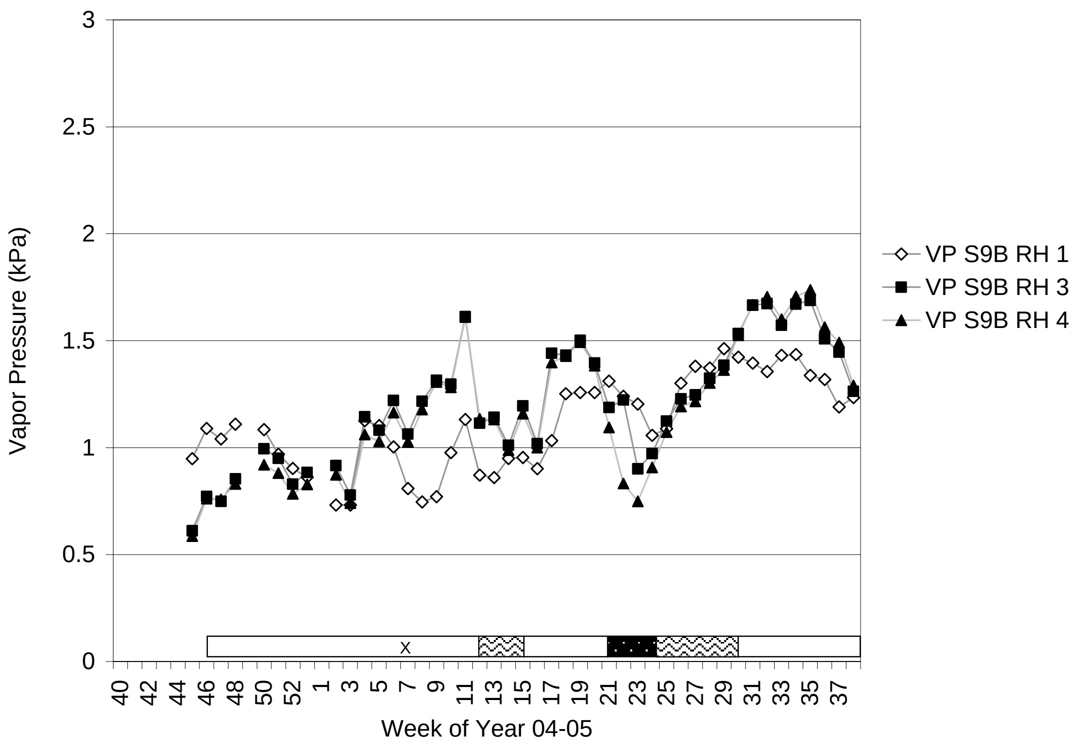


Figure B S10-1 S10 – Wood Moisture Content

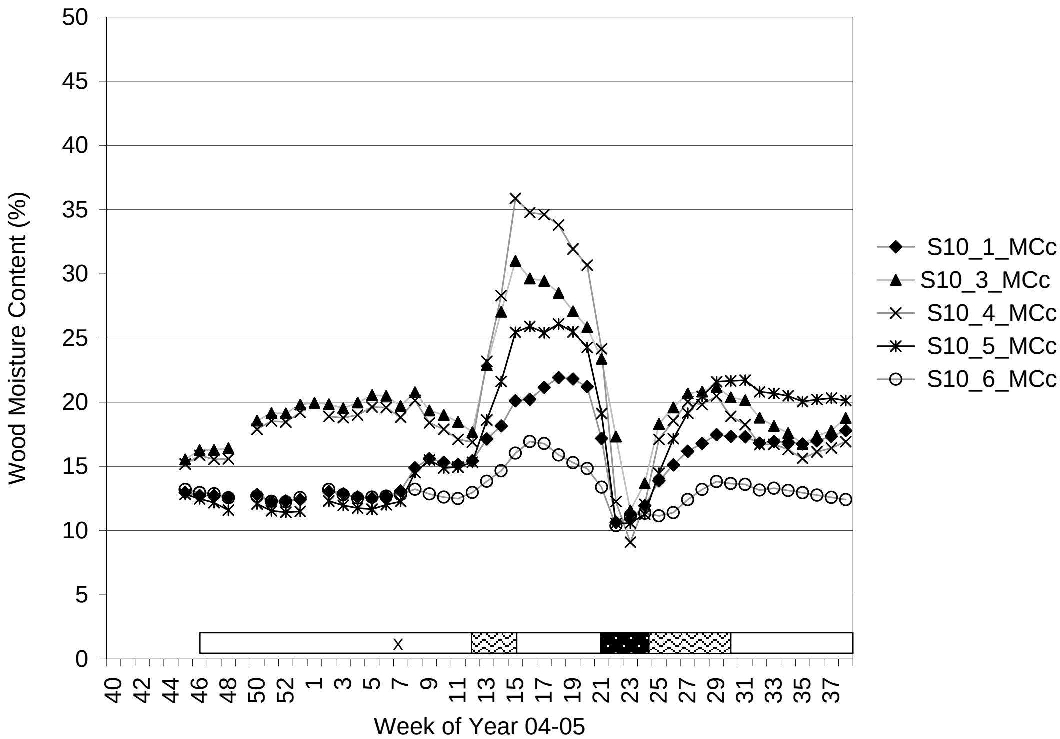


Figure B S10-2 S10 – Cavity Relative Humidity

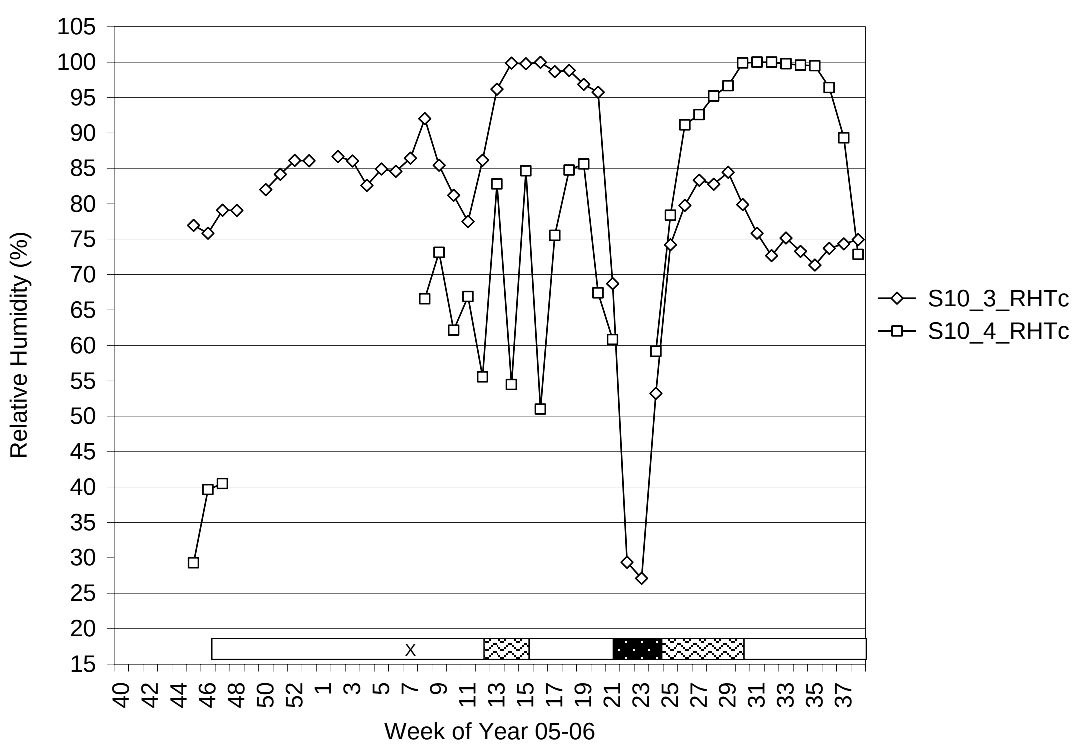


Figure B S10-3 S10 - Temperature

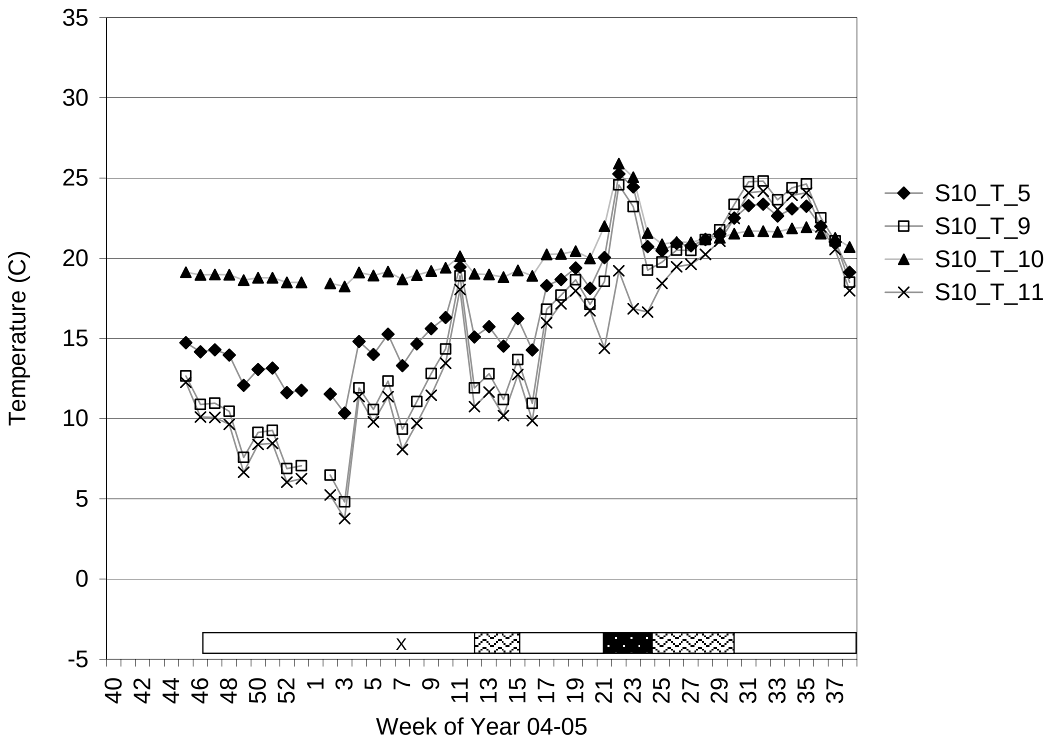


Figure B S10-4 S10 - Vapor Pressure

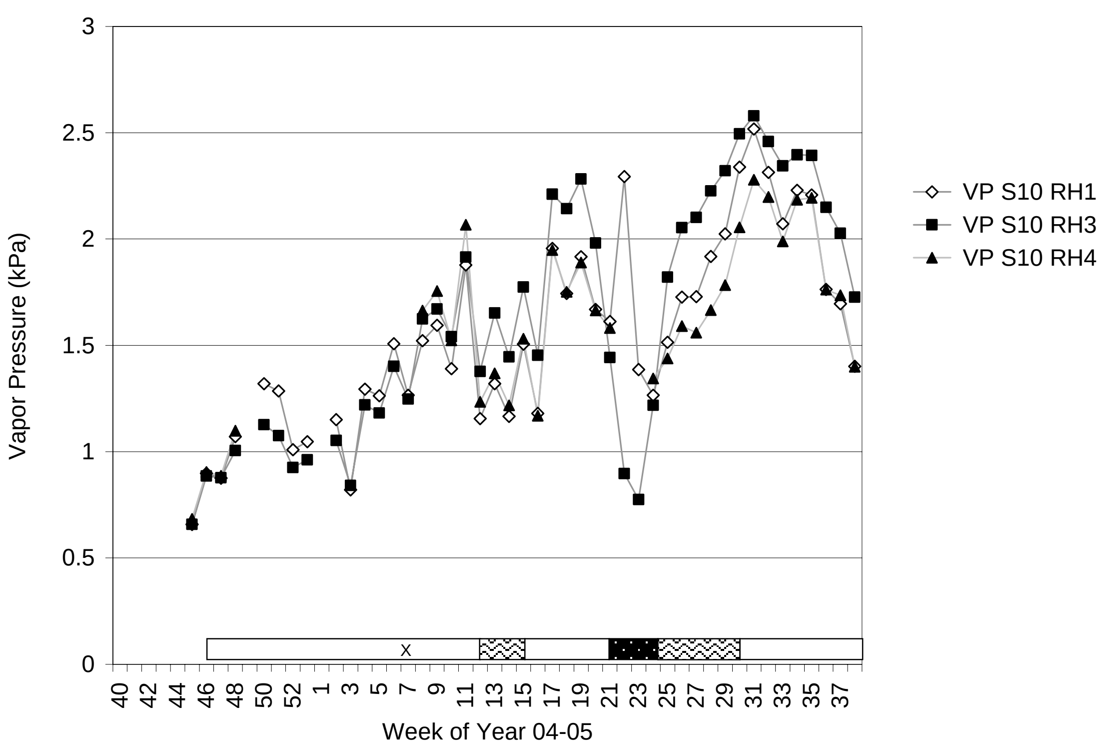


Figure B S10b-1 S10b – Wood Moisture Content

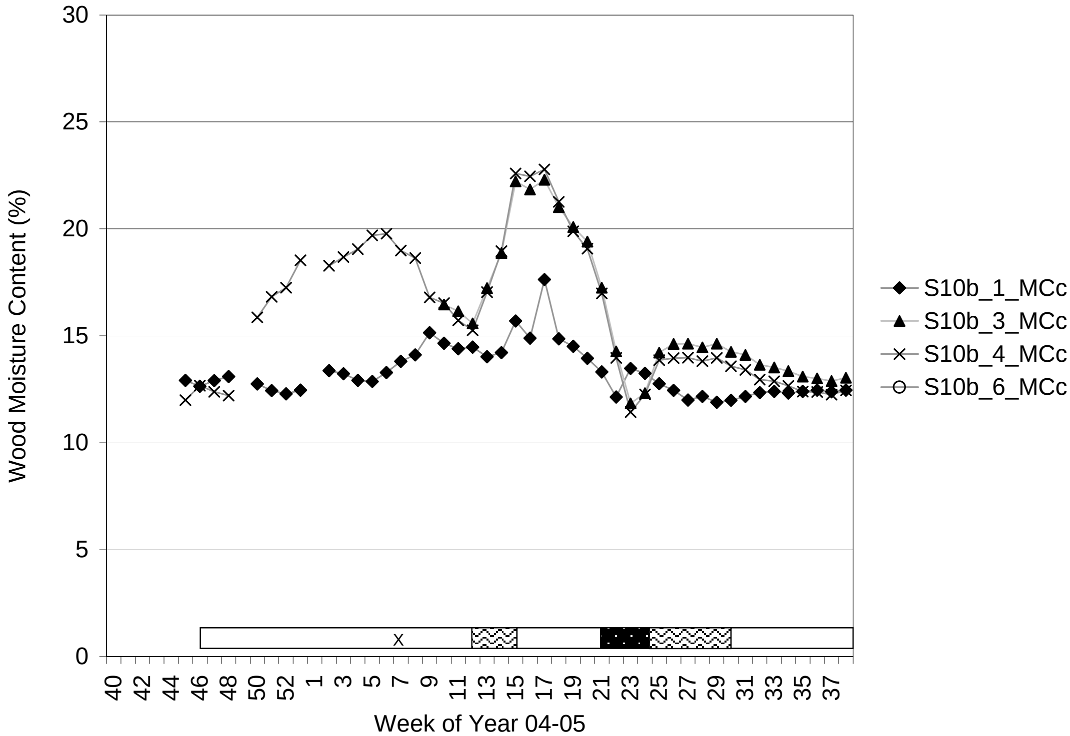


Figure B S10b-2 **S10b – Cavity Relative Humidity**

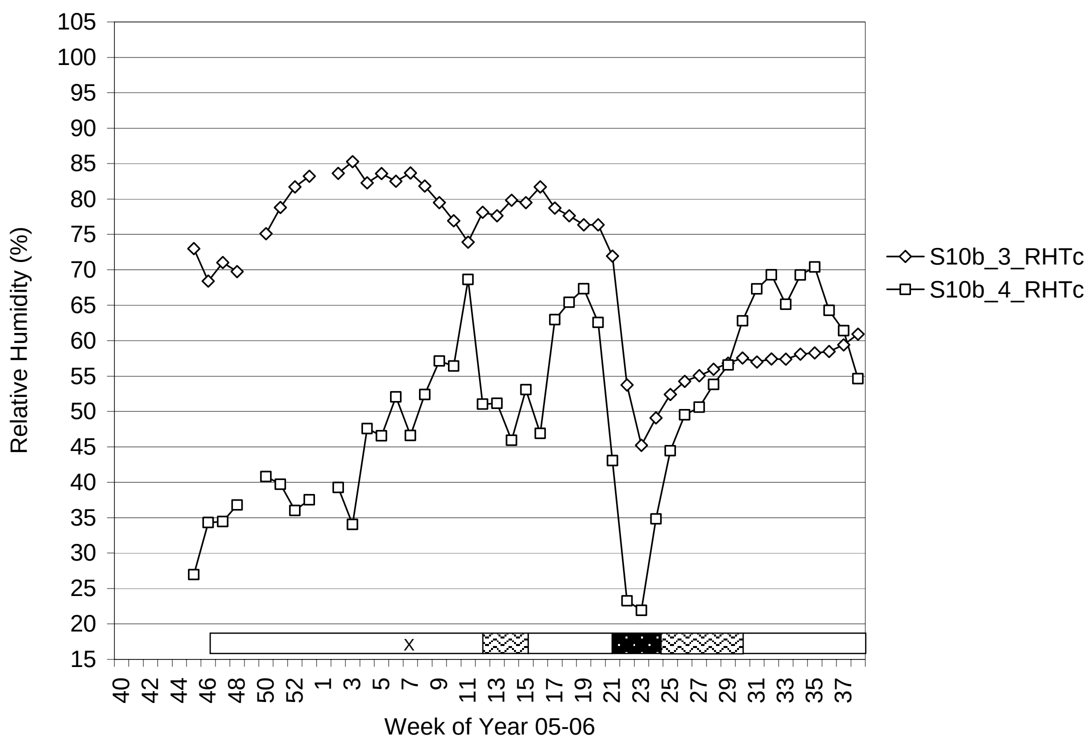


Figure B S10b-3 **S10b - Temperature**

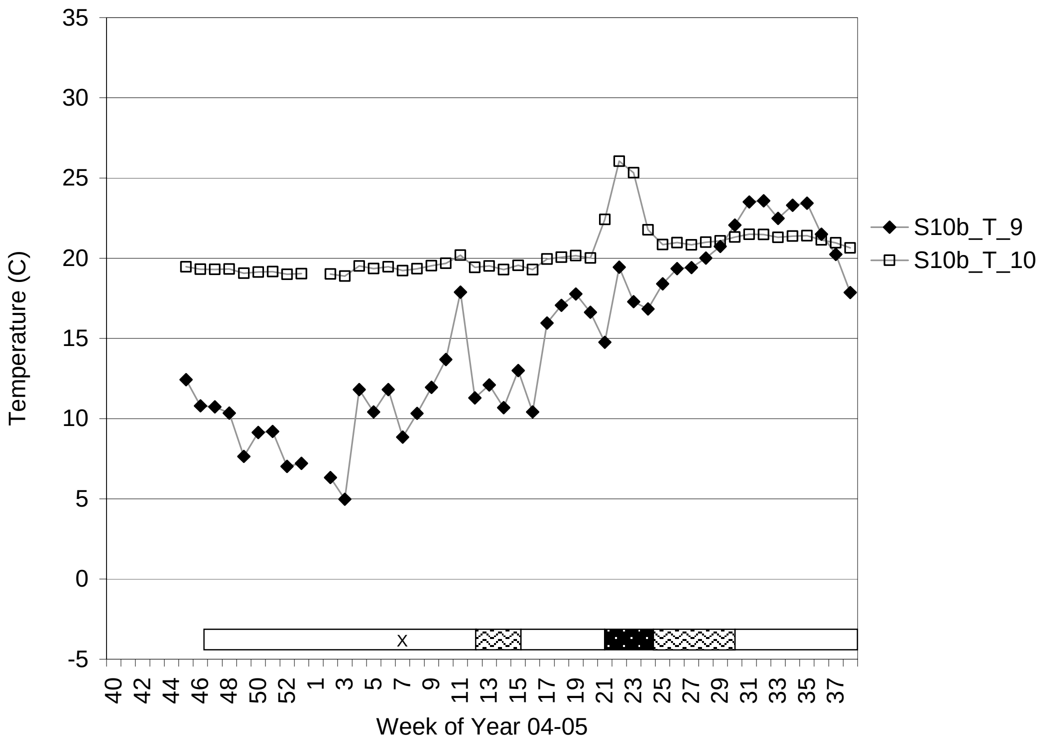


Figure B S10b-4 **S10b – Vapor Pressure**

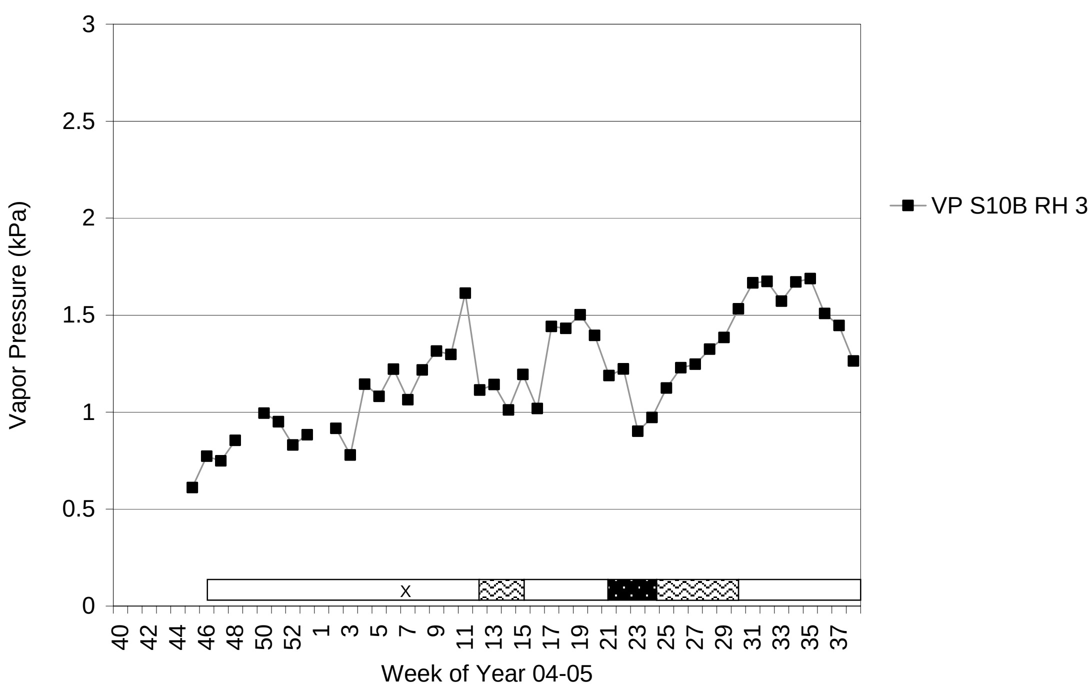


Figure B S11-1 **S11 – Wood Moisture Content**

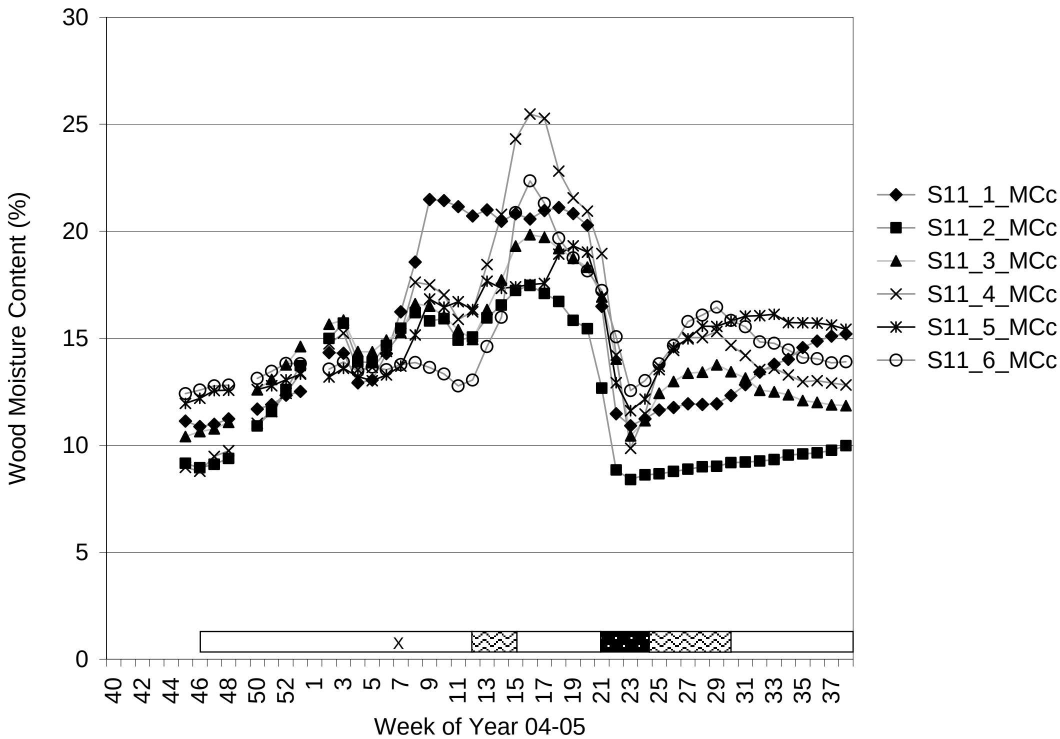


Figure B S11-2 **S11 – Cavity Relative Humidity**

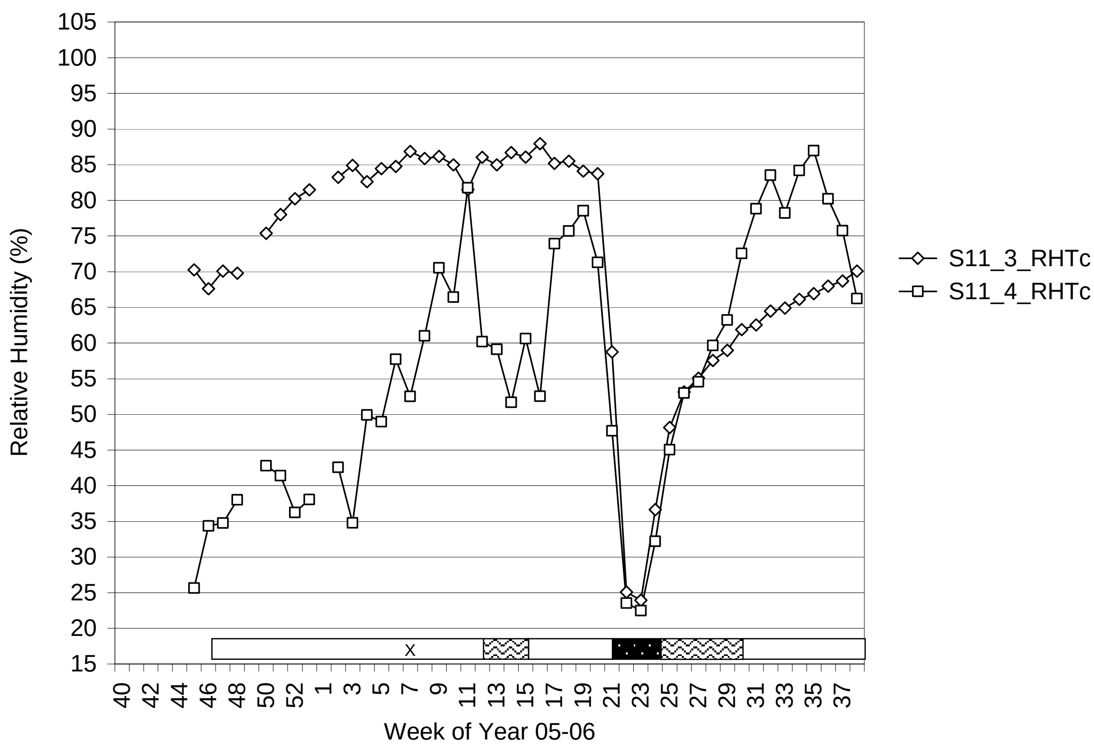


Figure B S11-3 **S11 - Temperature**

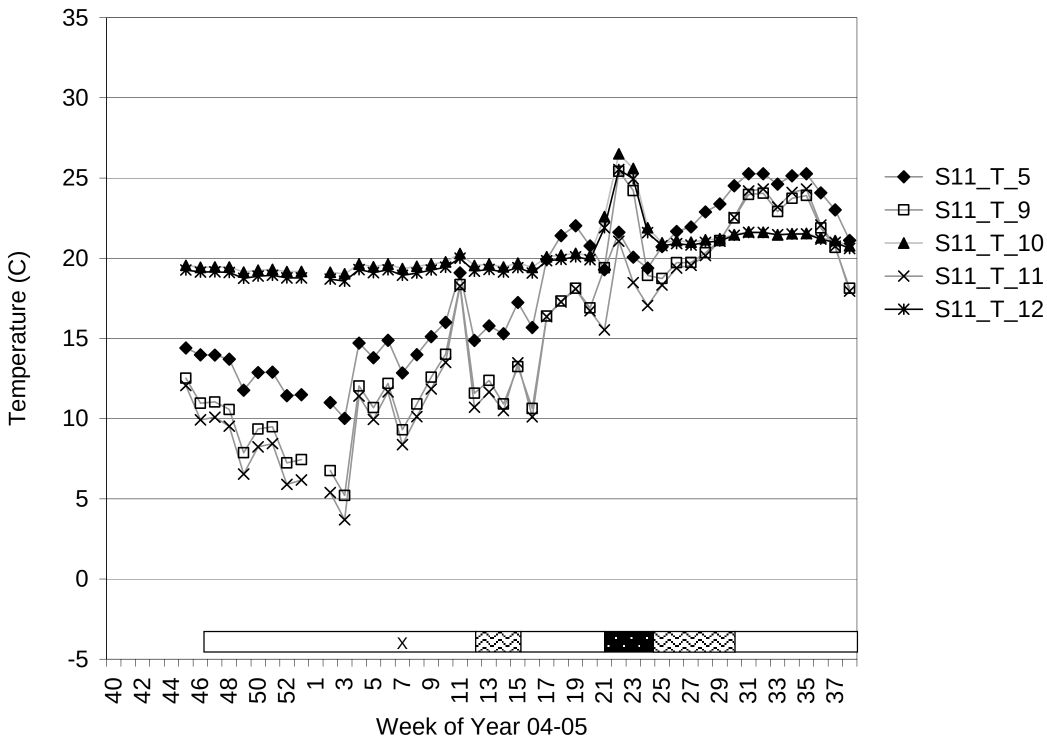


Figure B S11-4 **S11 – Vapor Pressure**

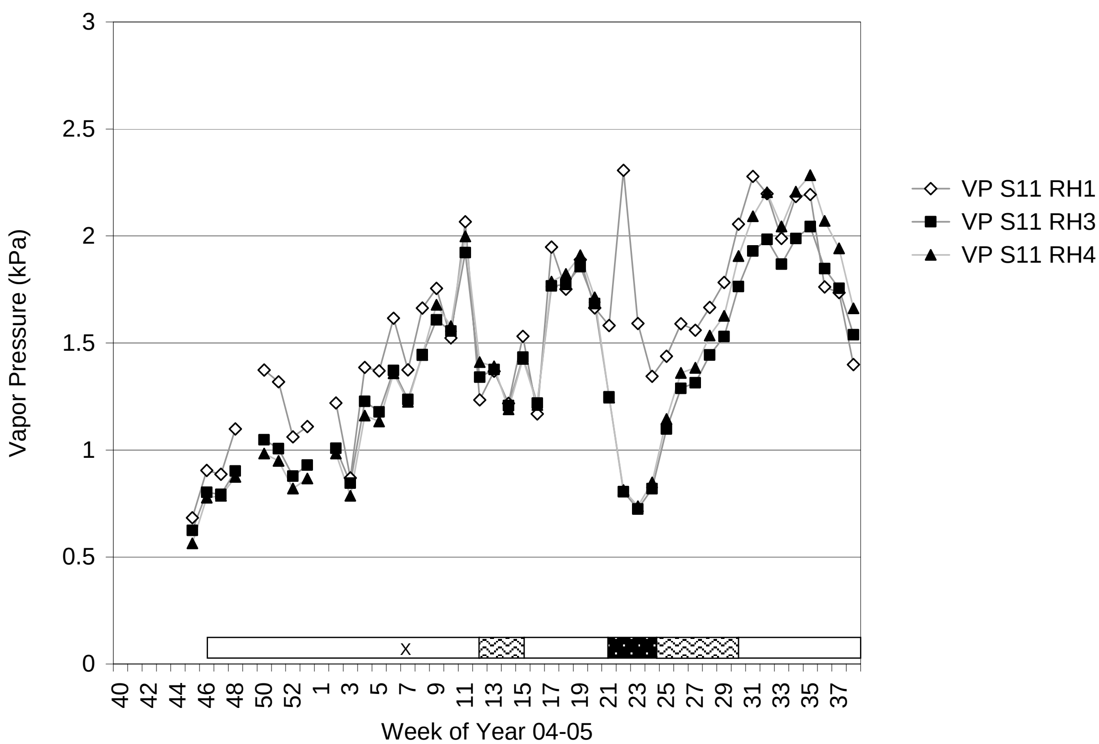


Figure B S12-1 **S12 – Wood Moisture Content**

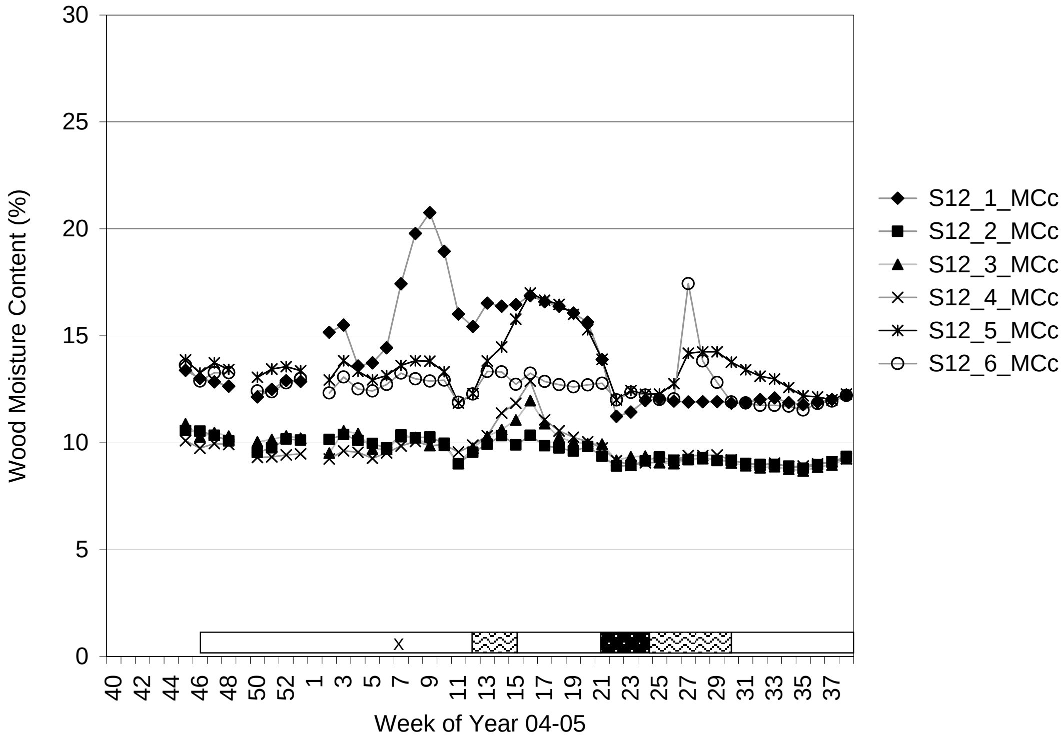


Figure B S12-2 S12 – Cavity Relative Humidity

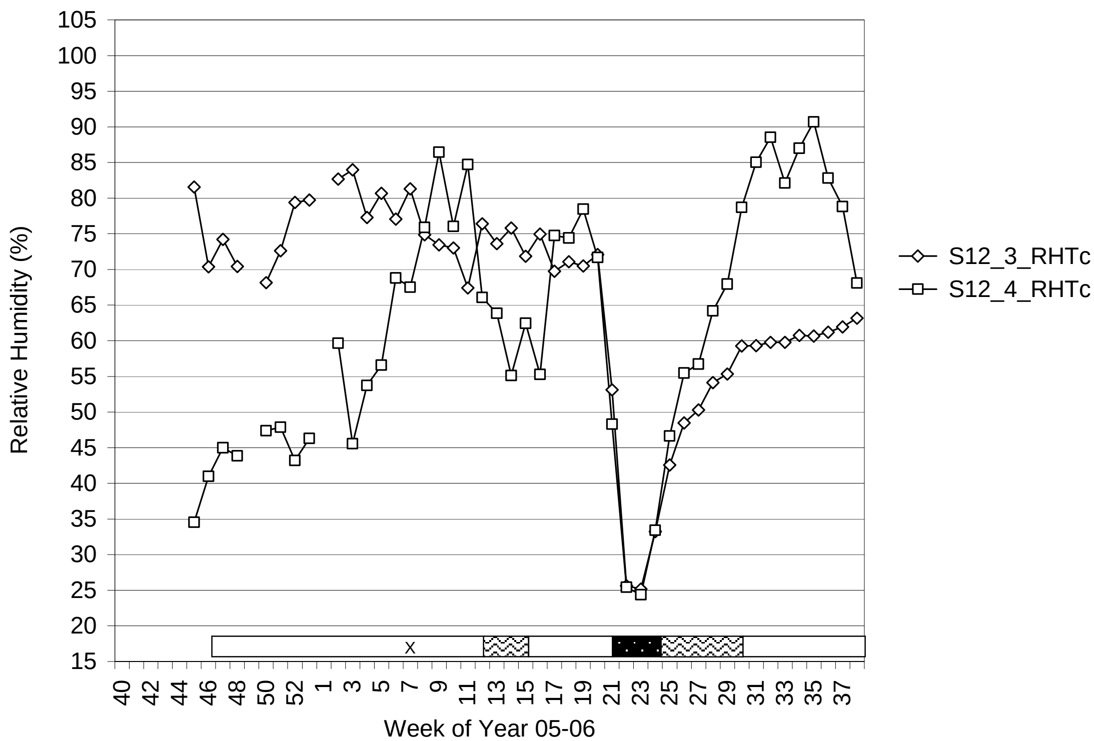


Figure B S12-3 S12 - Temperature

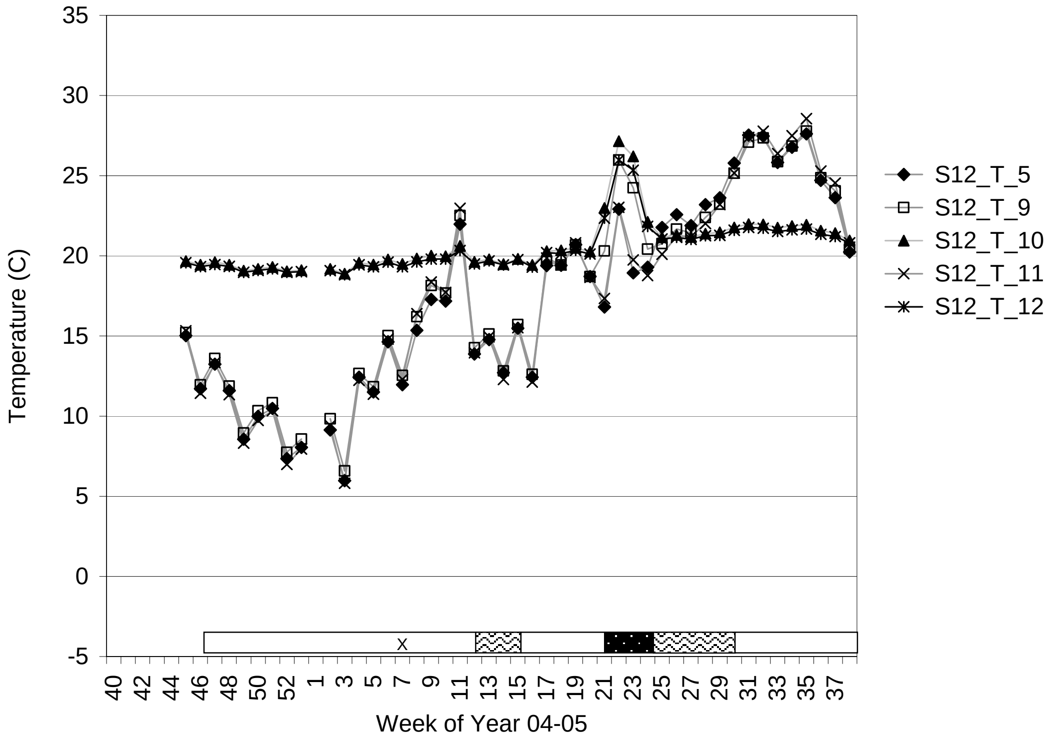


Figure B S12-4 12 – Vapor Pressure

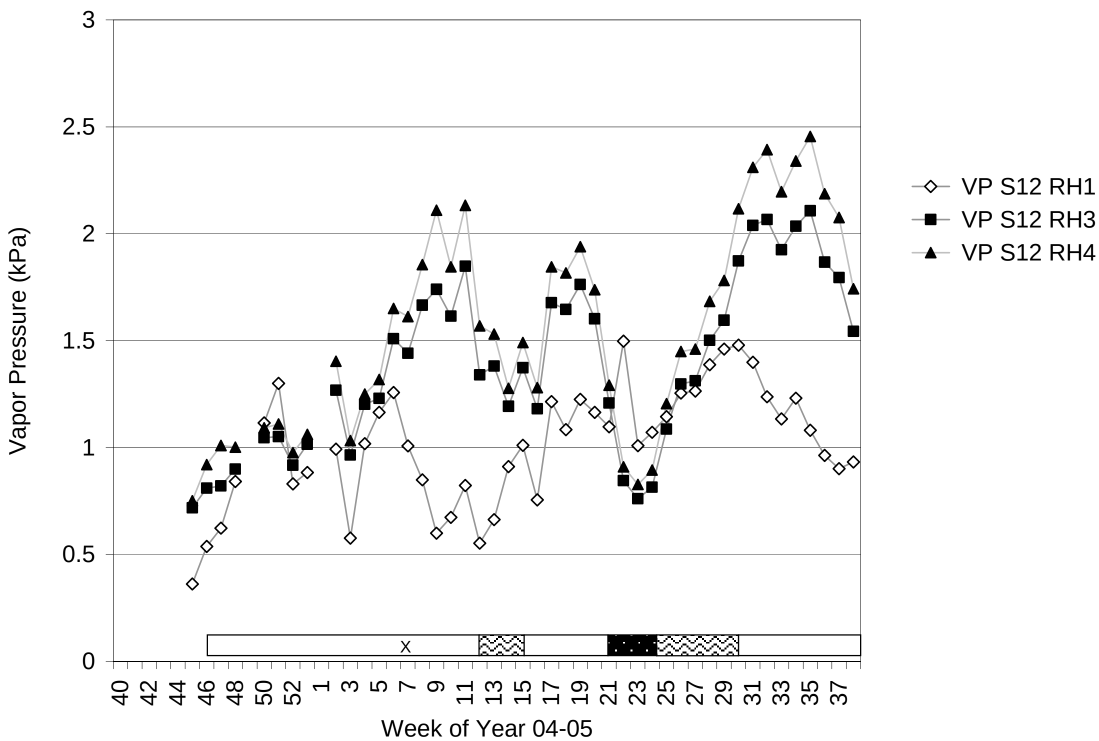


Figure B N3-1 N3 – Wood Moisture Content

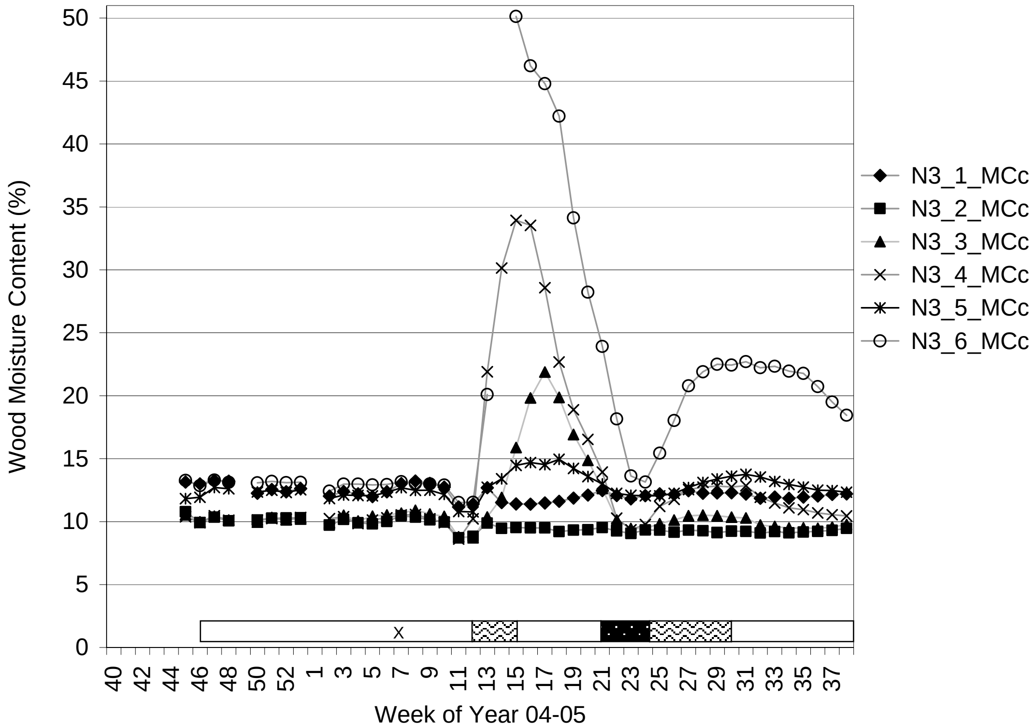


Figure B N3-2 N3 – Cavity Relative Humidity

Figure B N3-3 N3 - Temperature

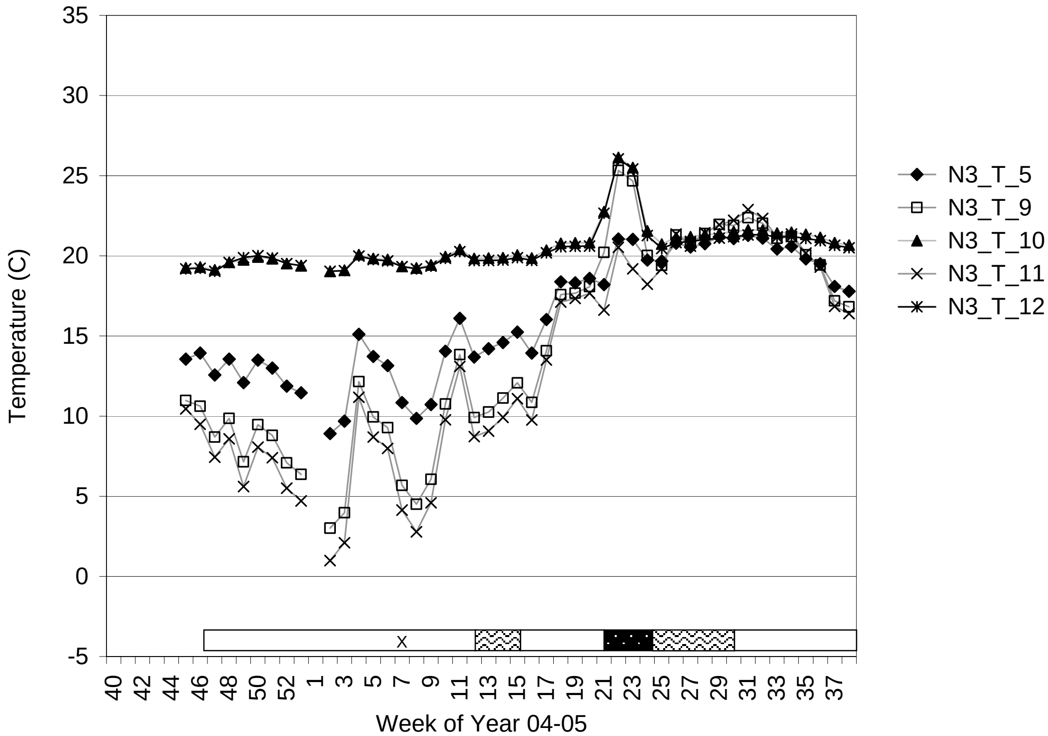


Figure B N3-4 N3 – Vapor Pressure

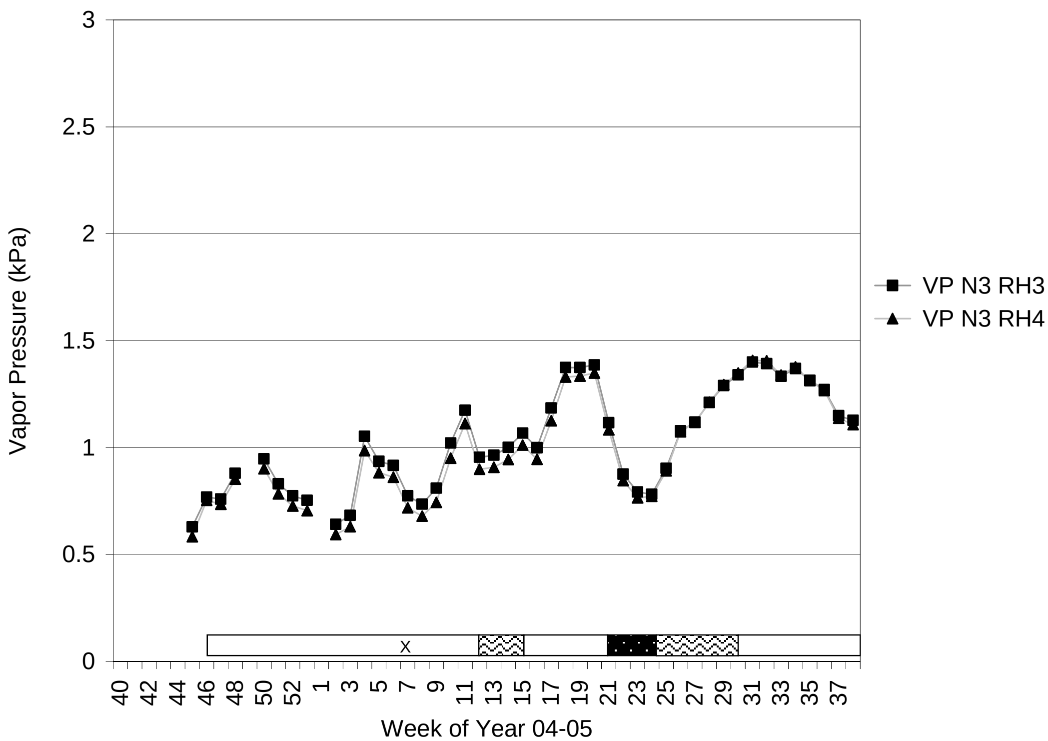


Figure B N4-1 N4 – Wood Moisture Content

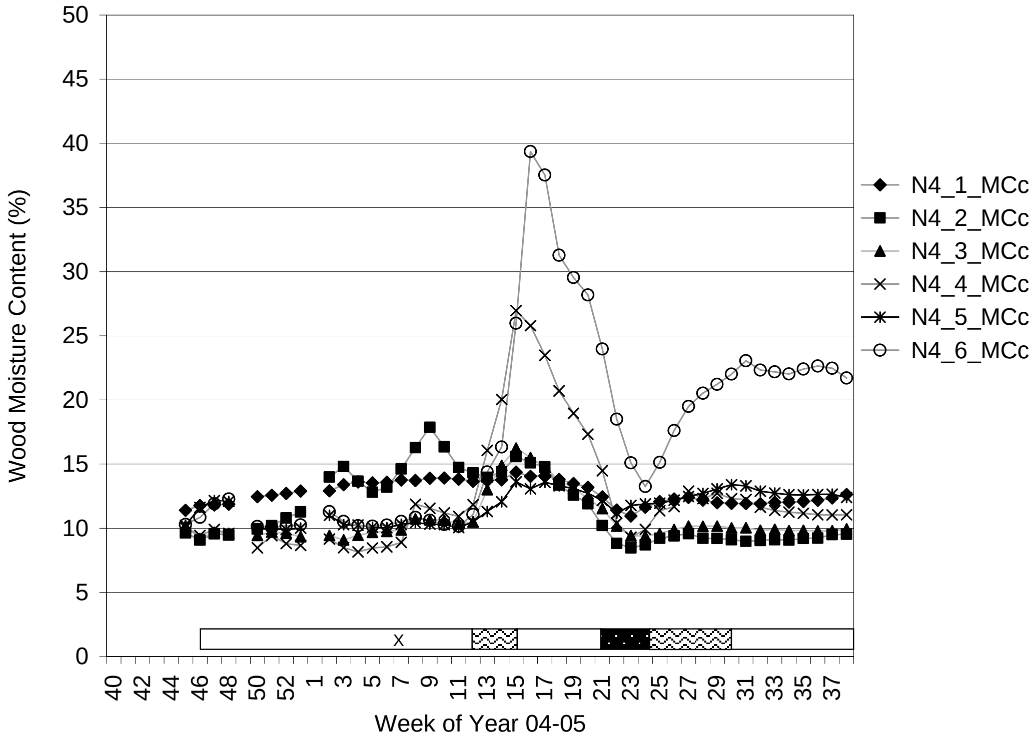


Figure B N4-2 N4 – Cavity Relative Humidity

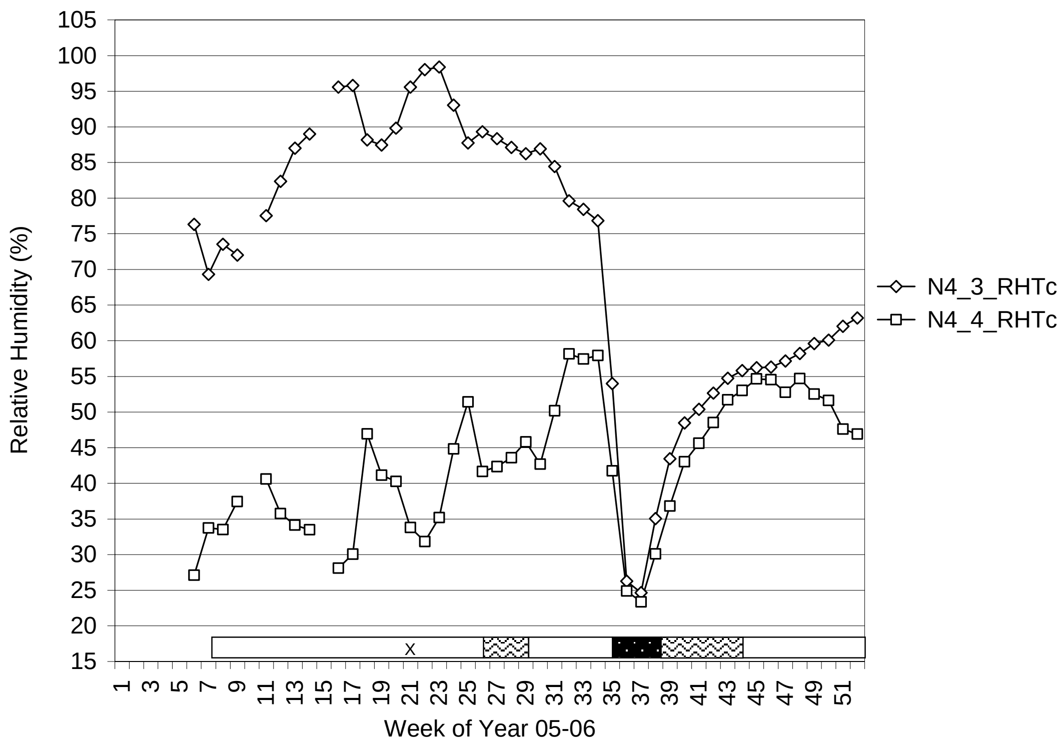


Figure B N4-3 N4 - Temperature

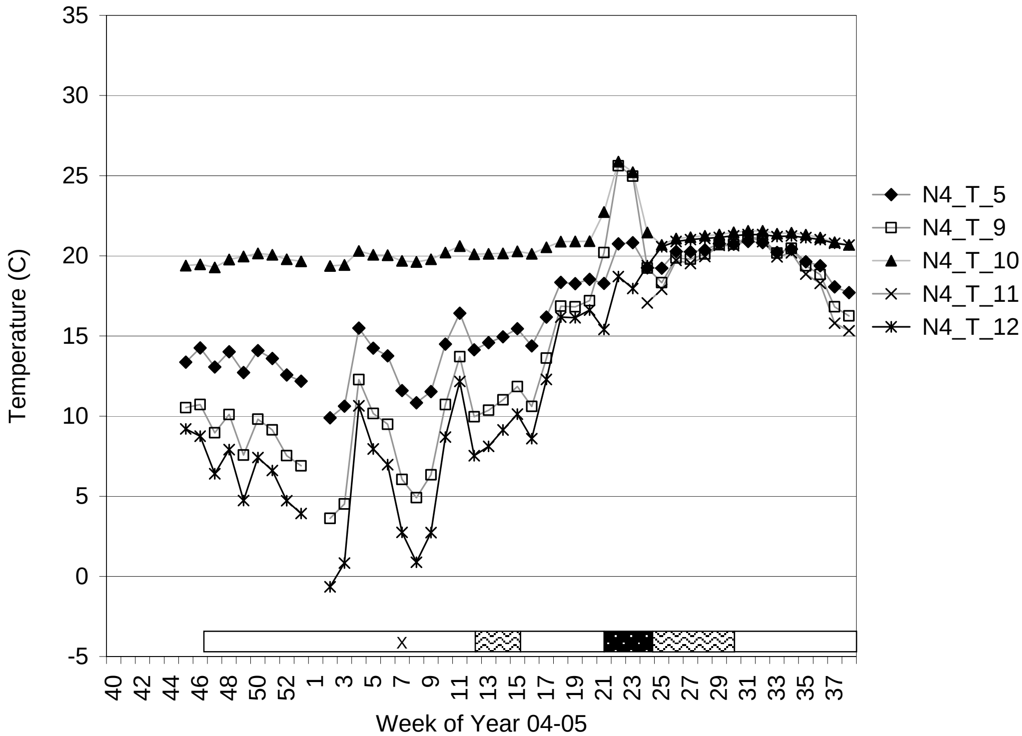


Figure B N4-4 N4 – Vapor Pressure

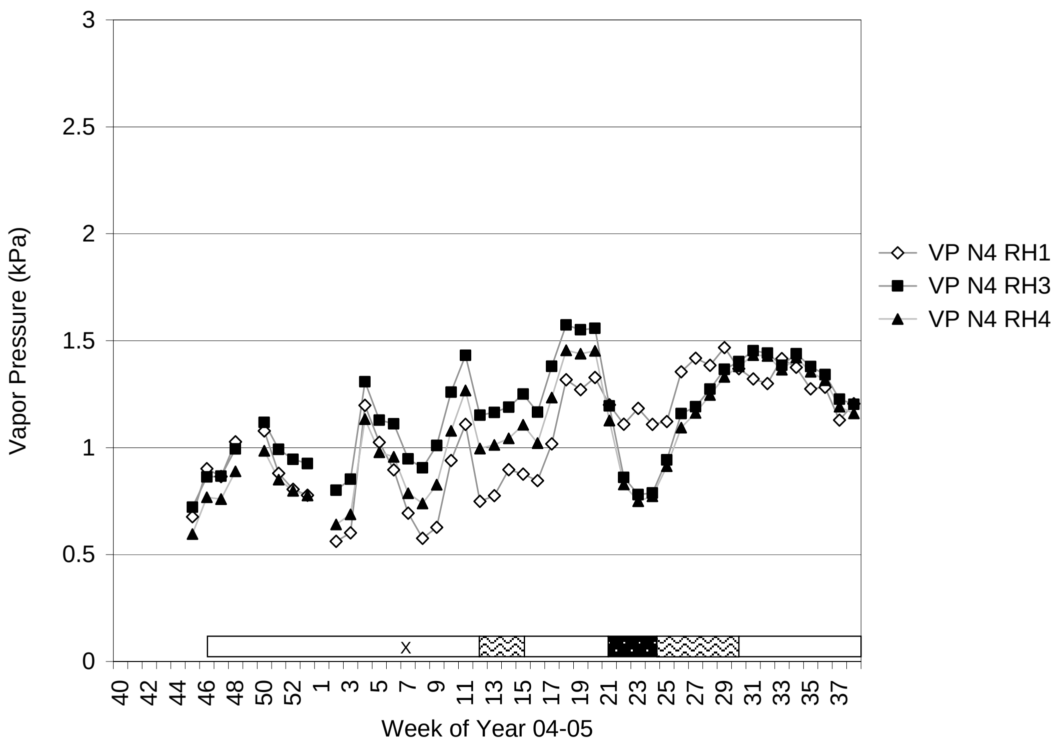


Figure B N5-1 N5 – Wood Moisture Content

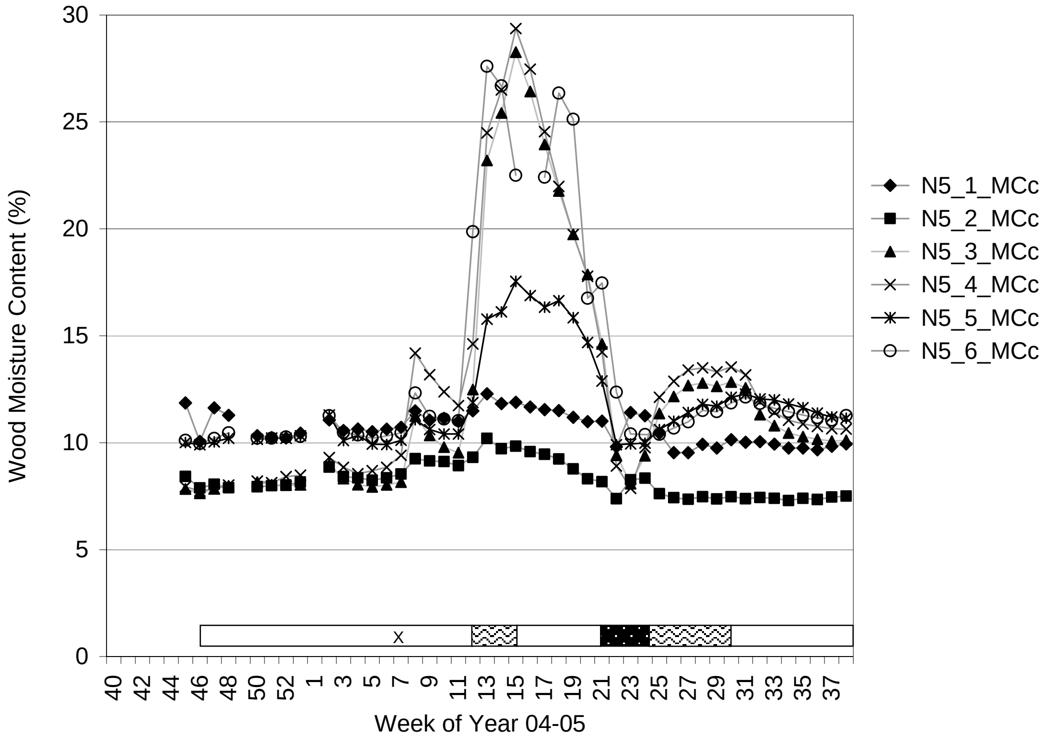


Figure B N5-2 N5 – Cavity Relative Humidity

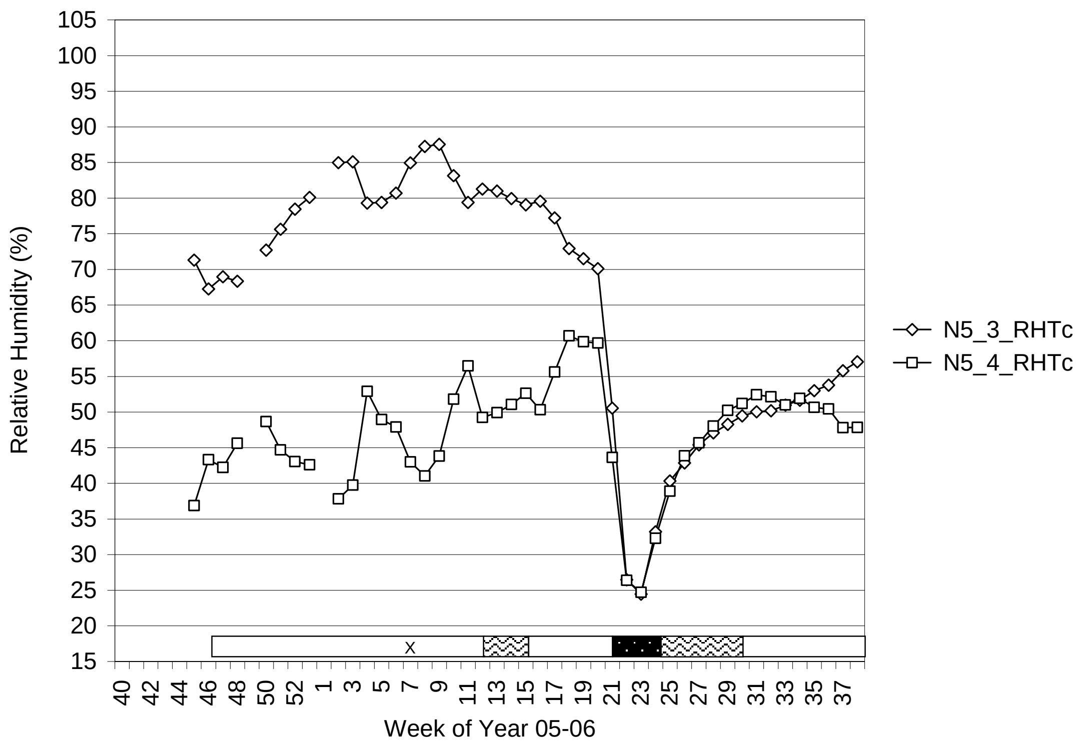


Figure B N5-3 N5 - Temperature

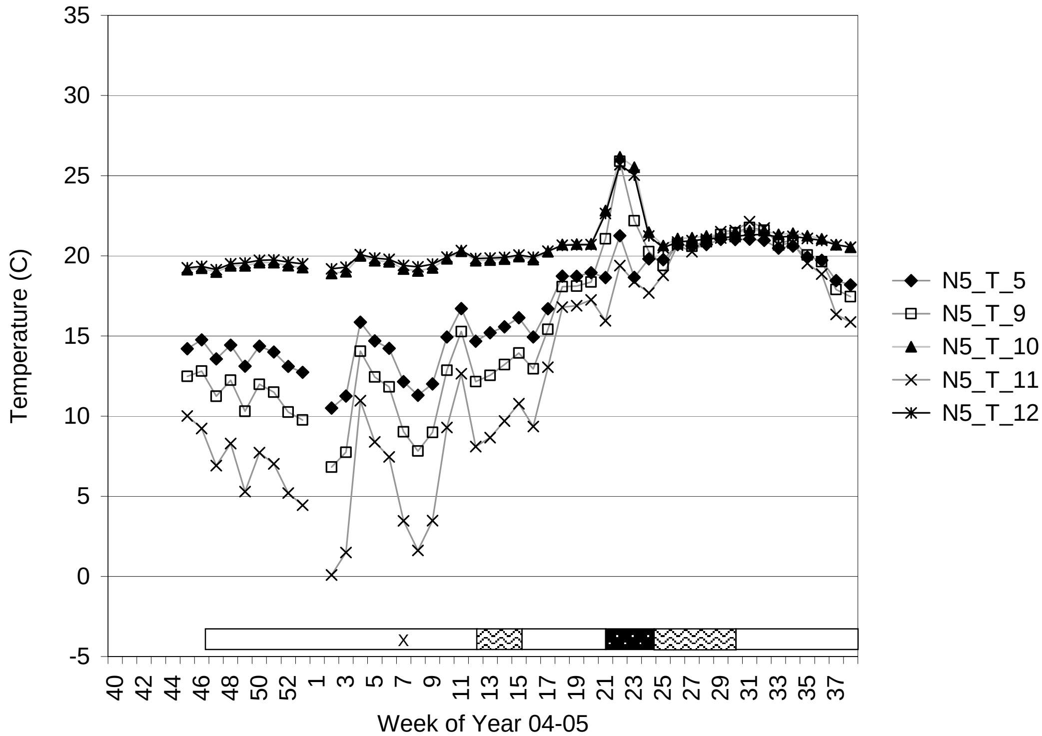


Figure B N5-4 N5 – Vapor Pressure

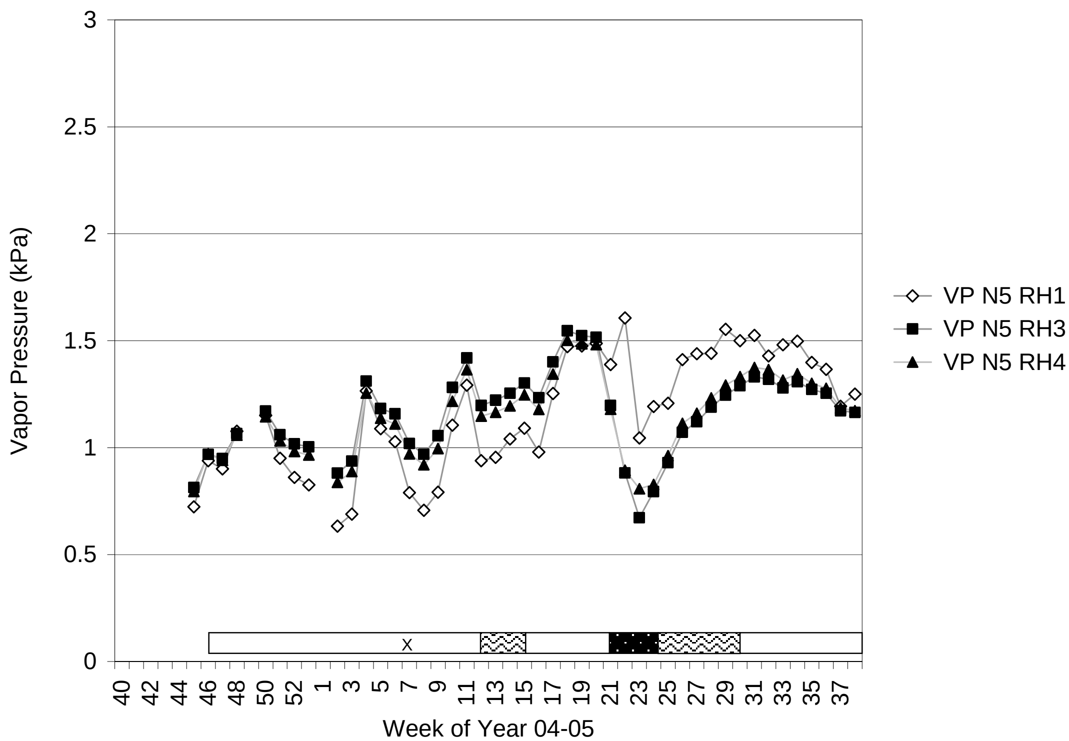


Figure B N6-1 N6 – Wood Moisture Content

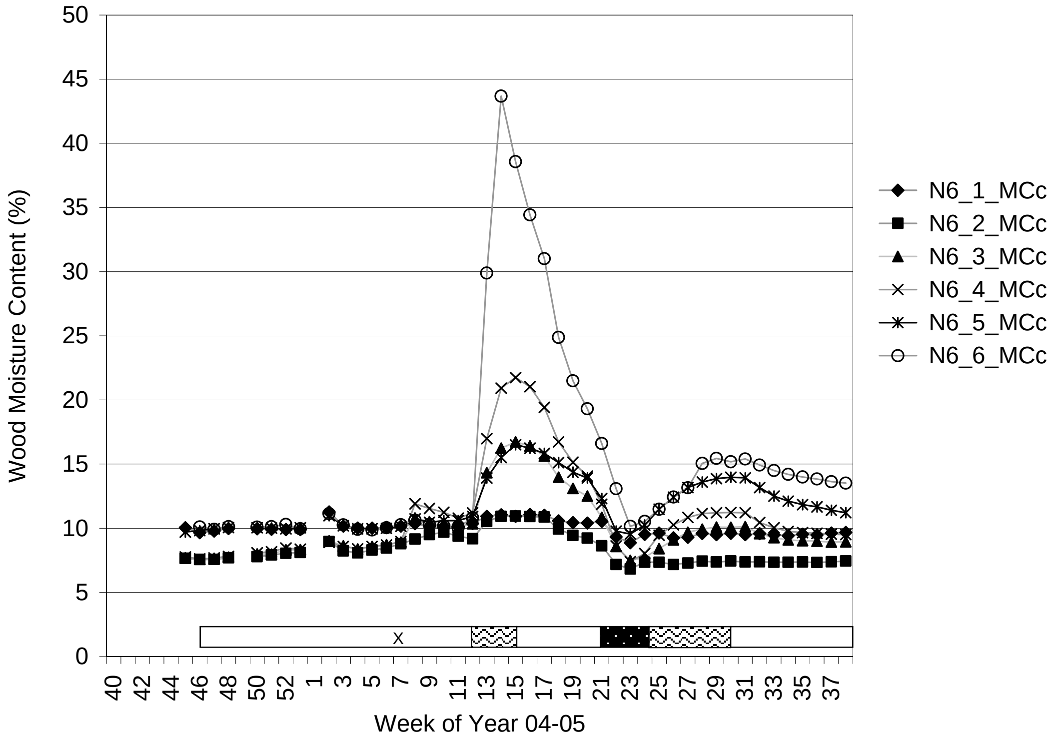


Figure B N6-2 N6 – Cavity Relative Humidity

Figure B N6-3 N6 - Temperature

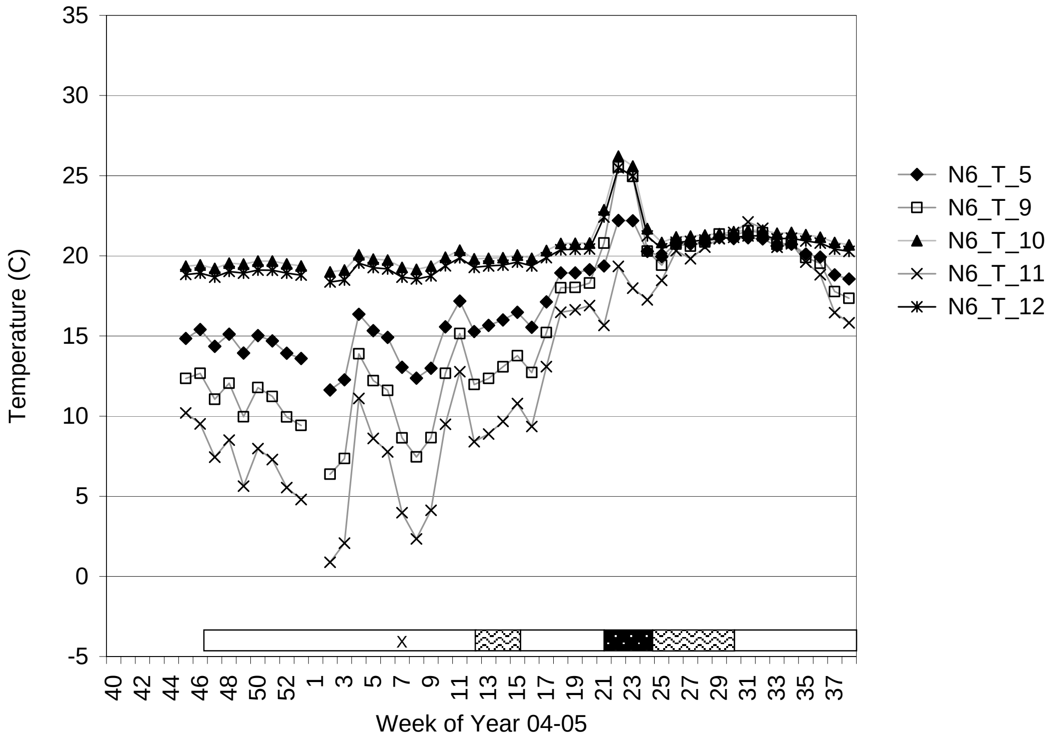


Figure B N6-4 N6 – Vapor Pressure

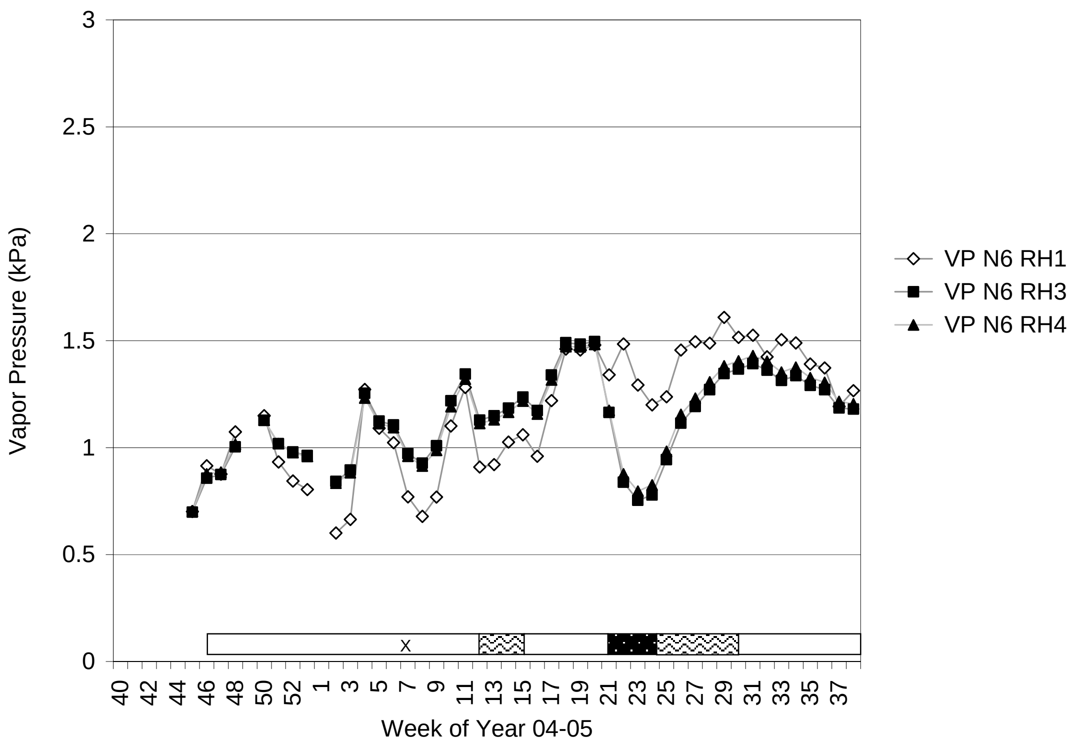


Figure B N7-1 N7 – Wood Moisture Content

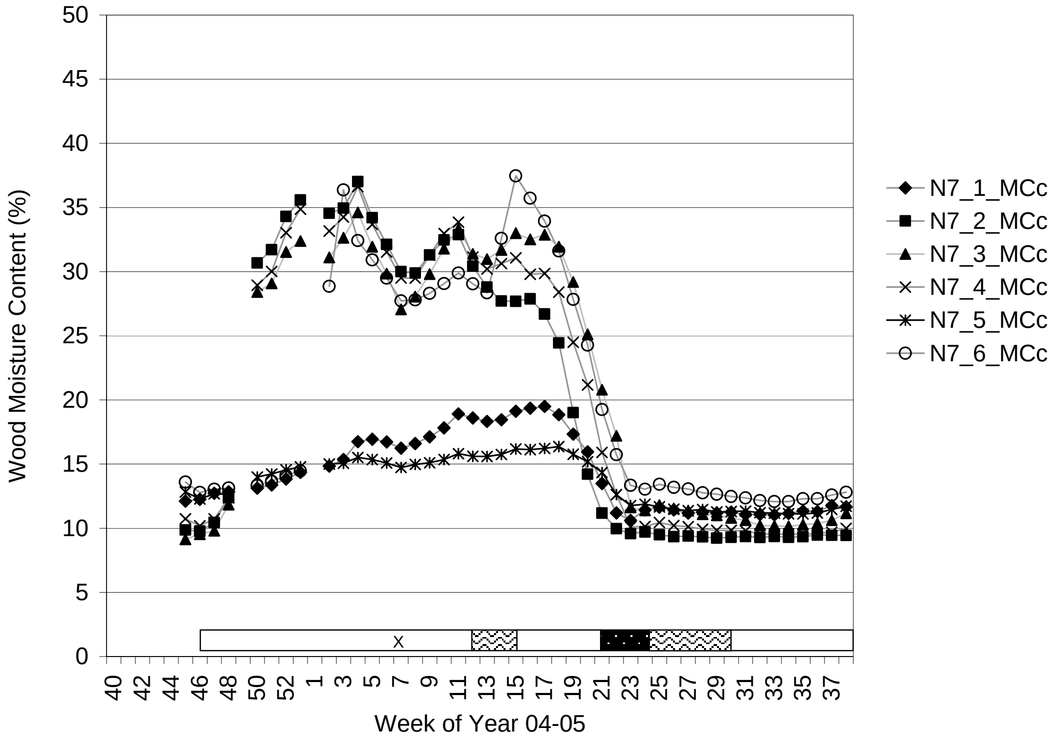


Figure B N7-2 N7 – Cavity Relative Humidity

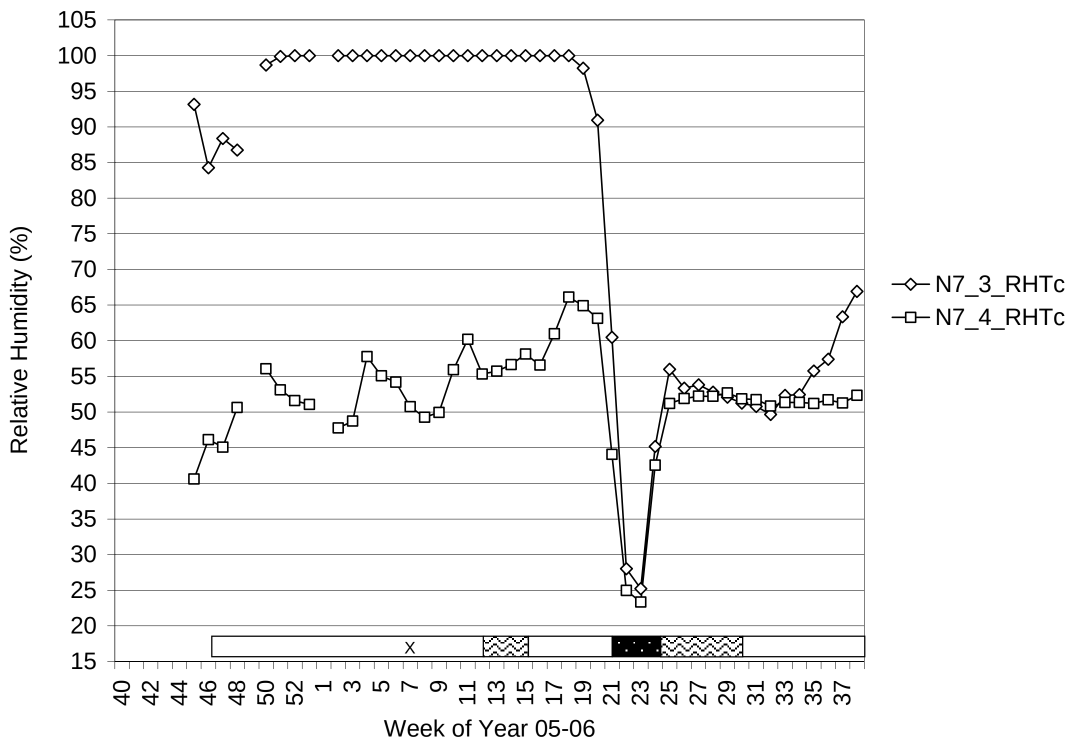


Figure B N7-3 N7 - Temperature

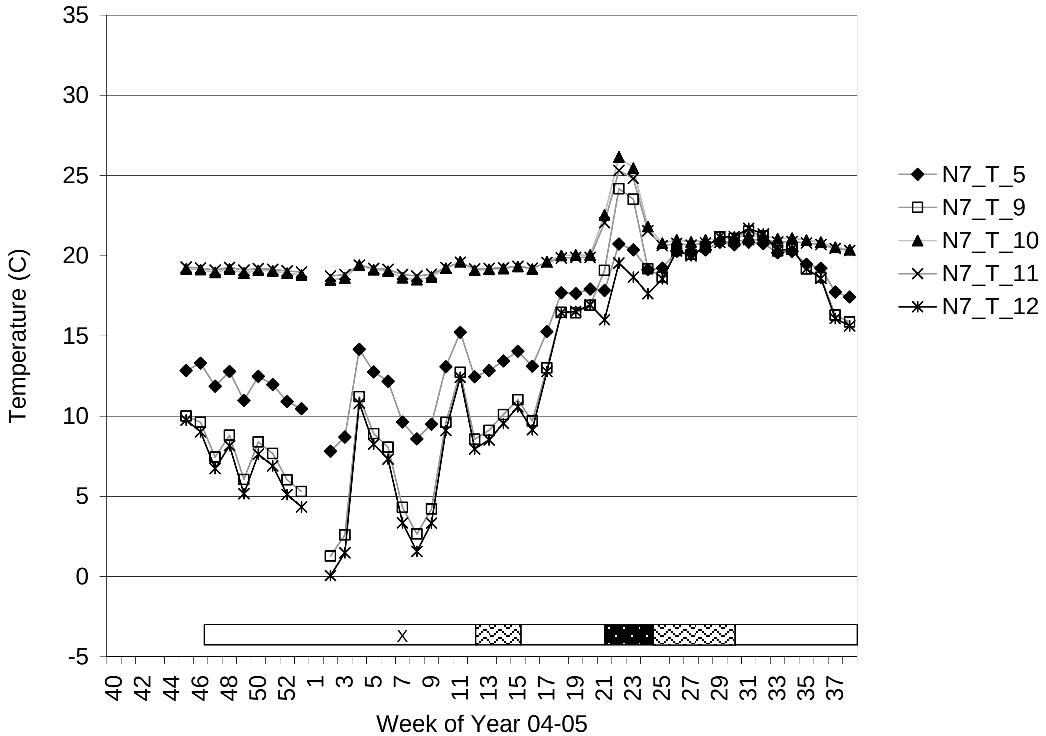


Figure B N7-4 N7 – Vapor Pressure

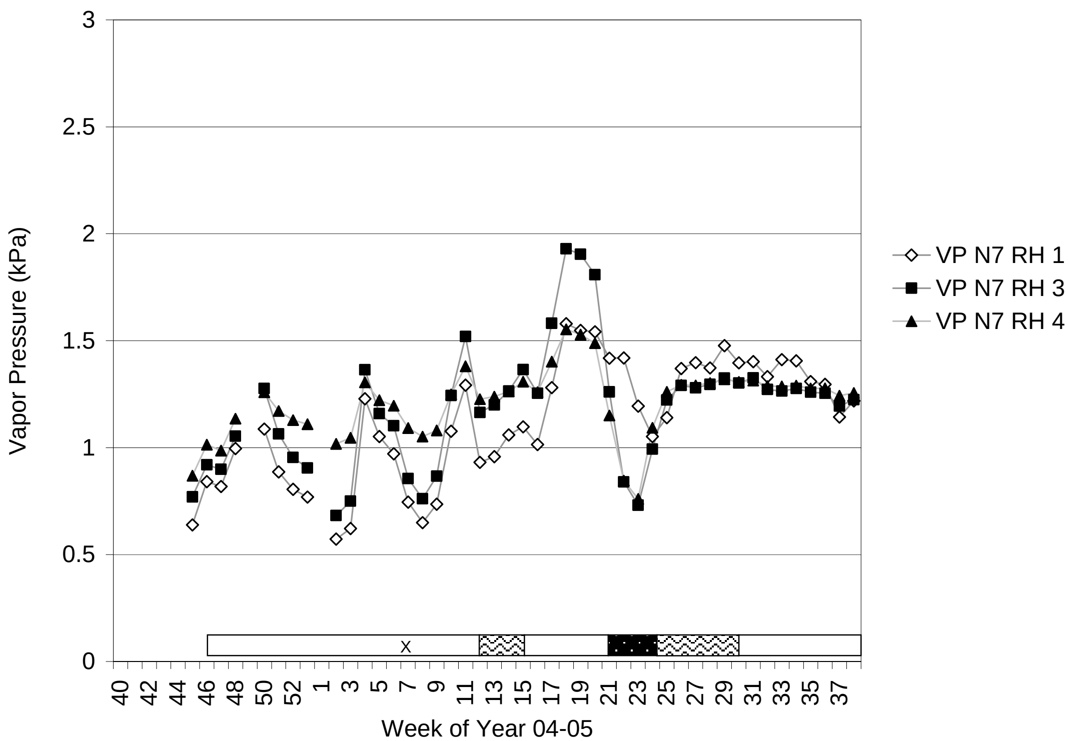


Figure B N8-1 N8 – Wood Moisture Content

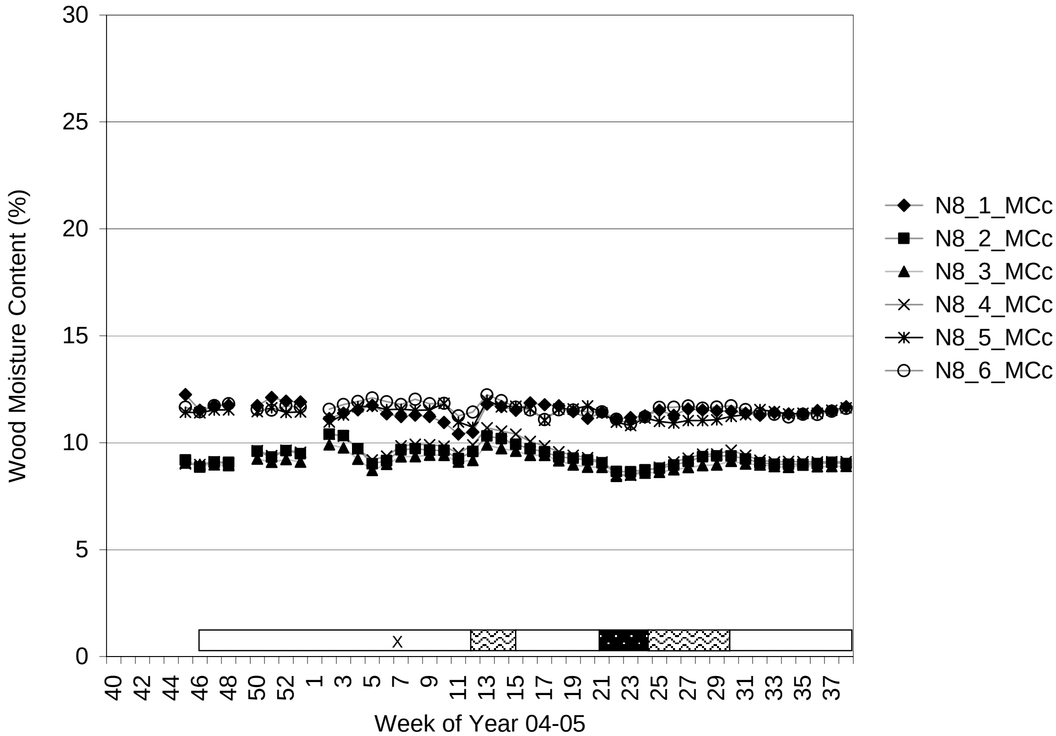


Figure B N8-2 N8 – Cavity Relative Humidity

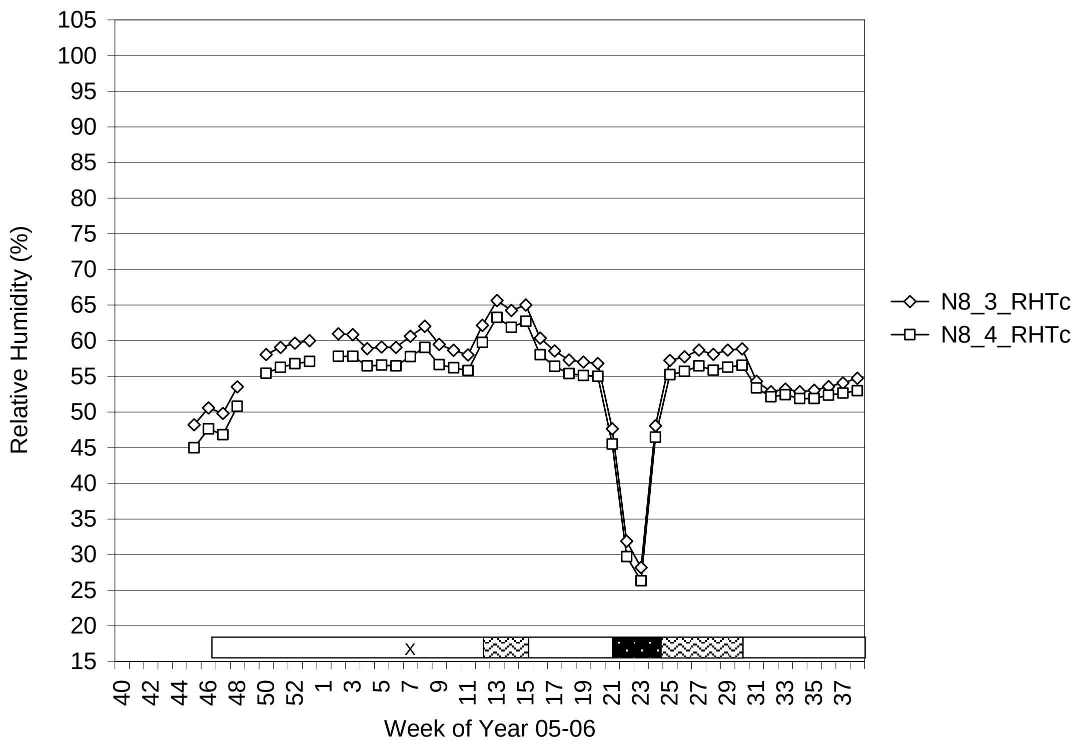


Figure B N8-3 N8 - Temperature

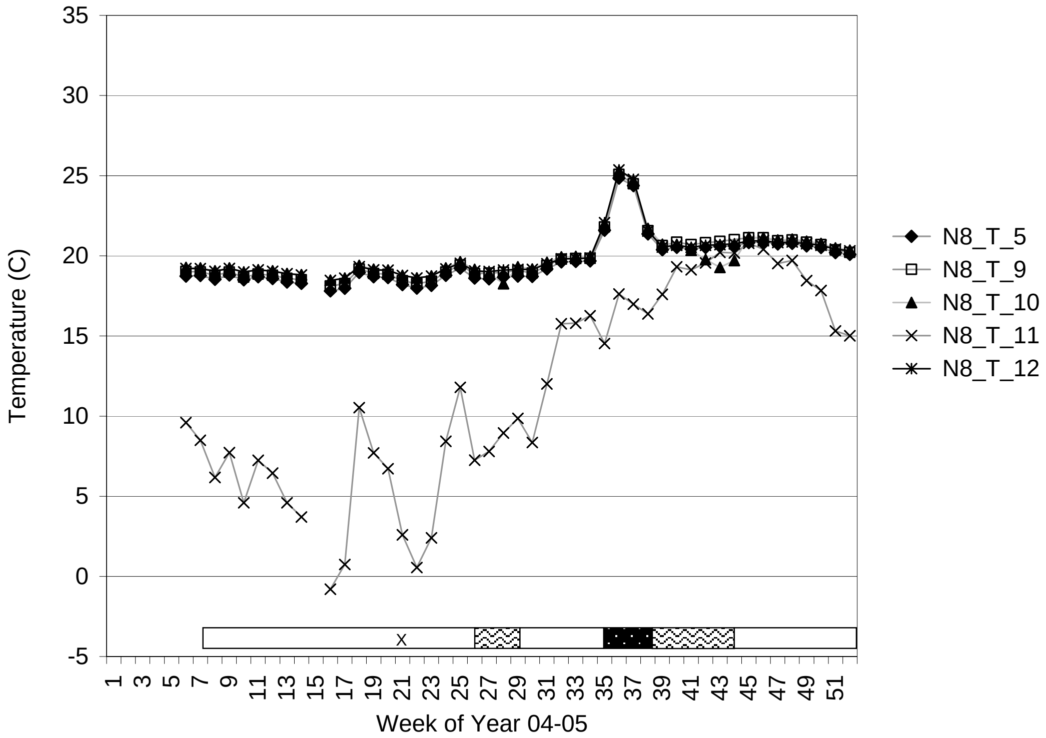
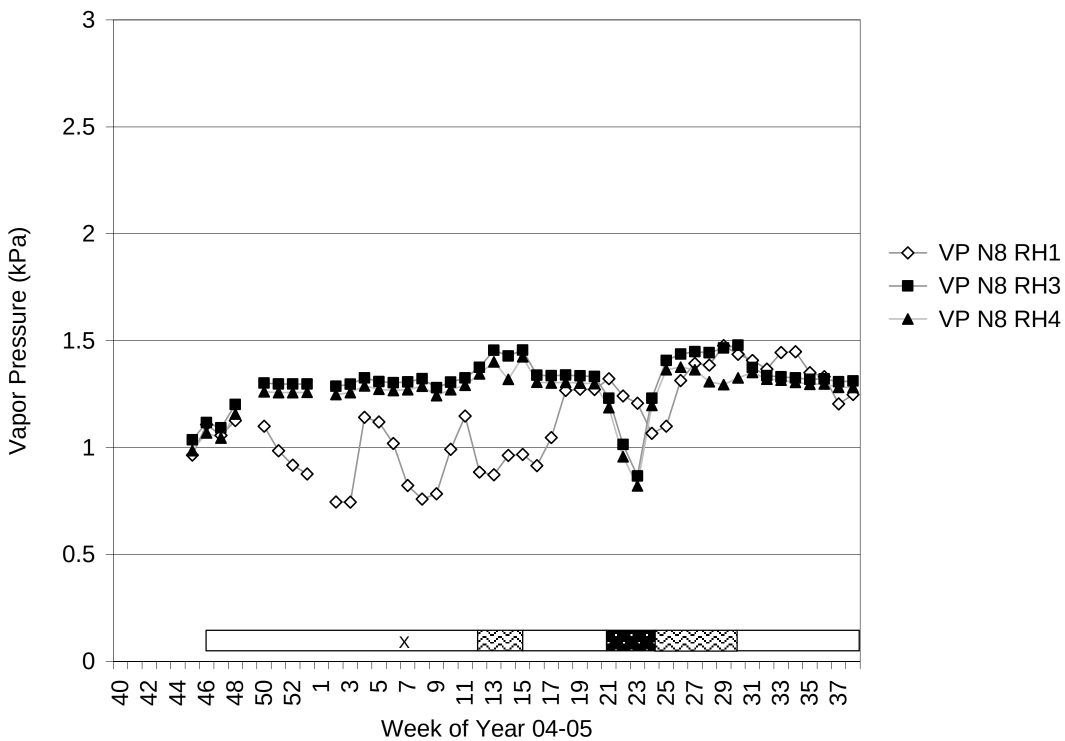


Figure B N8-3 N8 – Vapor Pressure



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

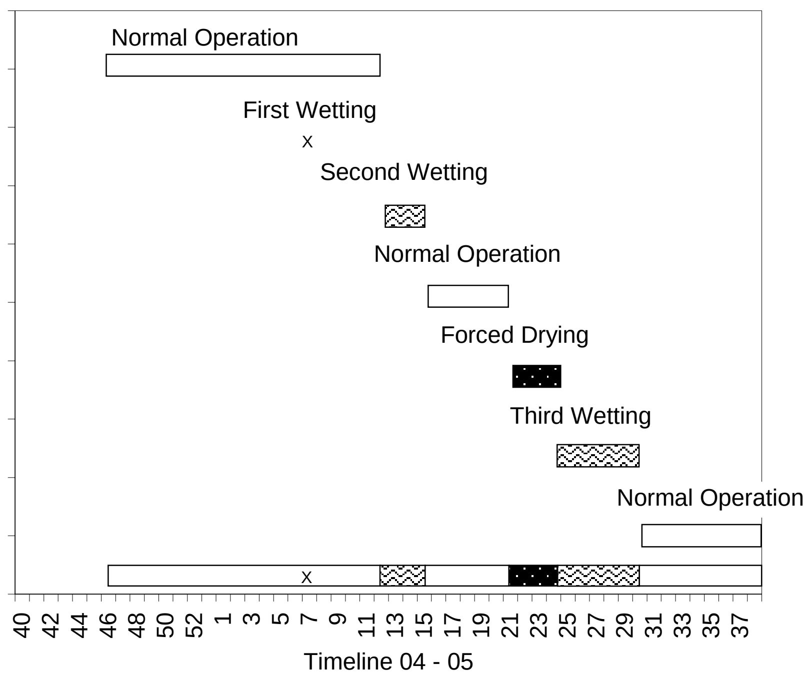


Figure B S1-1 S1 – Wood Moisture Content

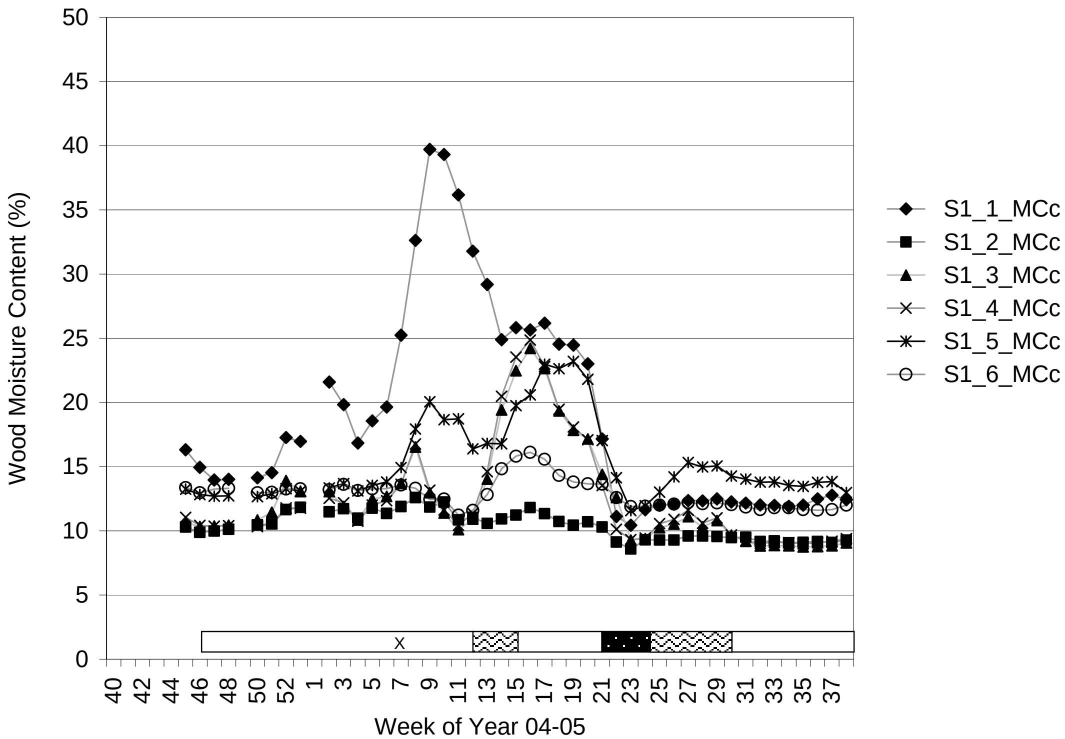


Figure B S1-2 S1 – Cavity Relative Humidity

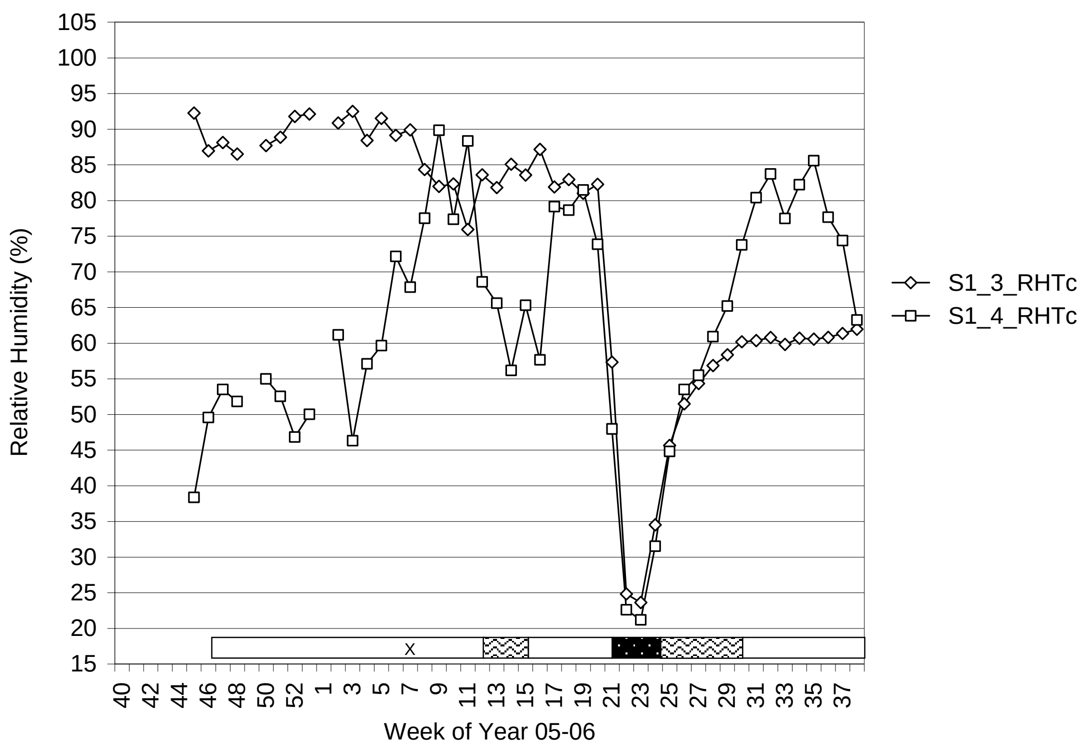


Figure B S1-3 S1 - Temperature

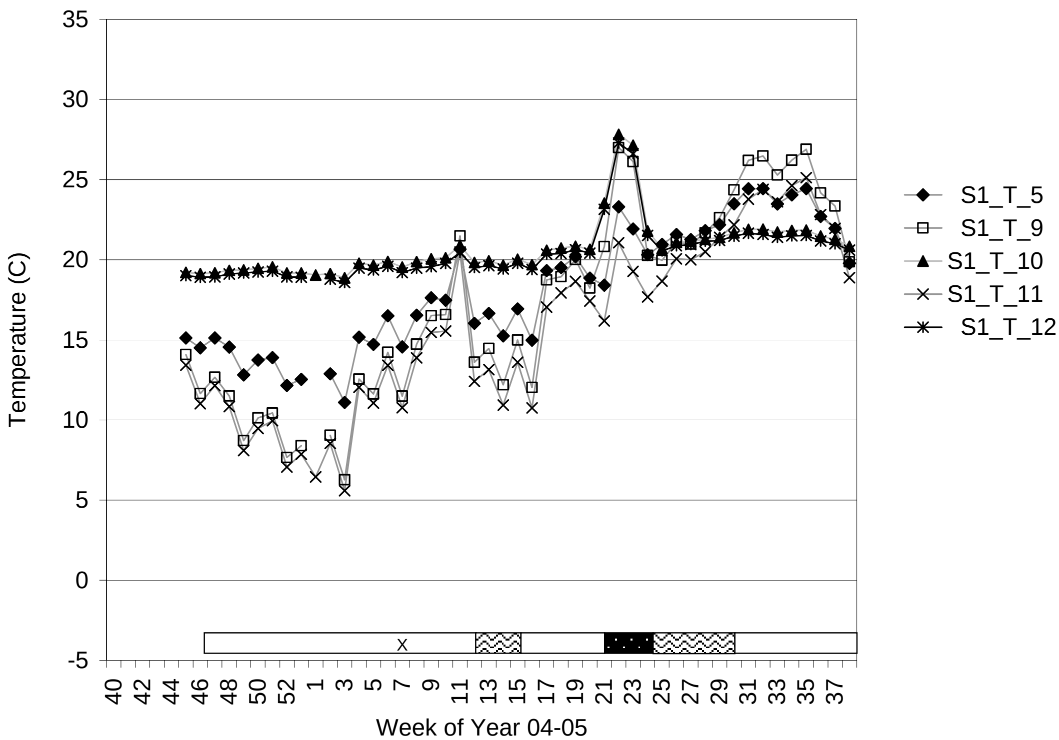


Figure B S1-4 S1 – Vapor Pressure

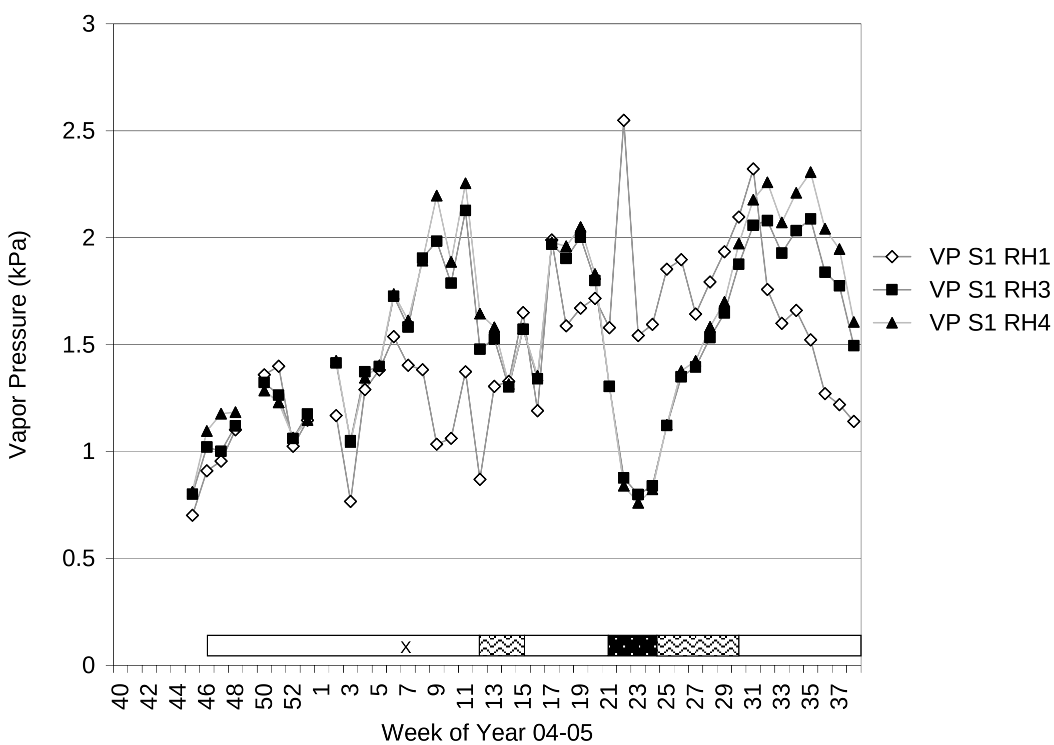


Figure B S2-1 S2– Wood Moisture Content

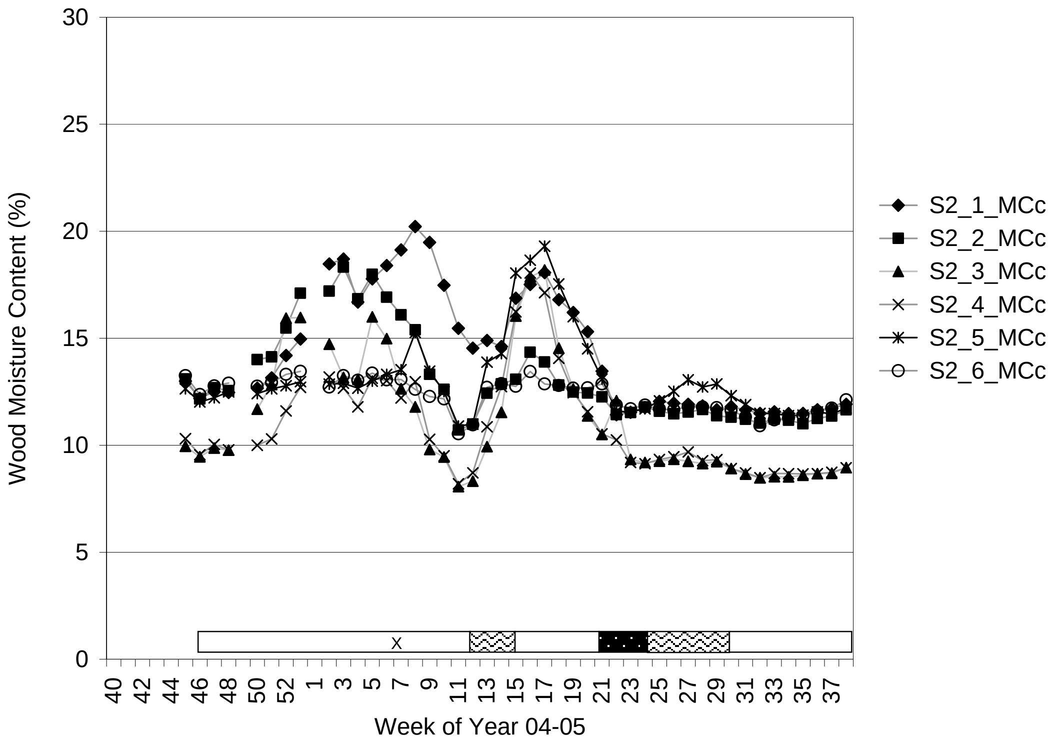


Figure B S2-2 S2– Cavity Relative Humidity

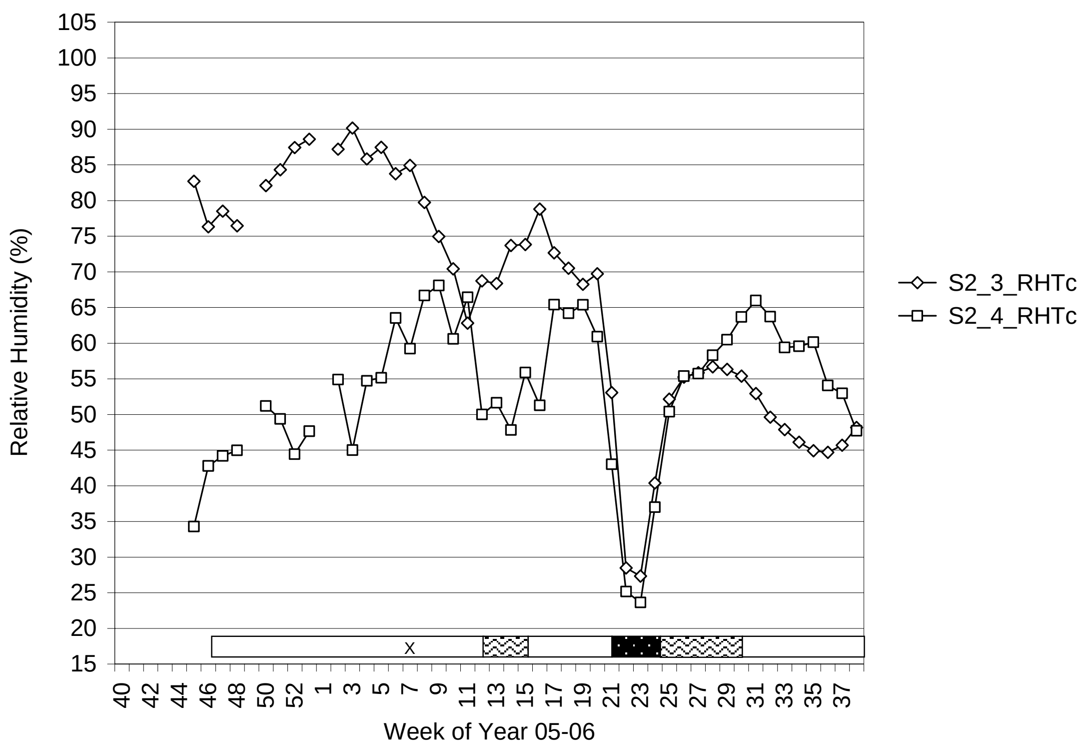


Figure B S2-3 S2- Temperature

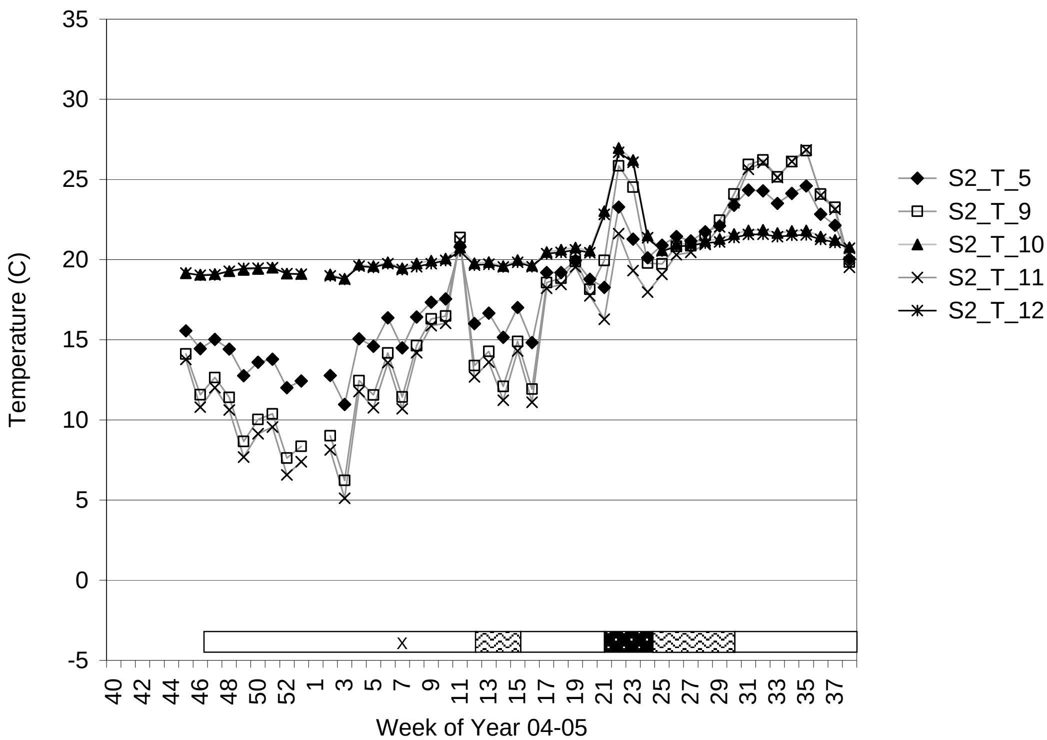


Figure B S2-4 S2 – Vapor Pressure

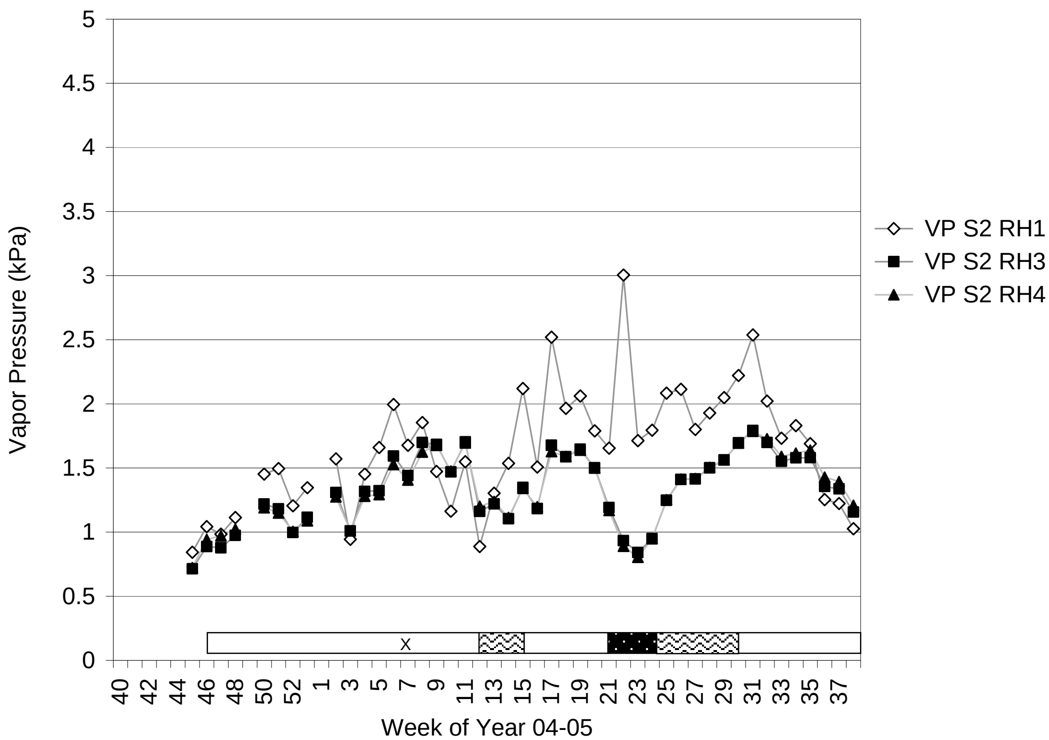


Figure B S3-1 S3 – Wood Moisture Content

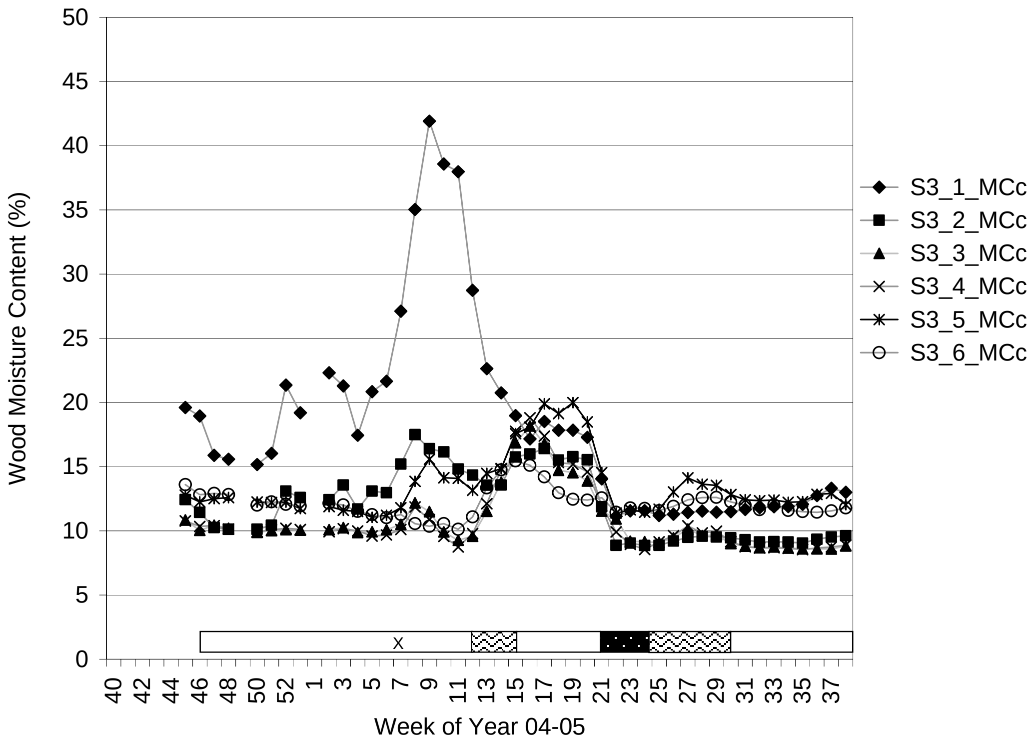


Figure B S3-2 S3 – Cavity Relative Humidity

Figure B S3-3 S3 - Temperature

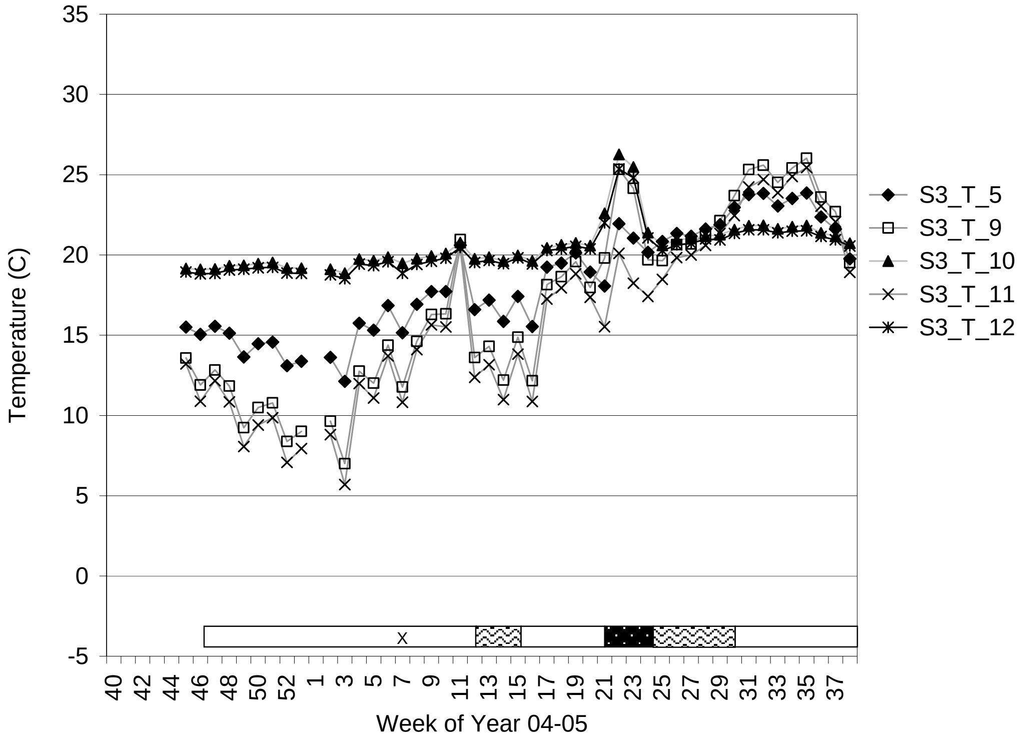


Figure B S3-4 S3 – Vapor Pressure

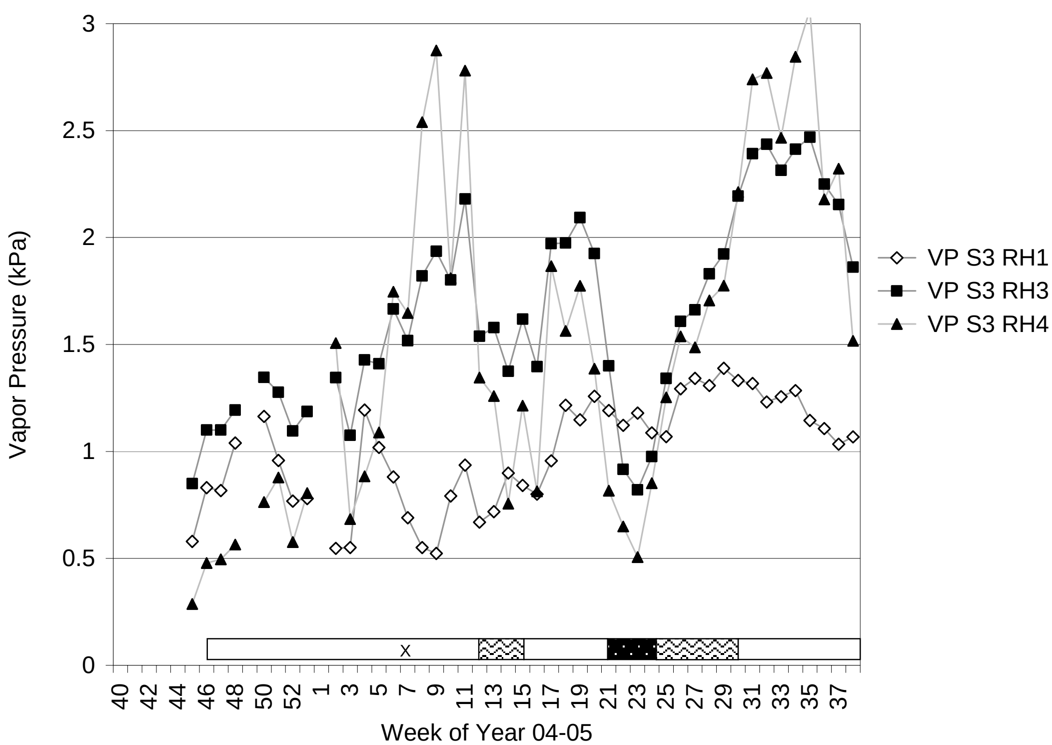


Figure B S4-1 **S4 – Wood Moisture Content**

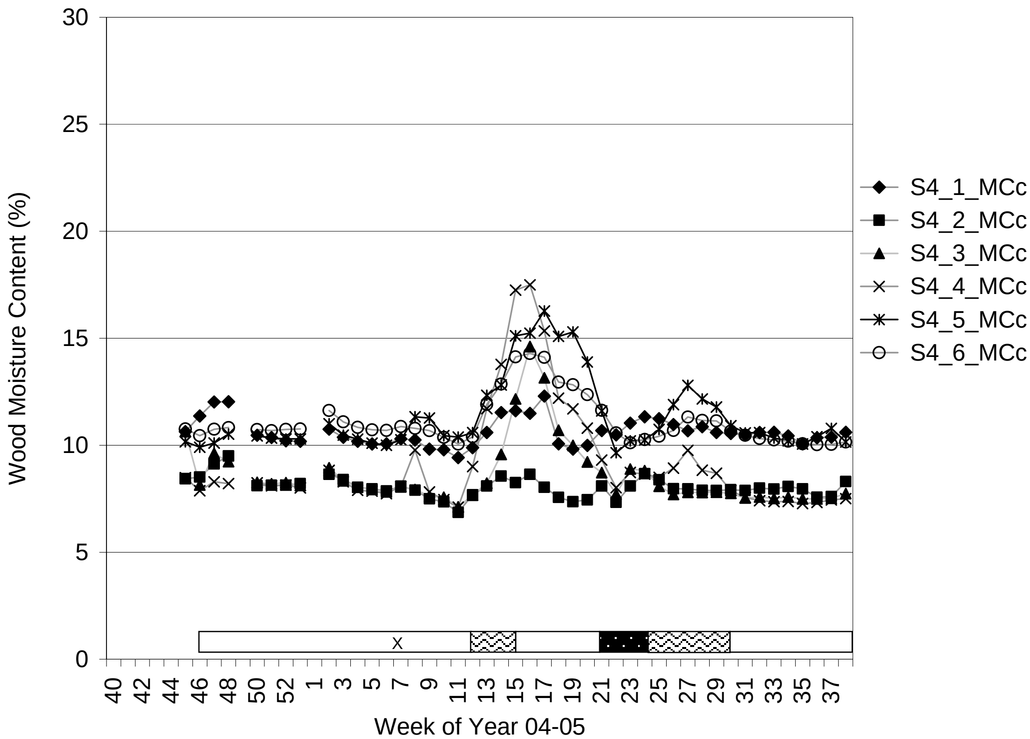


Figure B S4-2 **S4 – Cavity Relative Humidity**

4

Figure B S4-3 S4- Temperature

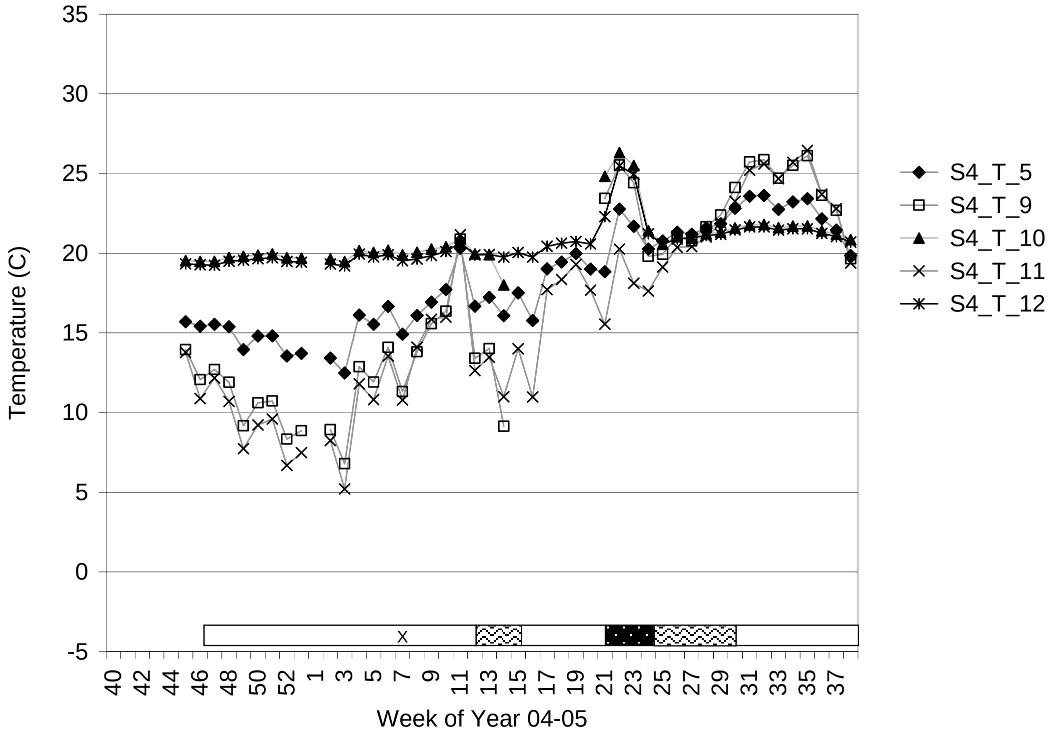


Figure B S4-4 S4 - Vapor Pressure

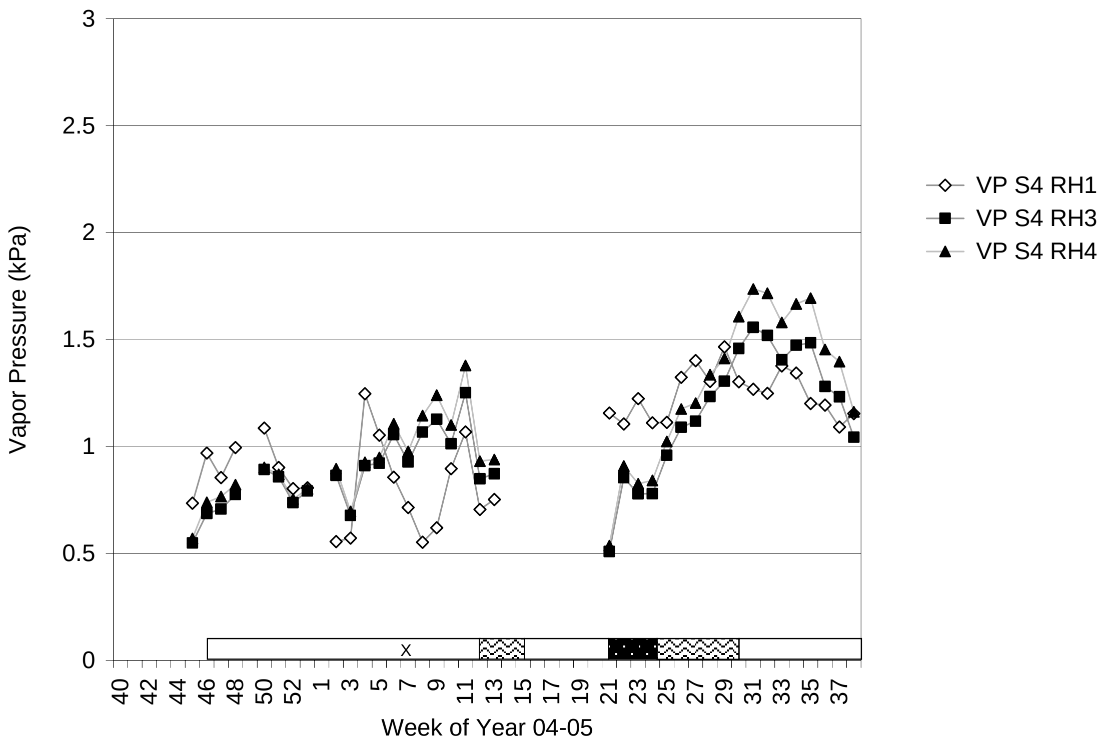


Figure B S5-1 S5 – Wood Moisture Content

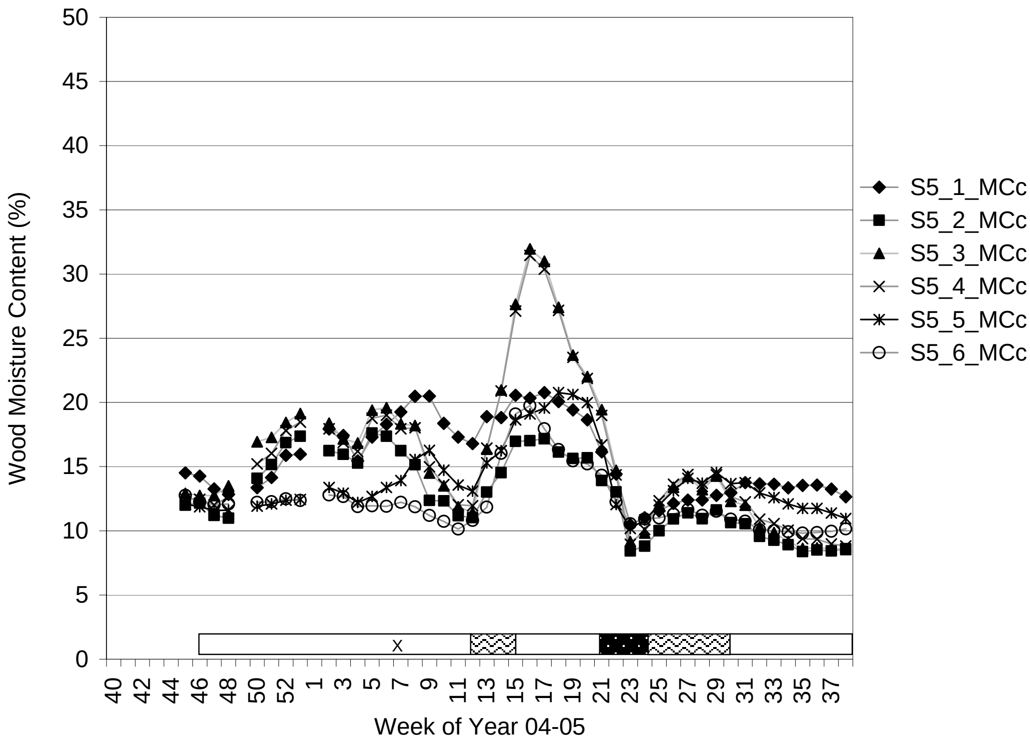


Figure B S5-2 S5 – Cavity Relative Humidity

Figure B S5-3 S5 - Temperature

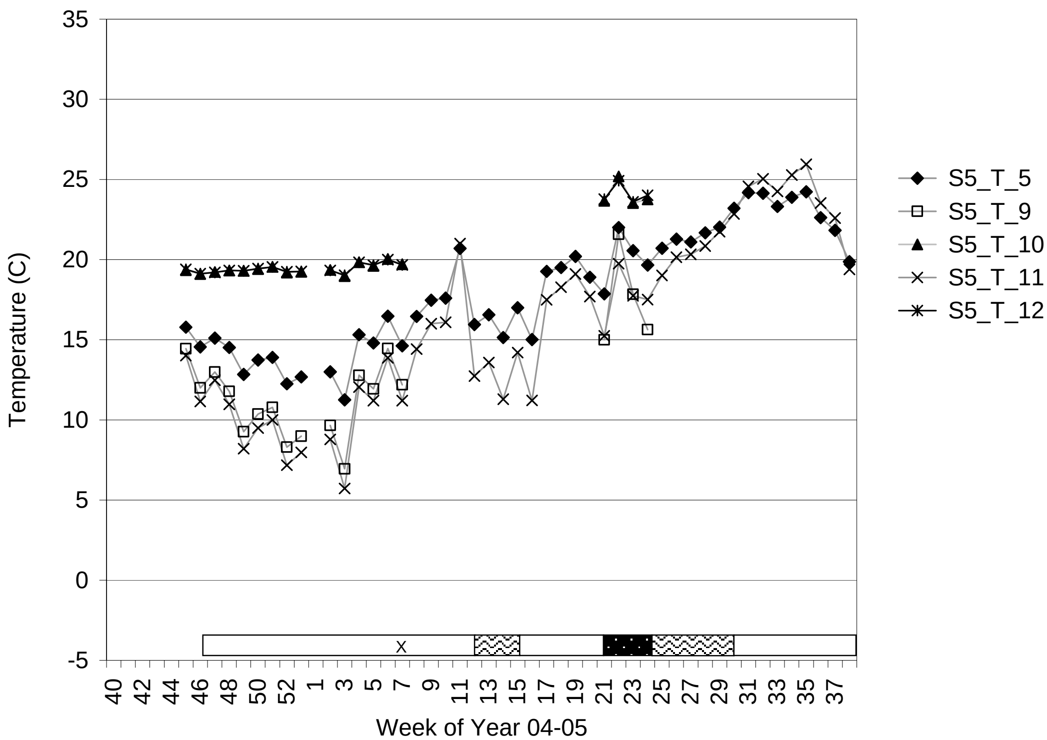


Figure B S5-4 S5 – Vapor Pressure

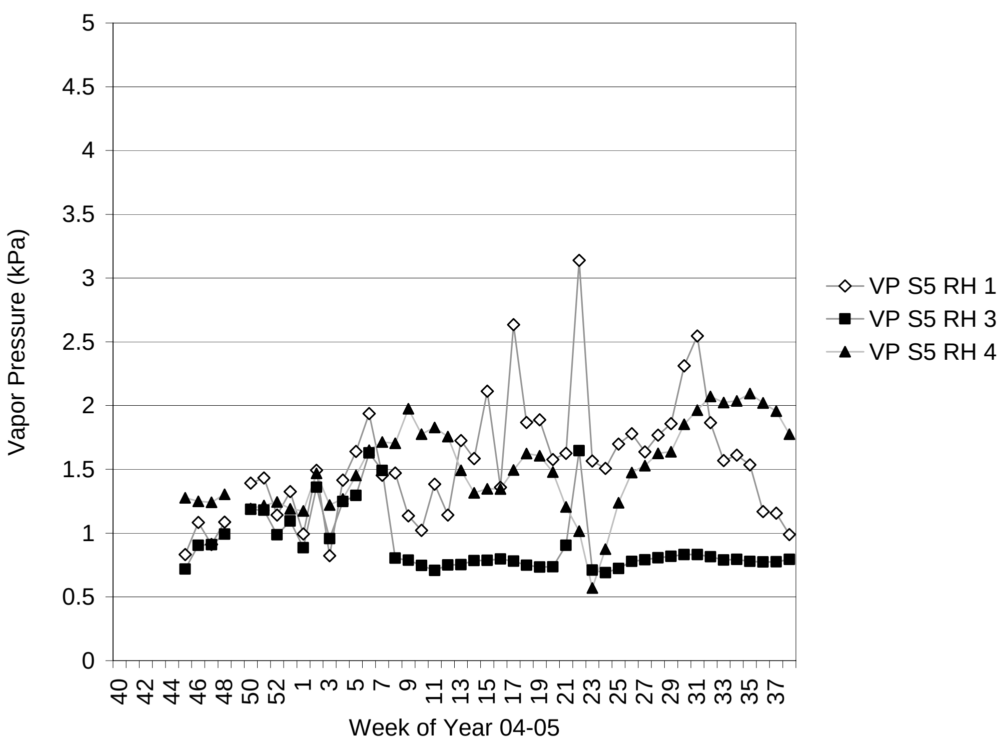


Figure B S6-1 S6 – Wood Moisture Content

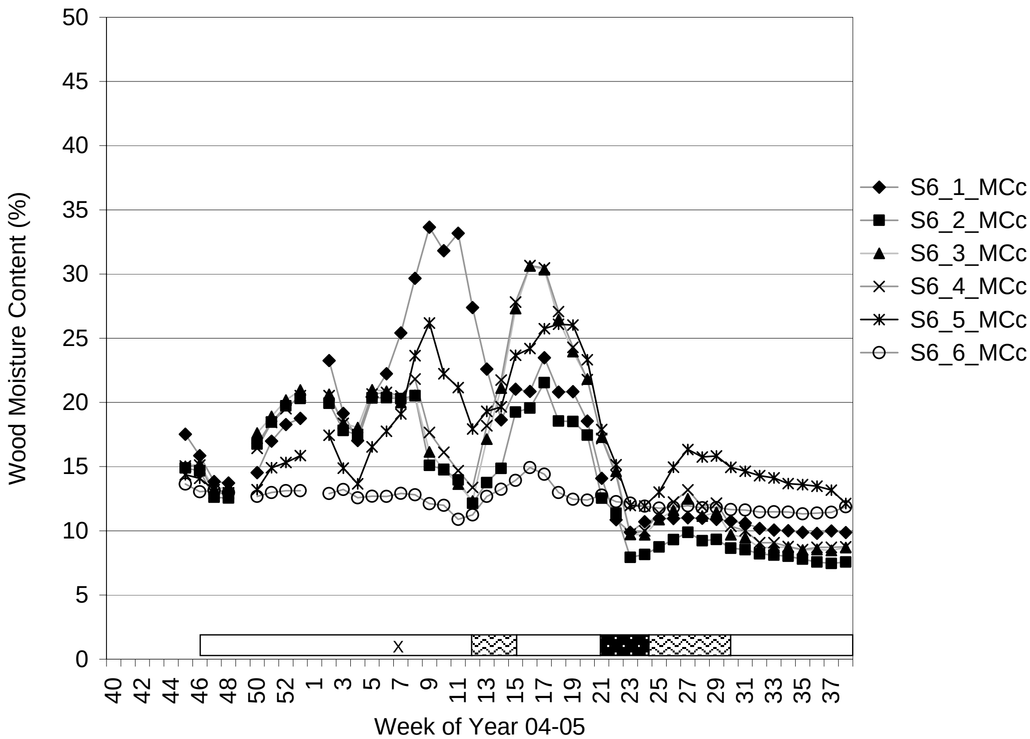


Figure B S6-2 S6 – Cavity Relative Humidity

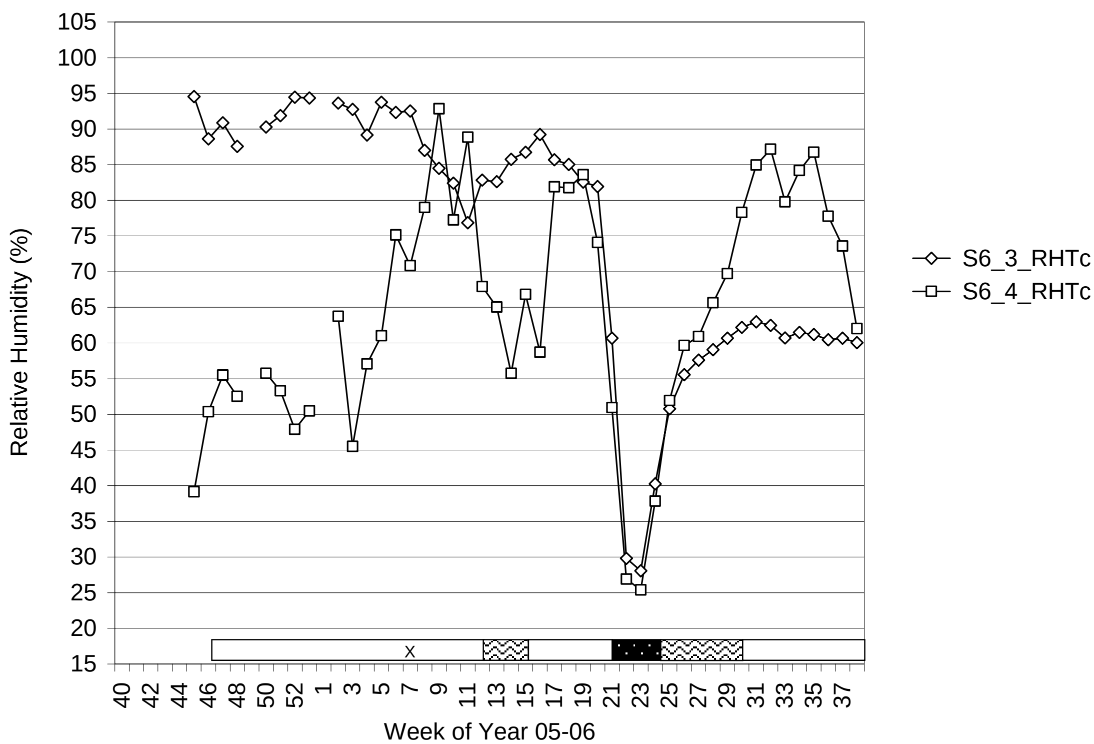


Figure B S6-3 S6 - Temperature

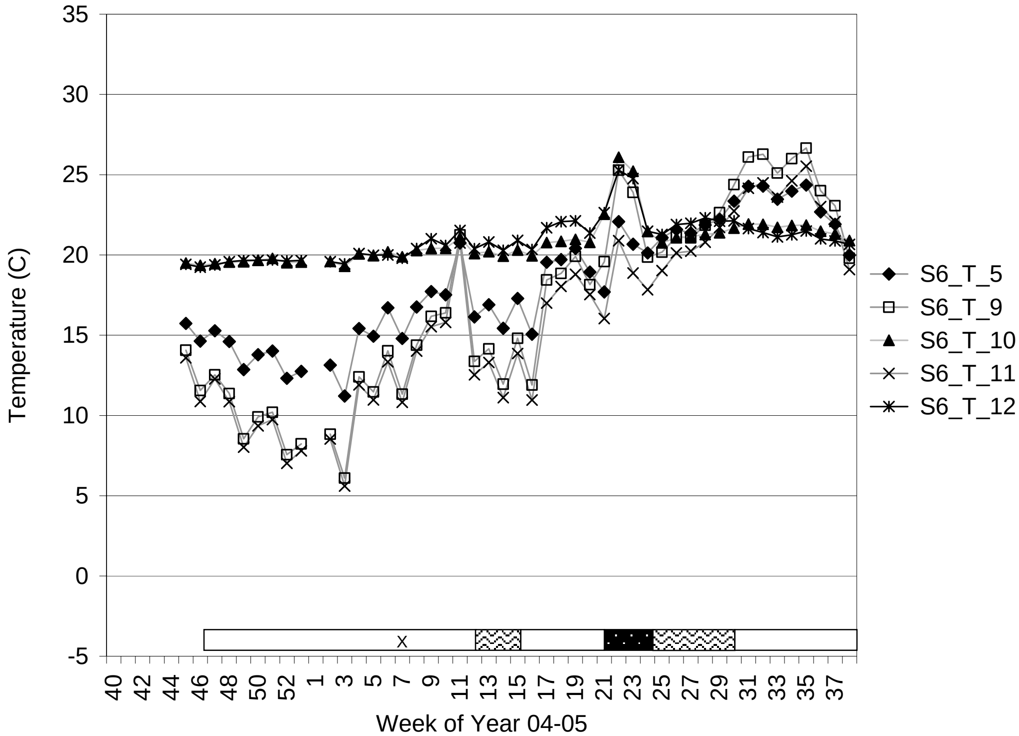


Figure B S6-4 S6 – Vapor Pressure

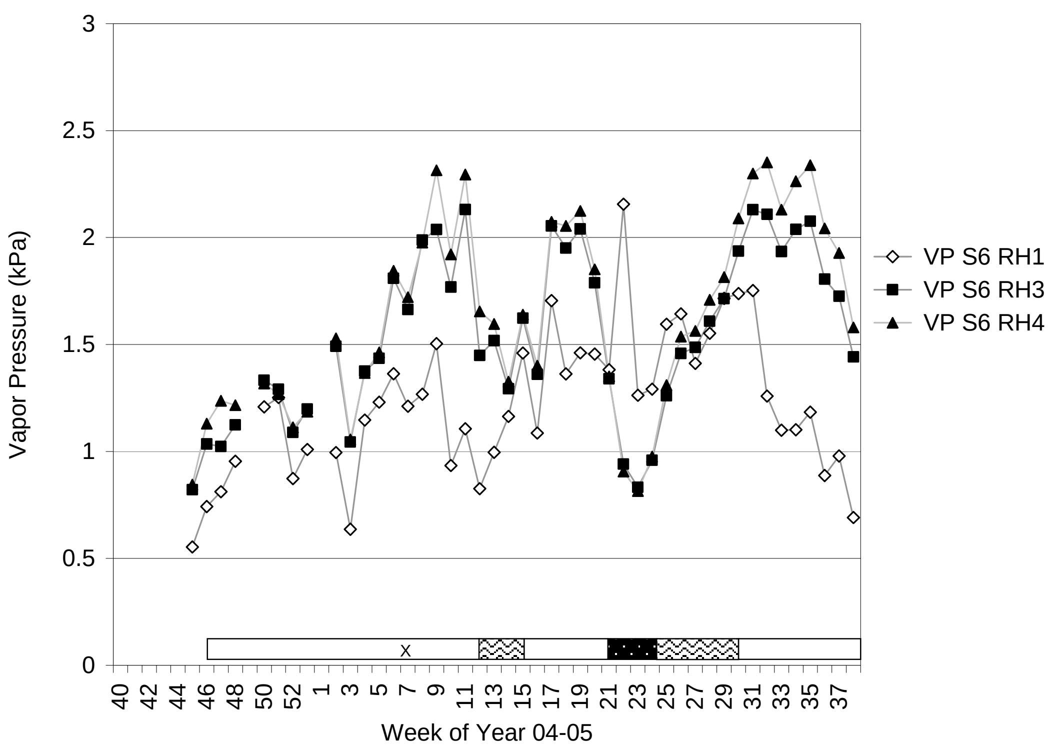


Figure B S7-1 S7 – Wood Moisture Content

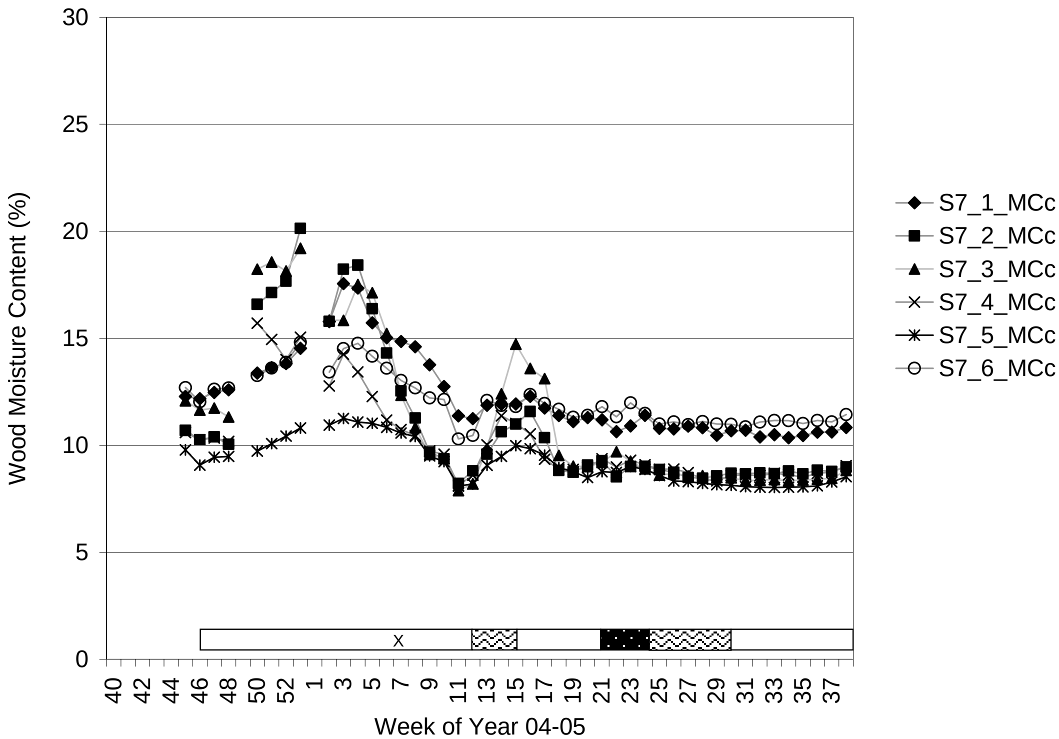


Figure B S7-2 S7 – Cavity Relative Humidity

Figure B S7-3 S7 - Temperature

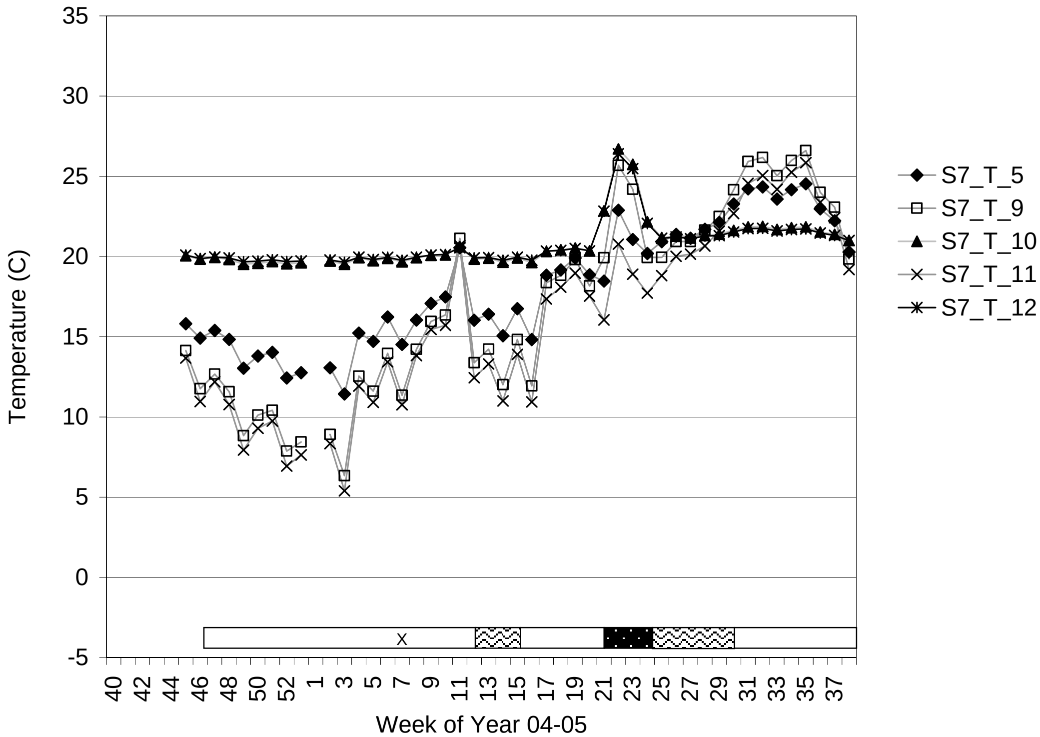


Figure B S7-4 S7 – Vapor Pressure

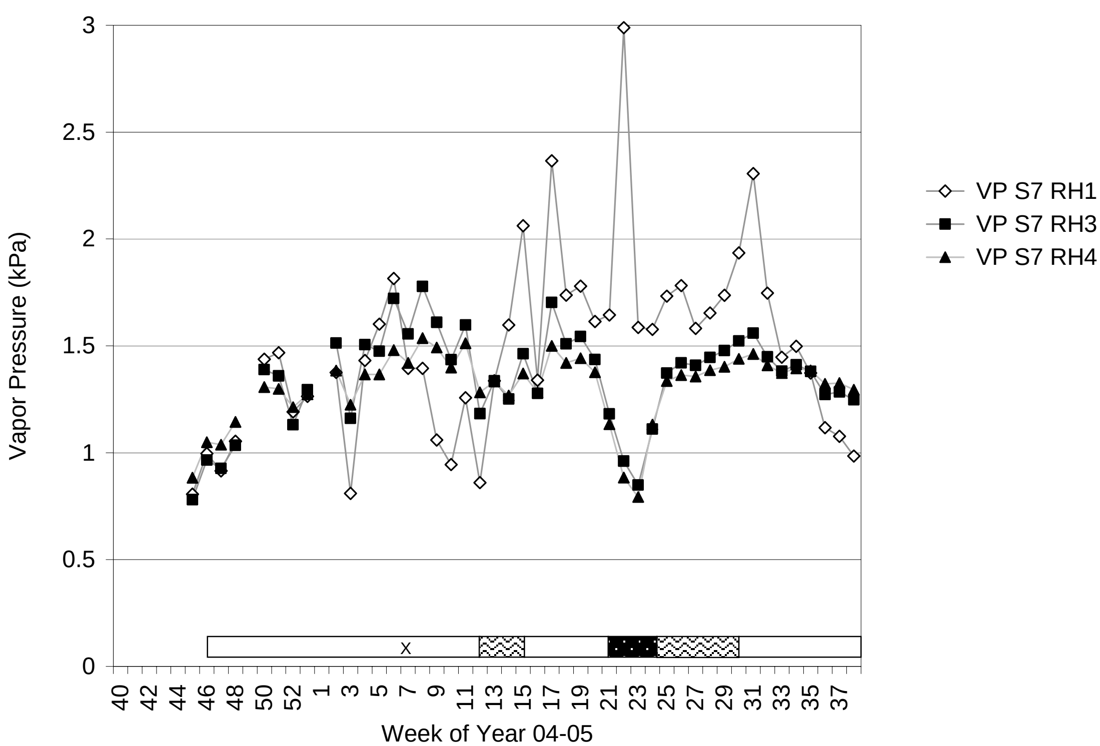


Figure B S8-1 S8 – Wood Moisture Content

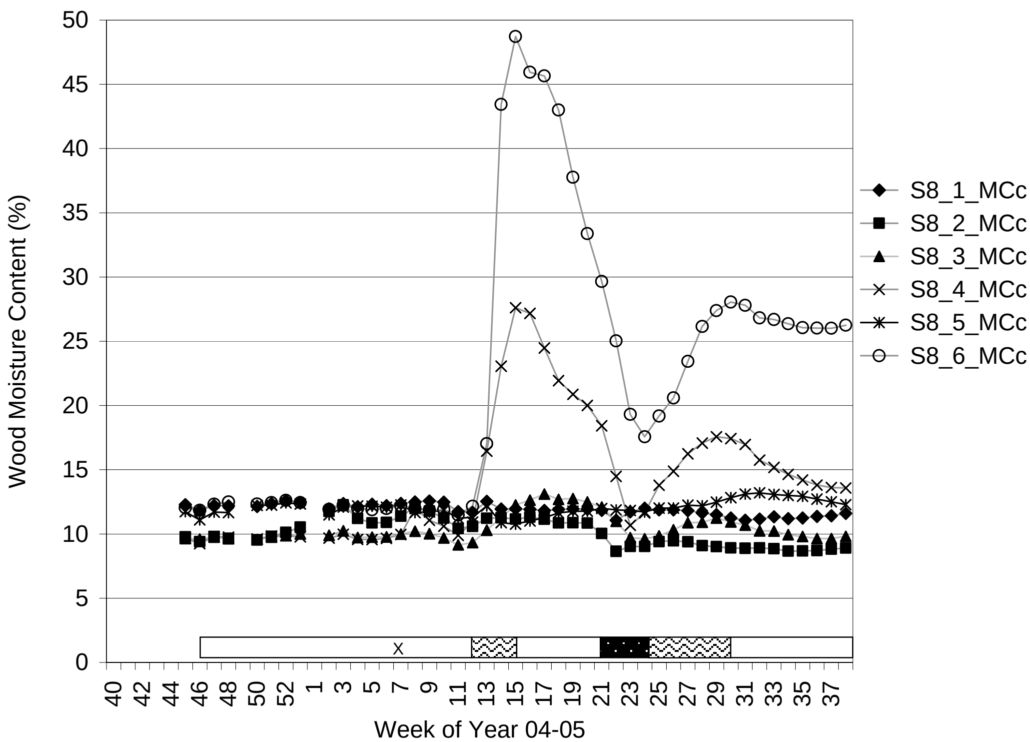


Figure B S8-2 S8 – Cavity Relative Humidity

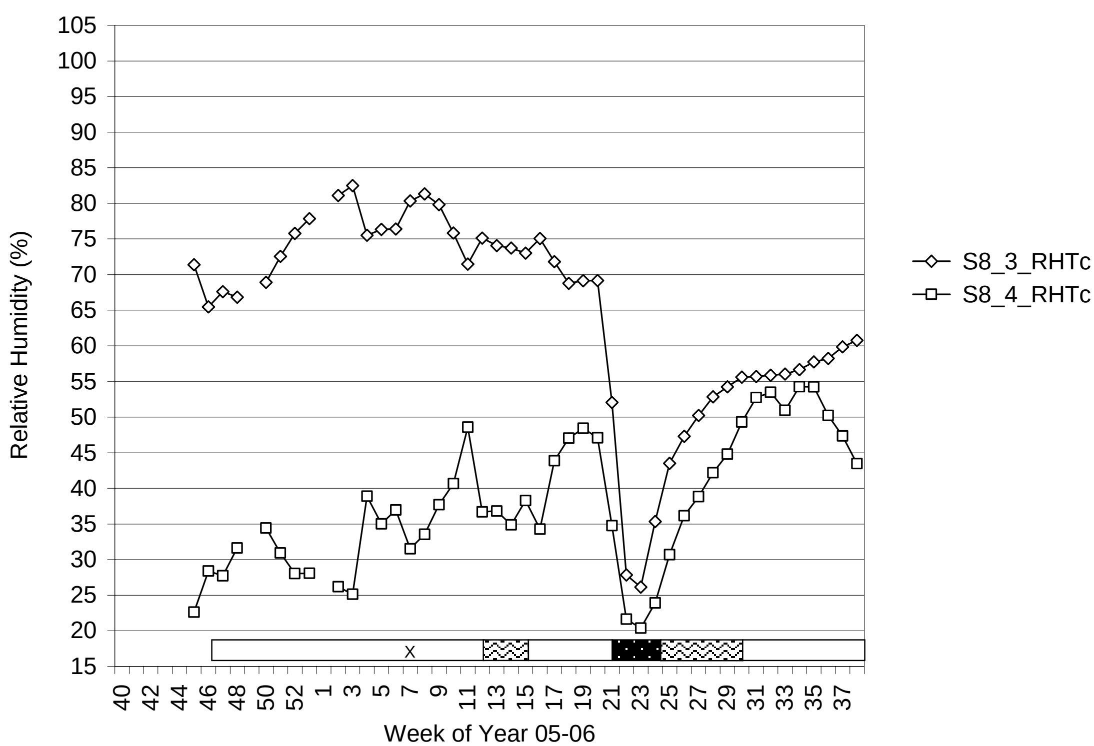


Figure B S8-3 S8 - Temperature

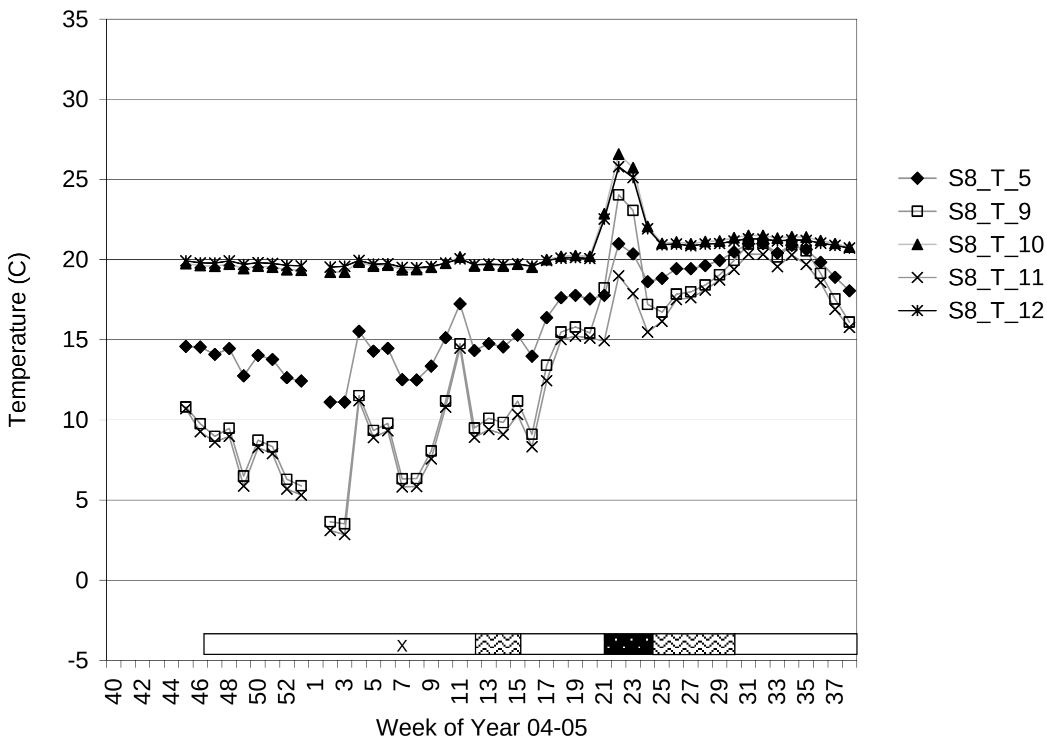


Figure B S8-4 S8 – Vapor Pressure

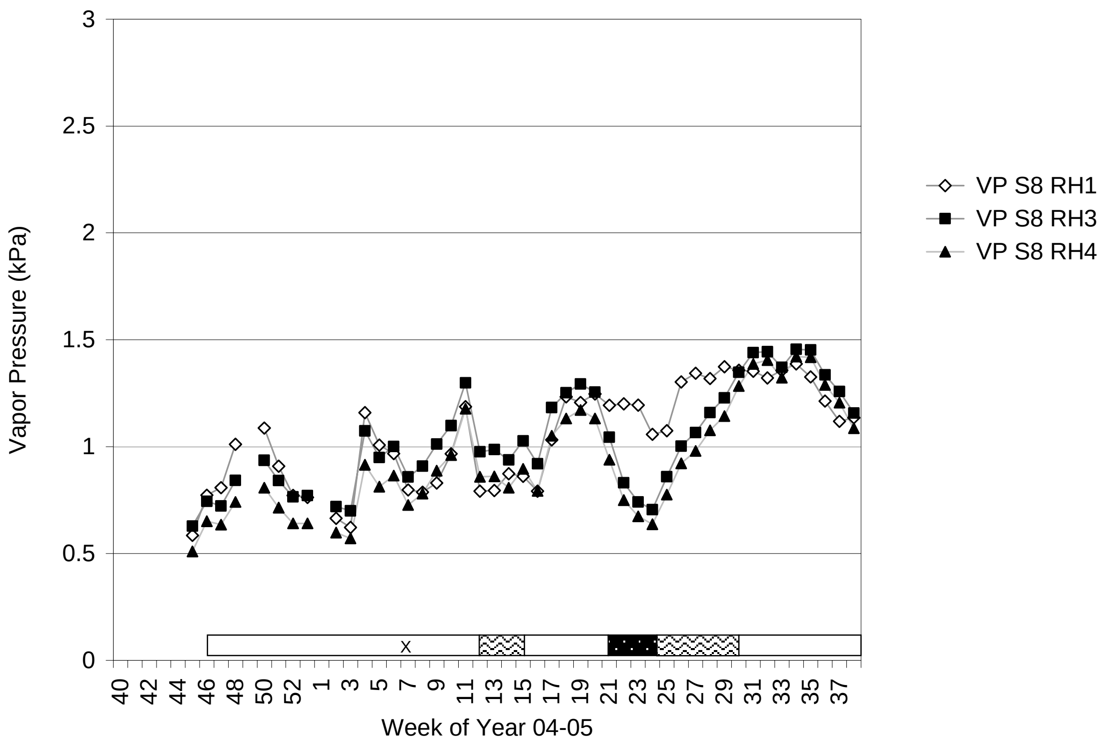


Figure B S8-1 S9 – Wood Moisture Content

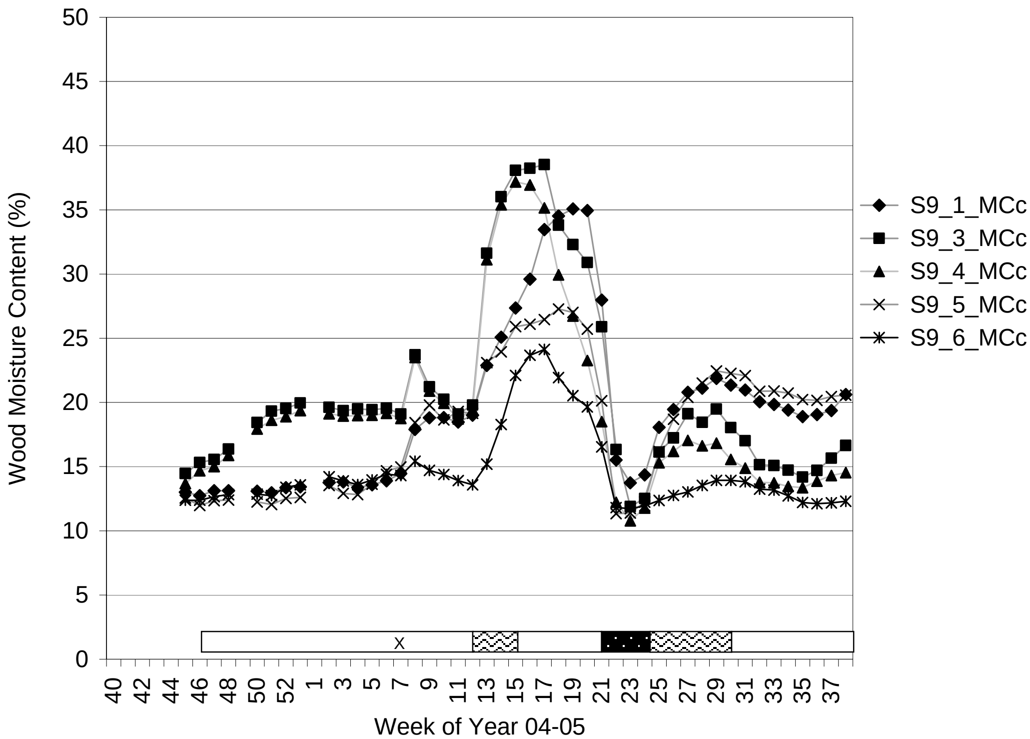


Figure B S9-2 S9 – Cavity Relative Humidity

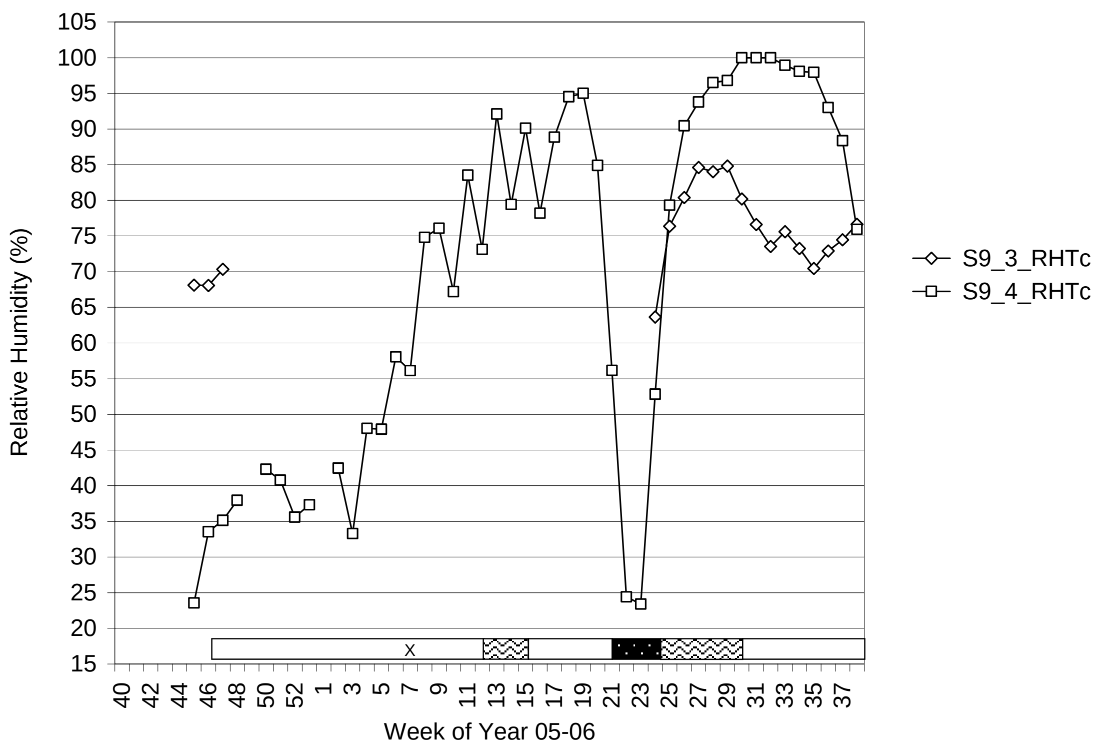


Figure B S9-3 S9 - Temperature

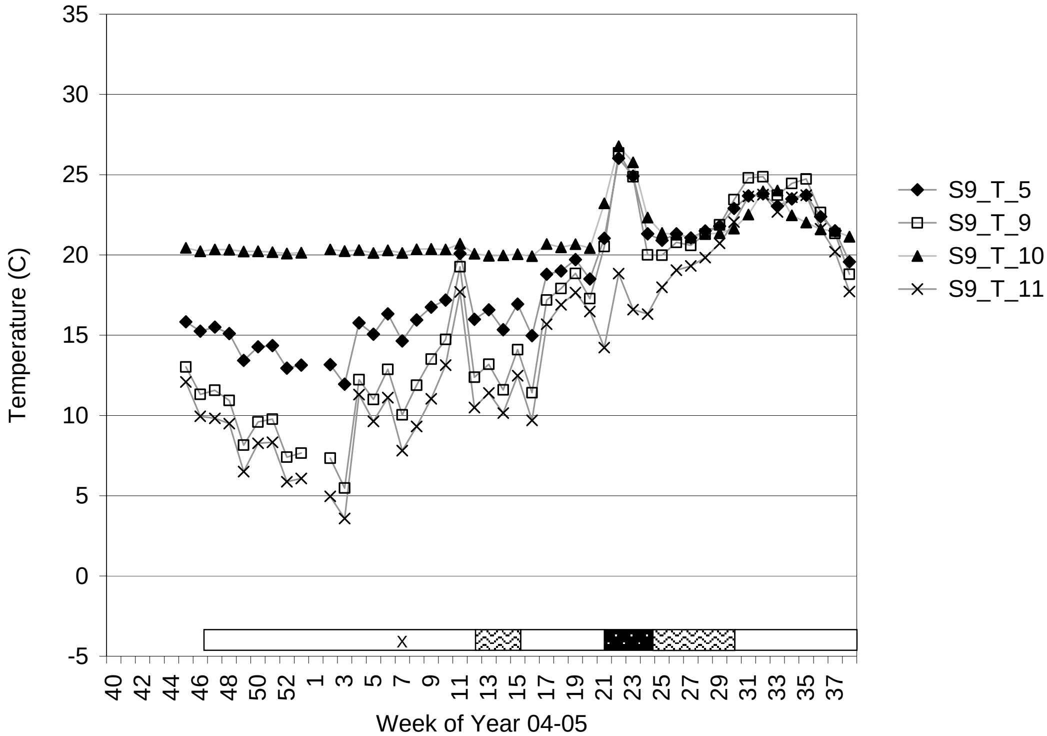


Figure B S9-4 S9 – Vapor Pressure

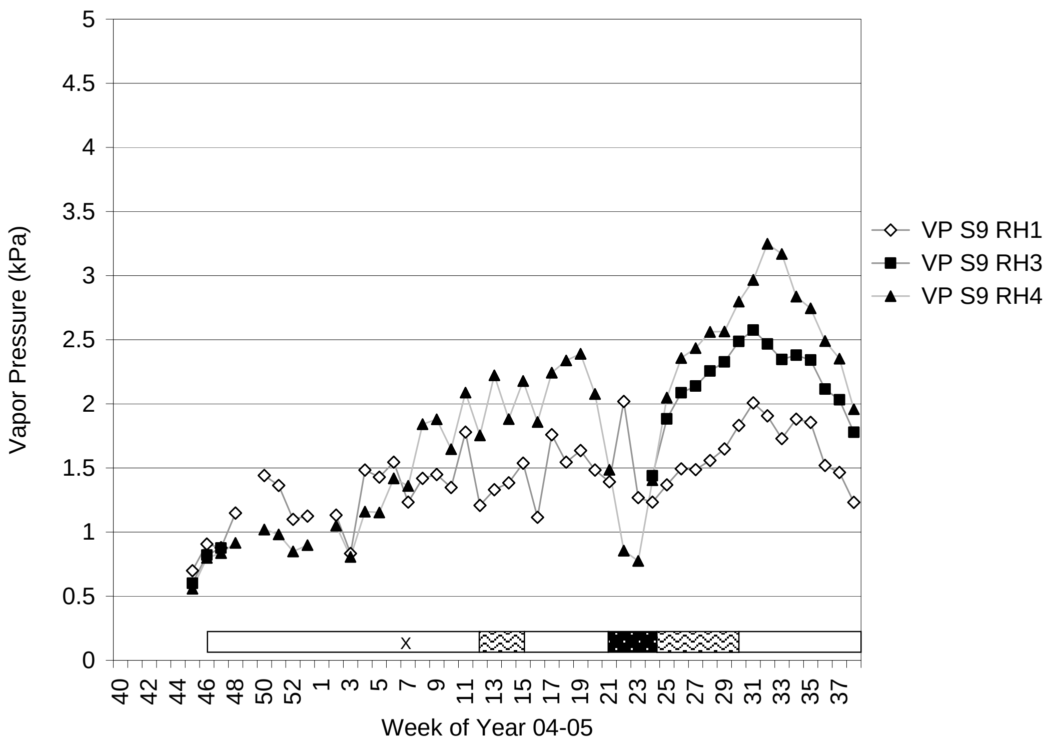


Figure B S9b-1 S9b – Wood Moisture Content

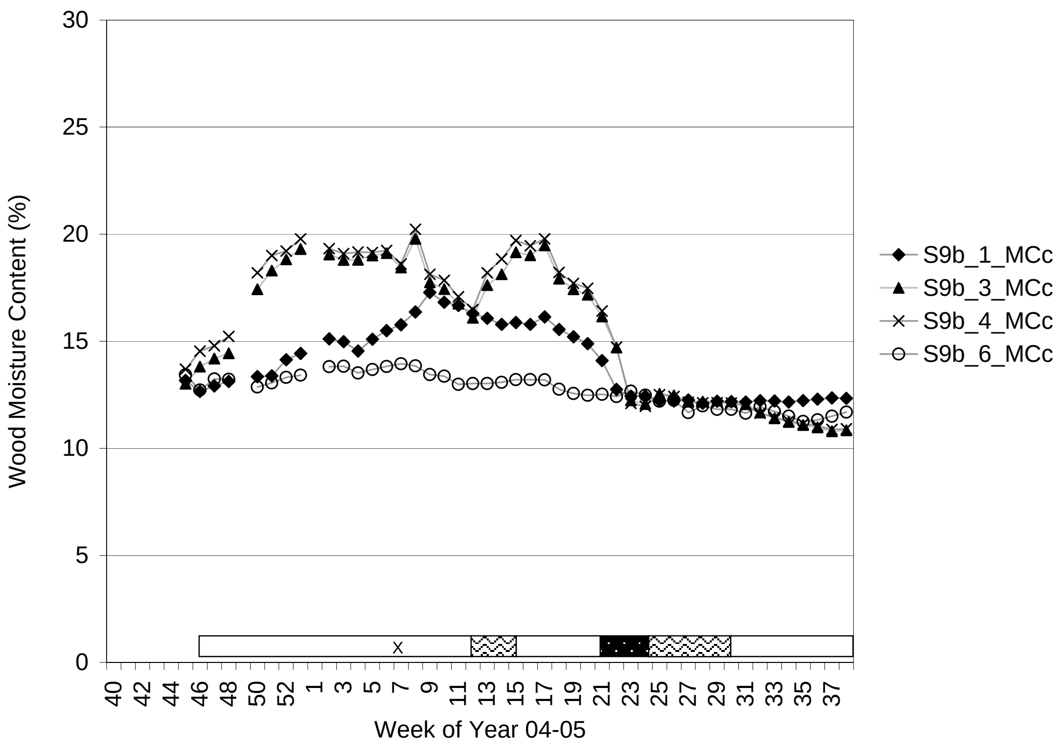


Figure B S9b-2 S9b – Cavity Relative Humidity

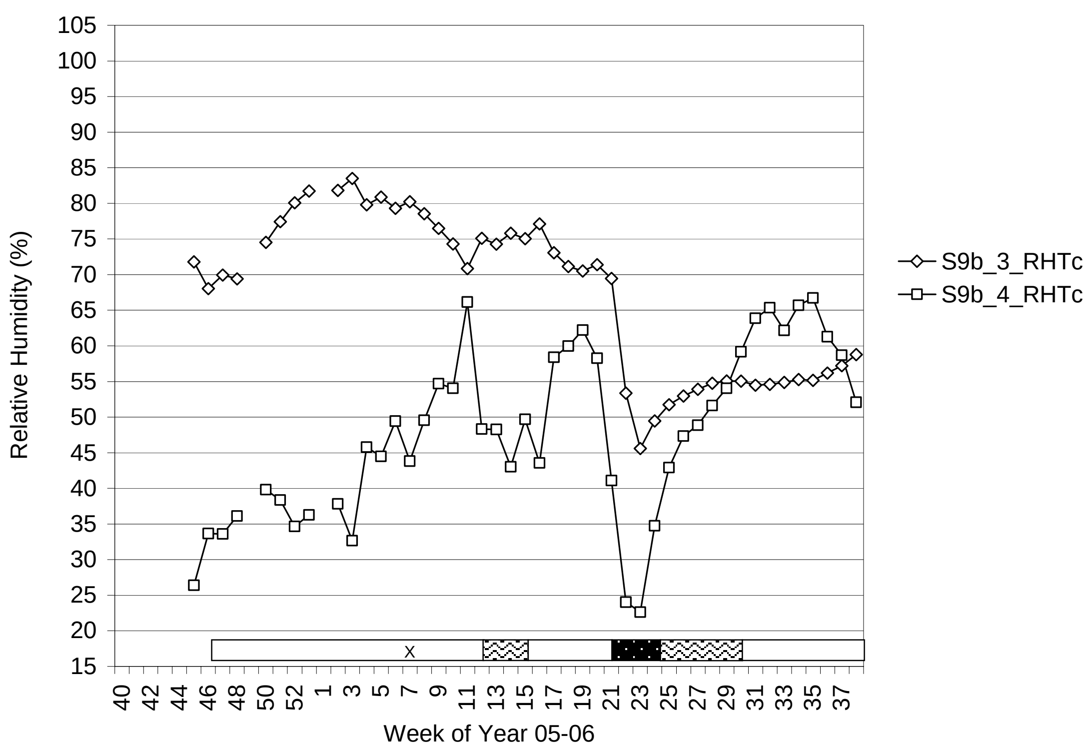


Figure B S9b-3   S9b - Temperature

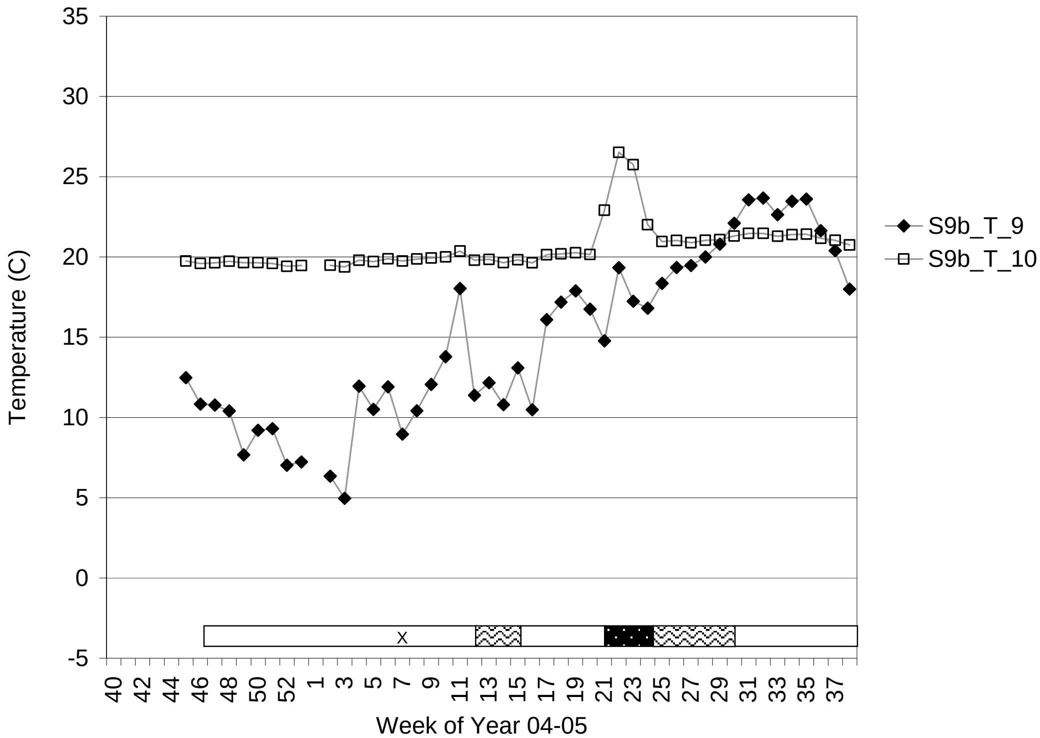


Figure B S9b-4   S9b – Vapor Pressure

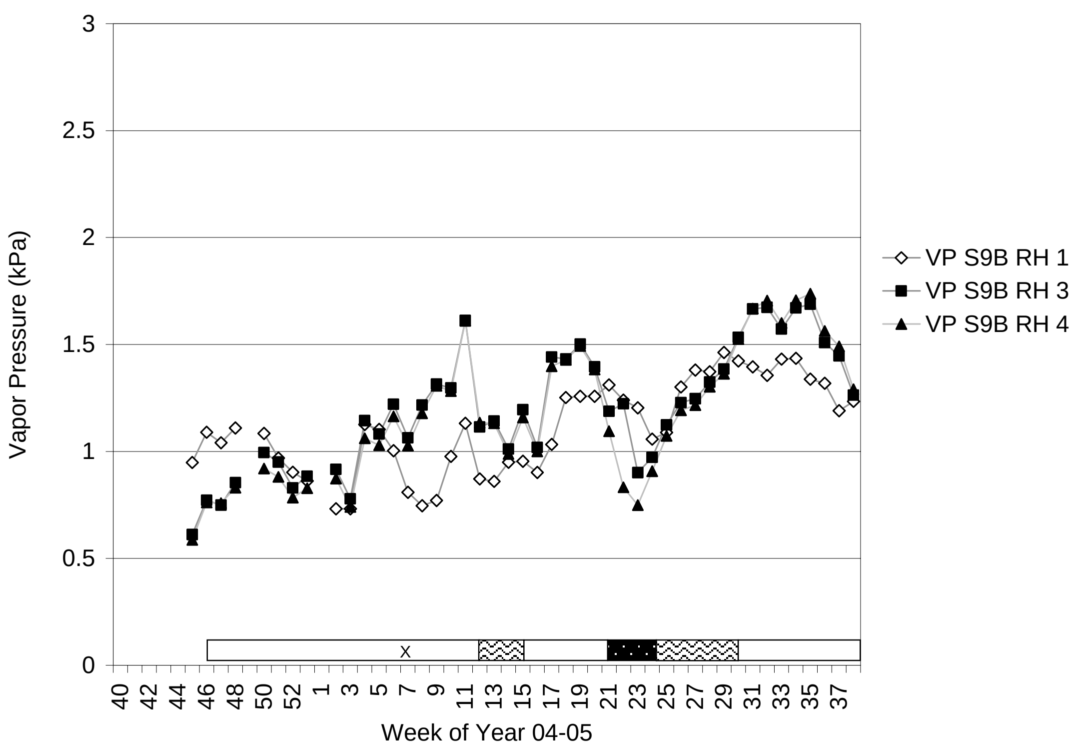


Figure B S10-1 S10 – Wood Moisture Content

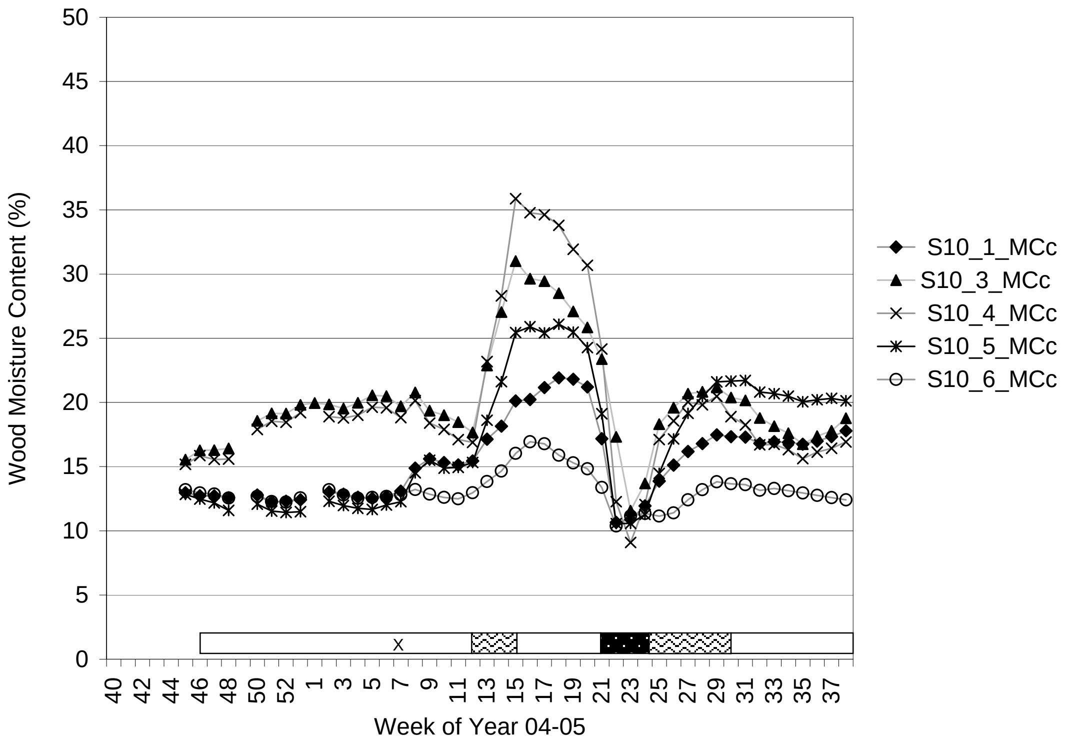


Figure B S10-2 S10 – Cavity Relative Humidity

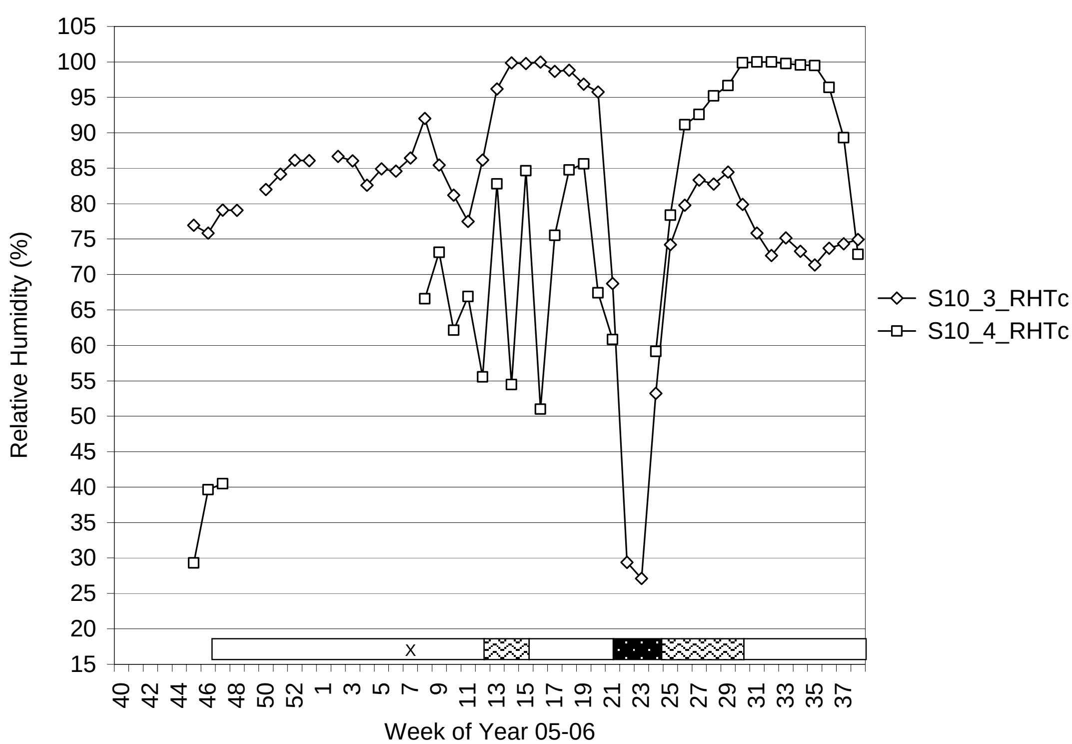


Figure B S10-3 S10 - Temperature

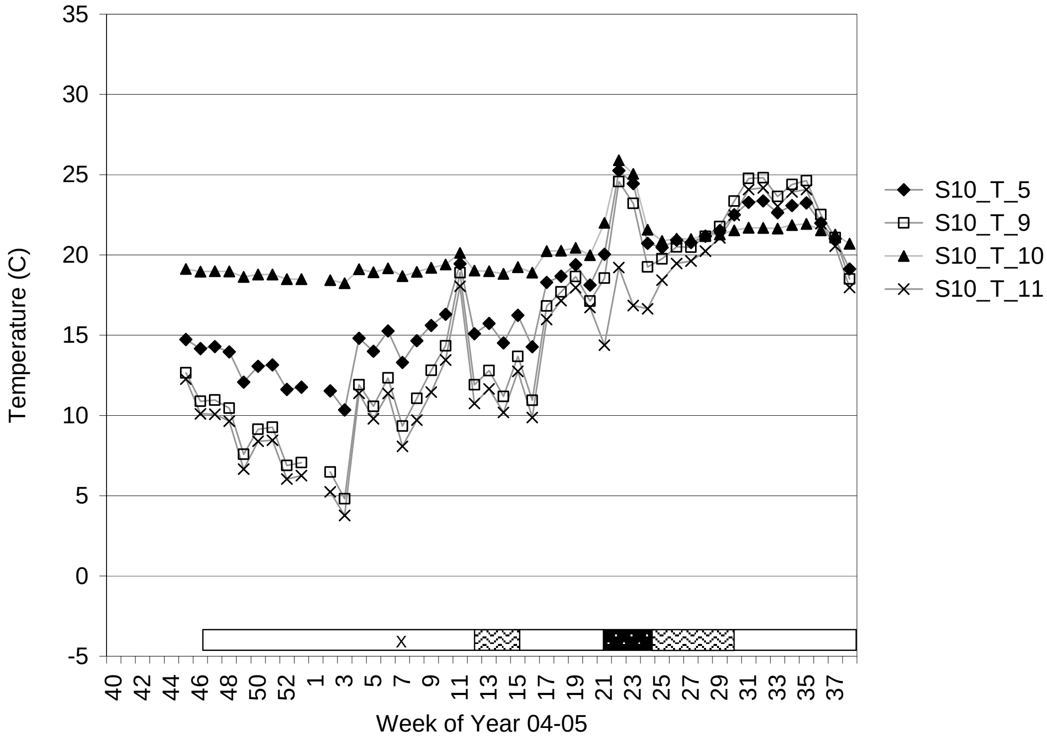


Figure B S10-4 S10 - Vapor Pressure

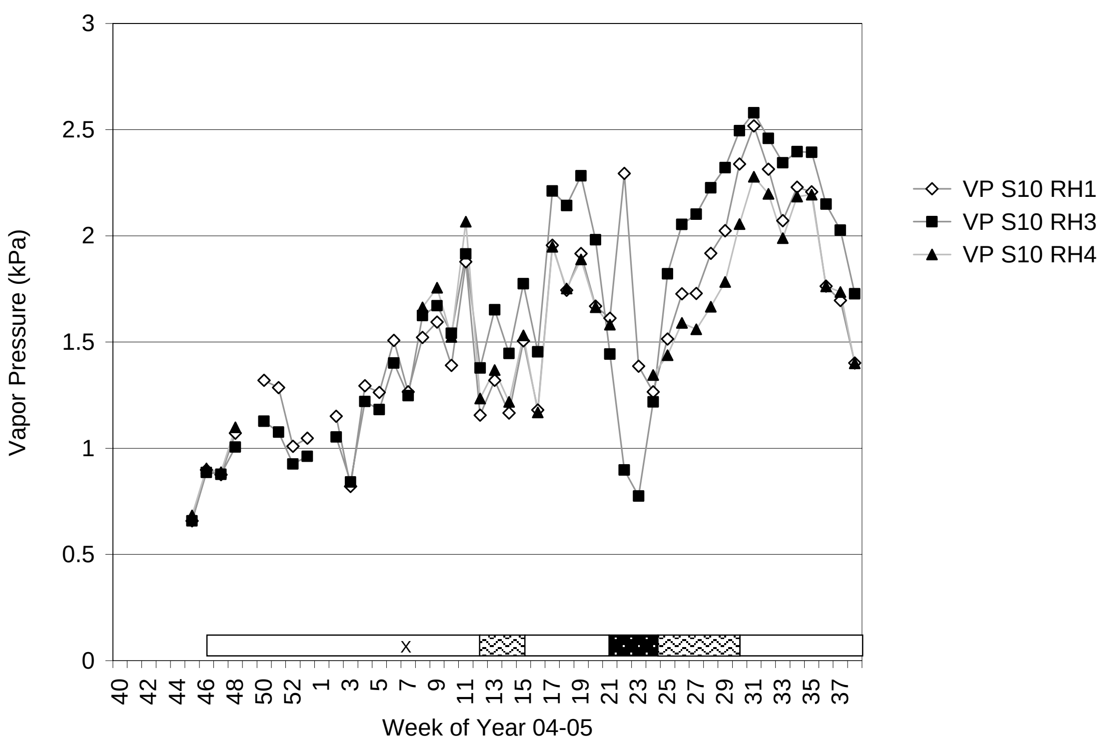


Figure B S10b-1 **S10b – Wood Moisture Content**

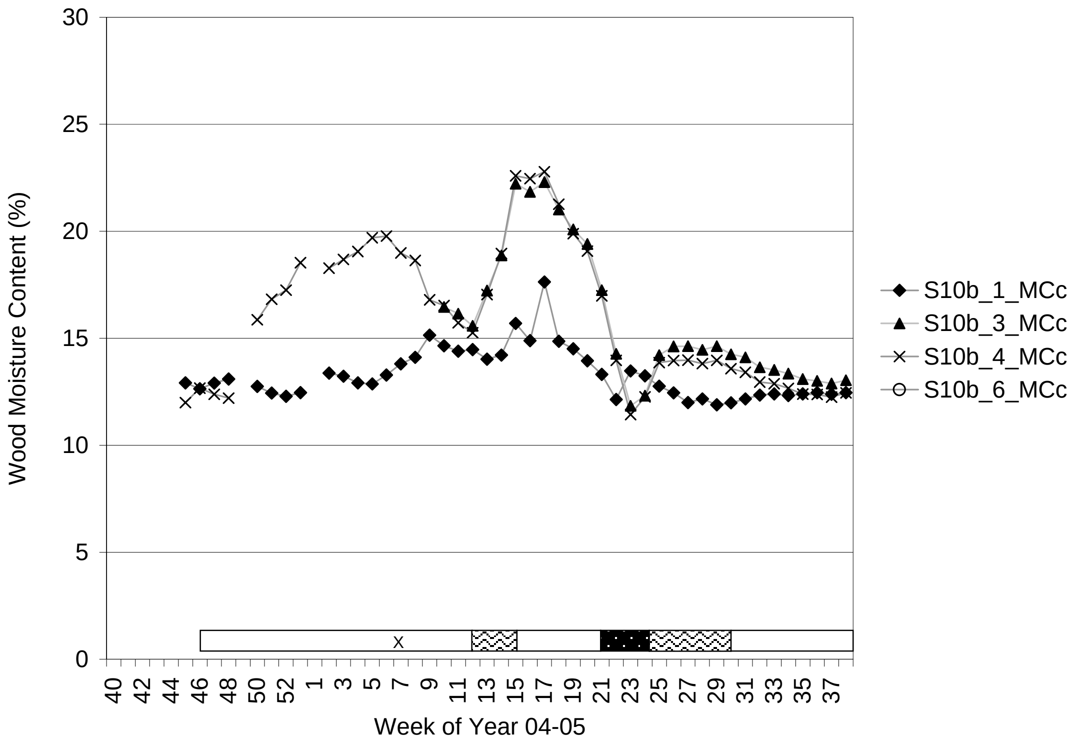


Figure B S10b-2 **S10b – Cavity Relative Humidity**

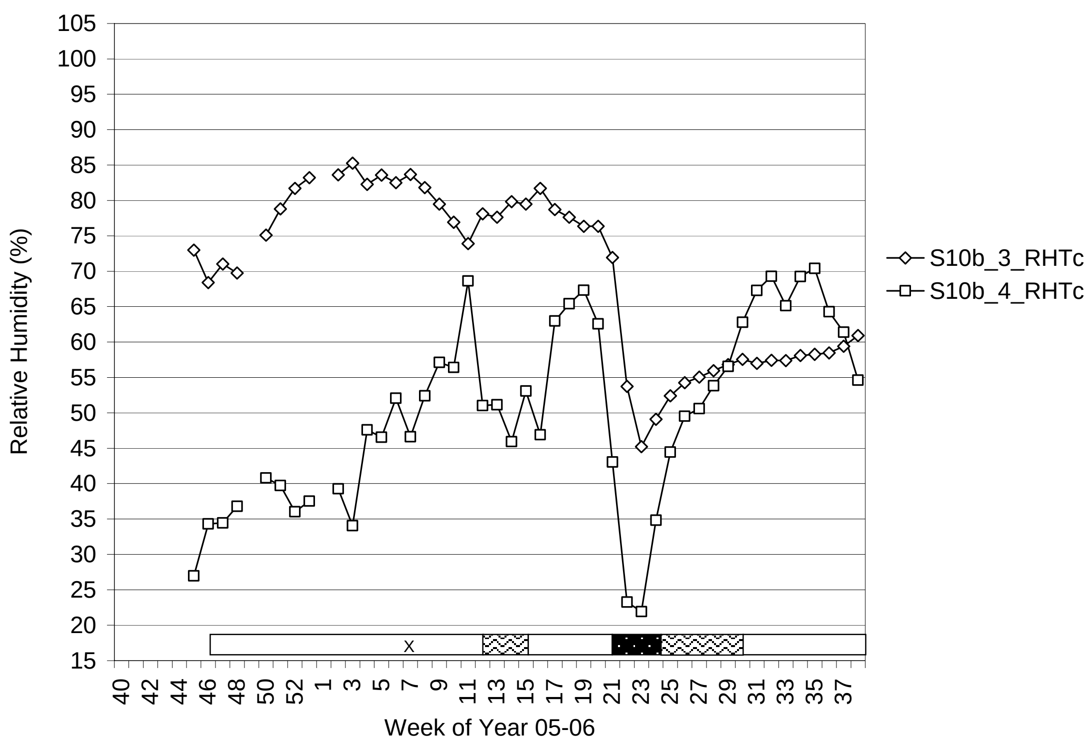


Figure B S10b-3 S10b - Temperature

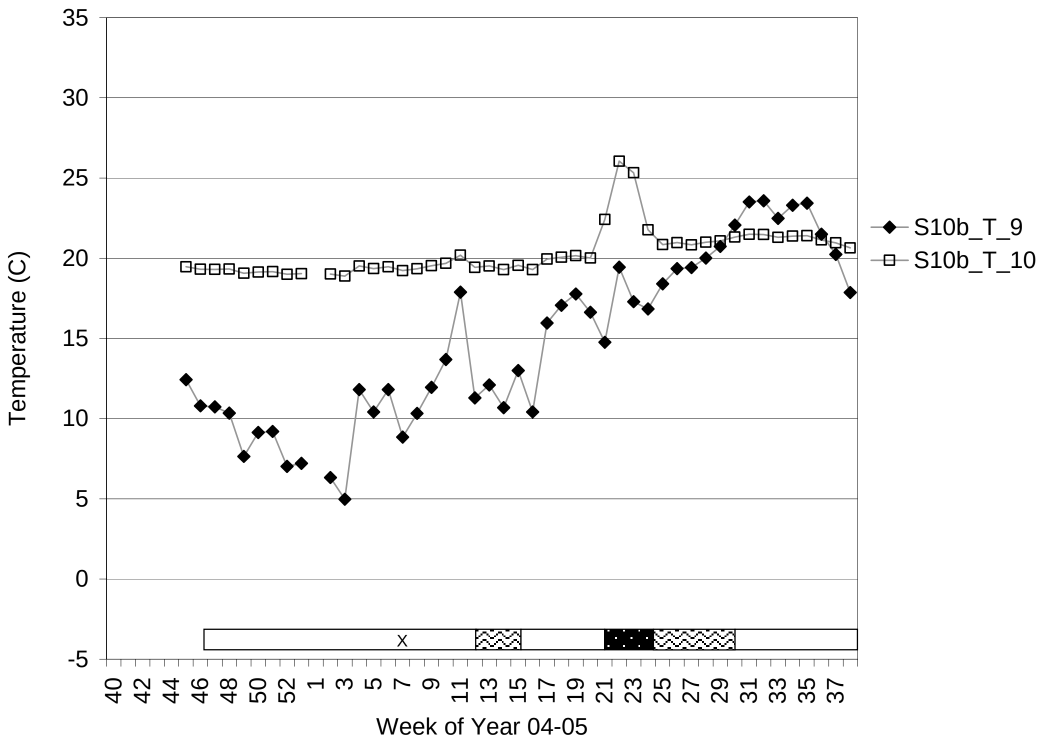


Figure B S10b-4 S10b – Vapor Pressure

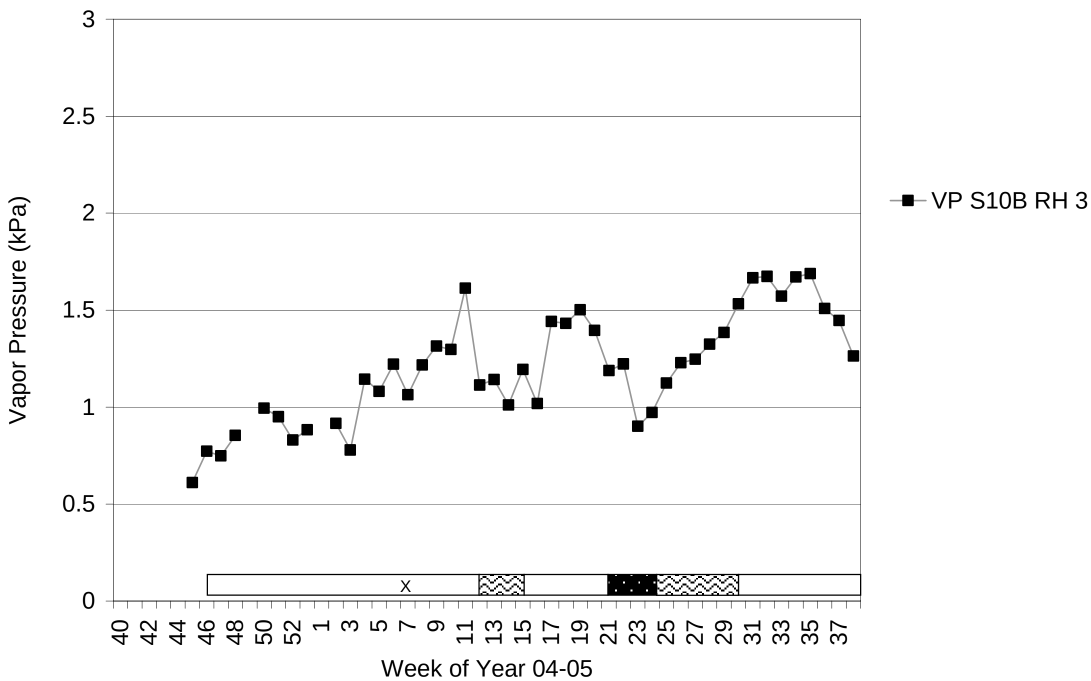


Figure B S11-1 **S11 – Wood Moisture Content**

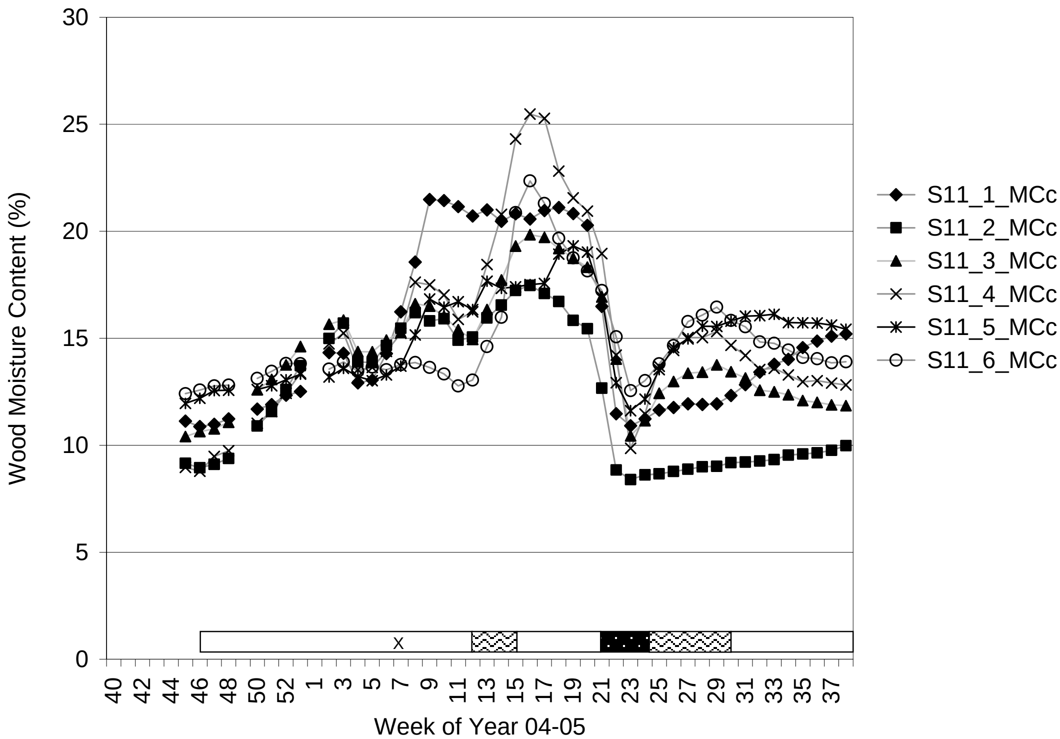


Figure B S11-2 **S11 – Cavity Relative Humidity**

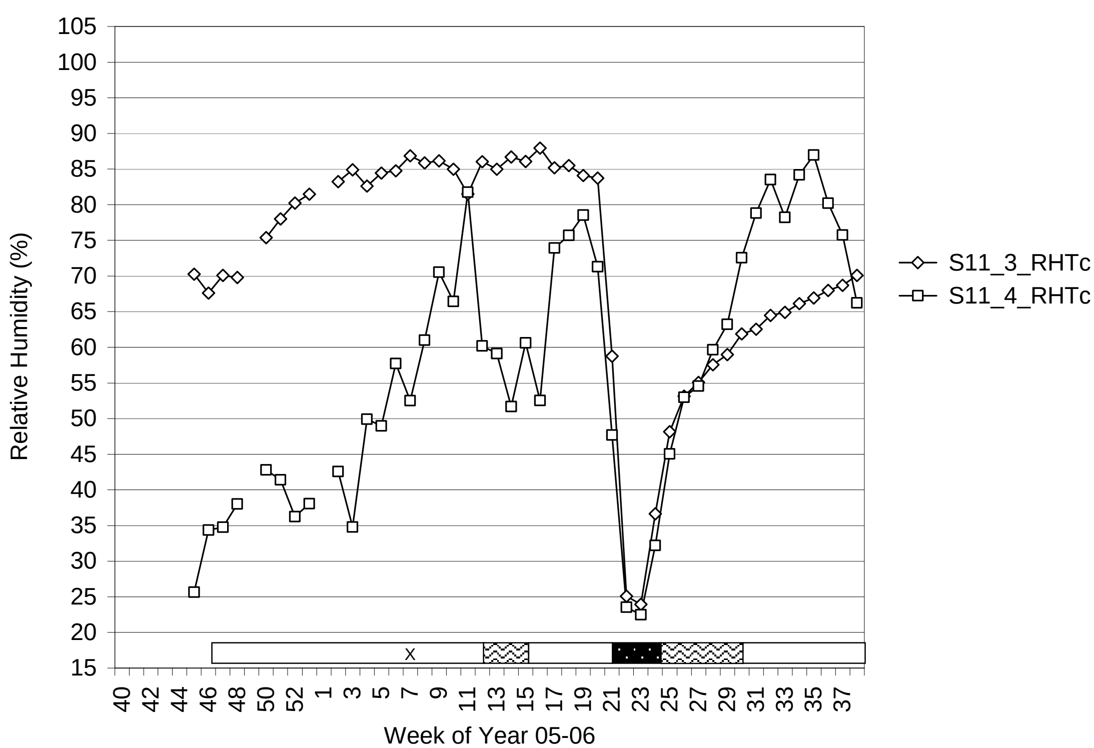


Figure B S11-3 **S11 - Temperature**

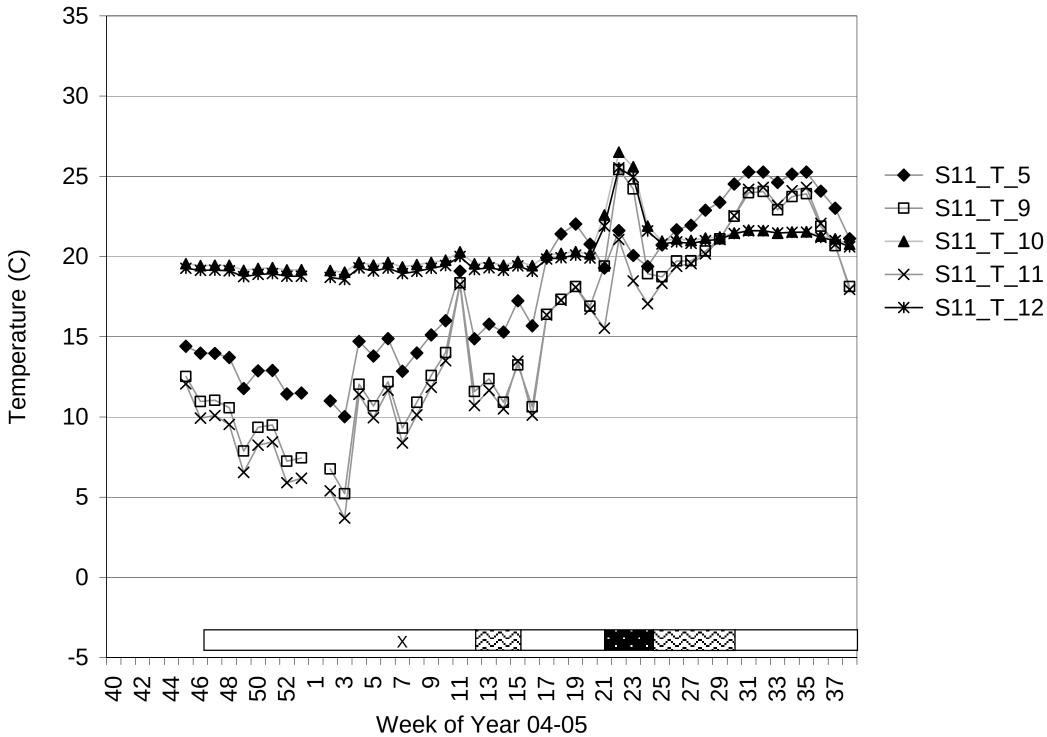


Figure B S11-4 **S11 – Vapor Pressure**

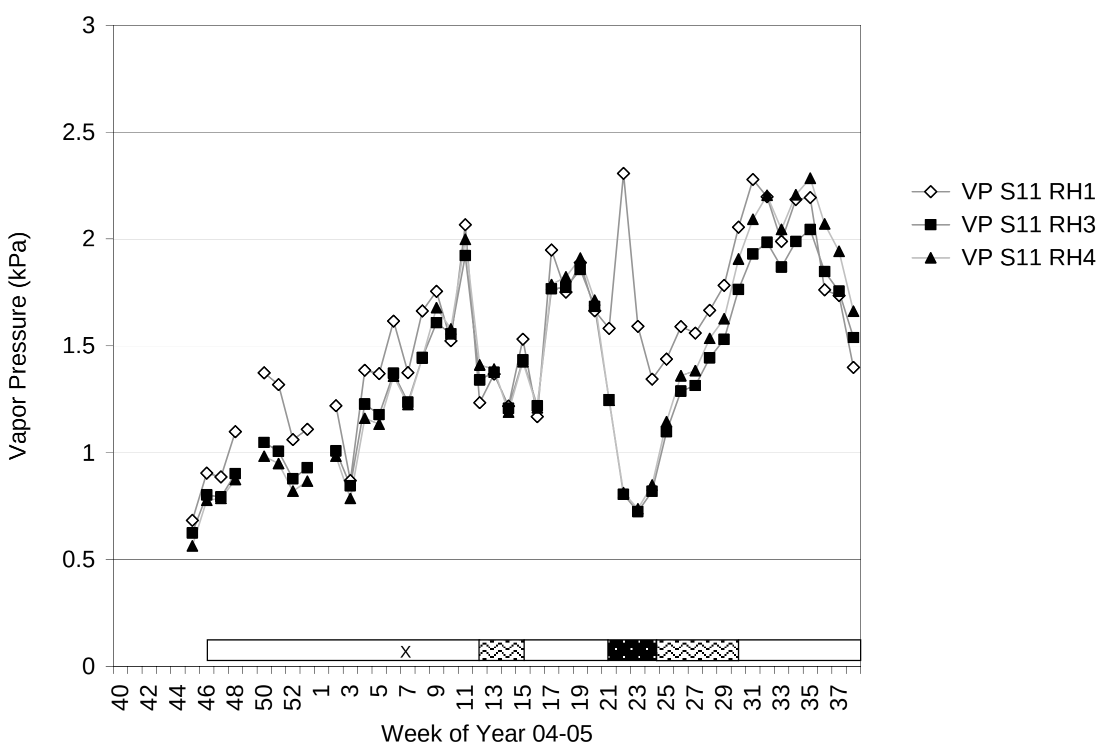


Figure B S12-1 S12 – Wood Moisture Content

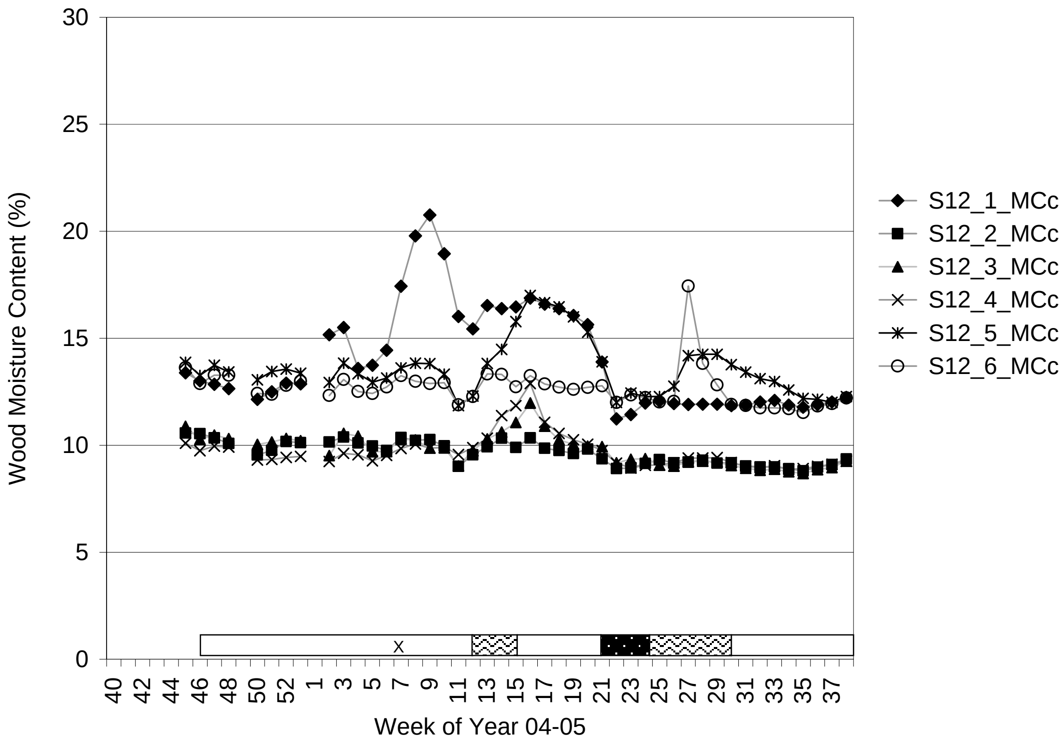


Figure B S12-2 S12 – Cavity Relative Humidity

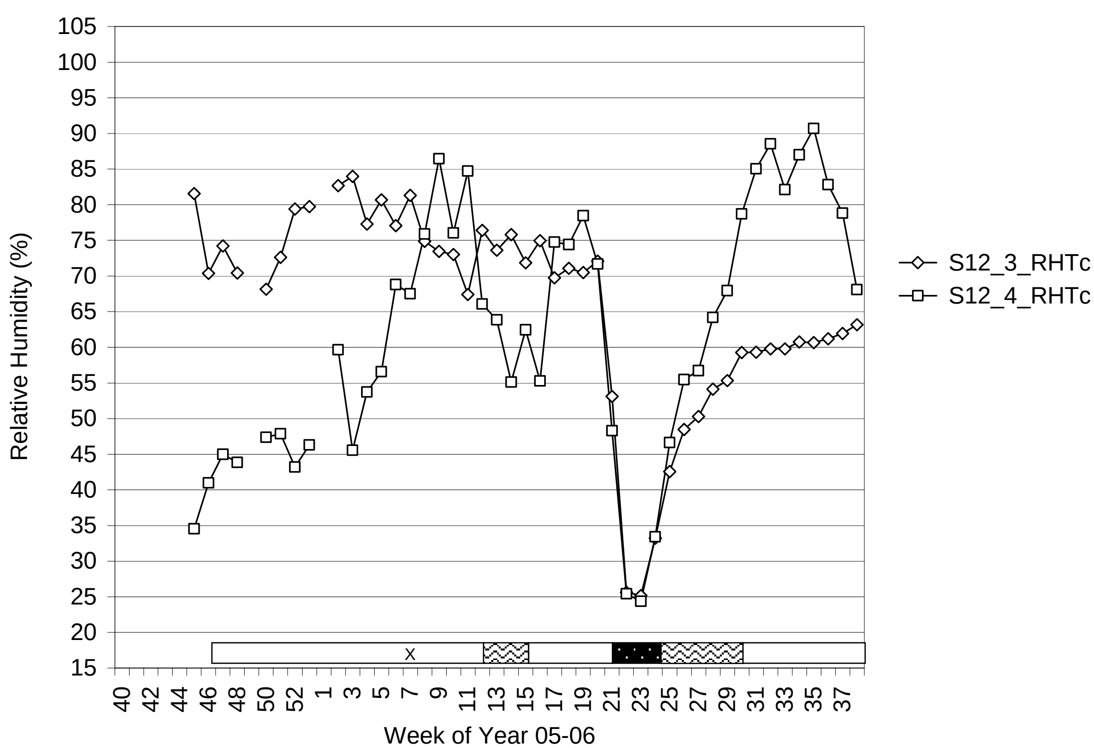


Figure B S12-3 S12 - Temperature

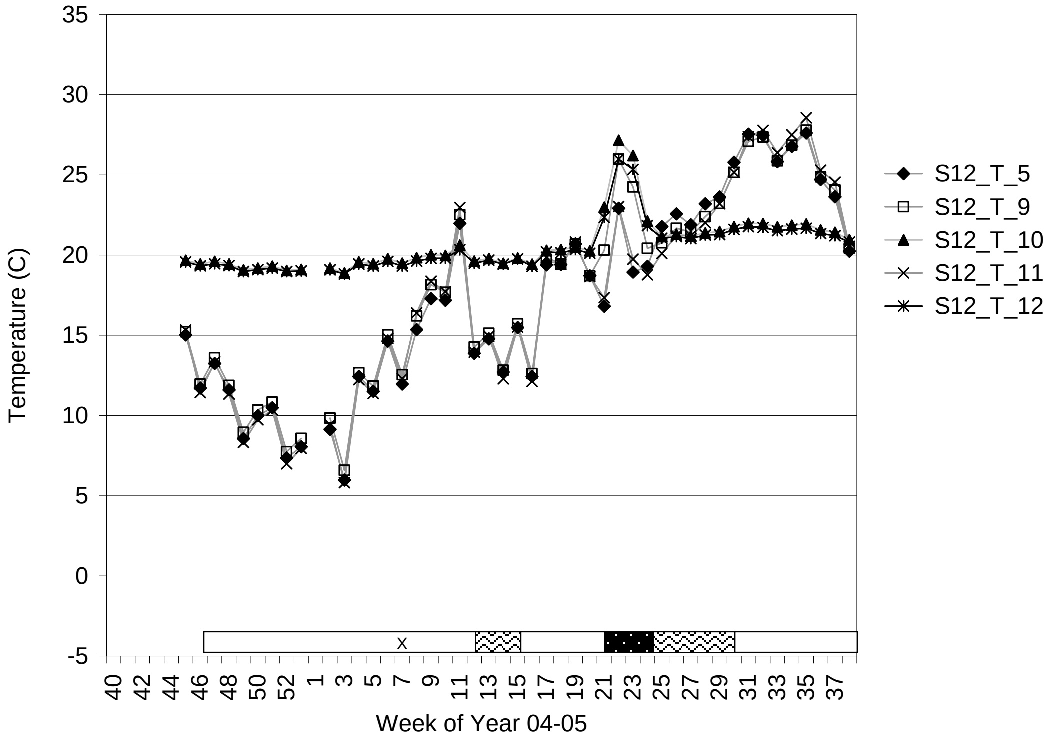


Figure B S12-4 12 – Vapor Pressure

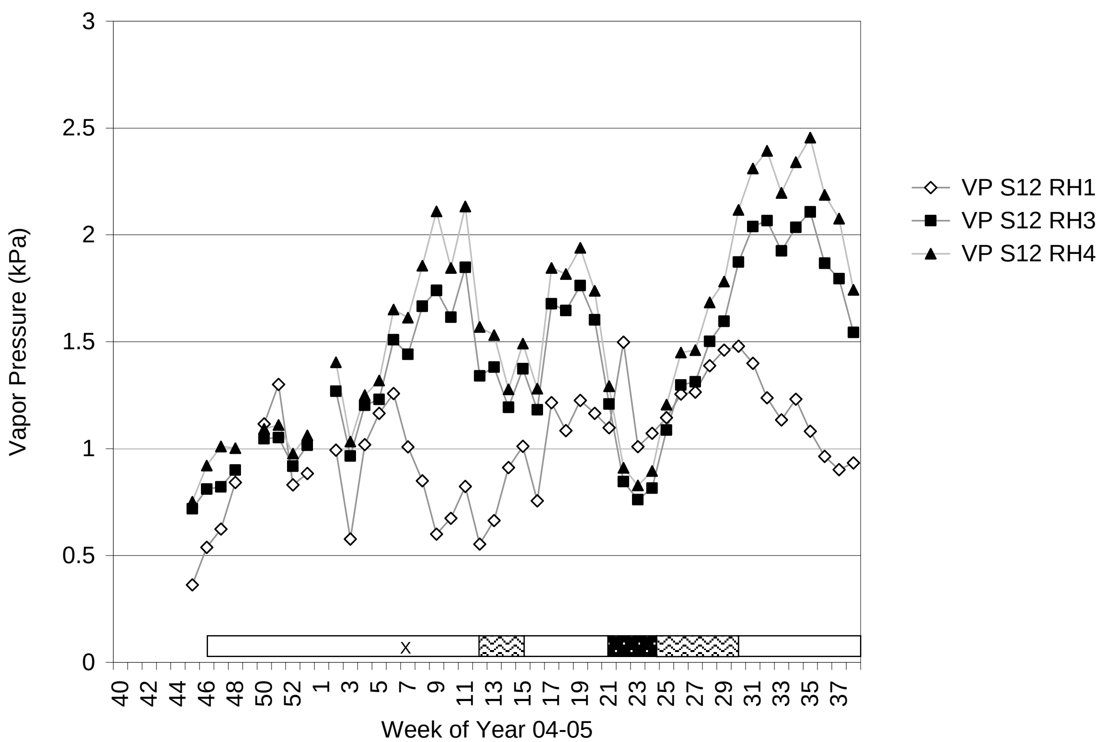


Figure B N3-1 N3 – Wood Moisture Content

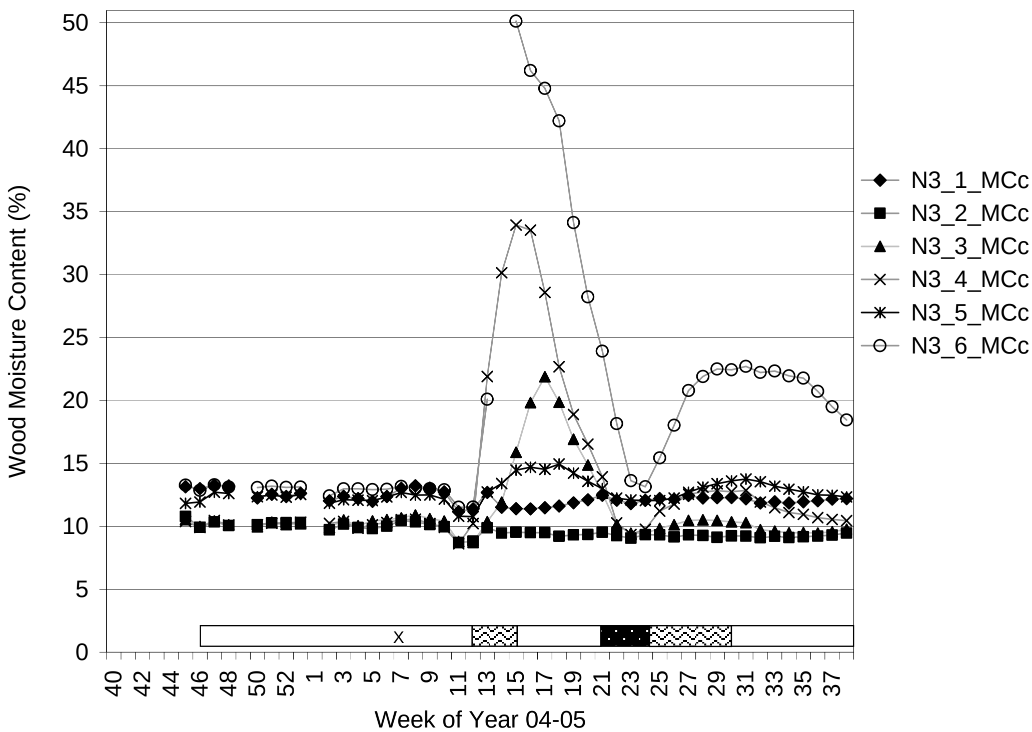


Figure B N3-2 N3 – Cavity Relative Humidity

Figure B N3-3 N3 - Temperature

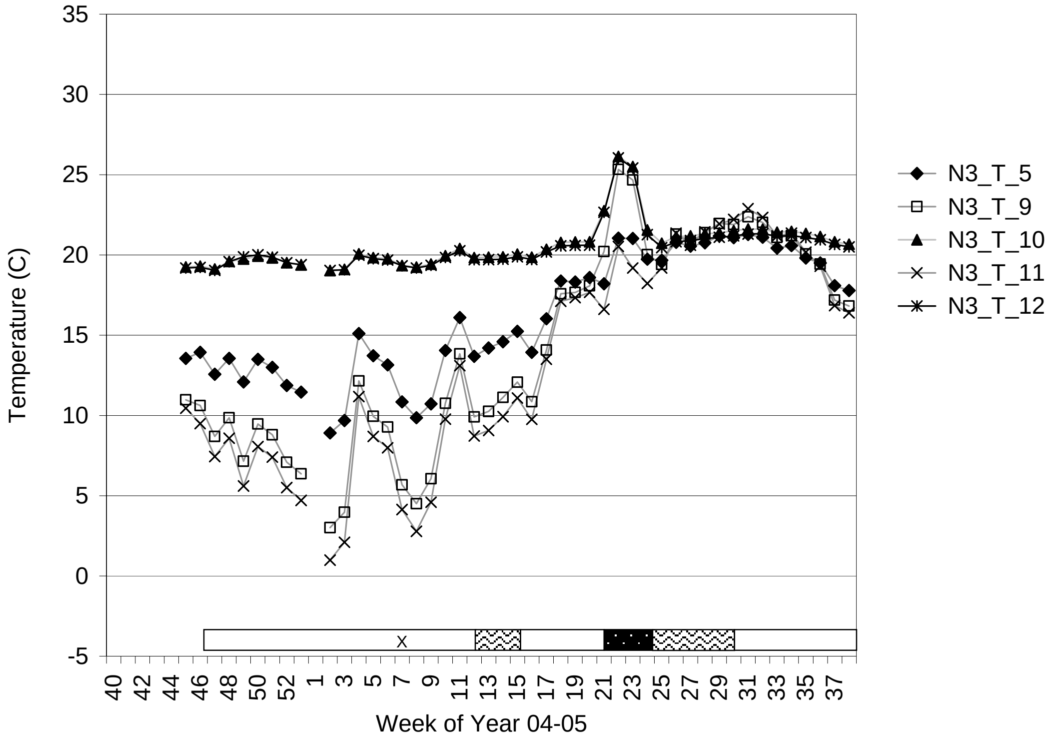


Figure B N3-4 N3 – Vapor Pressure

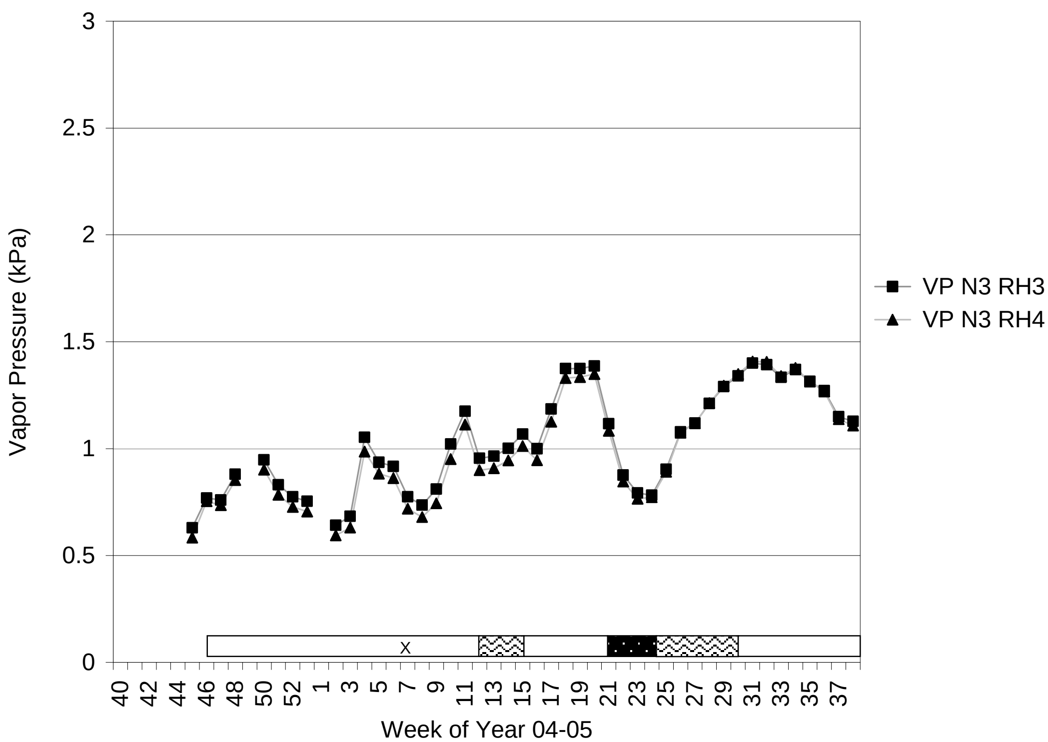


Figure B N4-1 N4 – Wood Moisture Content

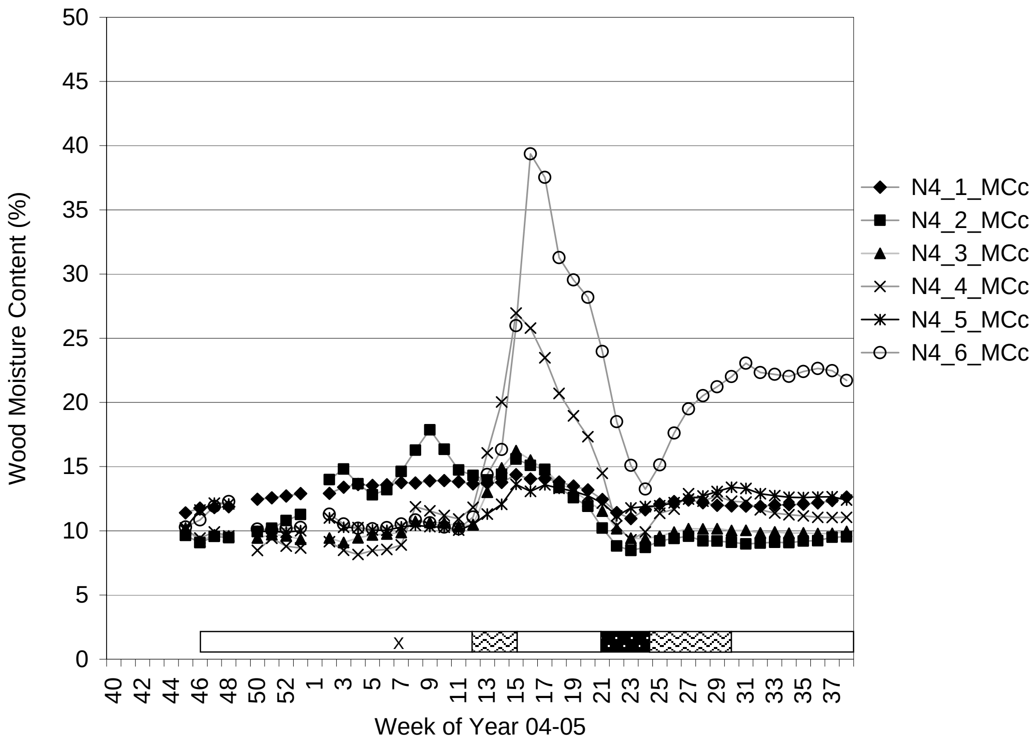


Figure B N4-2 N4 – Cavity Relative Humidity

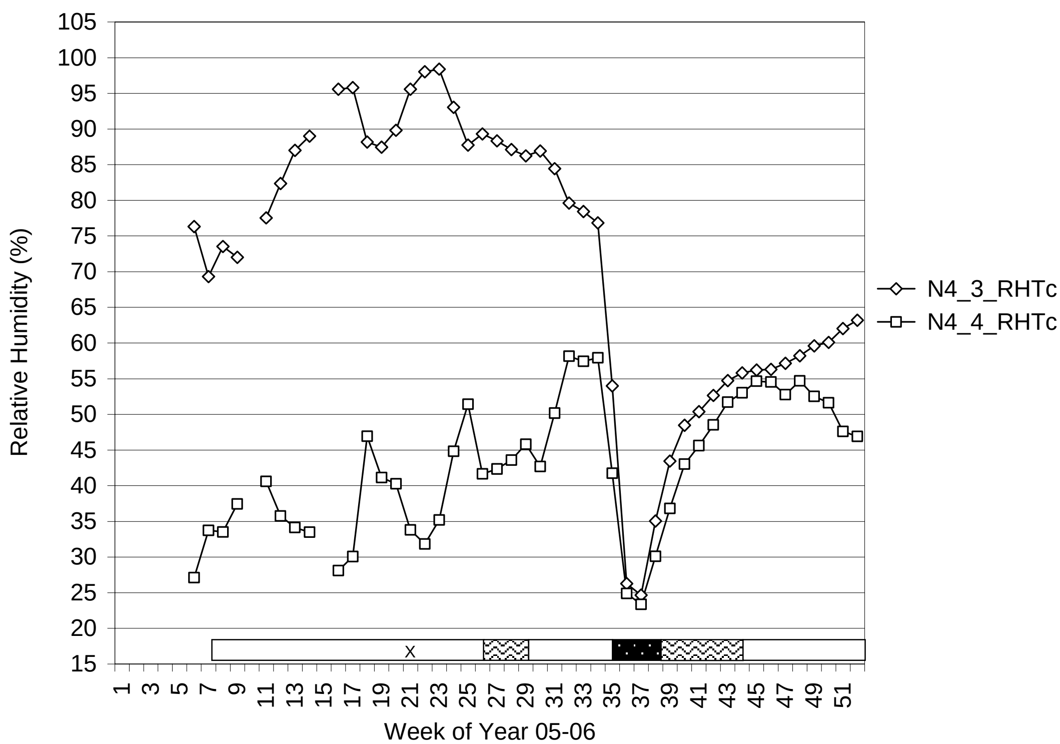


Figure B N4-3   N4 - Temperature

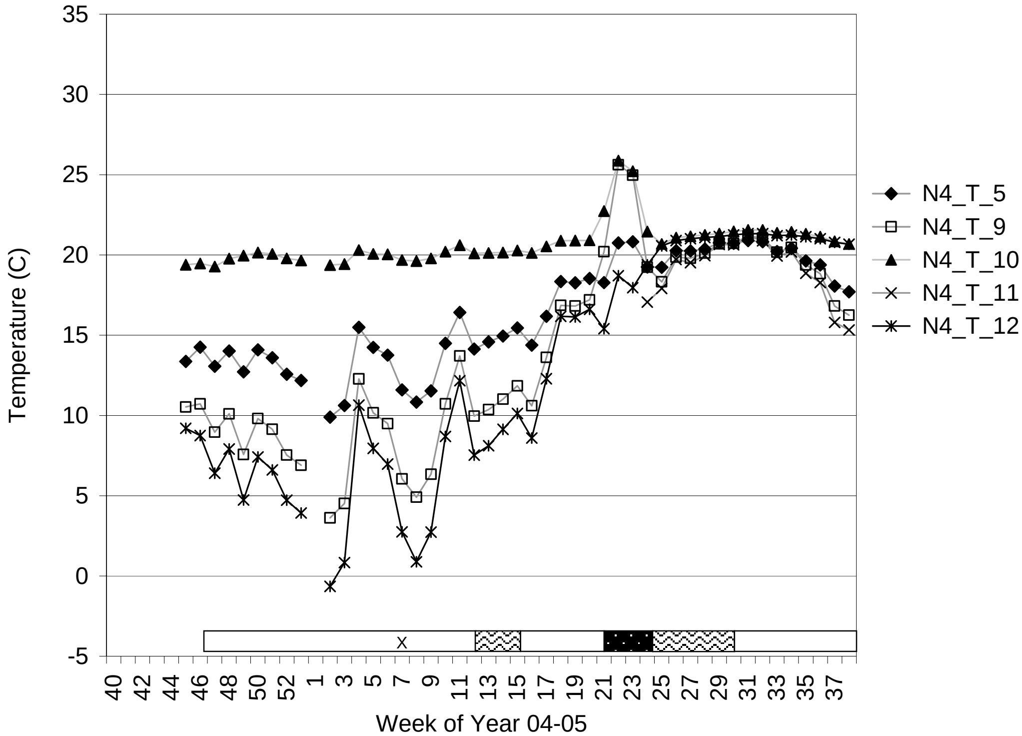


Figure B N4-4   N4 – Vapor Pressure

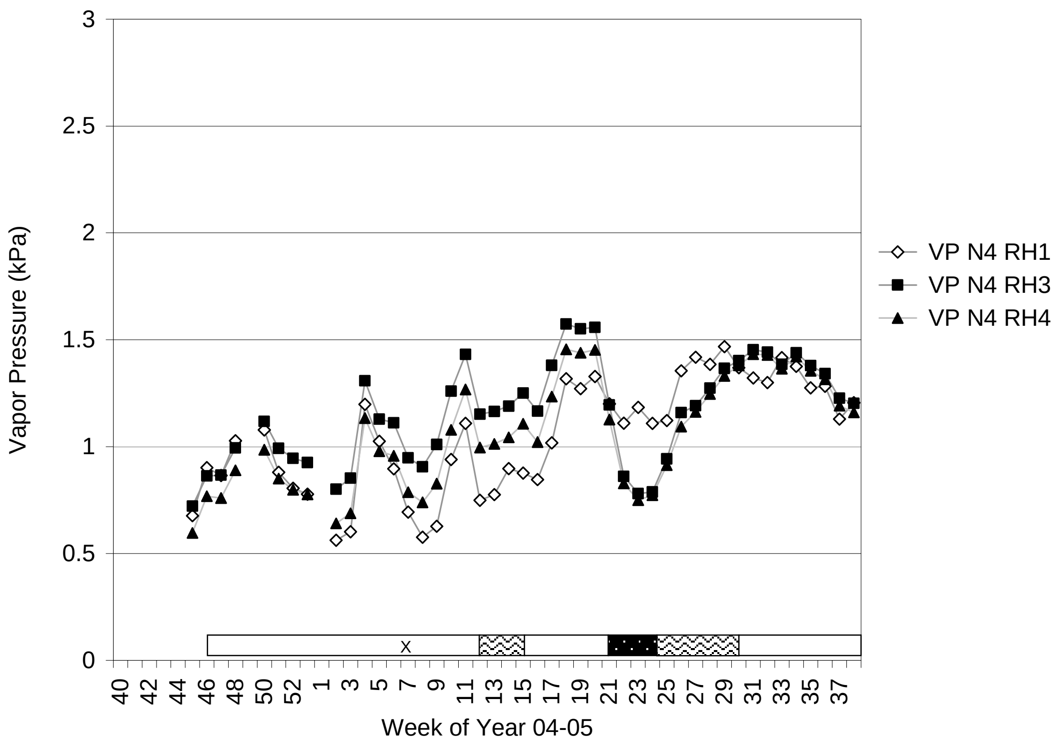


Figure B N5-1 N5 – Wood Moisture Content

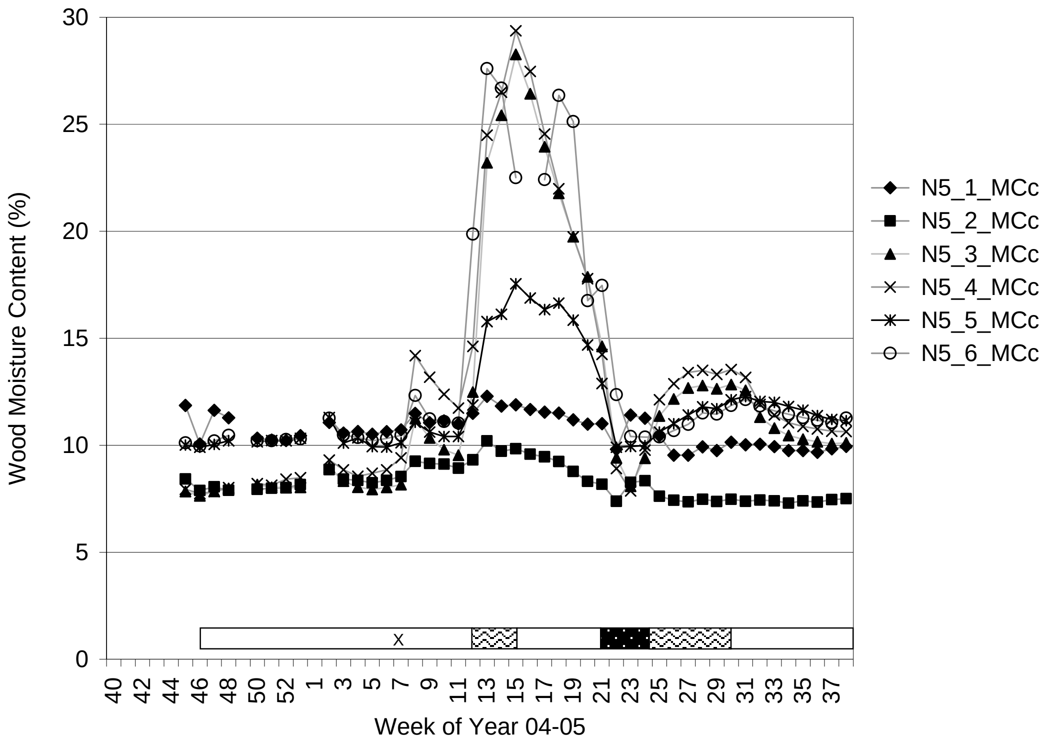


Figure B N5-2 N5 – Cavity Relative Humidity

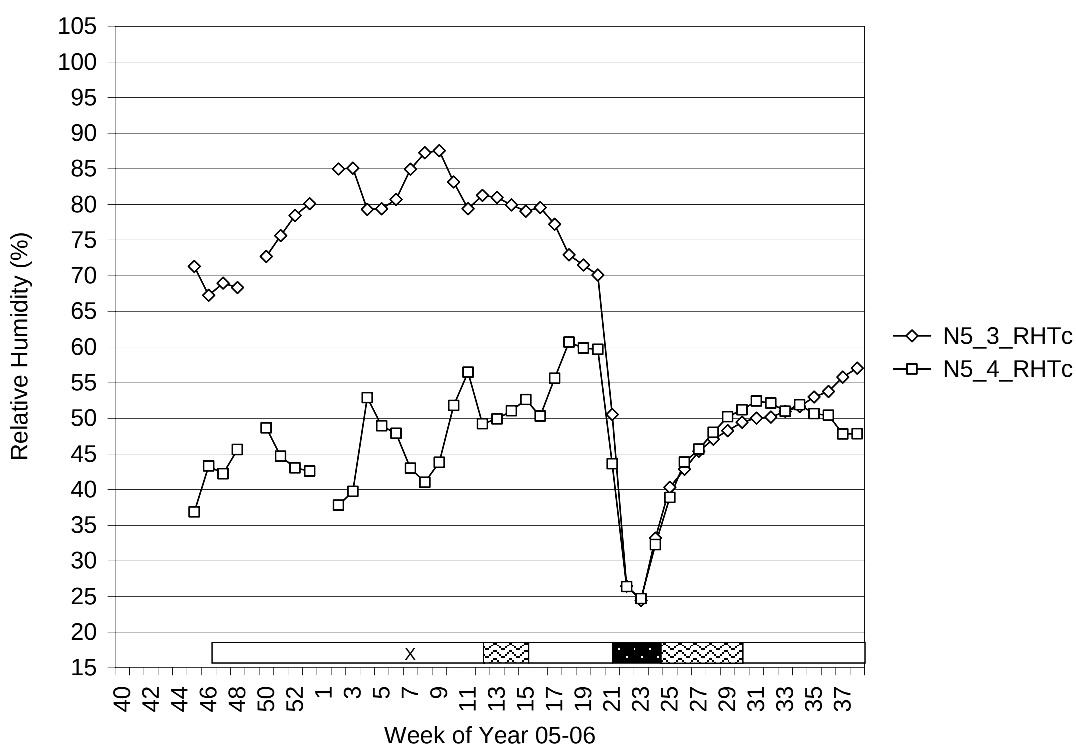


Figure B N5-3 N5 - Temperature

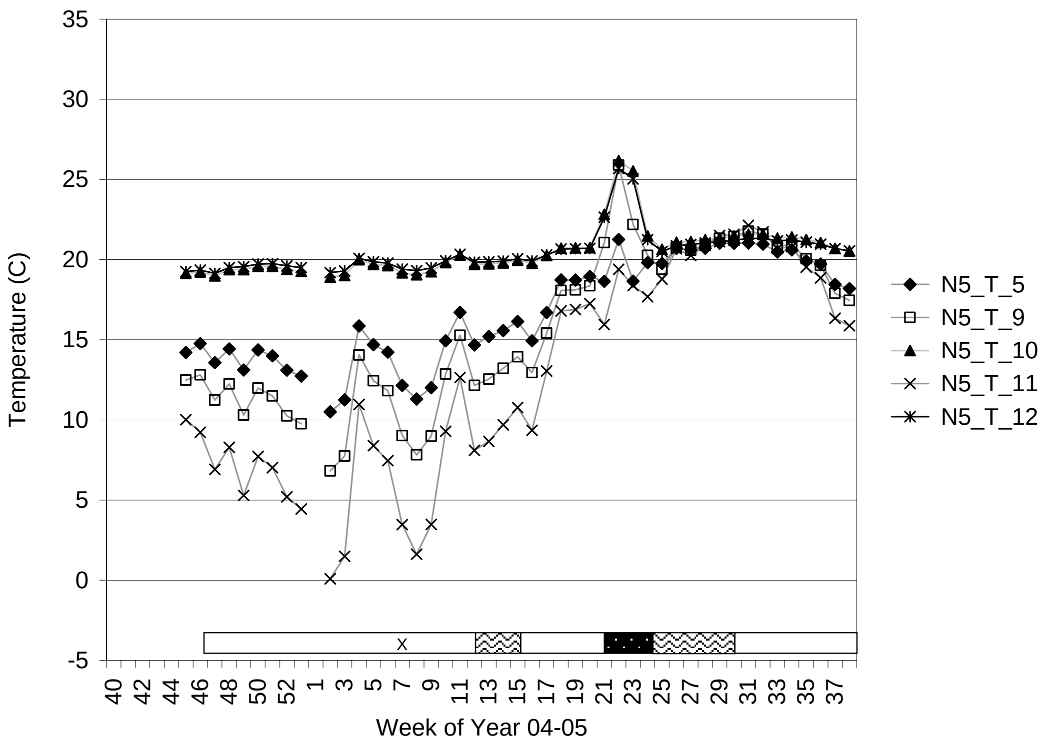


Figure B N5-4 N5 – Vapor Pressure

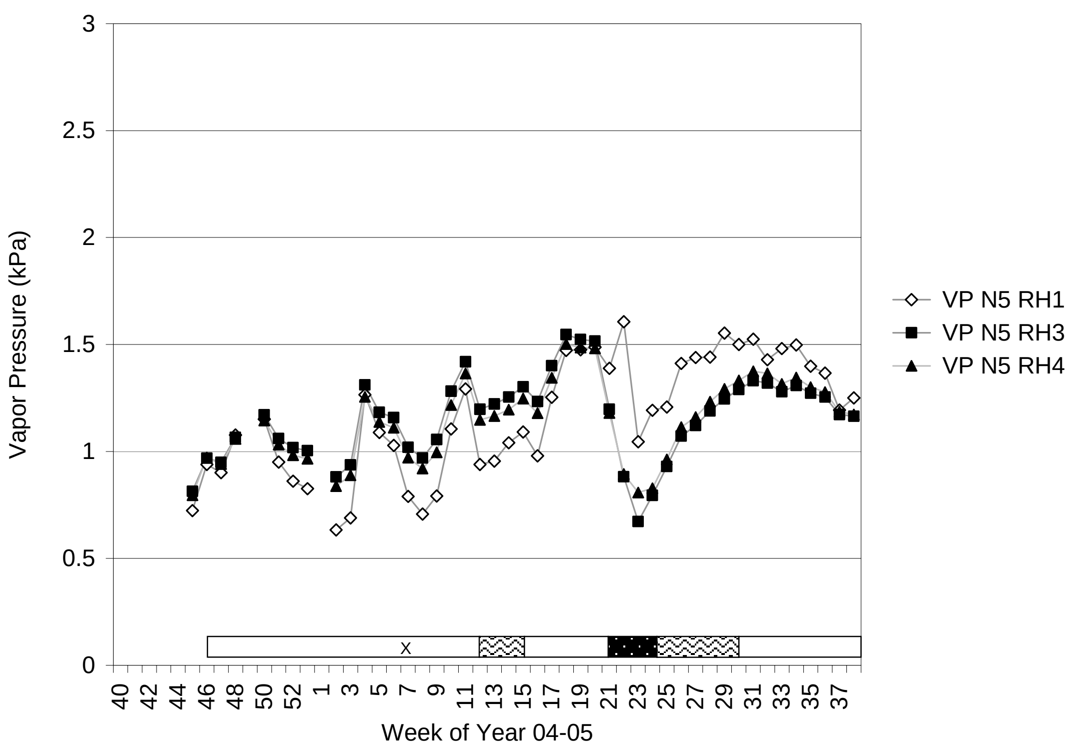


Figure B N6-1 N6 – Wood Moisture Content

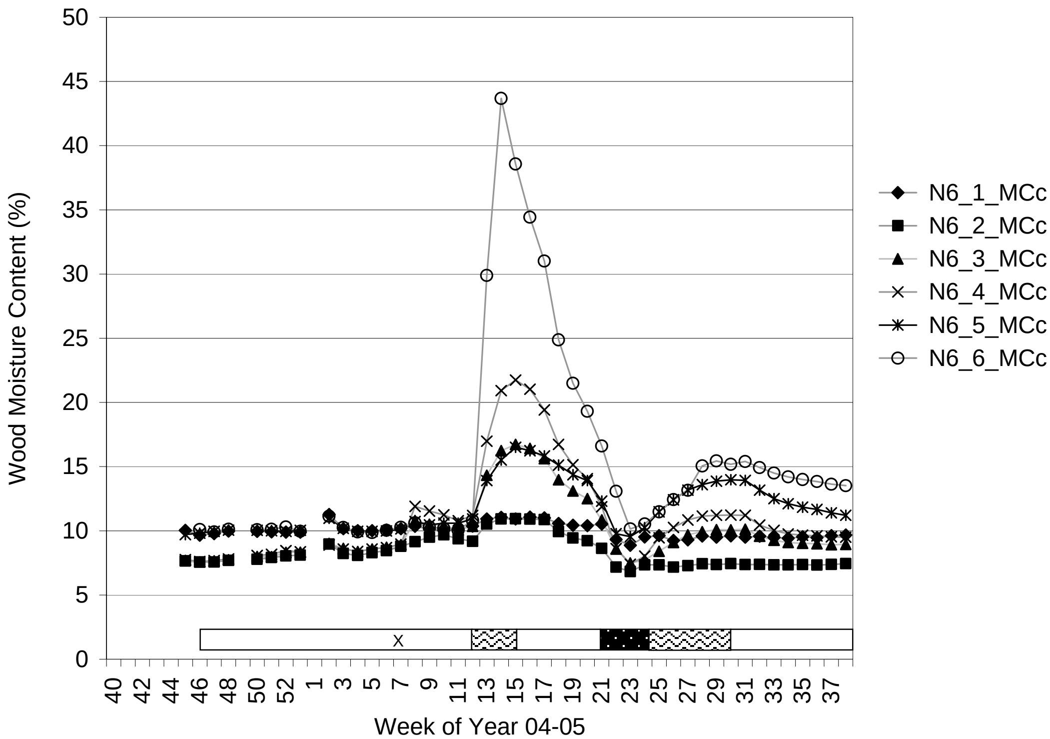


Figure B N6-2 N6 – Cavity Relative Humidity

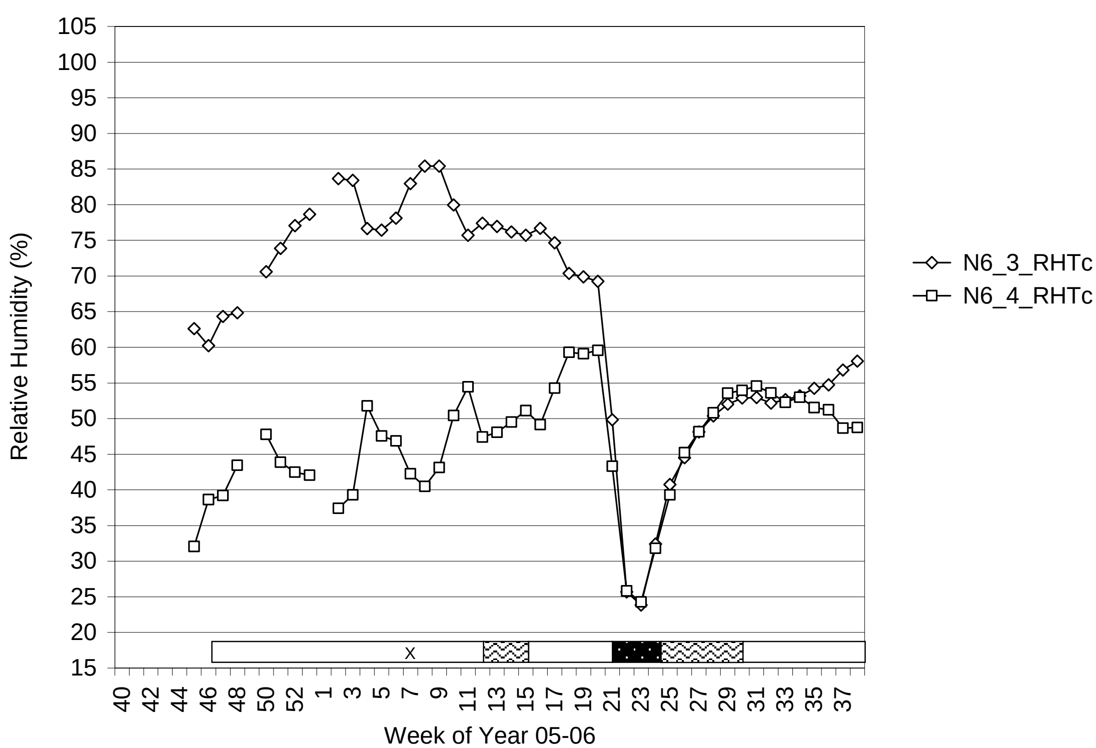


Figure B N6-3   N6 - Temperature

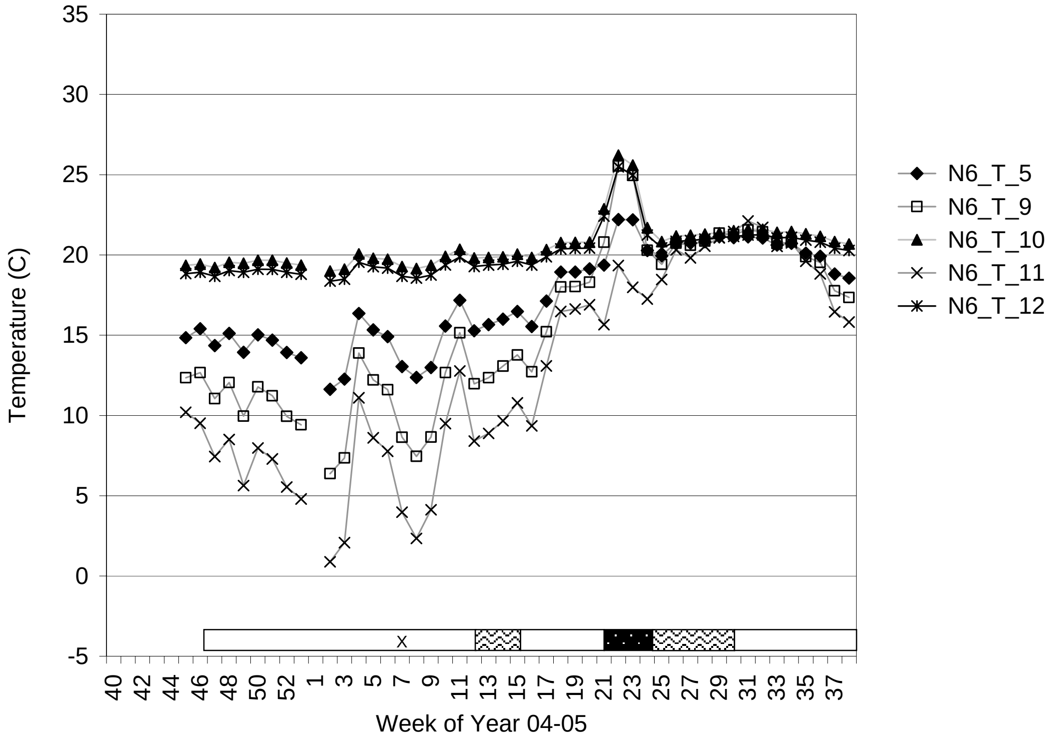


Figure B N6-4   N6 – Vapor Pressure

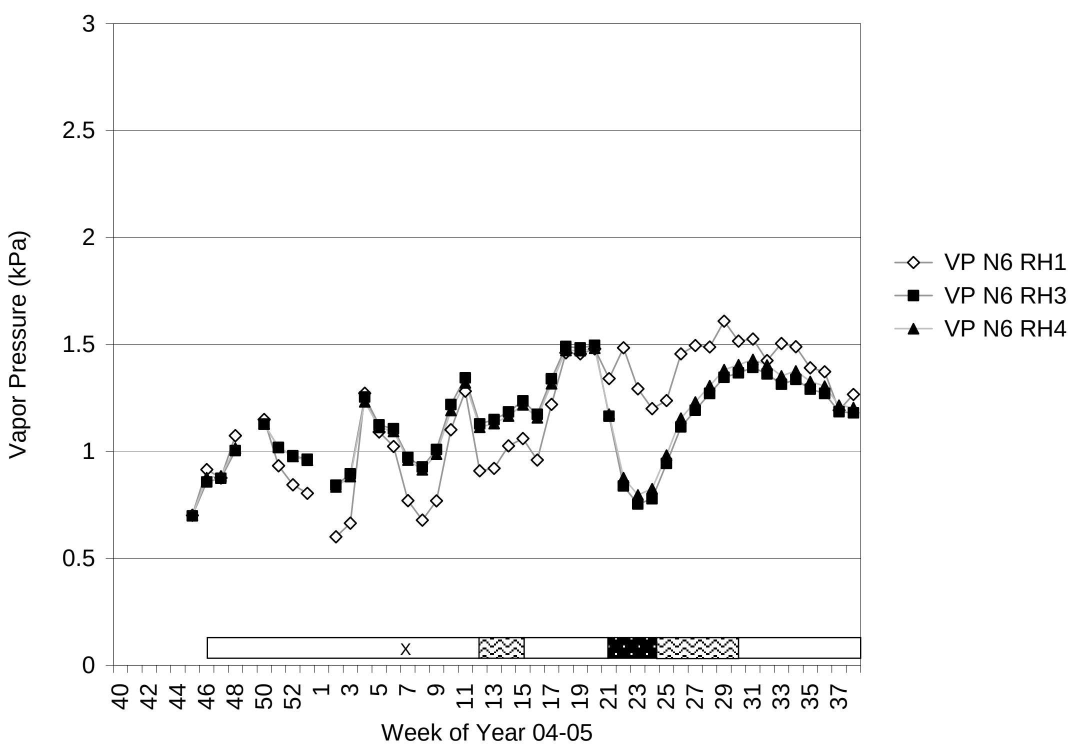


Figure B N7-1 N7 – Wood Moisture Content

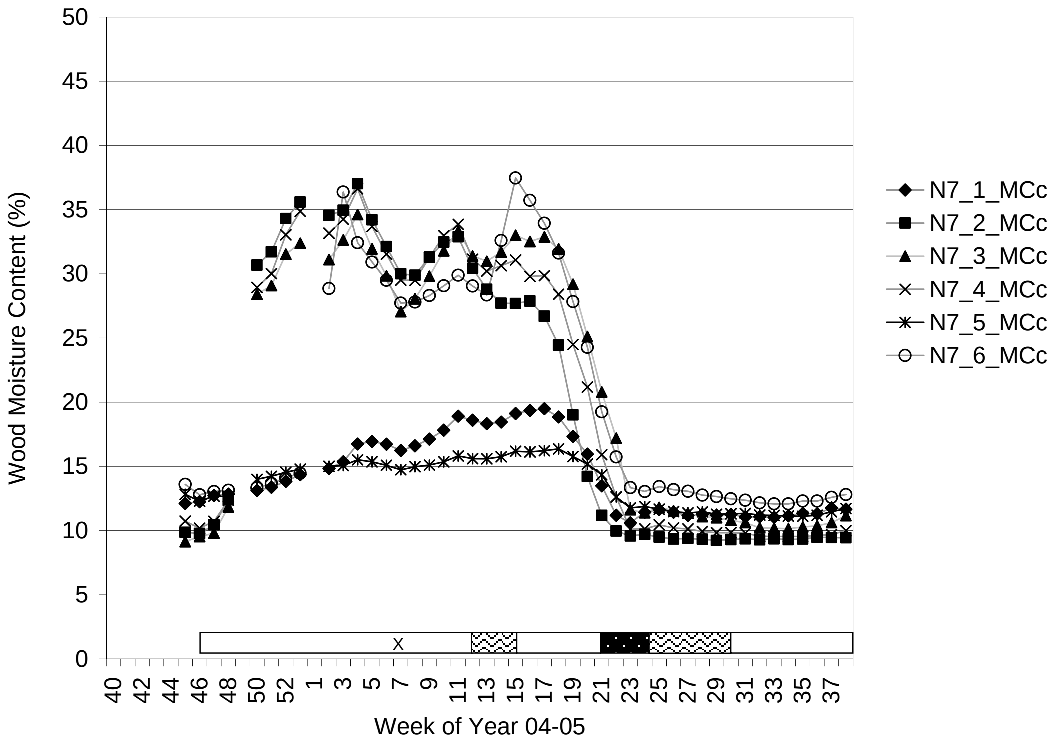


Figure B N7-2 N7 – Cavity Relative Humidity

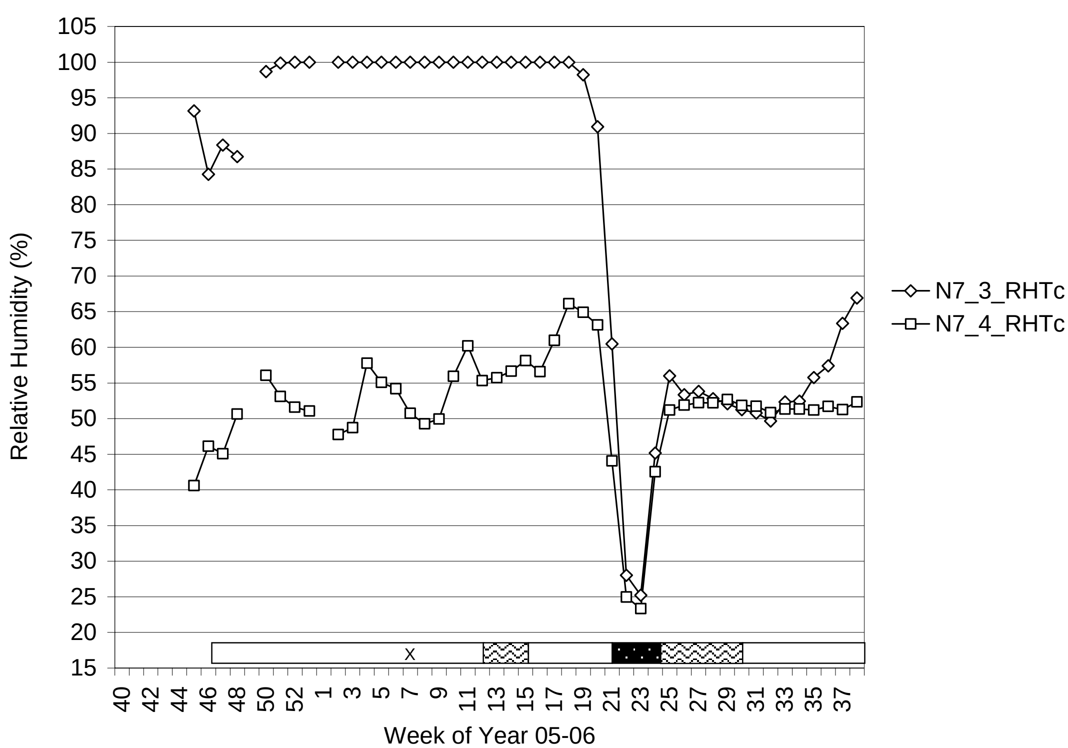


Figure B N7-3 N7 - Temperature

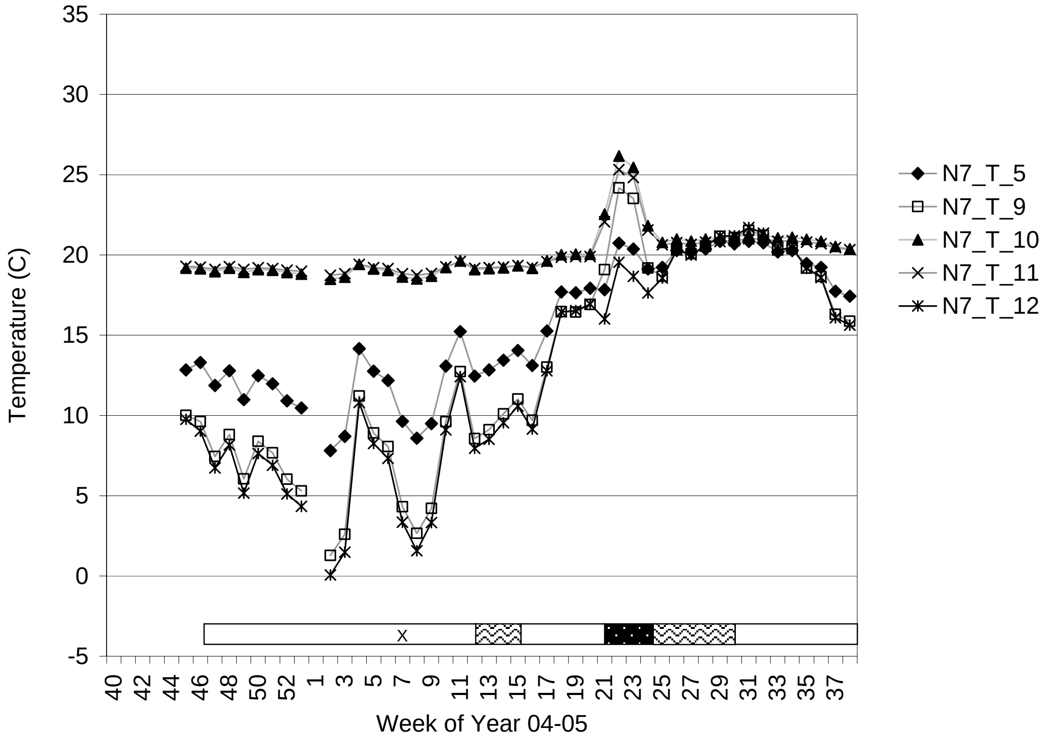


Figure B N7-4 N7 – Vapor Pressure

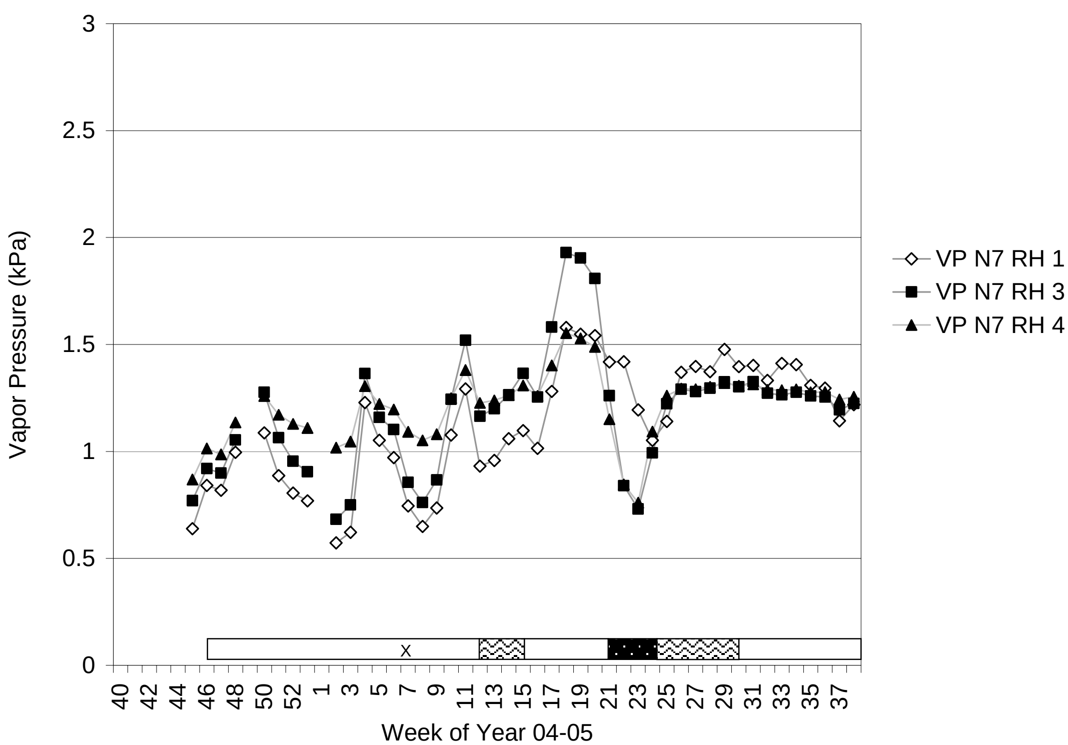


Figure B N8-1 N8 – Wood Moisture Content

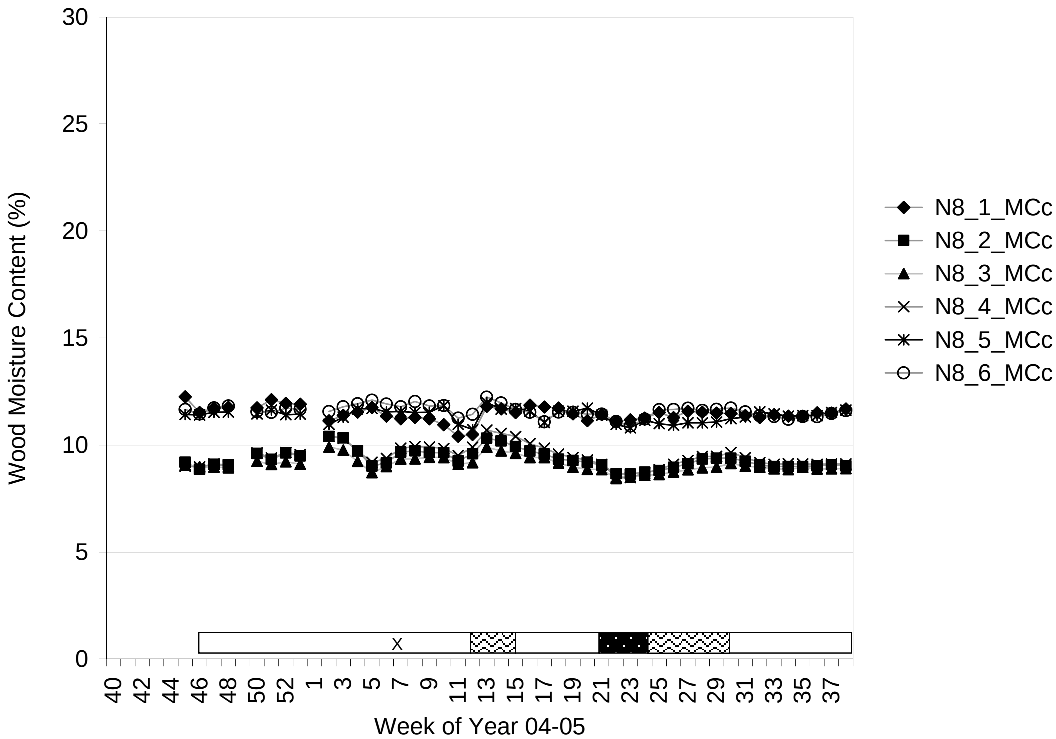


Figure B N8-2 N8 – Cavity Relative Humidity

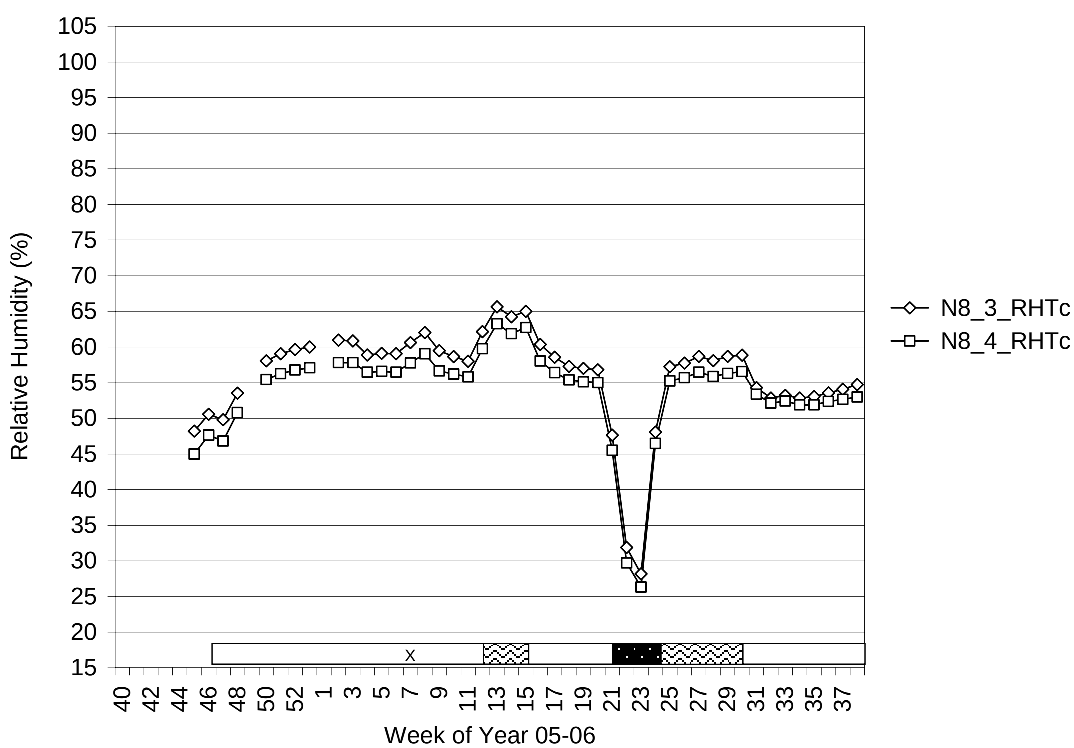


Figure B N8-3 N8 - Temperature

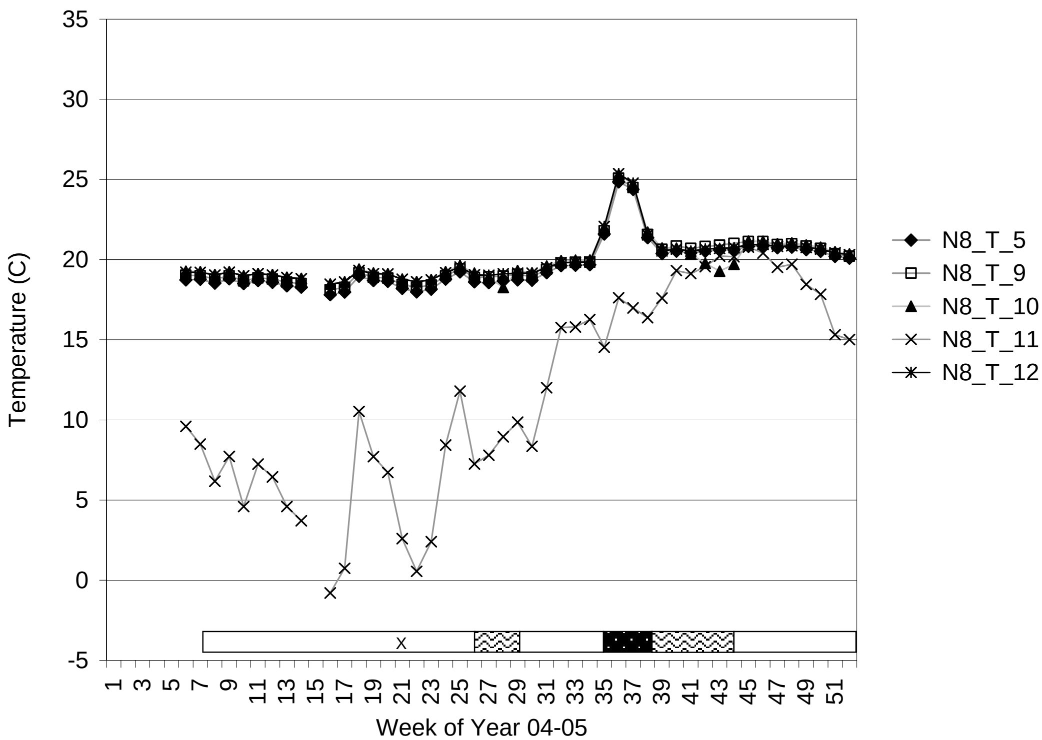
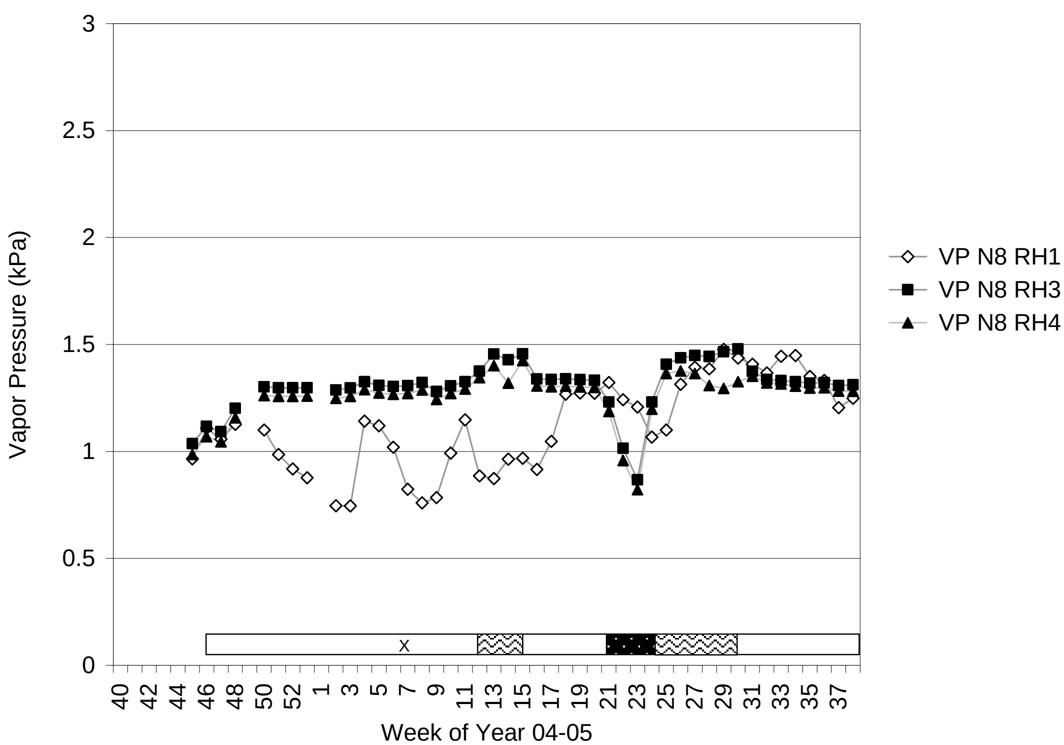


Figure B N8-3 N8 – Vapor Pressure



Appendix C

Test Cycle 3 Figures

October 1, 2005 to June 30, 2006

Figure C S1-1 S1 – Wood Moisture Content

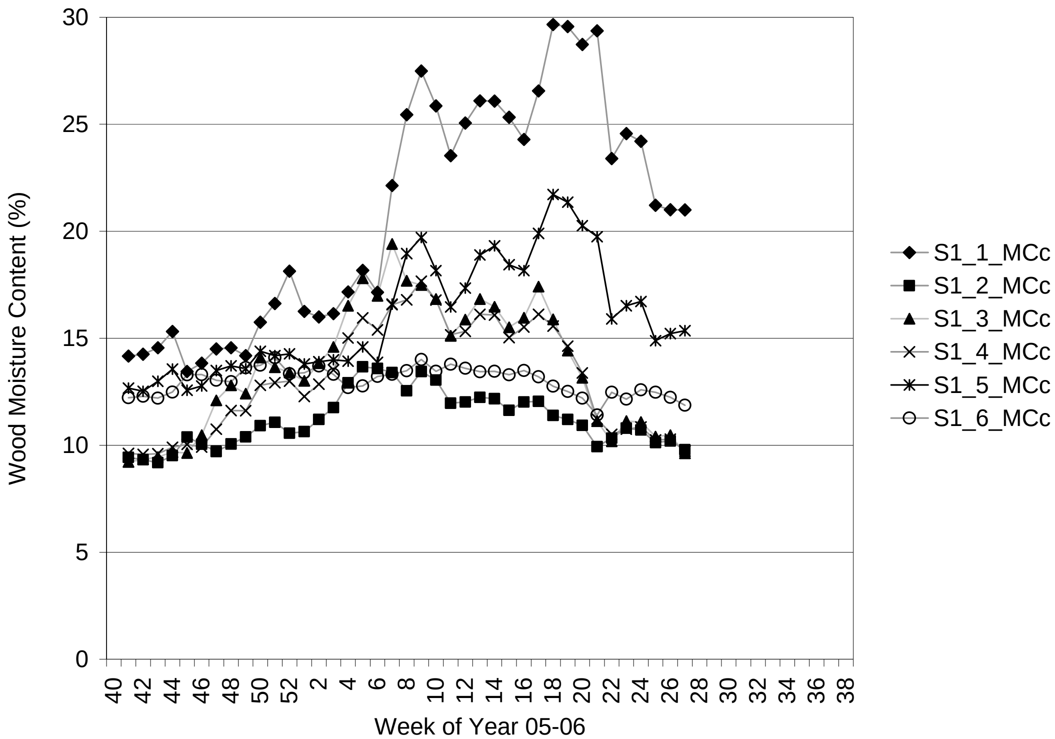


Figure C S1-2 S1 – Cavity Relative Humidity

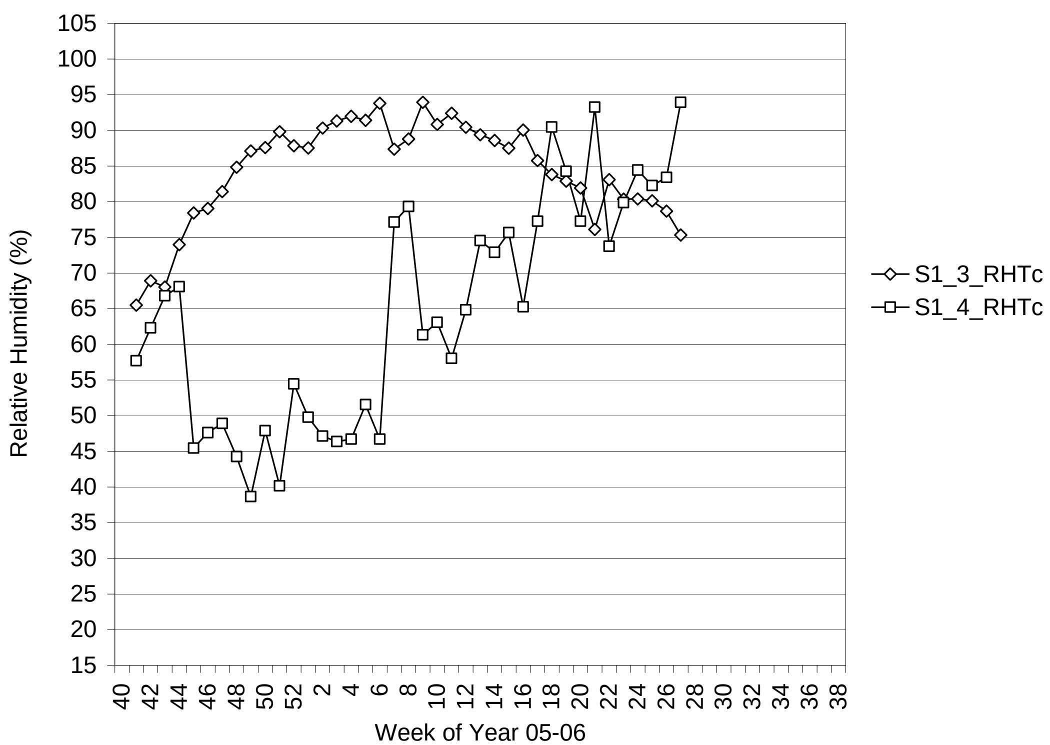


Figure C S1-3 S1 - Temperature

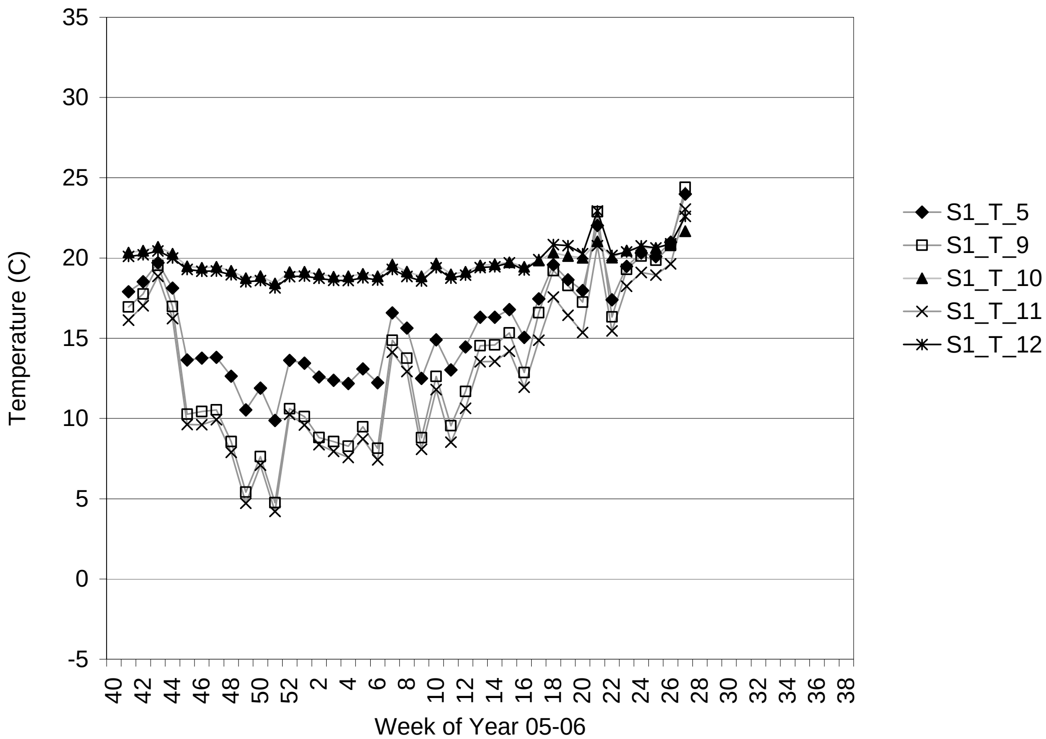


Figure C S1-4 S1 – Vapor Pressure

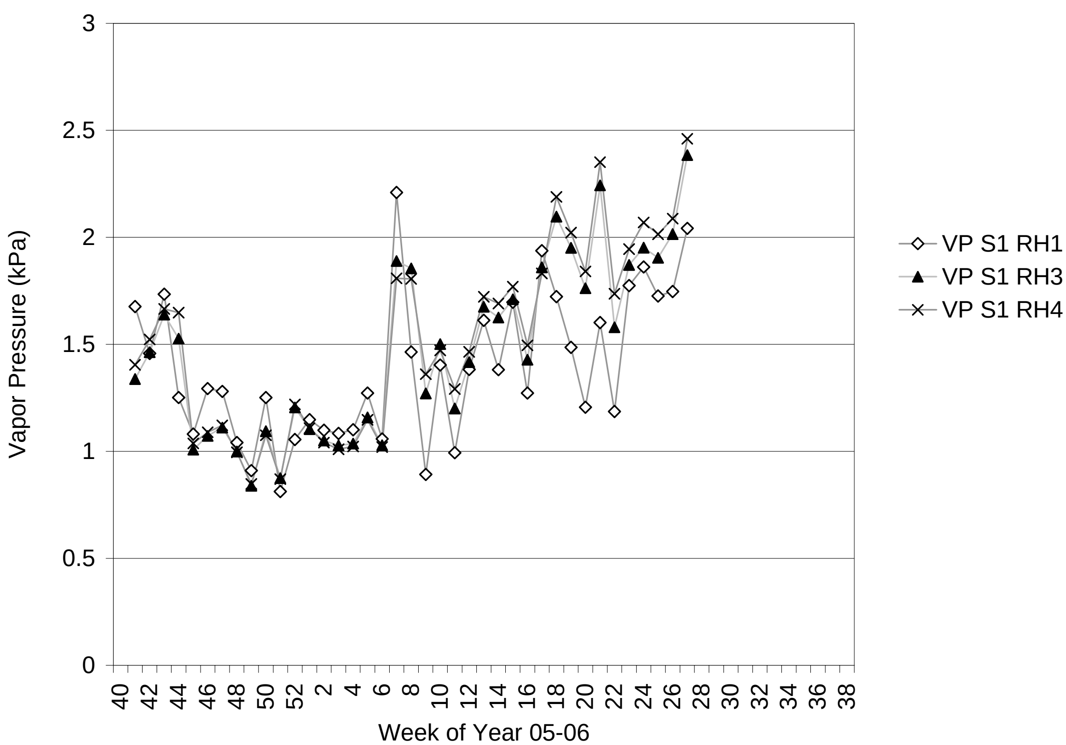


Figure C S2-1 S2 – Wood Moisture Content

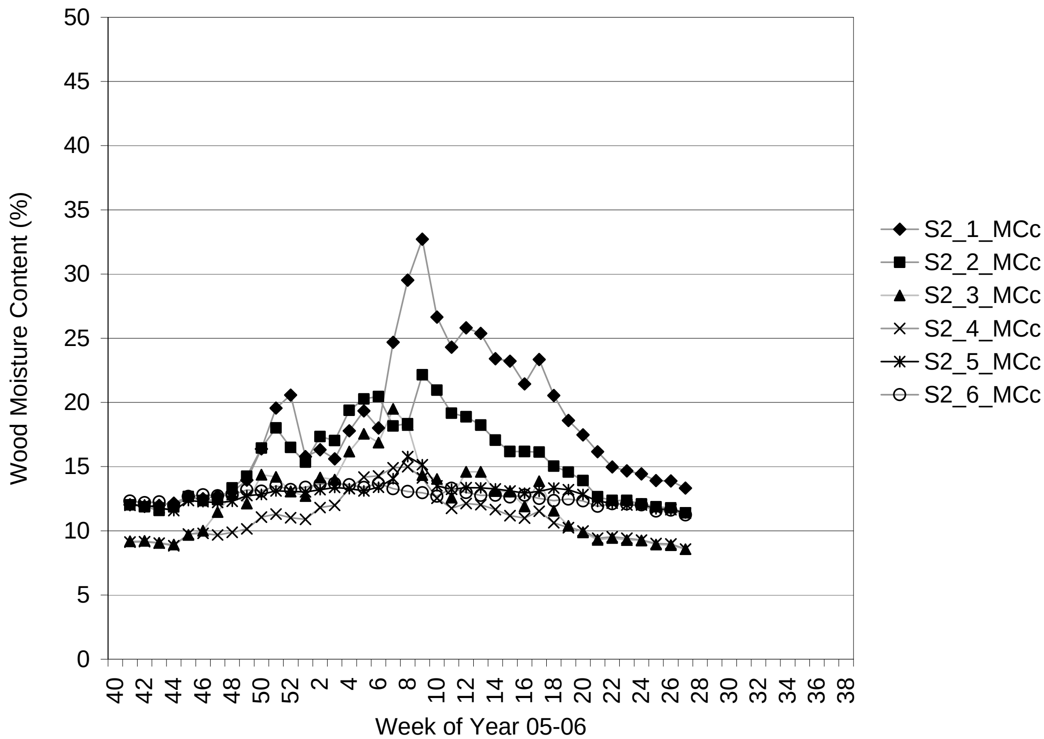


Figure C S2-2 S2 – Cavity Relative Humidity

Figure C S2-3 S2 – Temperature

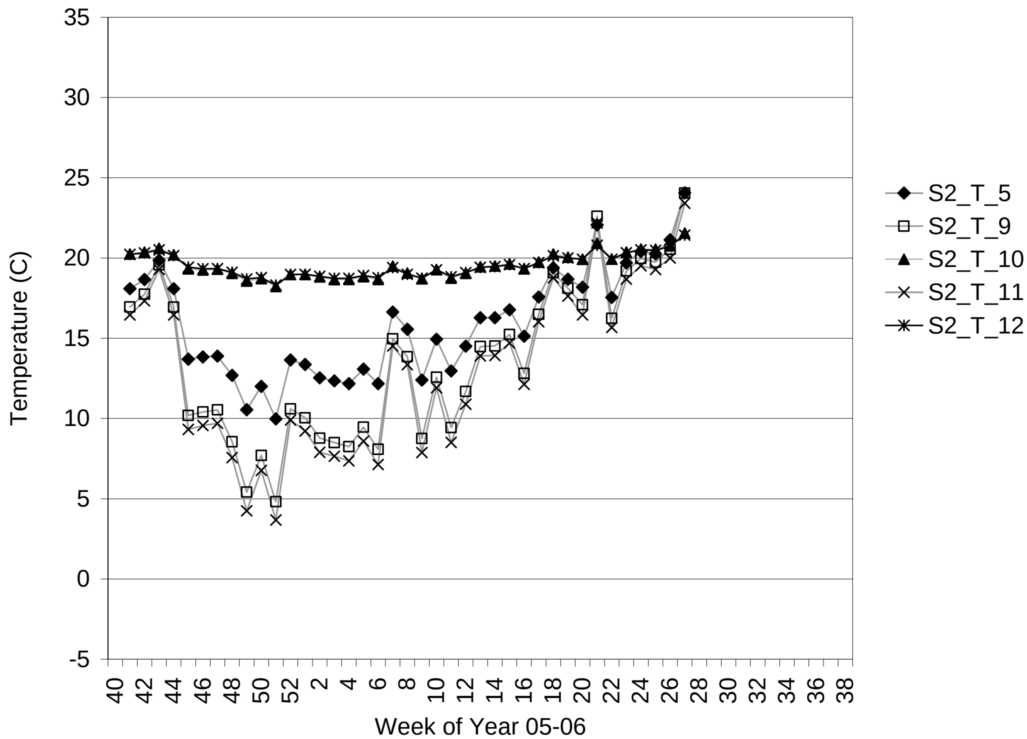


Figure C S2-4 S2 -- Vapor Pressure

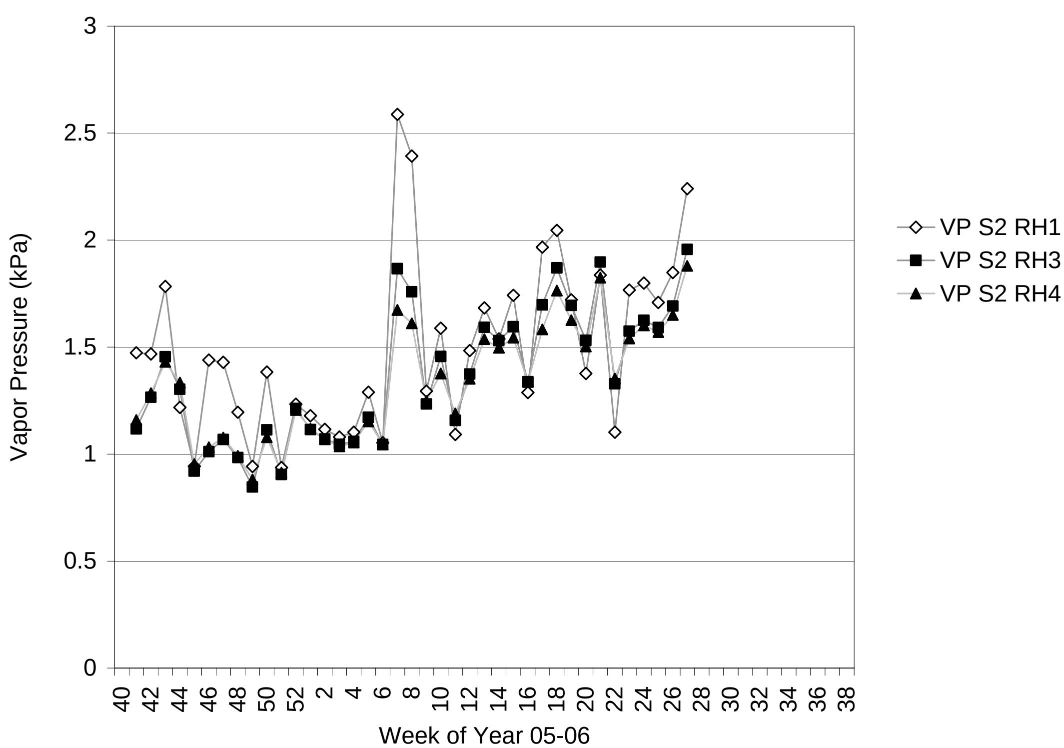


Figure C S3-1 S3 – Wood Moisture Content

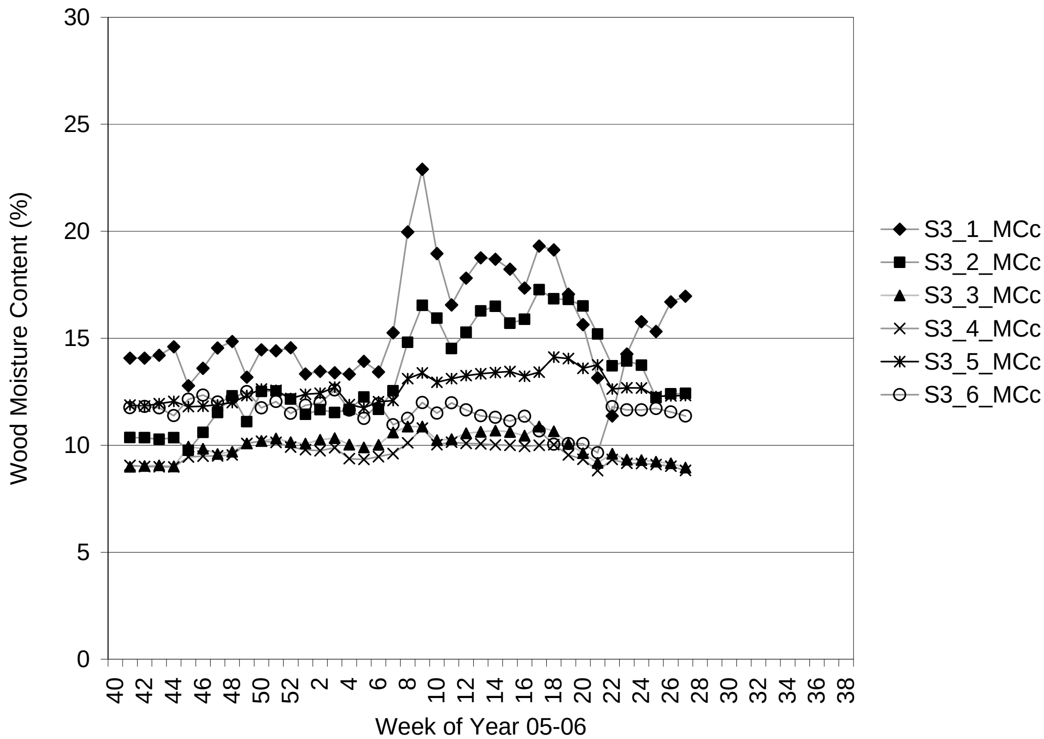


Figure C S3-2 S3 – Cavity Relative Humidity

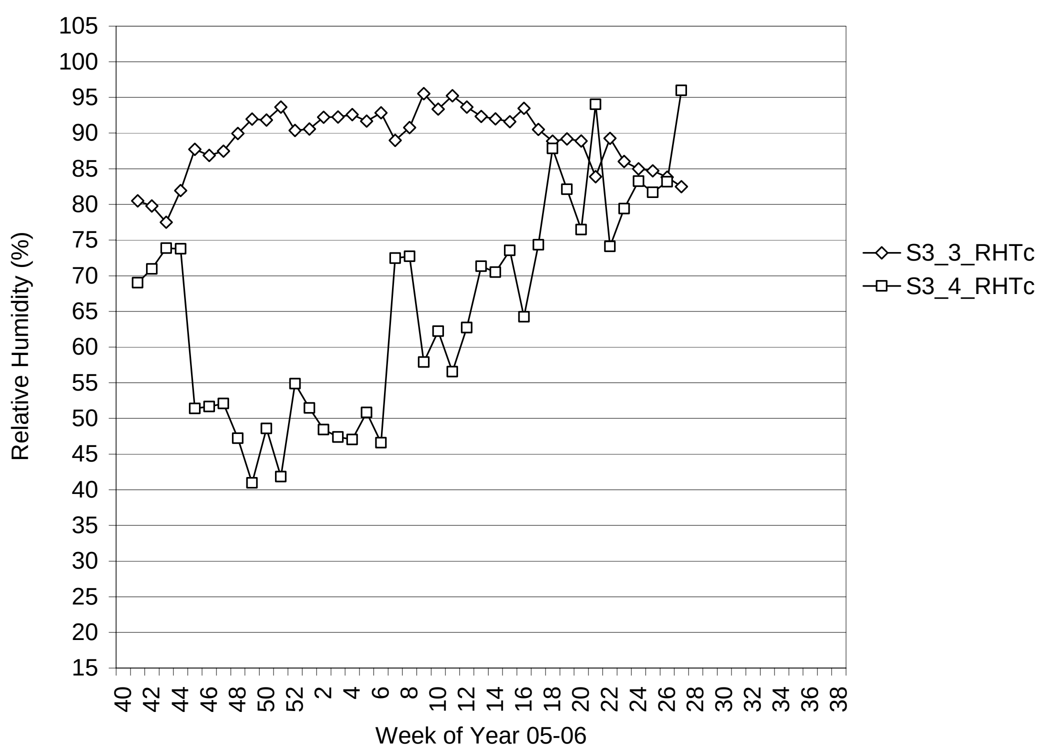


Figure C S3-3 S3 - Temperature

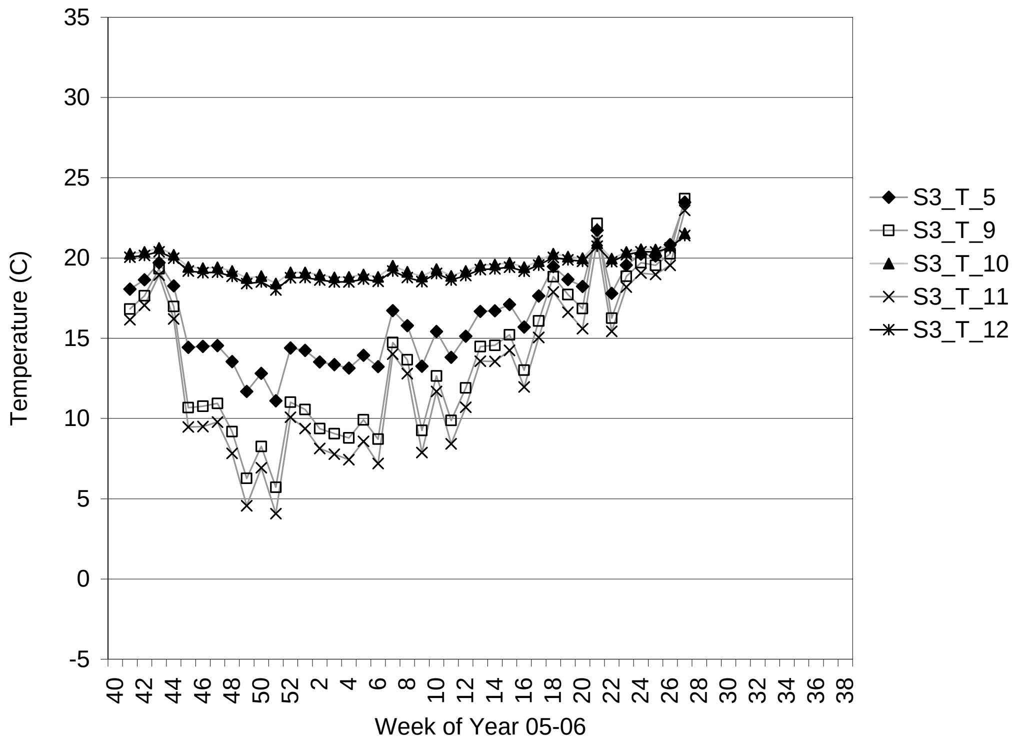


Figure C S3-4 S3 – Vapor Pressure

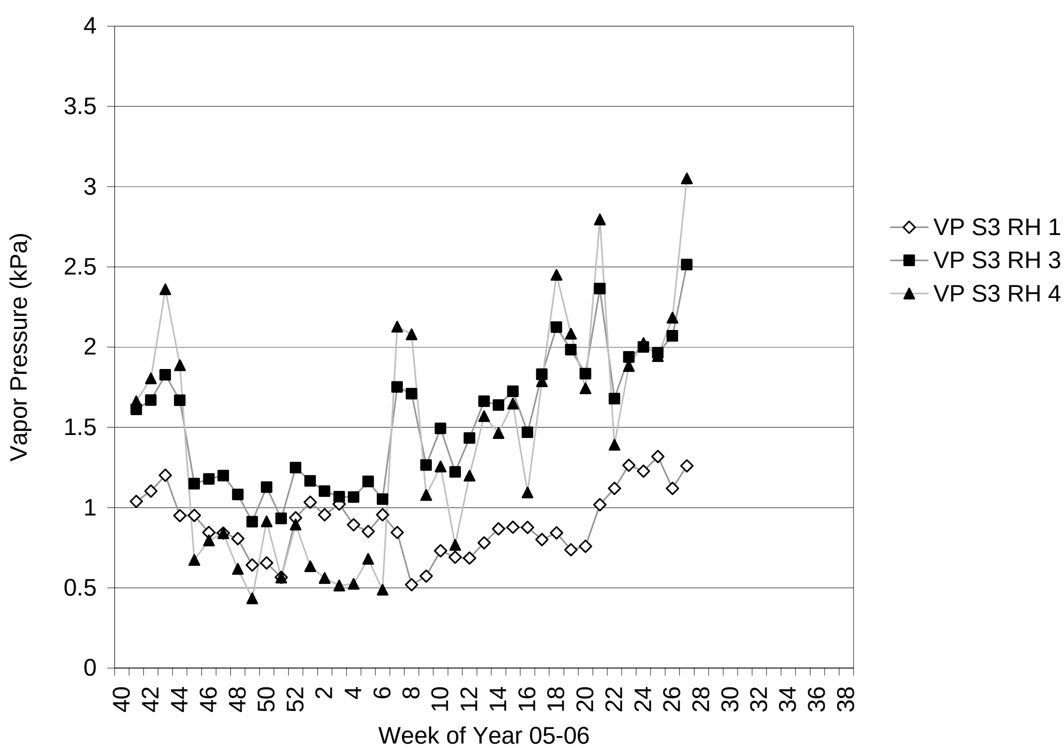


Figure C S4-1 S4 – Wood Moisture Content

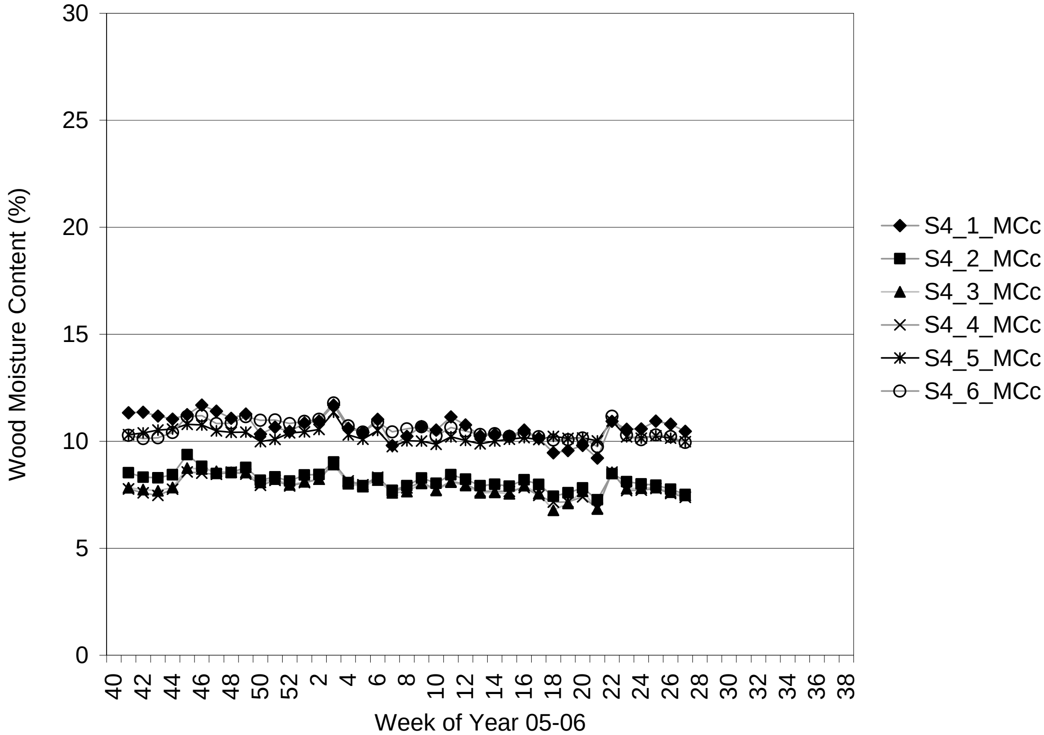


Figure C S4-2 S4 – Cavity Relative Humidity

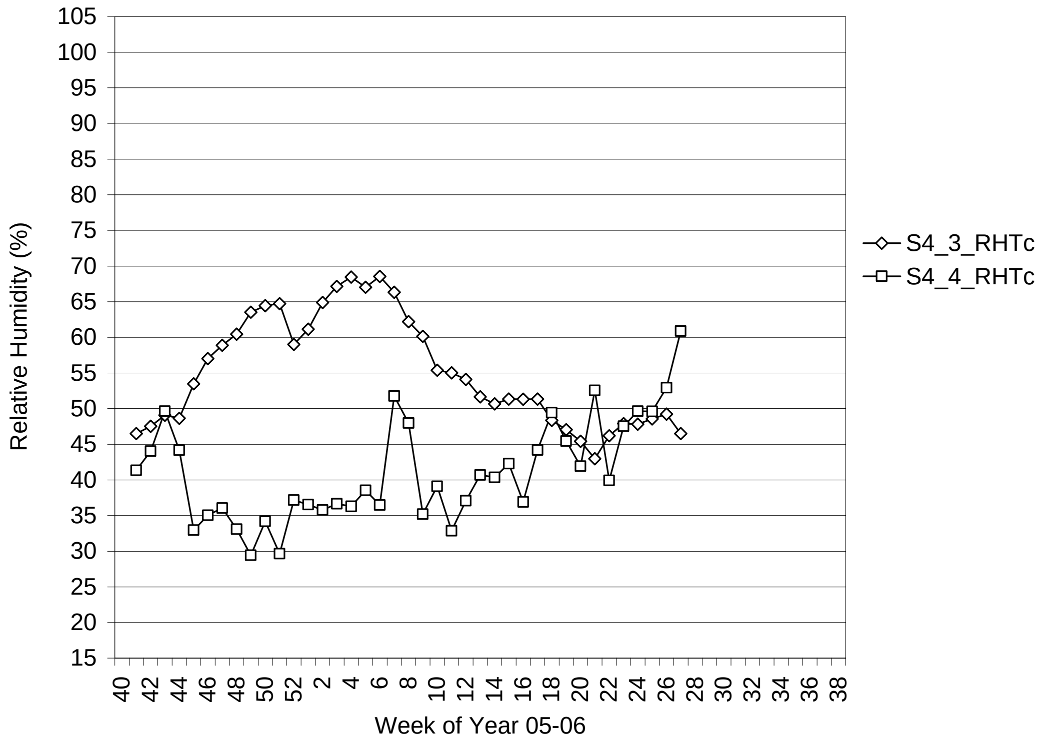


Figure C S4-3 S4 - Temperature

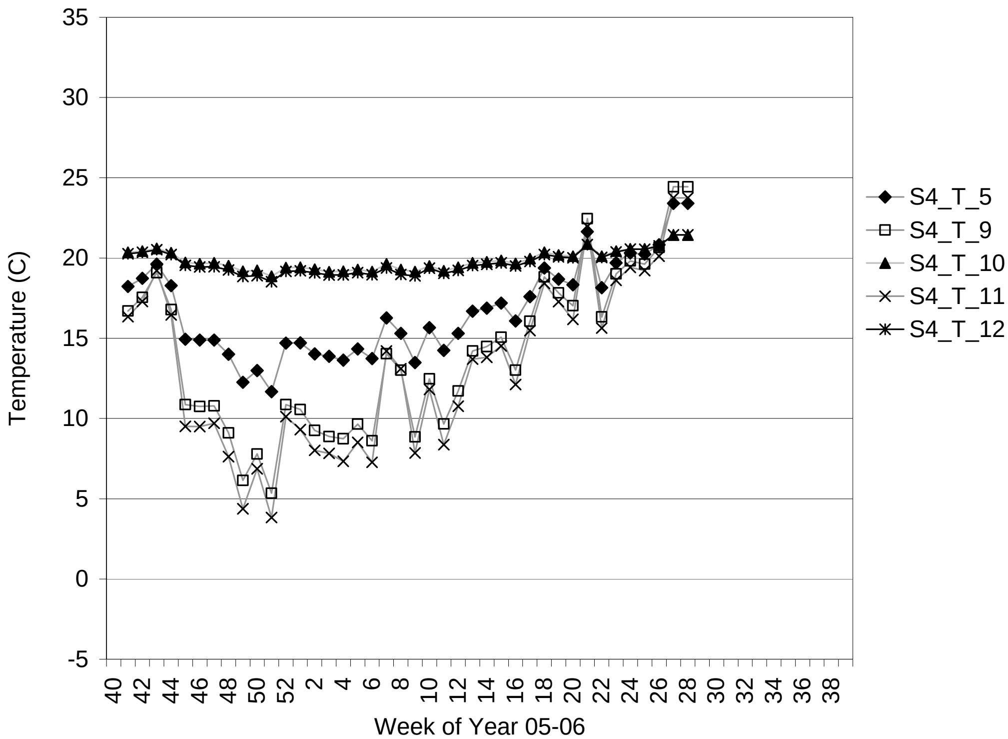


Figure C S4-4 S4 – Vapor Pressure

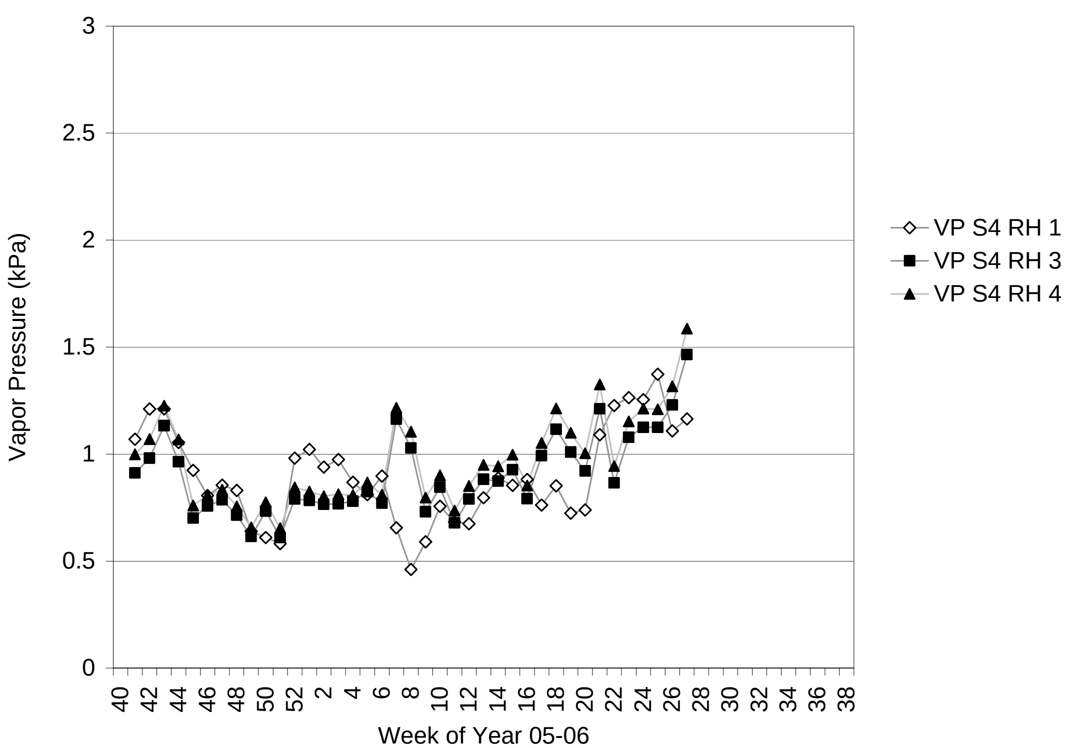


Figure C S5-1 S5 – Wood Moisture Content

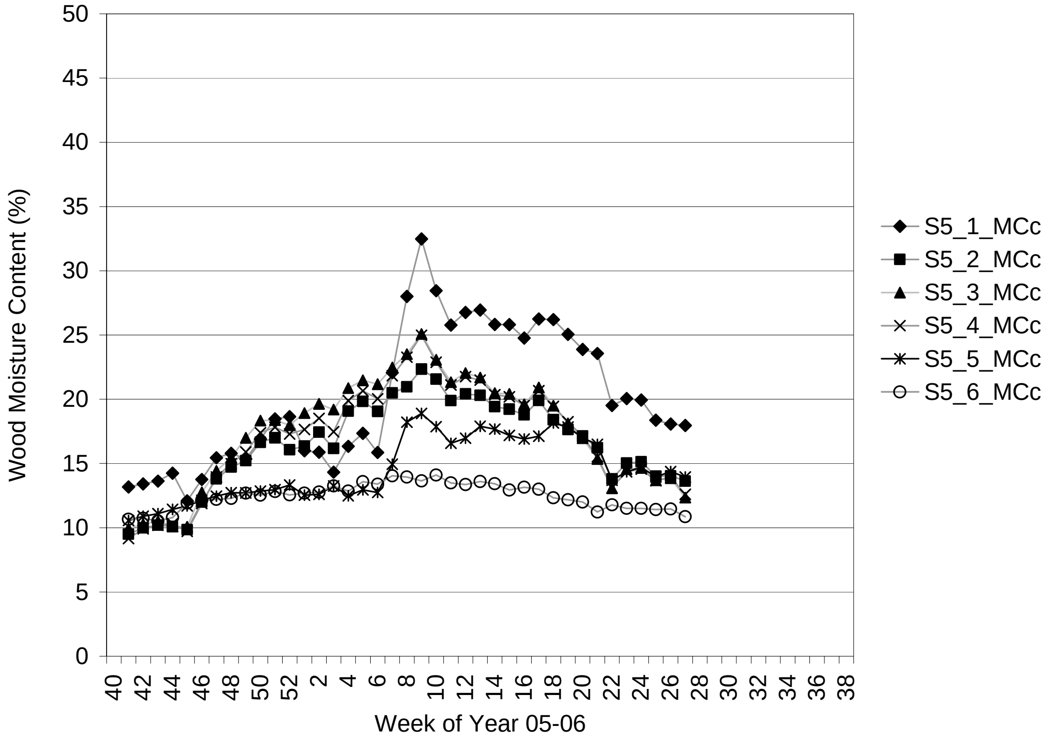


Figure C S5-2 S5 – Cavity Relative Humidity

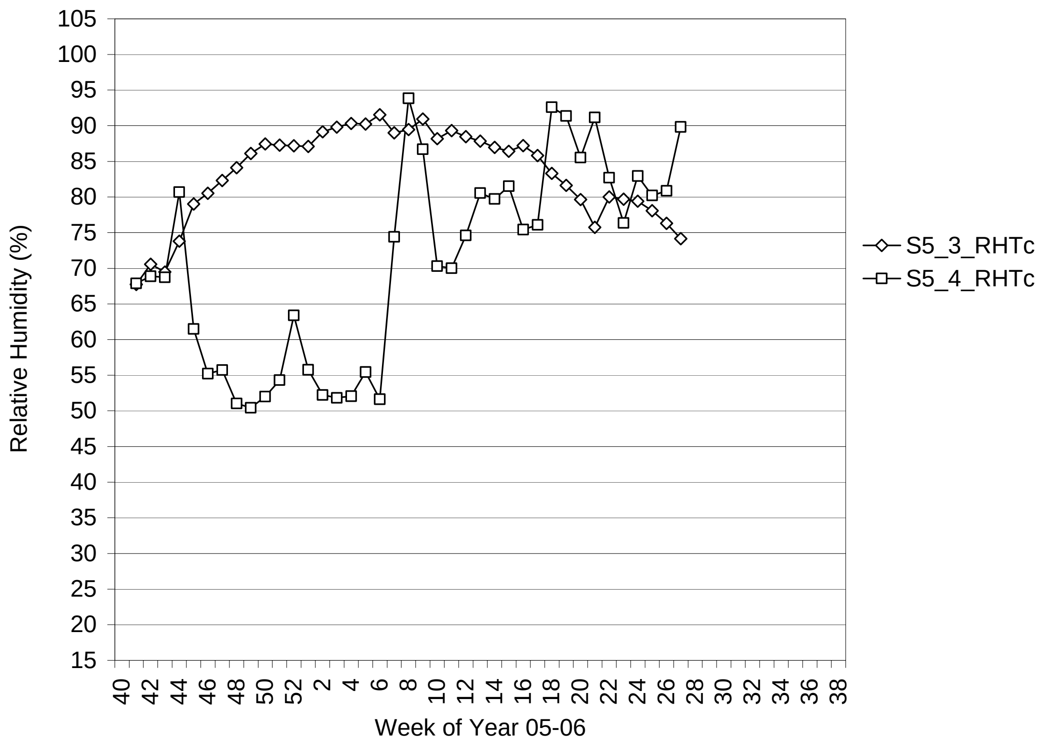


Figure C S5-3 S5 -- Temperature

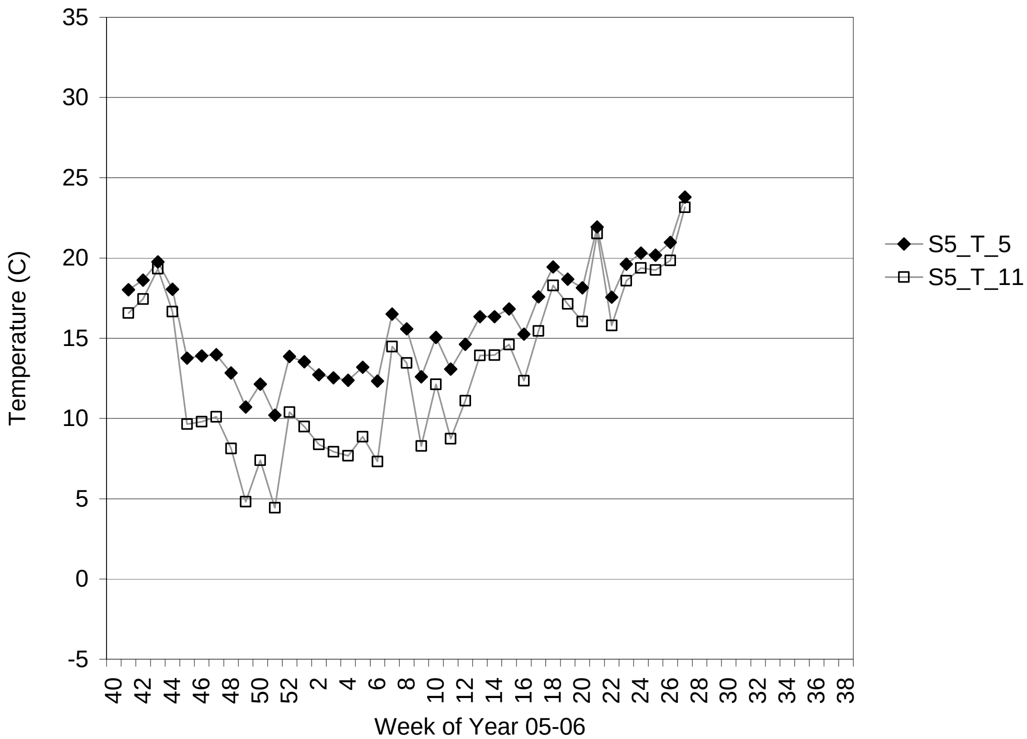


Figure C S5-4 S5 – Vapor Pressure

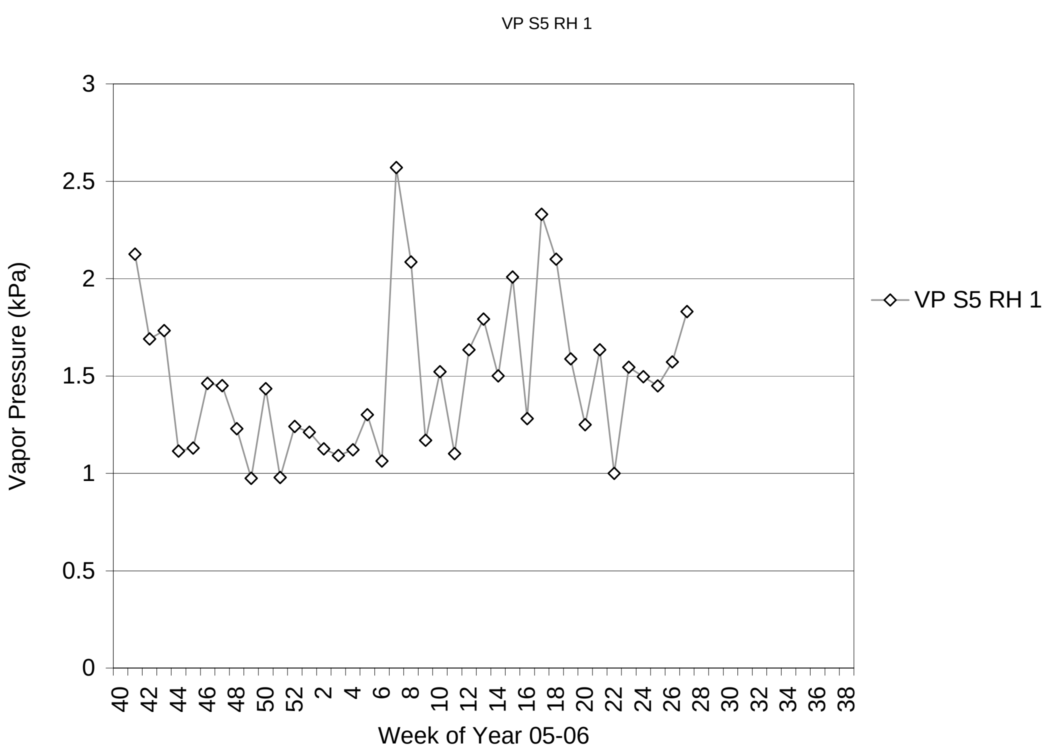


Figure C S6-1 **S6 – Wood Moisture Content**

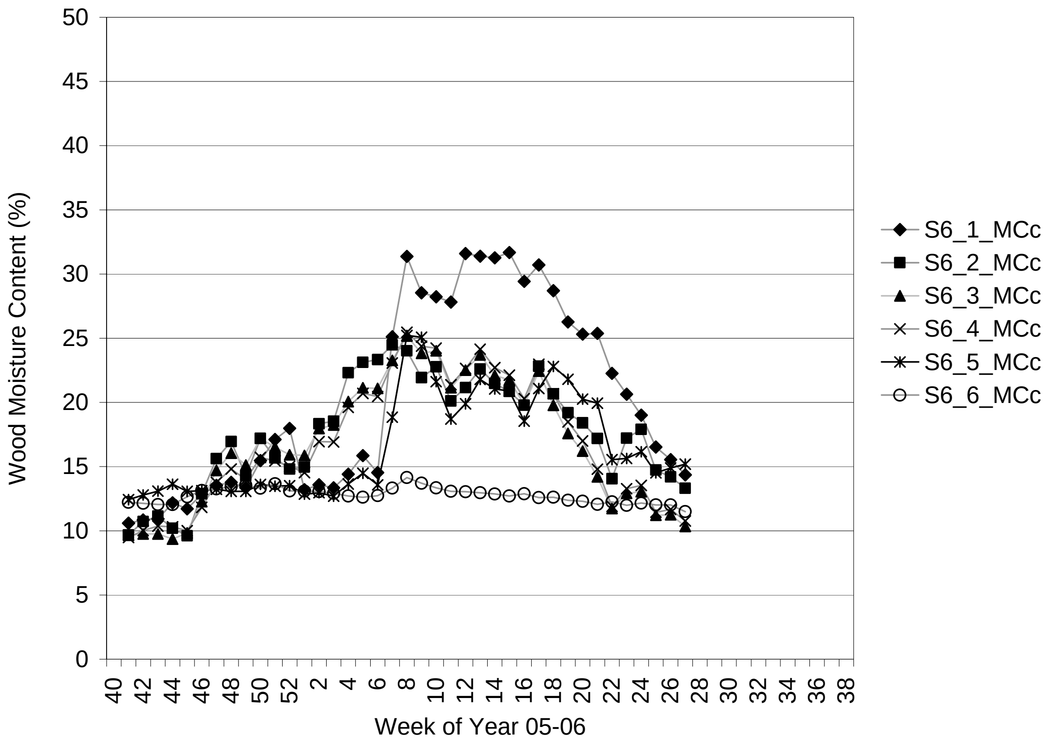


Figure C1 S6-2 **S6 – Cavity Relative Humidity**

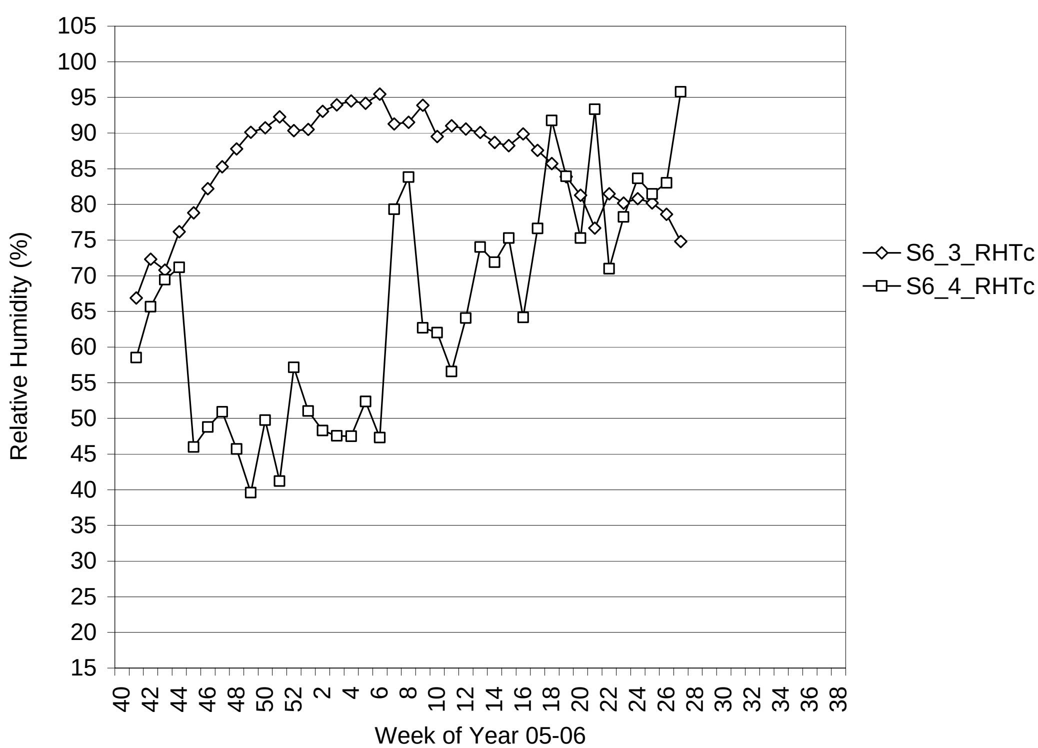


Figure C S6-3 **S6 - Temperature**

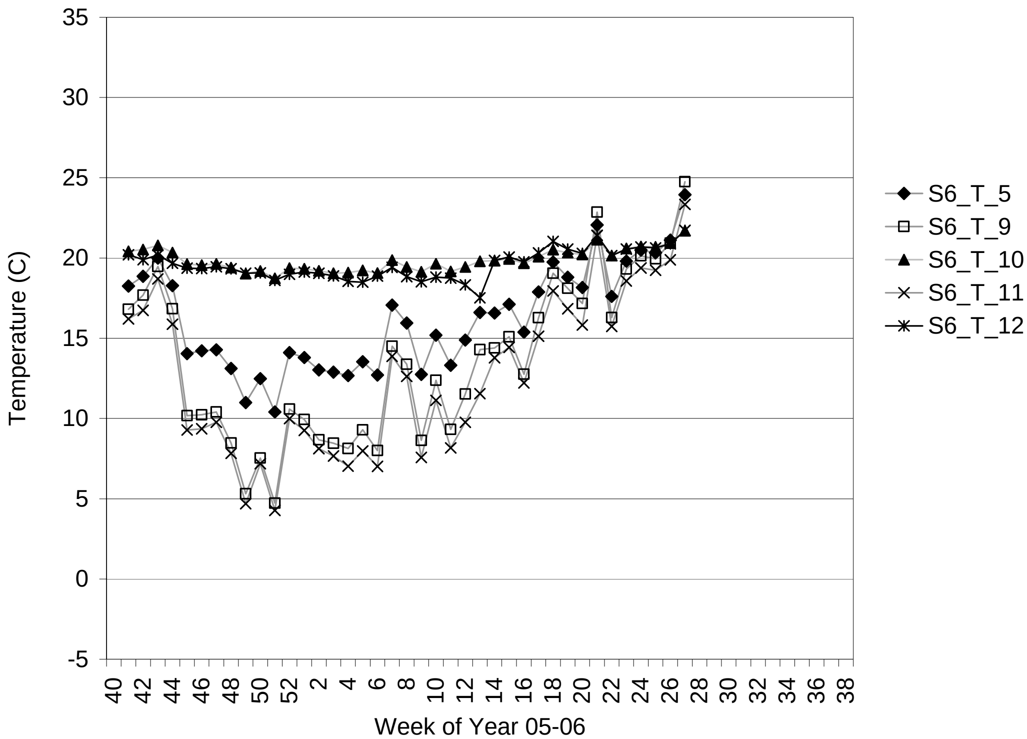


Figure C S6-4 **S6 – Vapor Pressure**

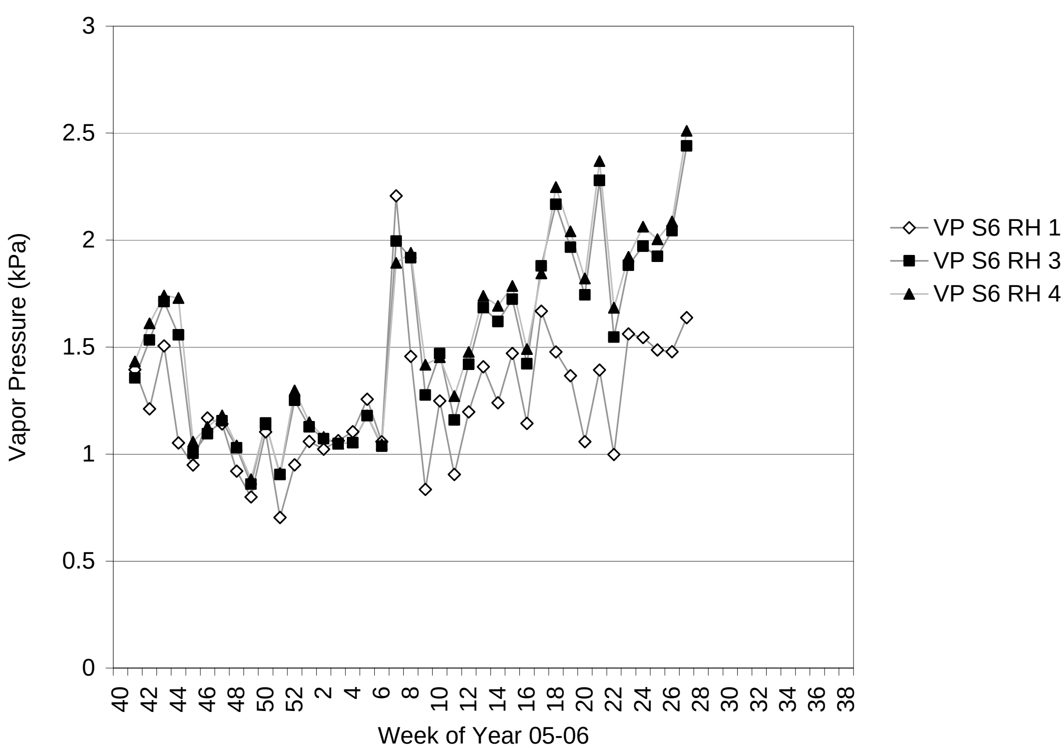


Figure C S7-1 S7 – Wood Moisture Content

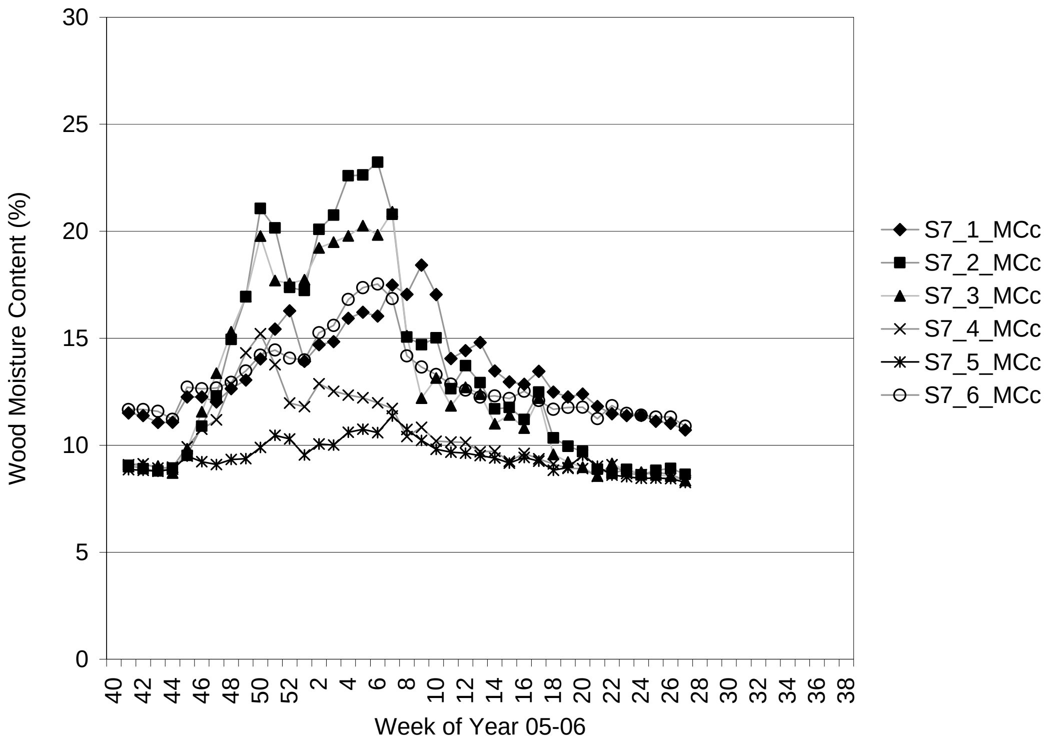


Figure C S7-2 S7 – Cavity Relative Humidity

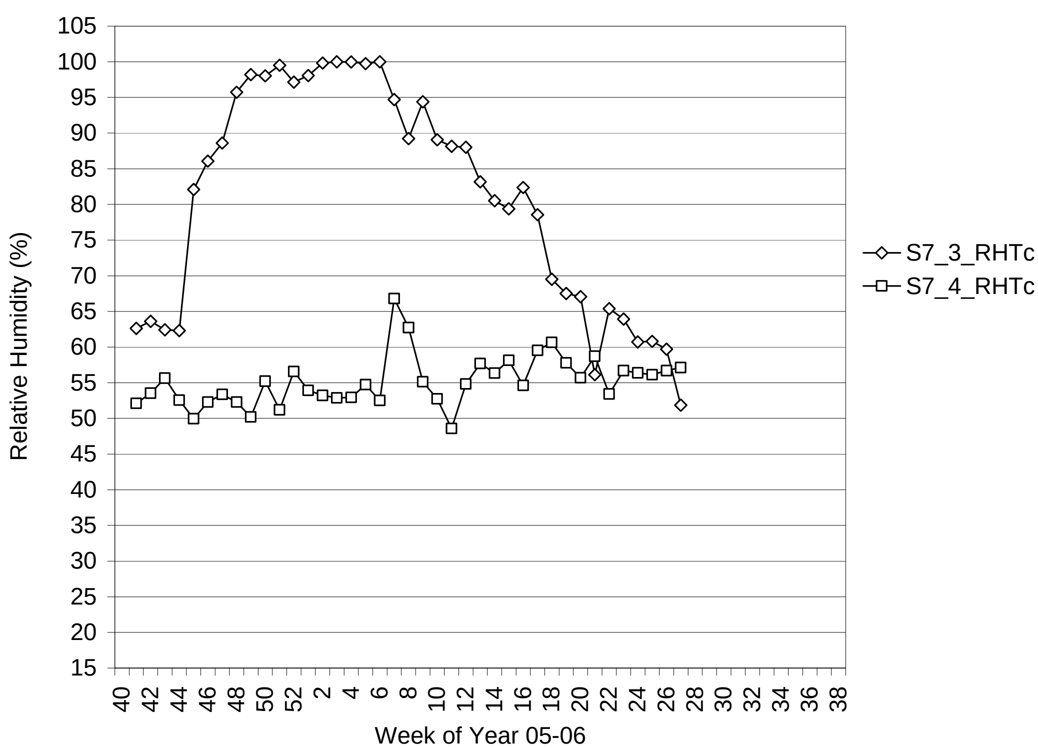


Figure C S7-3 S7 - Temperature

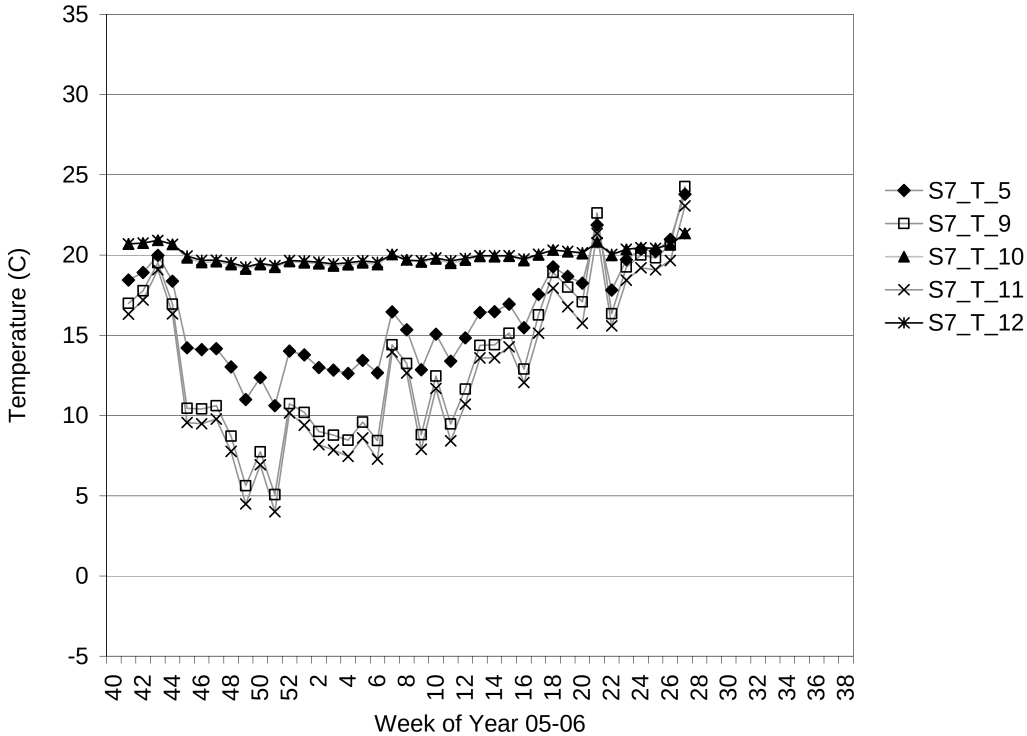


Figure C S7-4 S7 – Vapor Pressure

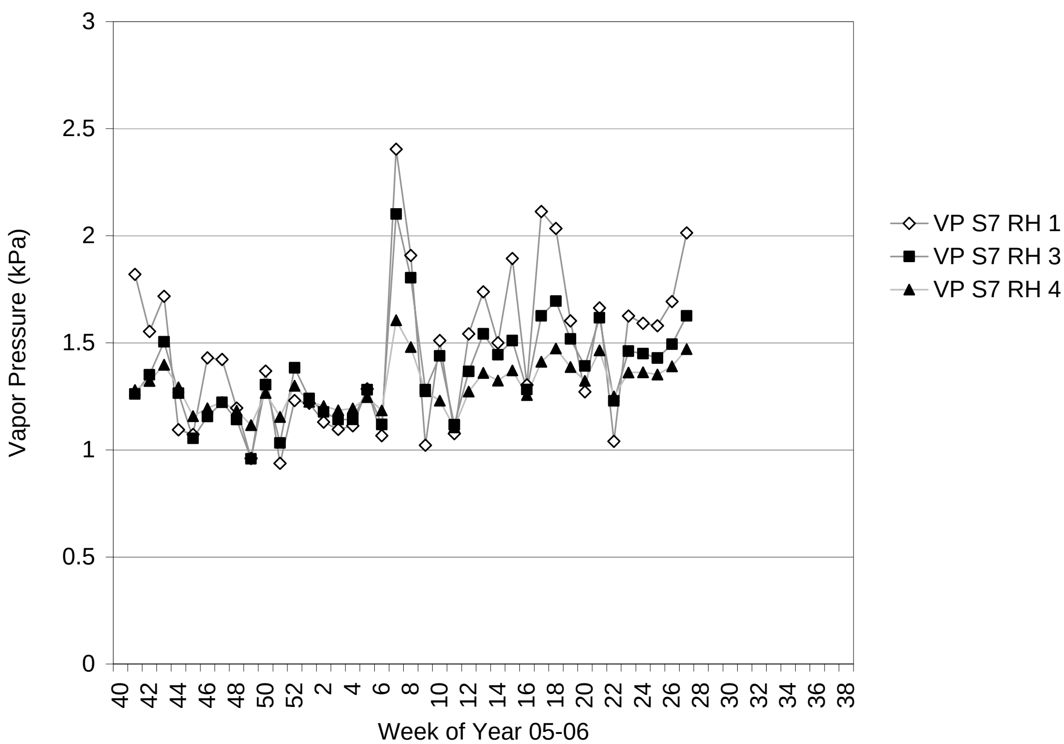


Figure C S8-1 S8 – Wood Moisture Content

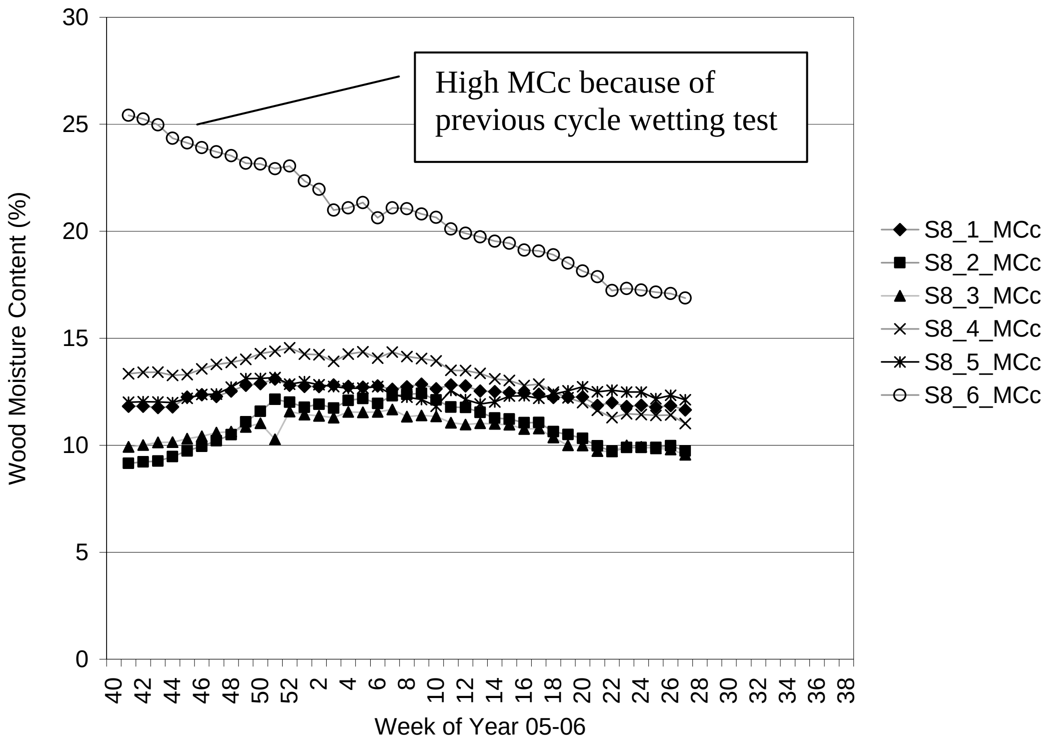


Figure C S8-2 S8 – Cavity Relative Humidity

Figure C S8-3 S8 - Temperature

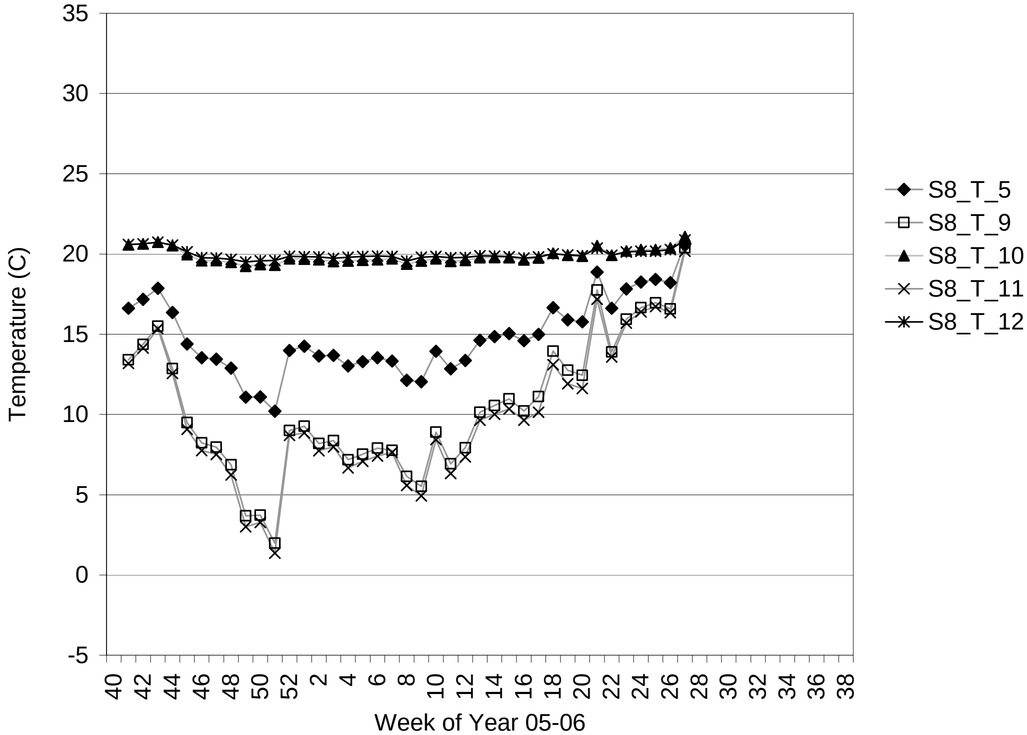


Figure C S8-4 S8 – Vapor Pressure

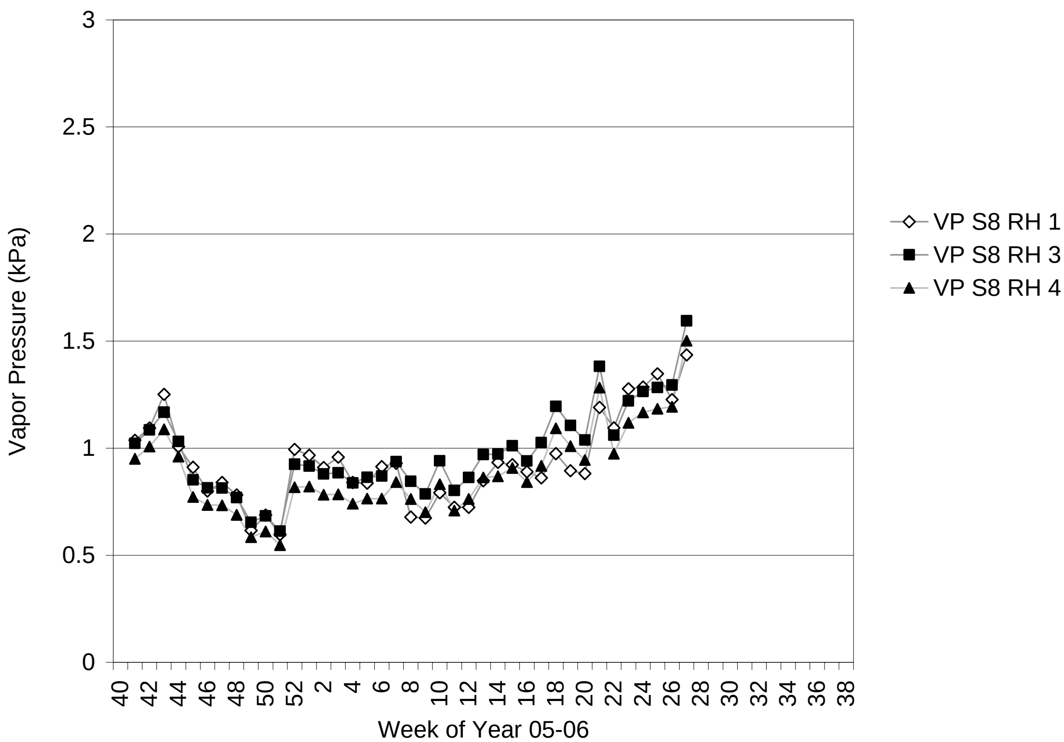


Figure C S9-1 S9 – Wood Moisture Content

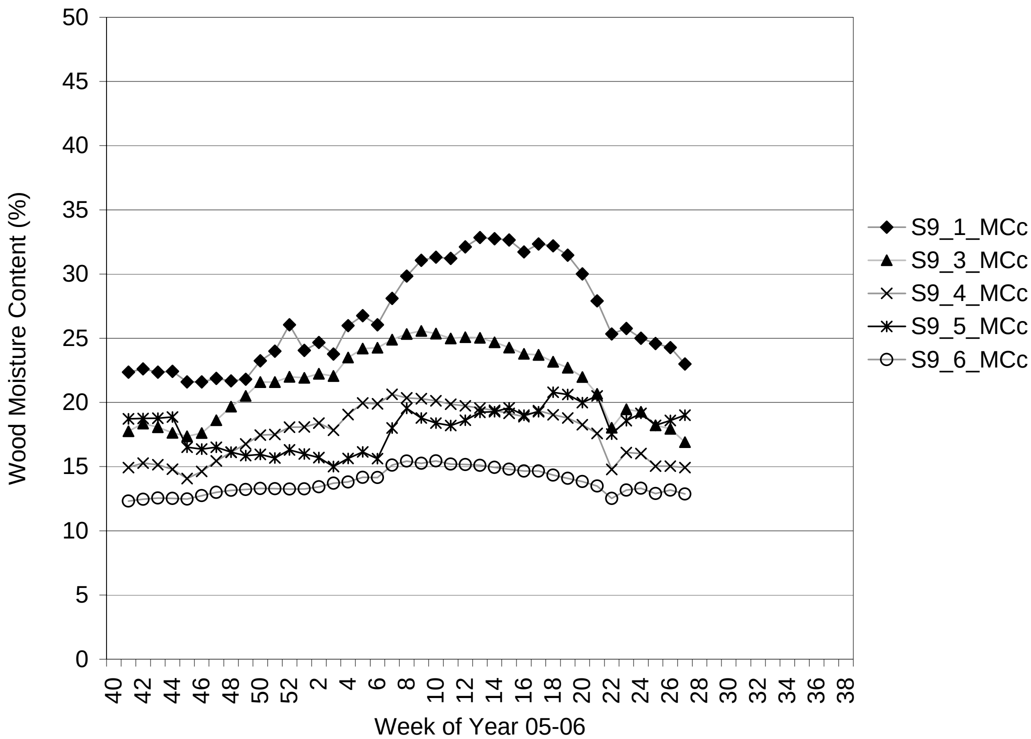


Figure C S9-2 A9 – Cavity Relative Humidity

Figure C S9-3 A9 - Temperature

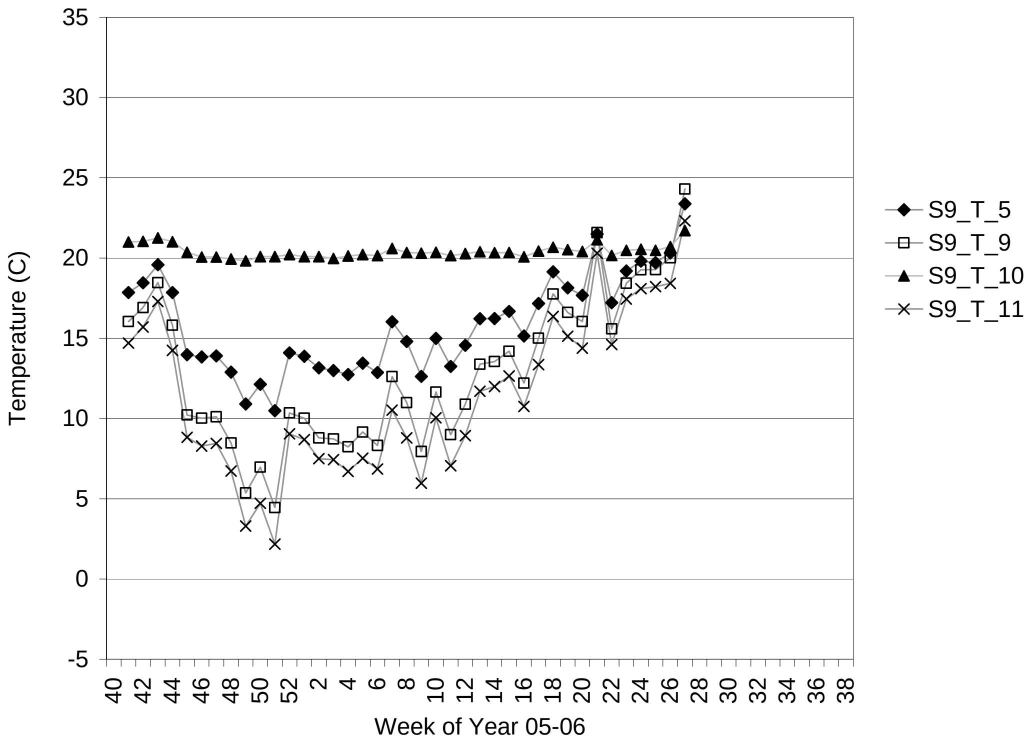


Figure C S9-4 S9 – Vapor Pressure

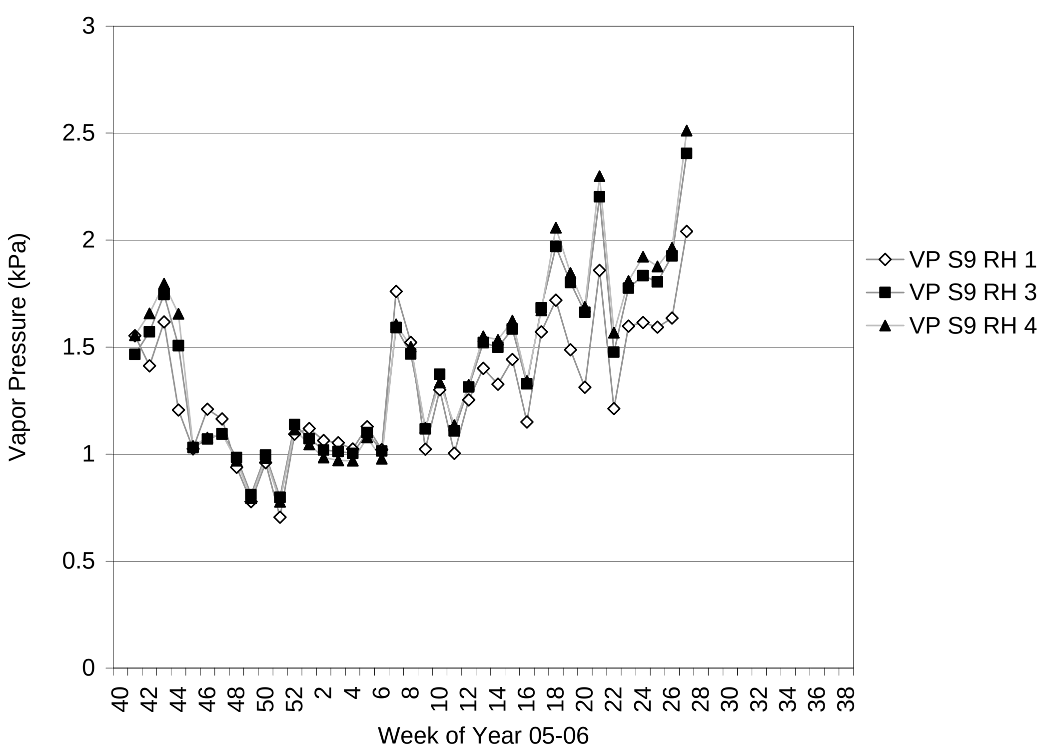


Figure C S9b-1 **S9b – Wood Moisture Content**

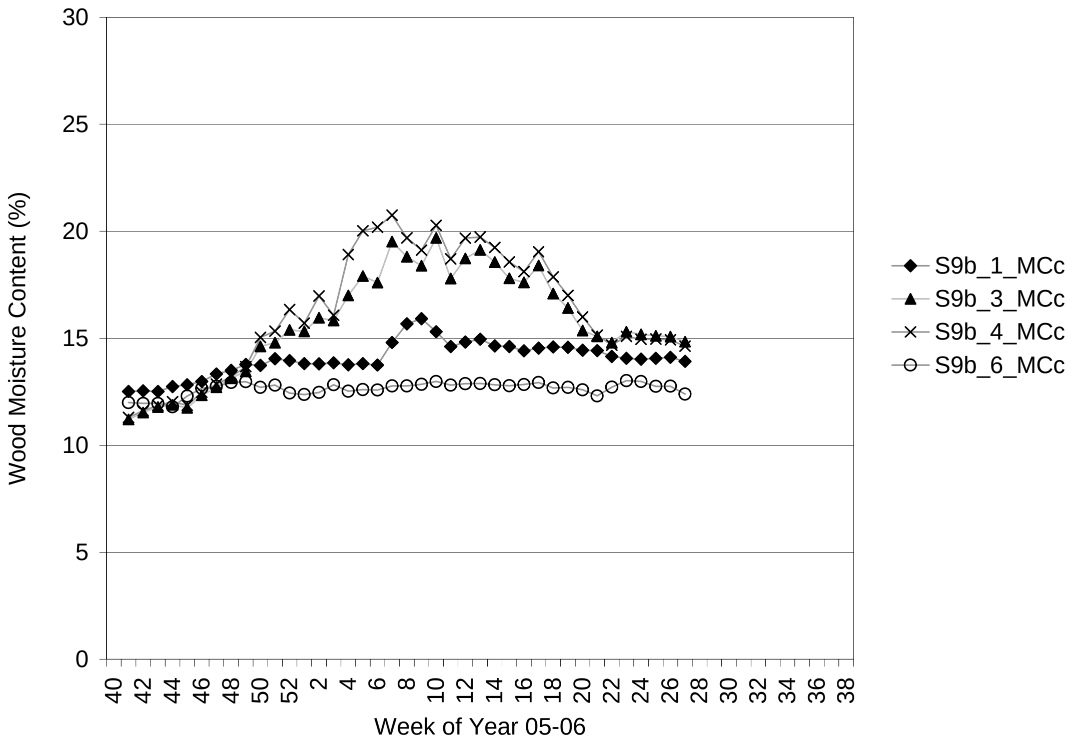


Figure C S9b-2 **S9b – Cavity Relative Humidity**

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

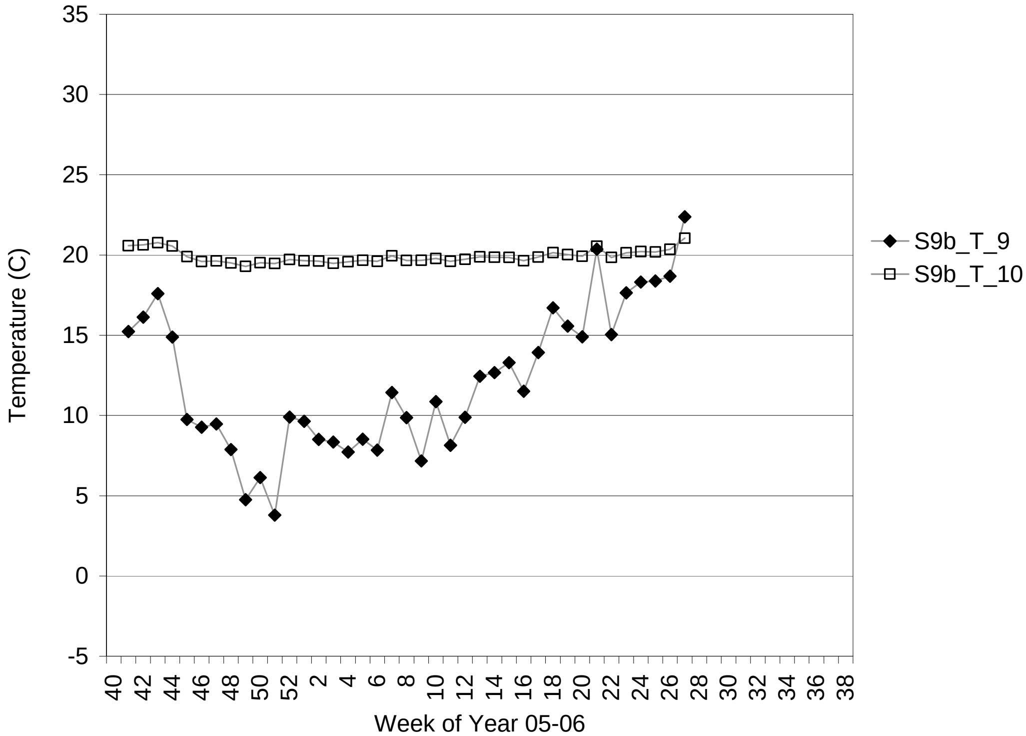


Figure C S9b-4 **S9b – Vapor Pressure**

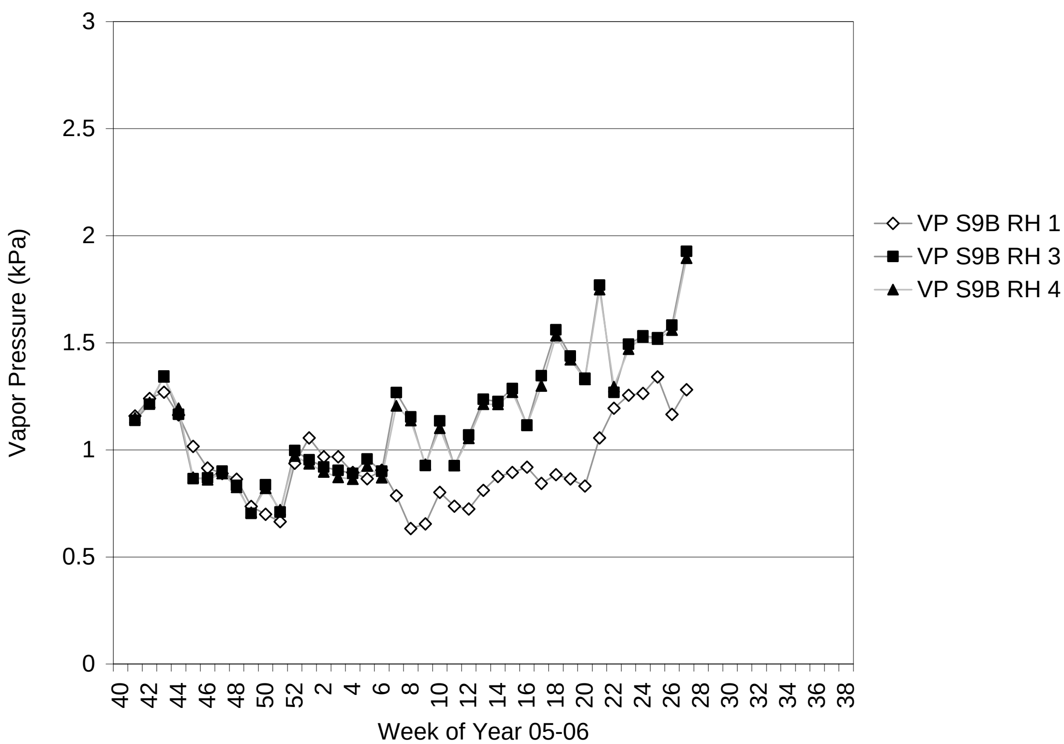


Figure C S10-1 S10 – Wood Moisture Content

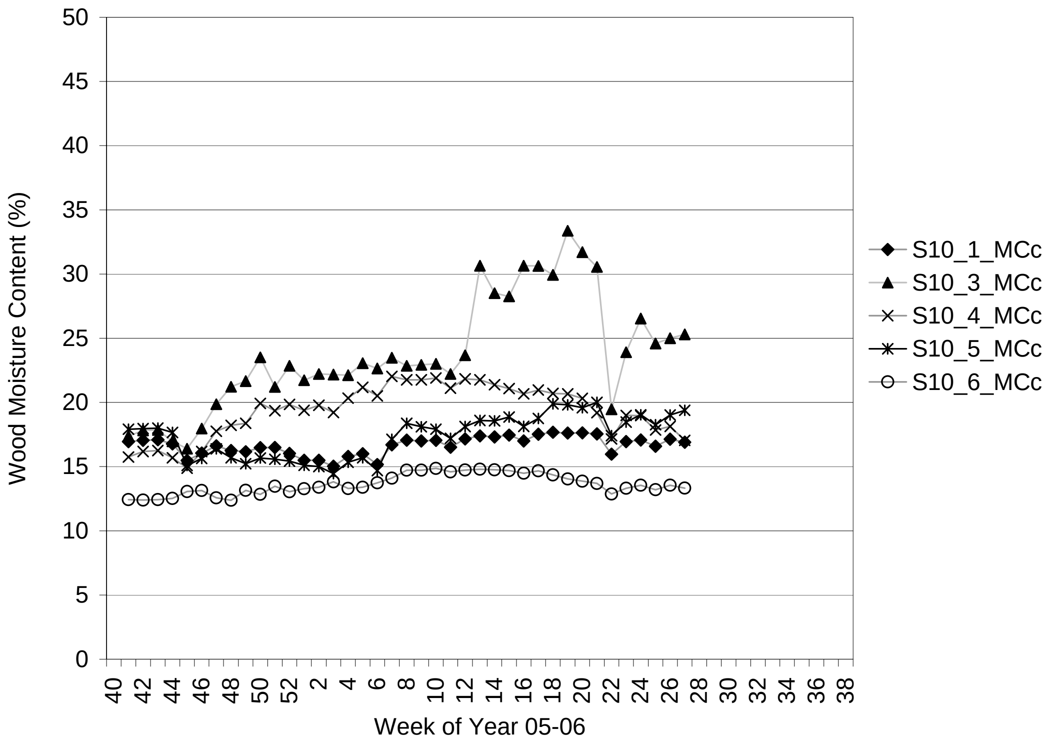


Figure C S10-2 S10 – Cavity Relative Humidity

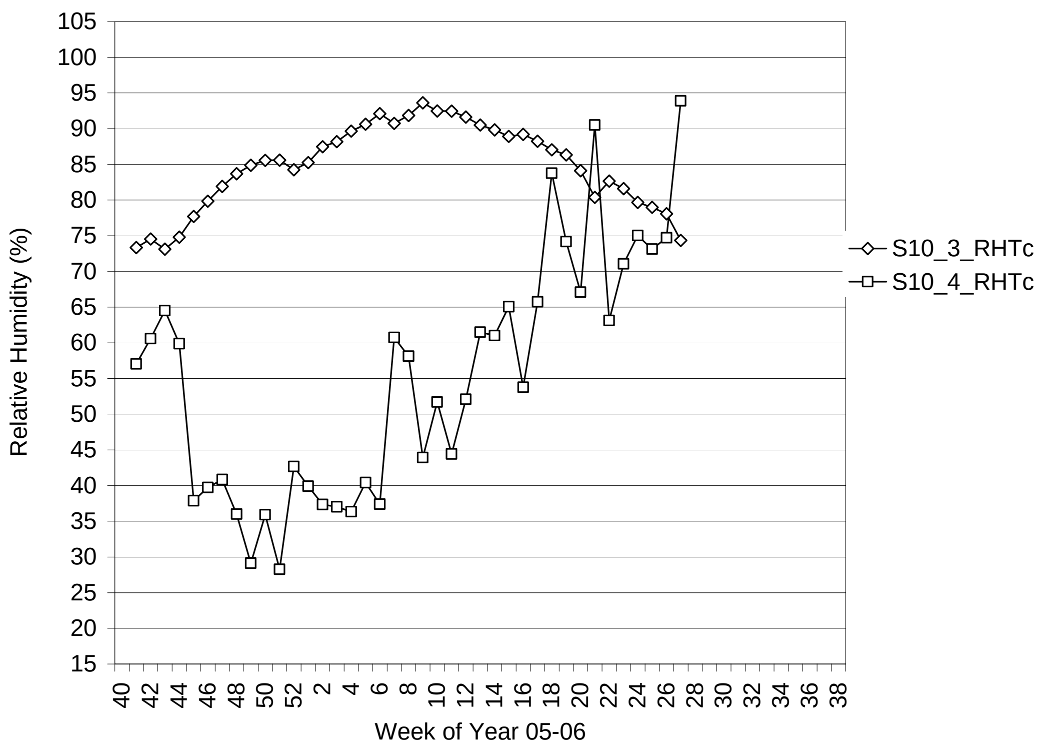


Figure C S10-3 S10- Temperature

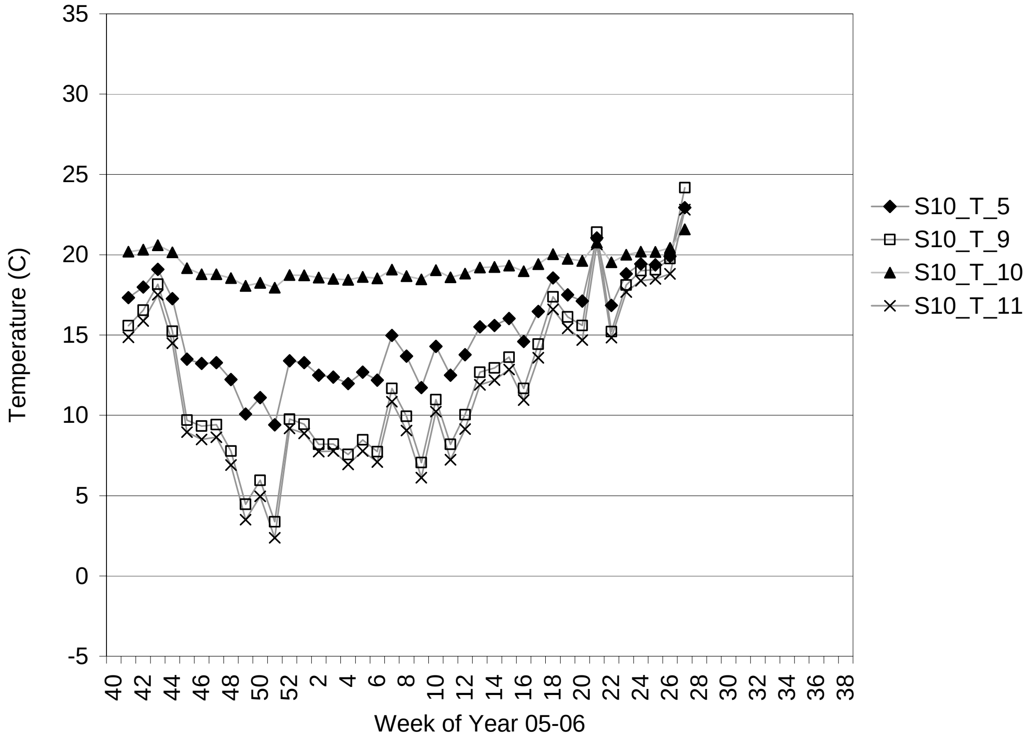


Figure C S10-4 S10 – Vapor Pressure

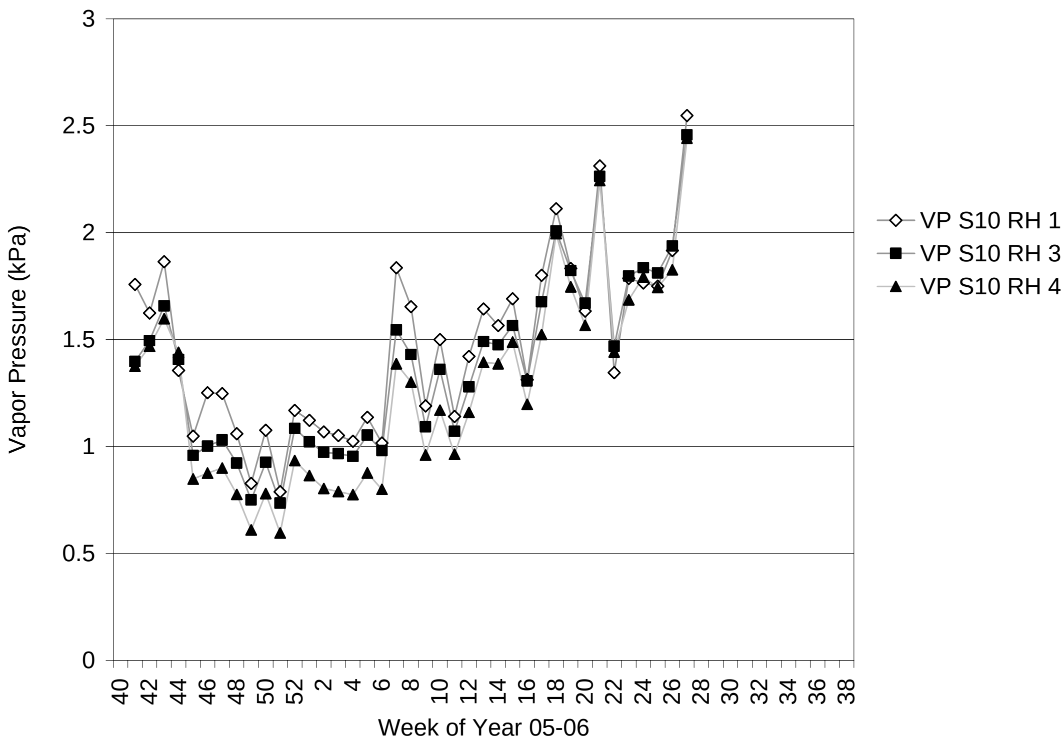


Figure C S10b-1 **S10b – Wood Moisture Content**

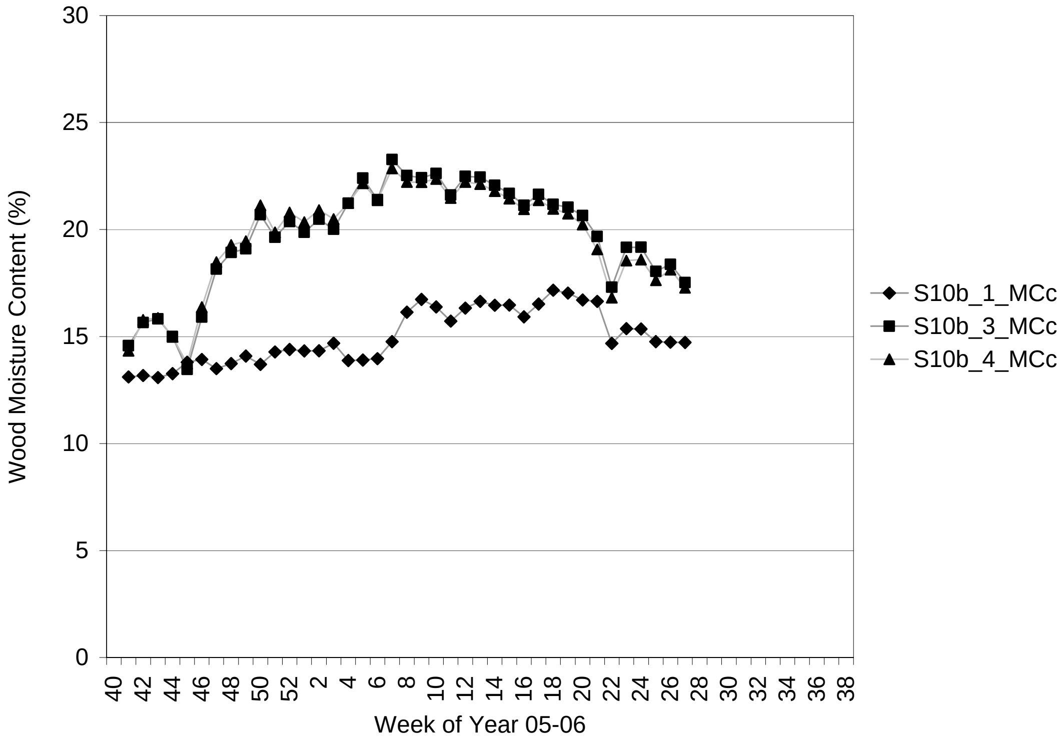


Figure C S10b-2 **S10b – Cavity Relative Humidity**

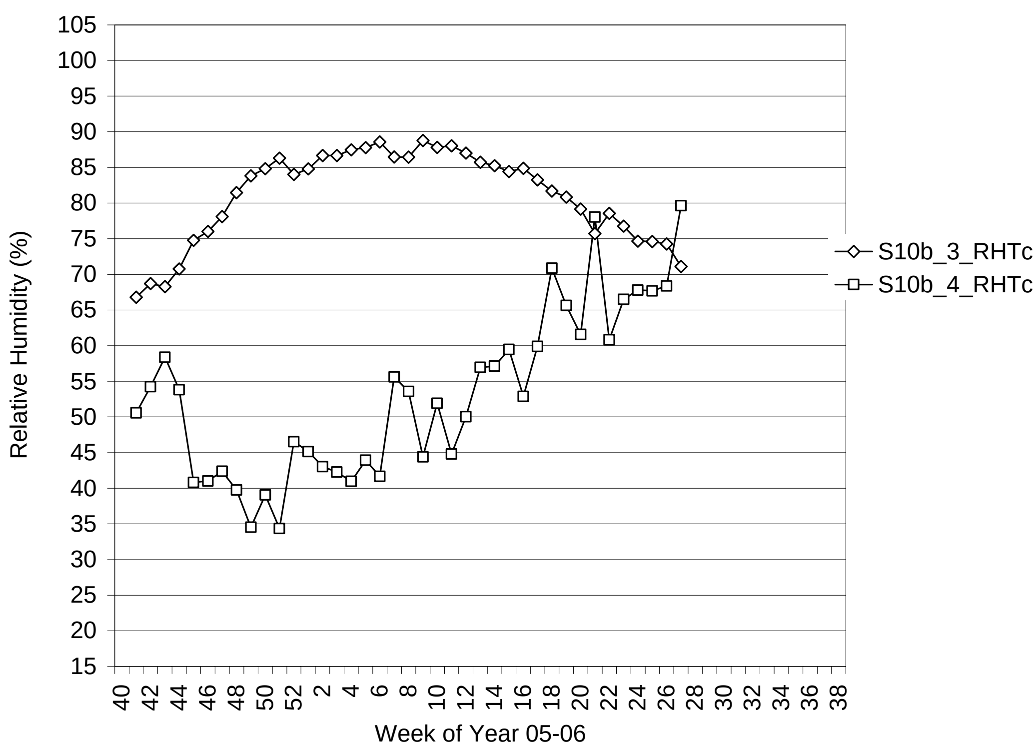


Figure C S10b-3 **S10b - Temperature**

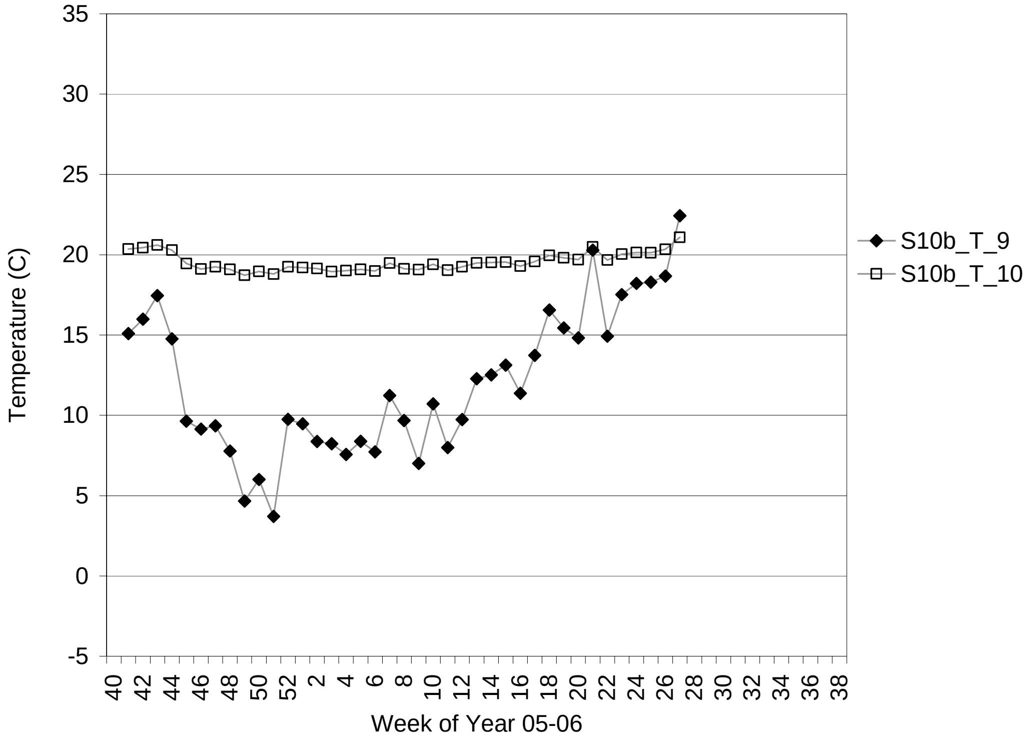


Figure C S10b-4 **S10b – Vapor Pressure**

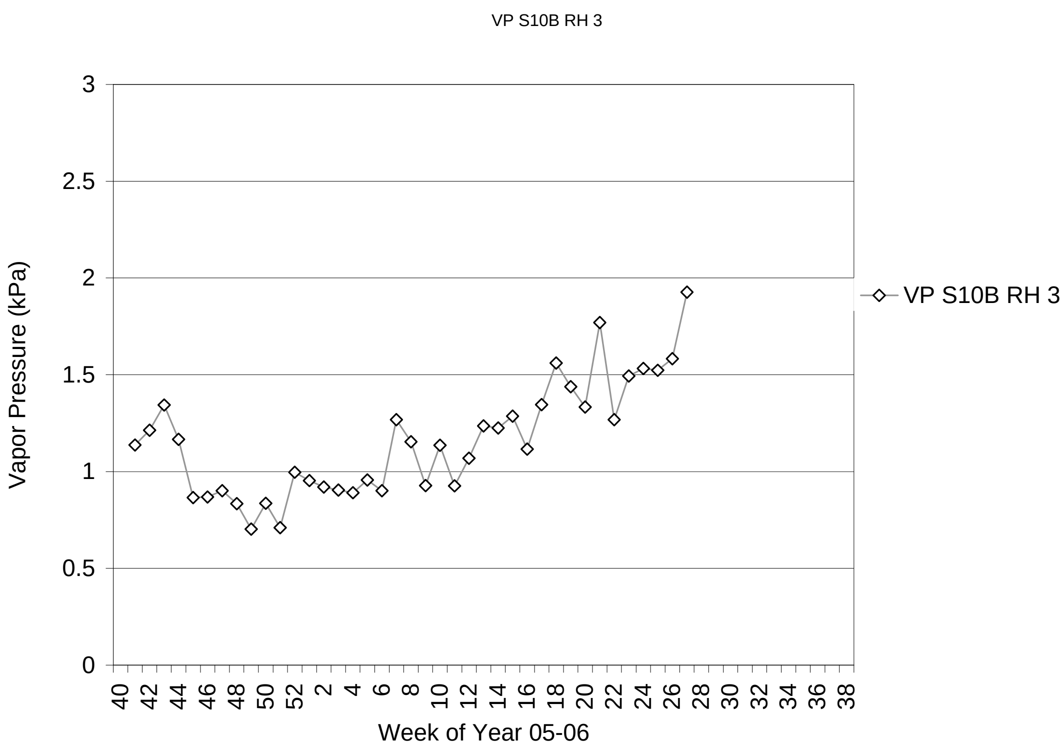


Figure C S11-1 **S11 – Wood Moisture Content**

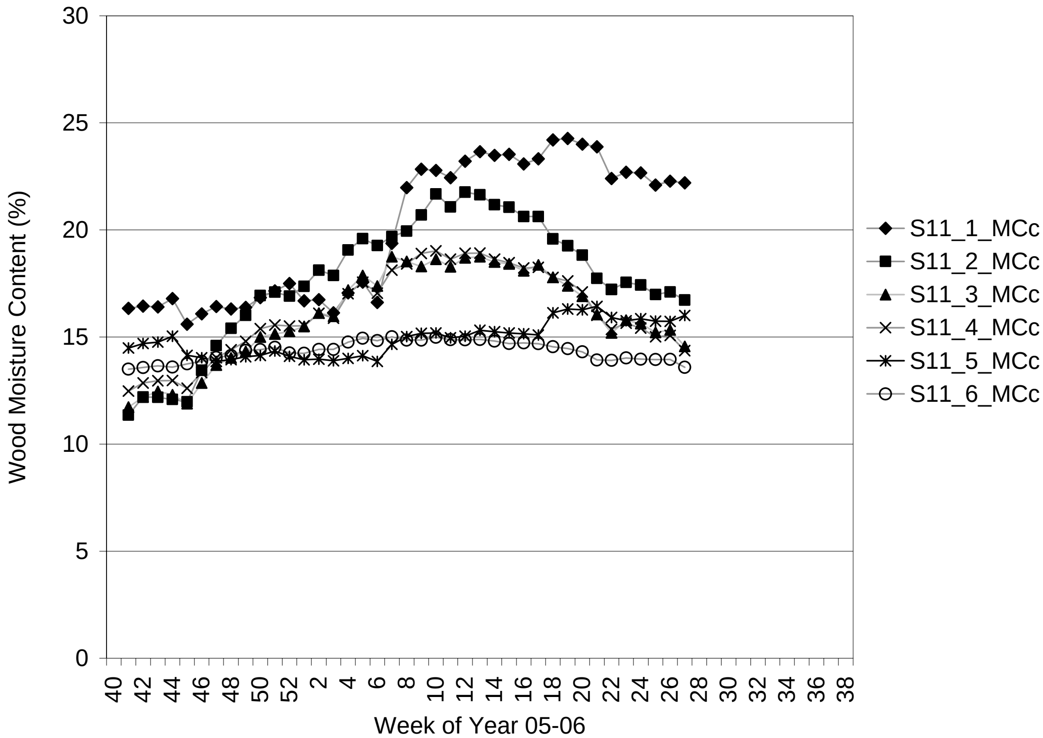


Figure C S11-2 **S11 – Cavity Relative Humidity**

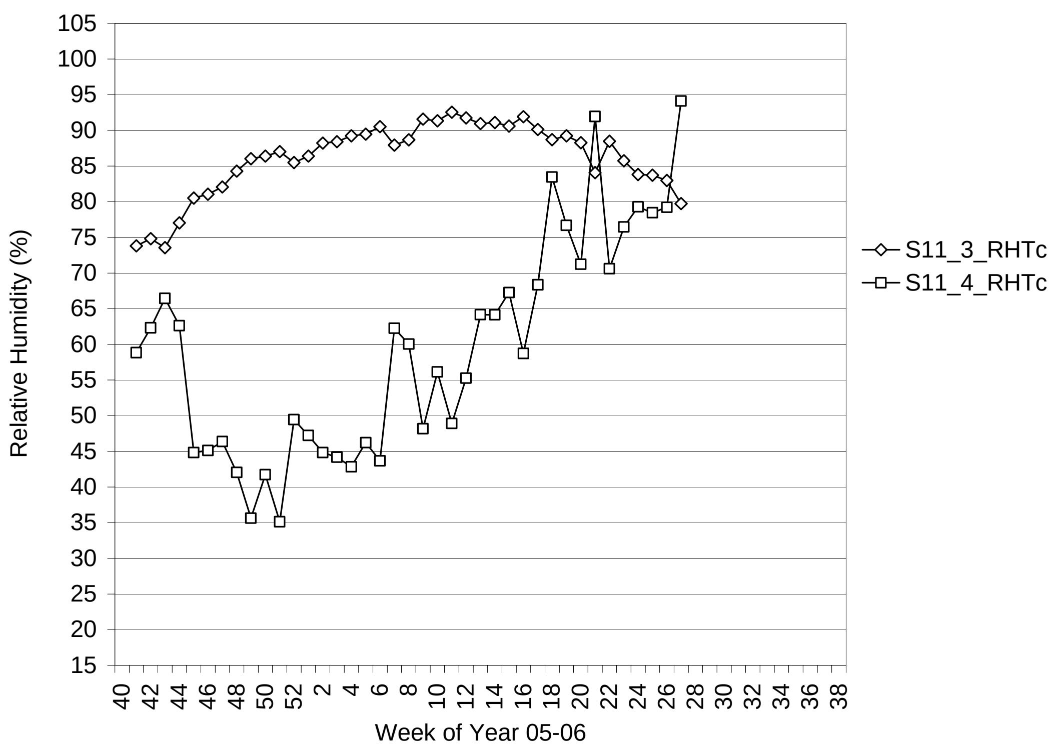


Figure C S11-3 **S11 - Temperature**

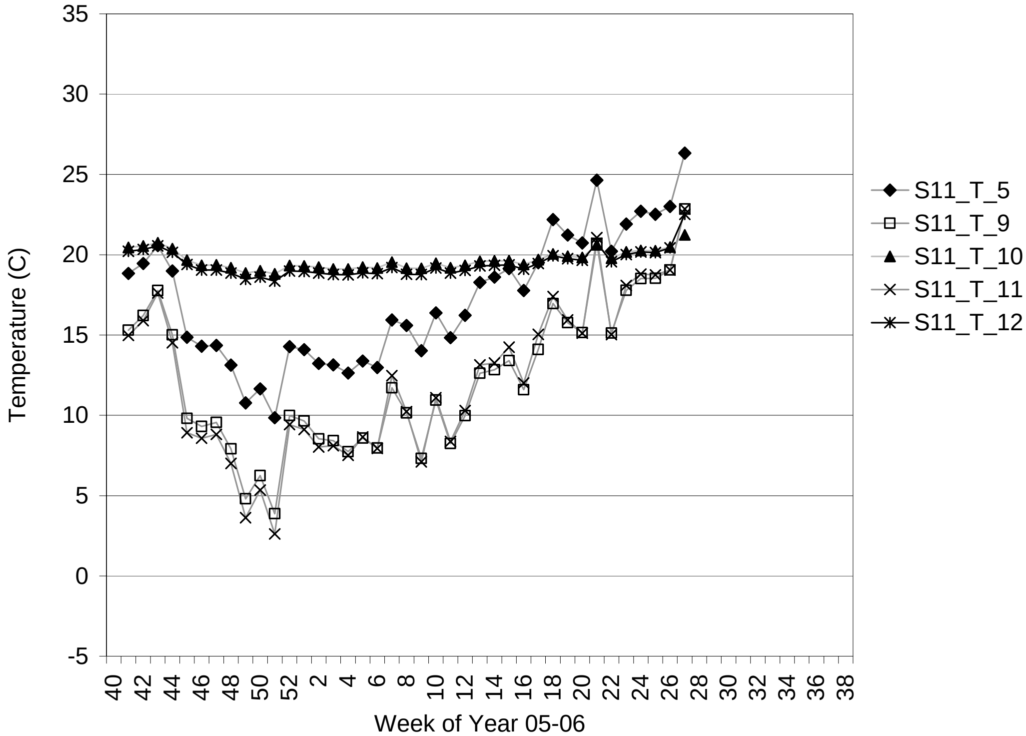


Figure C S11-4 **S11 – Vapor Pressure**

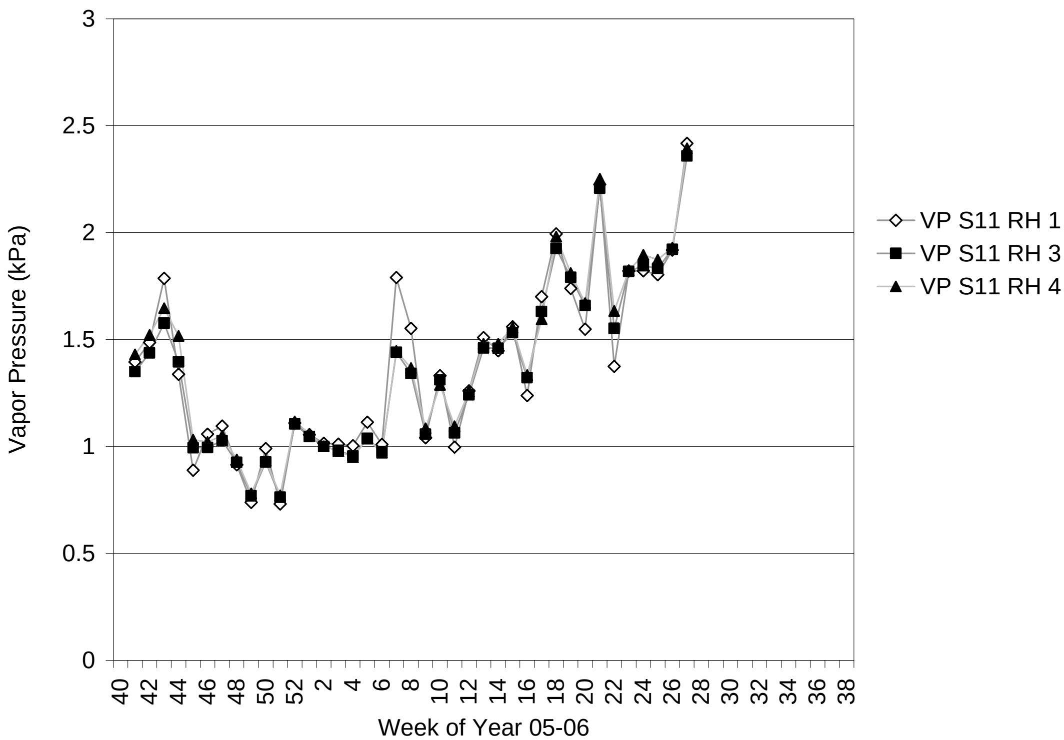


Figure C S11-1 **S12 – Wood Moisture Content**

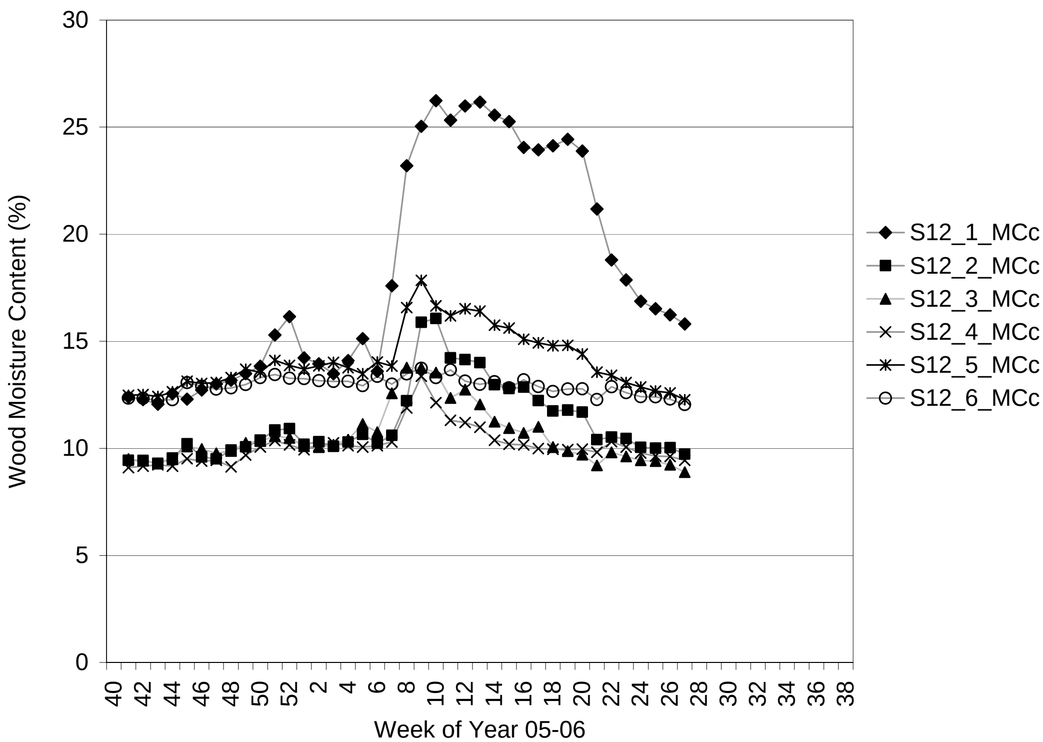


Figure C S11-2 **S12 – Cavity Relative Humidity**

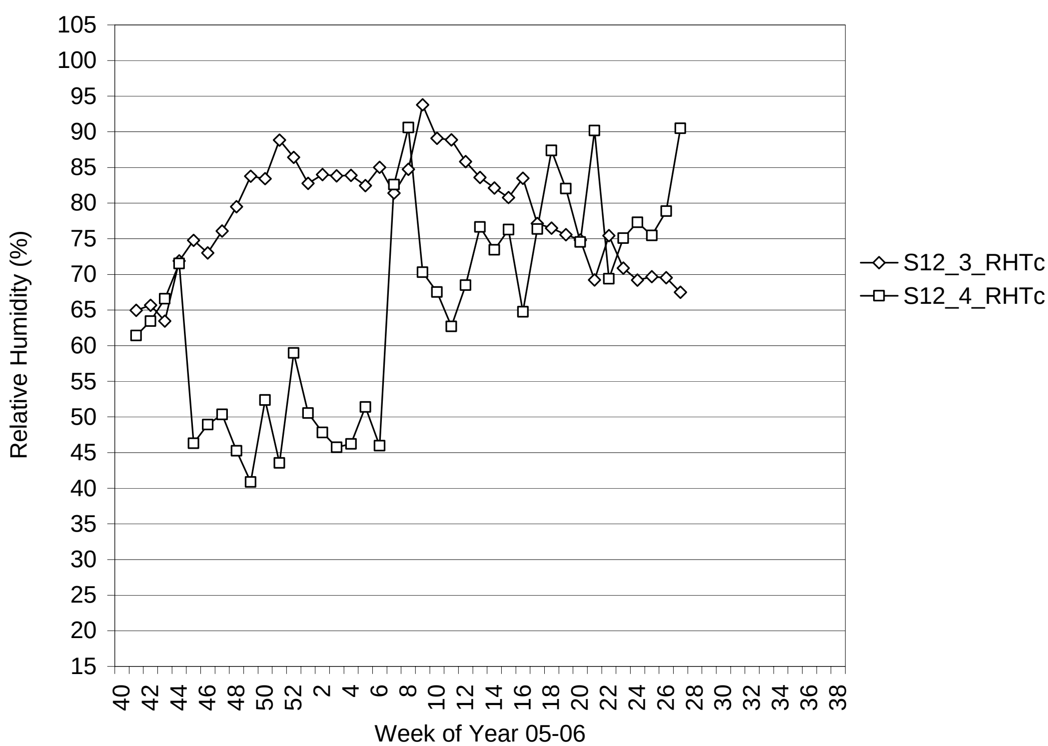


Figure C S11-3 **S12 - Temperature**

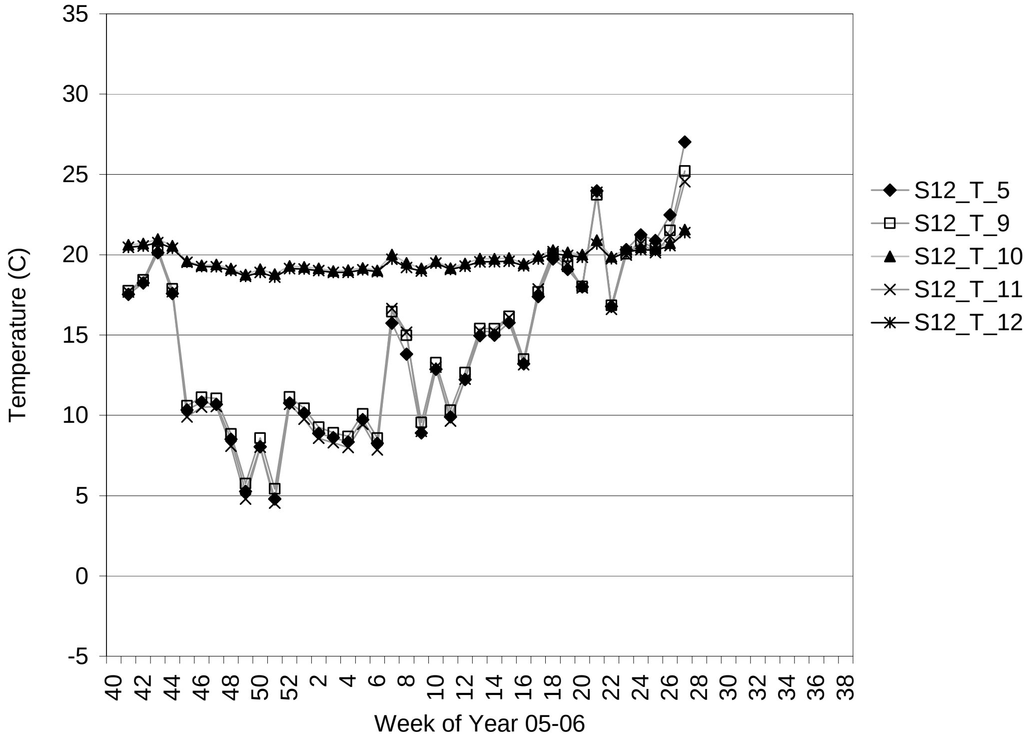


Figure C S11-4 **S12 – Vapor Pressure**

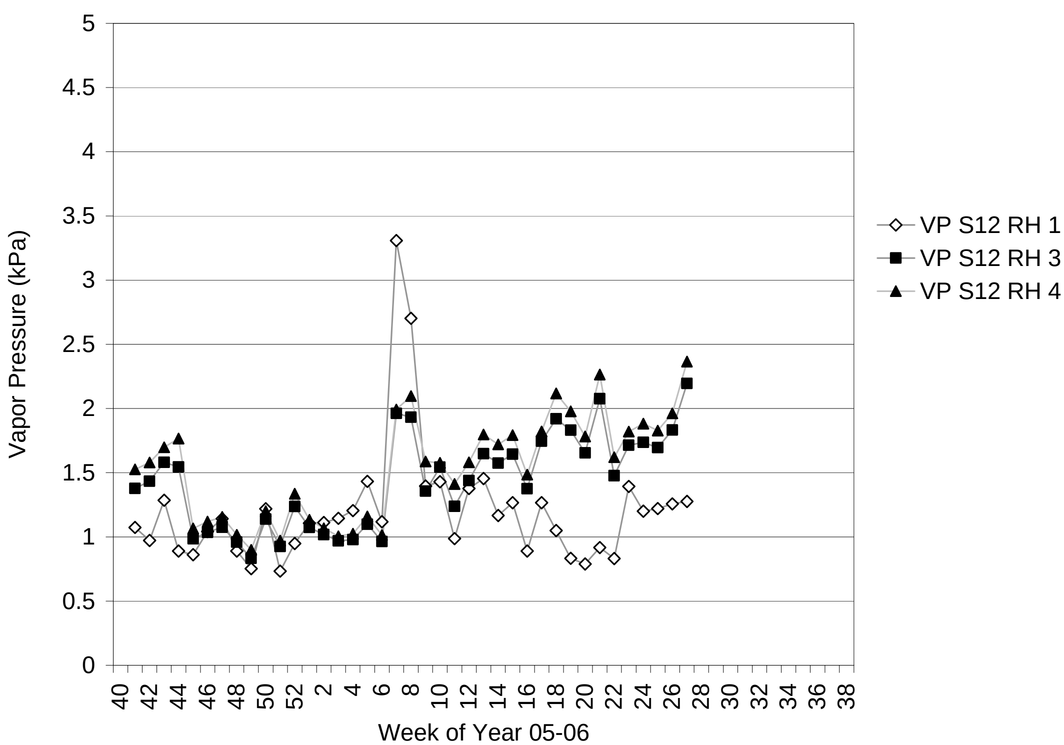


Figure C N3-1 **N3 – Wood Moisture Content**

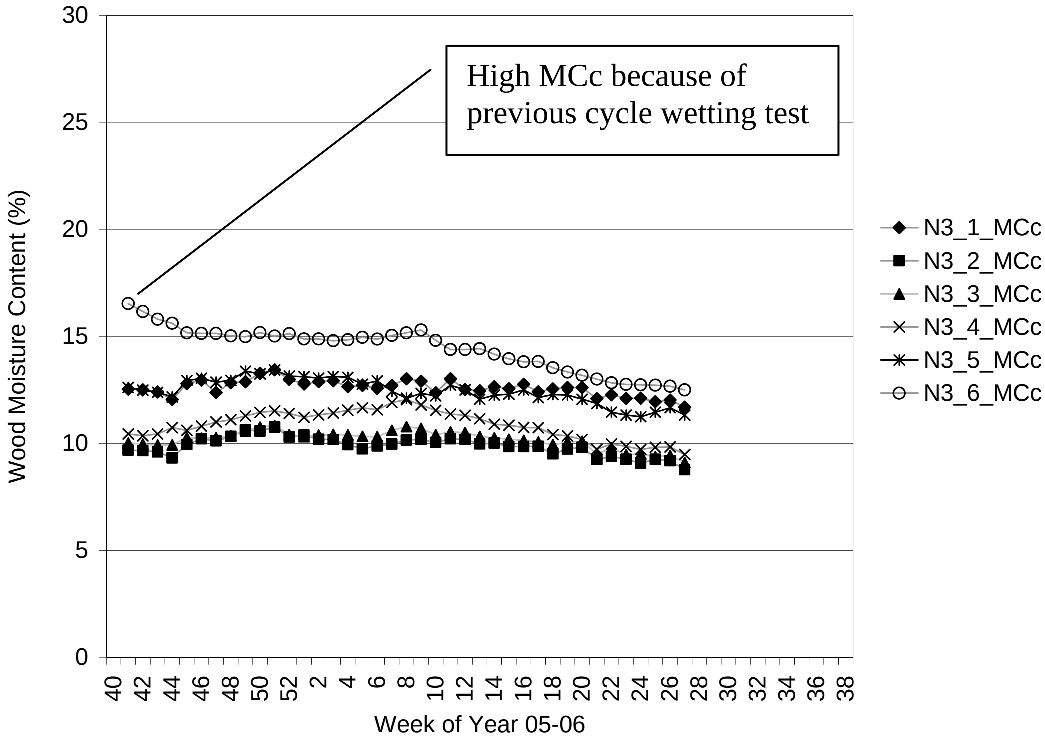


Figure C N3-2 **N3 – Cavity Relative Humidity**

Figure C N3-3 **N3 - Temperature**

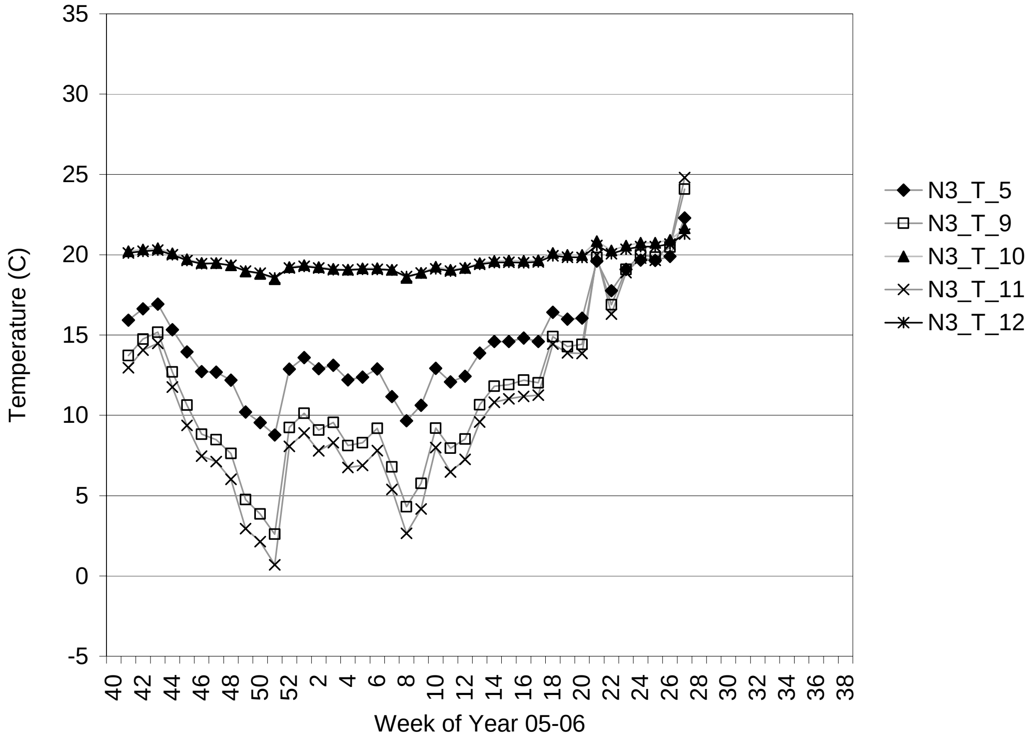


Figure C N3-4 **N3 – Vapor Pressure**

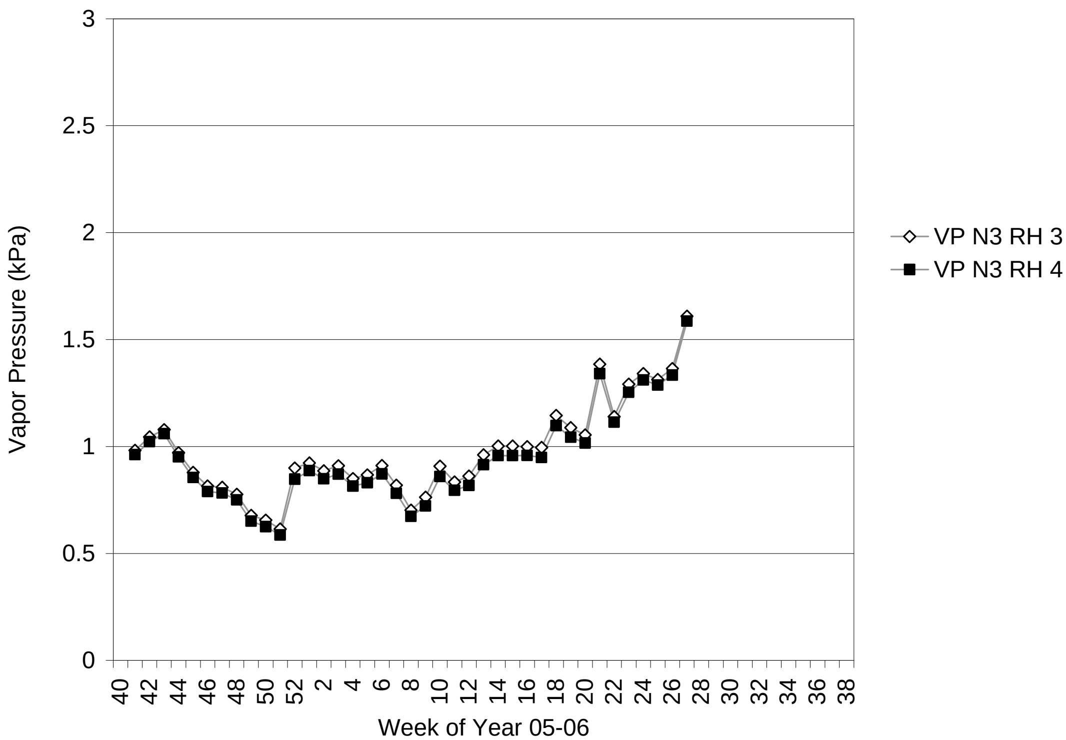


Figure C N4-1 **N4 – Wood Moisture Content**

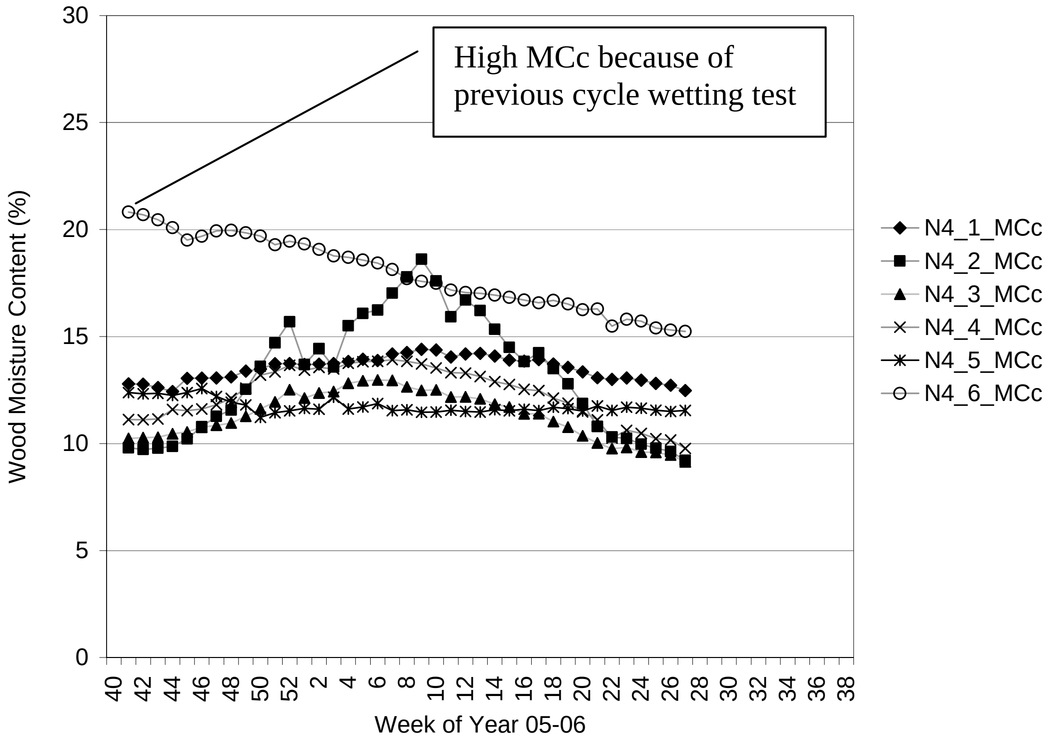


Figure C N4-2 **N4 – Cavity Relative Humidity**

Figure C N4-3 **N4 - Temperature**

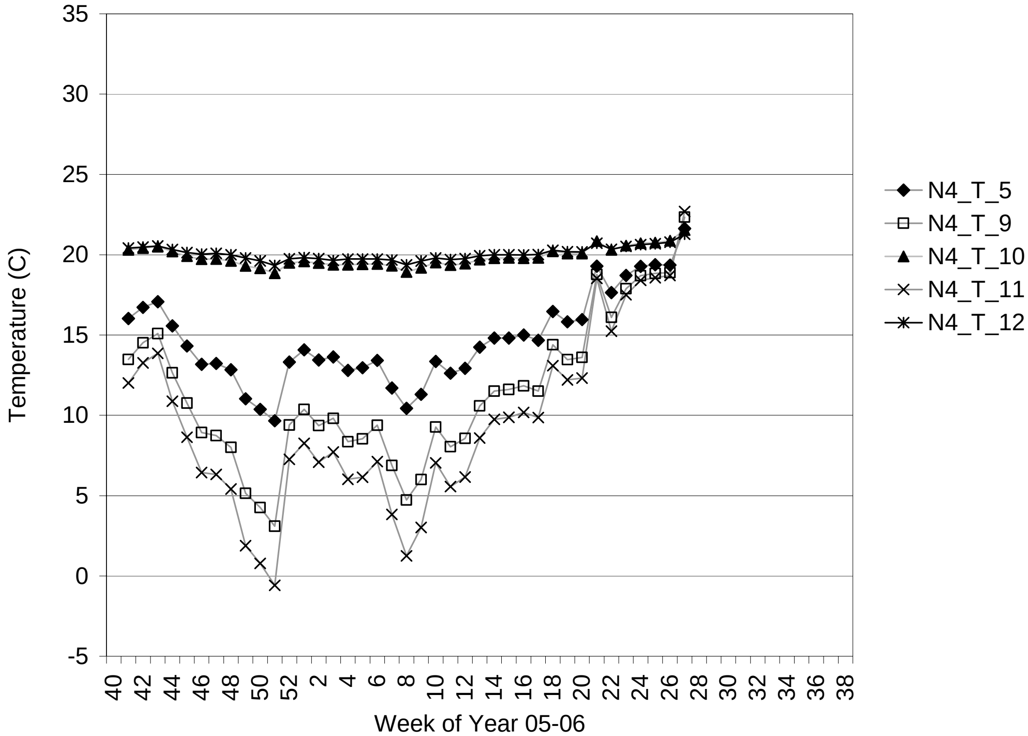


Figure C N4-4 **N4 – Vapor Pressure**

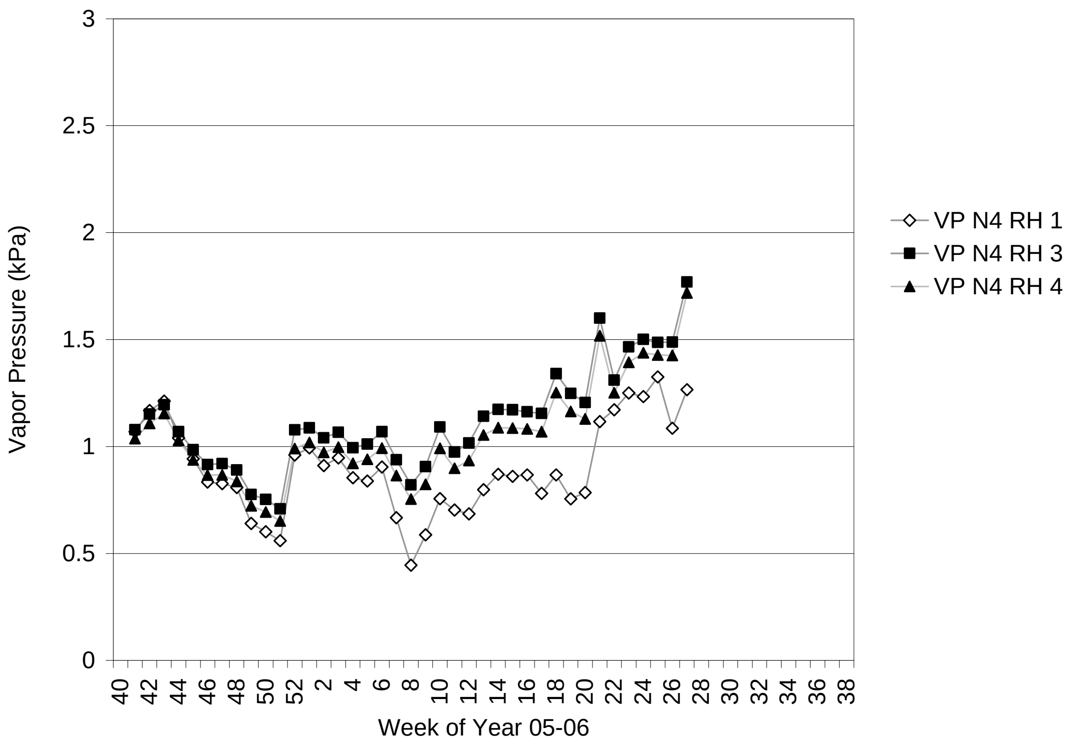


Figure C N5-1 **N5 – Wood Moisture Content**

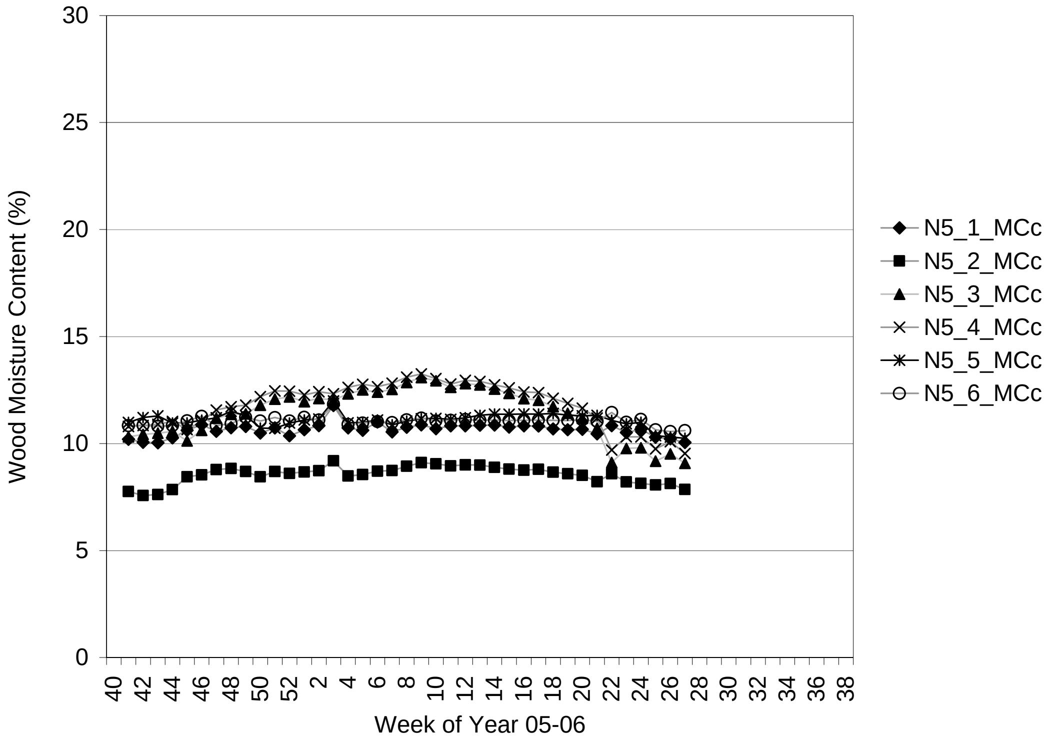


Figure C N5-2 **N5 – Cavity Relative Humidity**

Figure C N5-3 **N5 - Temperature**

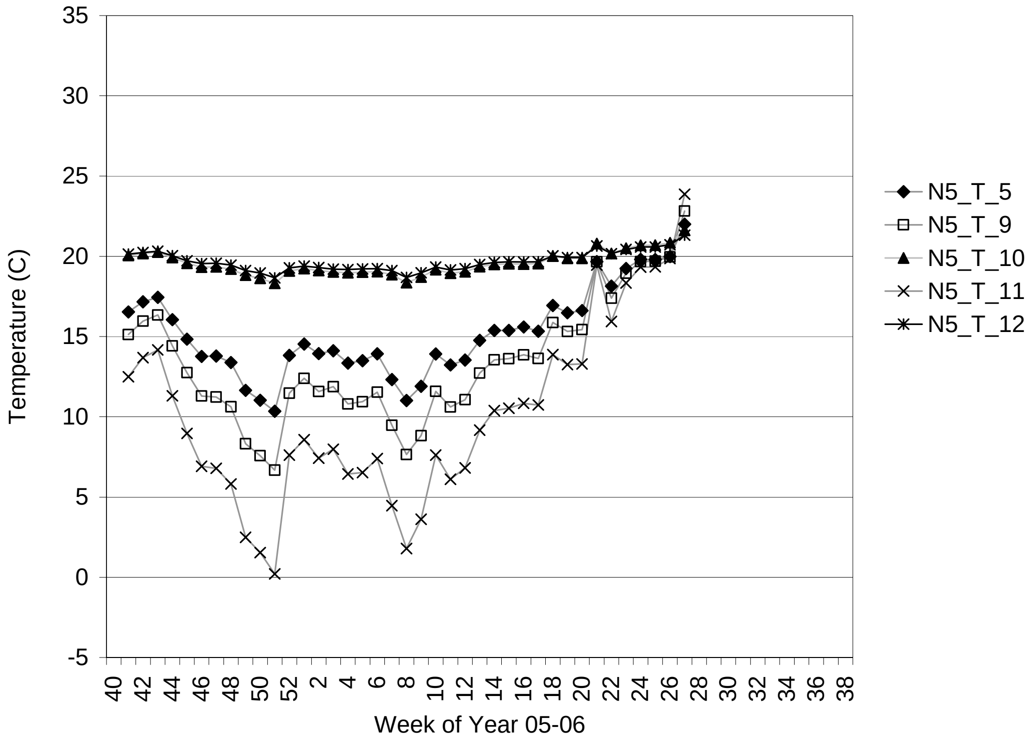


Figure C N5-4 **N5 – Vapor Pressure**

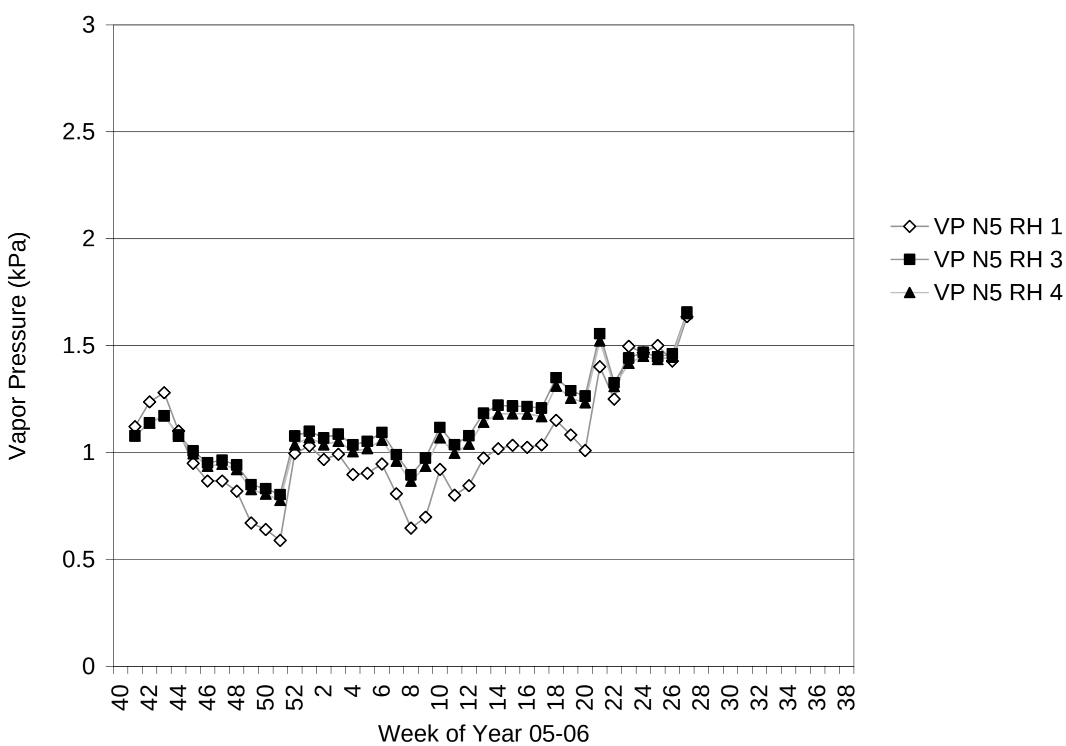


Figure C N6-1 N6 – Wood Moisture Content

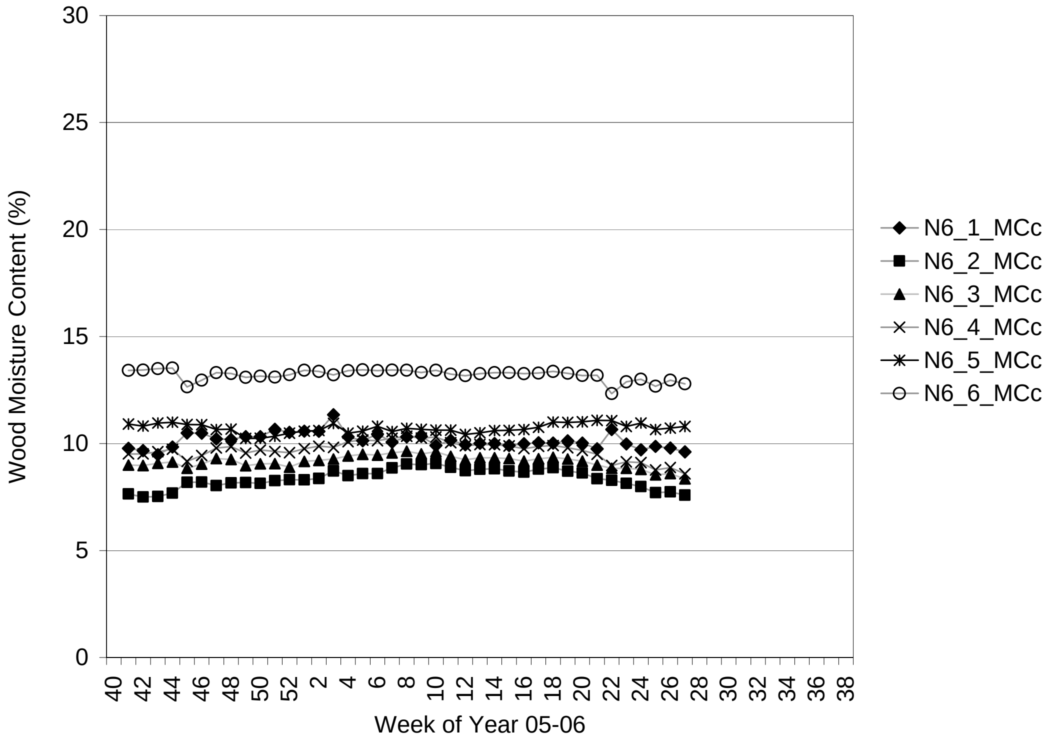


Figure C N6-2 N6 – Cavity Relative Humidity

Figure C N6-3 **N6 - Temperature**

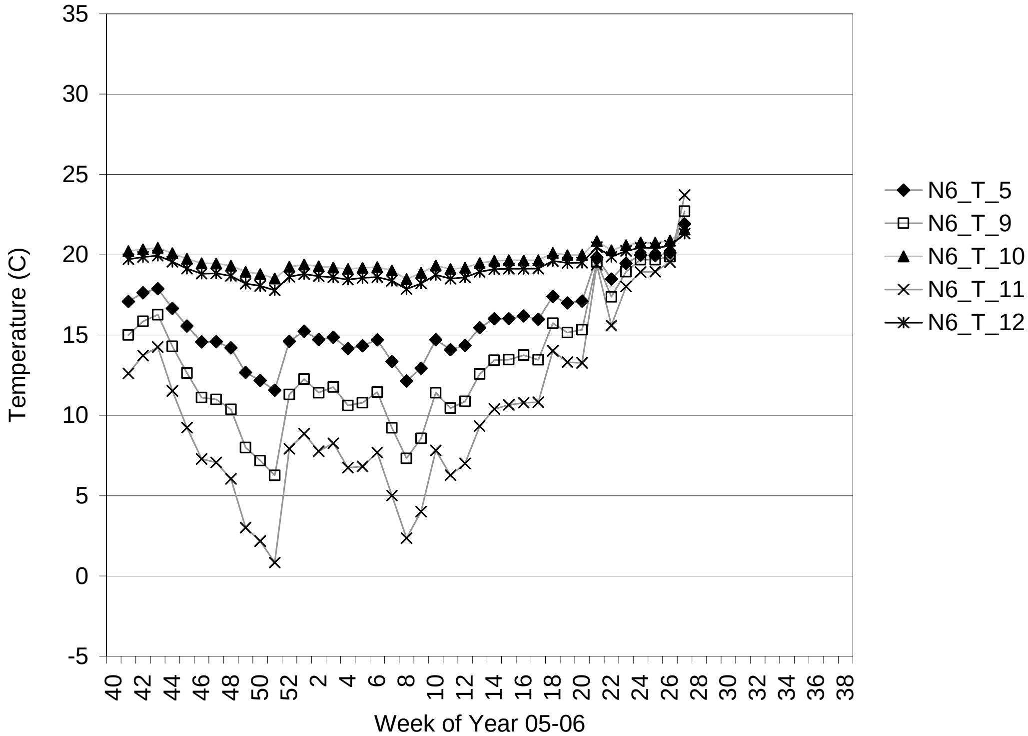


Figure C N6-4 **N6 – Vapor Pressure**

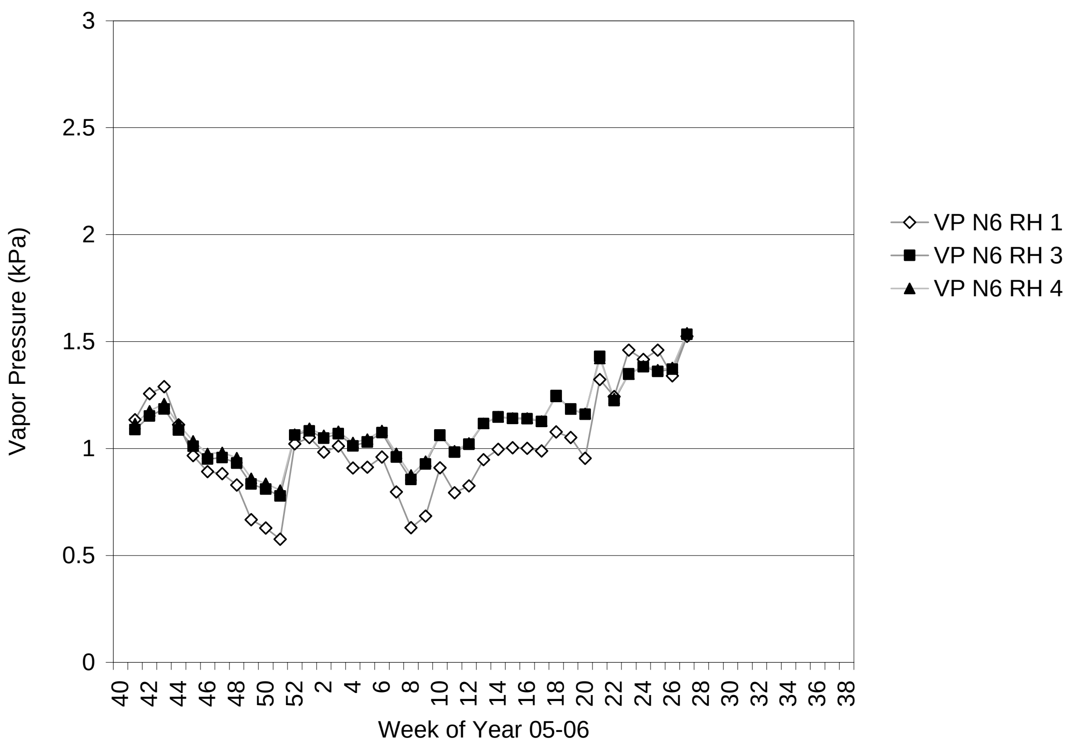


Figure C N7-1 **N7 – Wood Moisture Content**

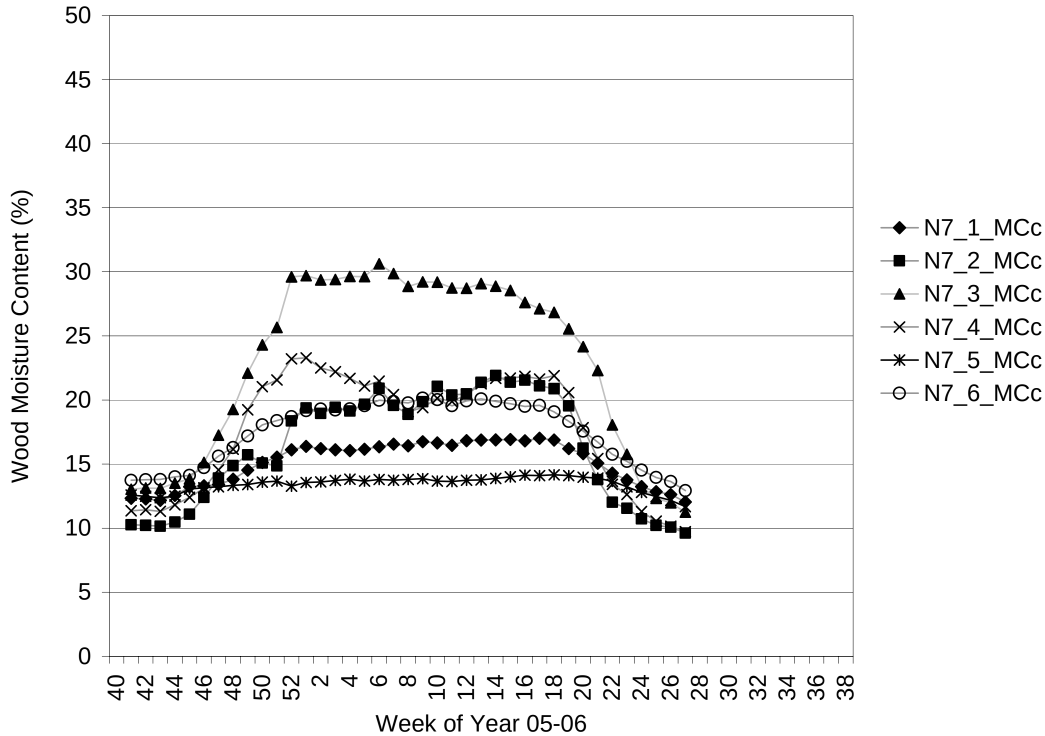


Figure C N7-2 **N7 – Cavity Relative Humidity**

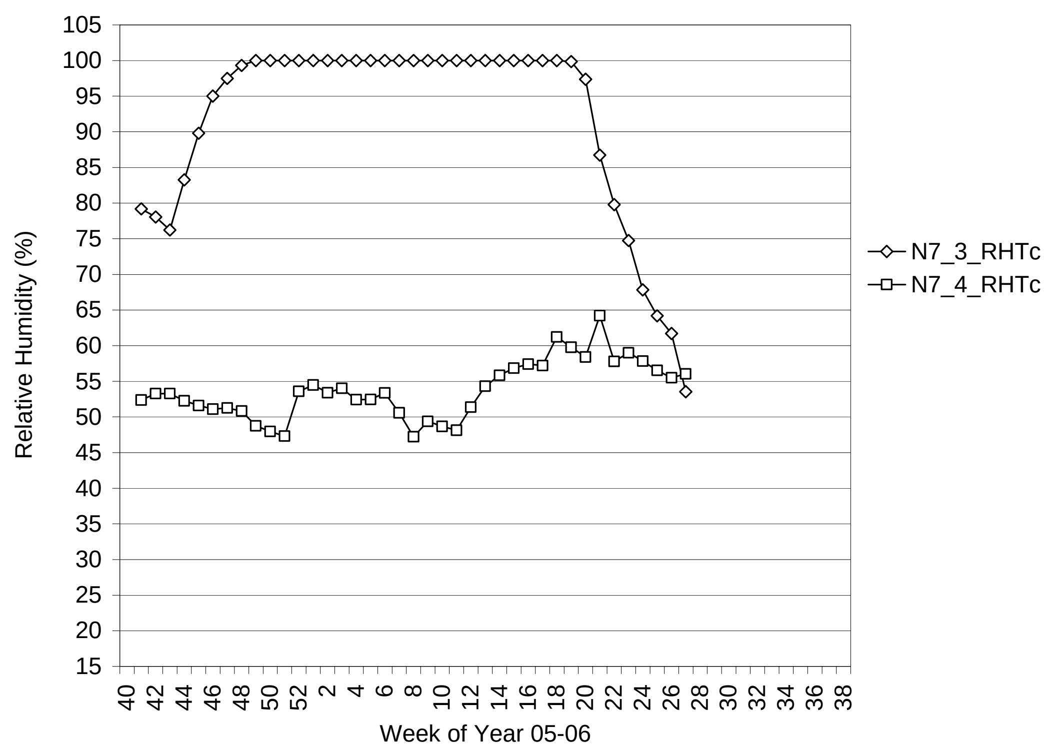


Figure C N7-3 **N7 - Temperature**

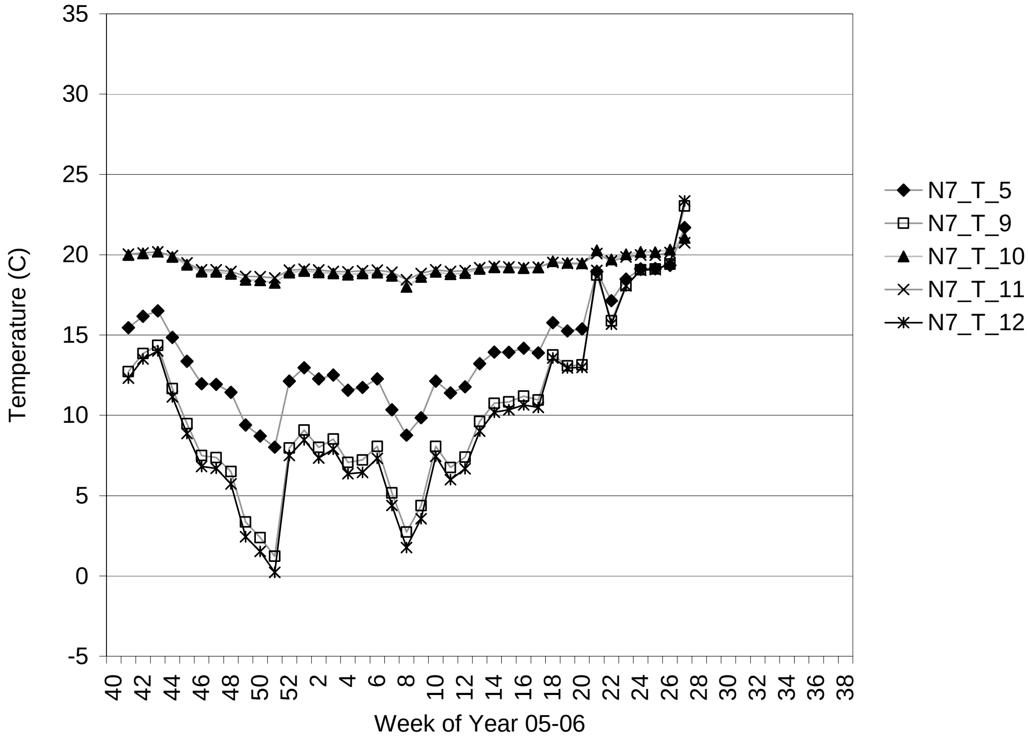


Figure C N7-4 **N7 – Vapor Pressure**

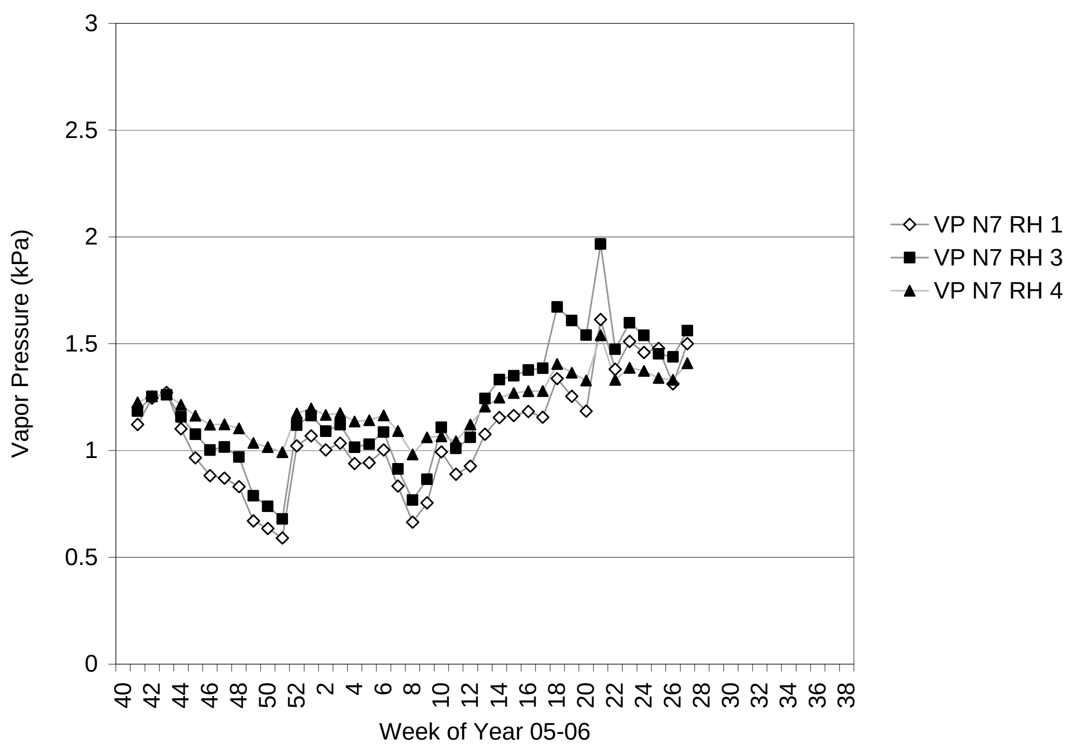


Figure C N81 **N8 – Wood Moisture Content**

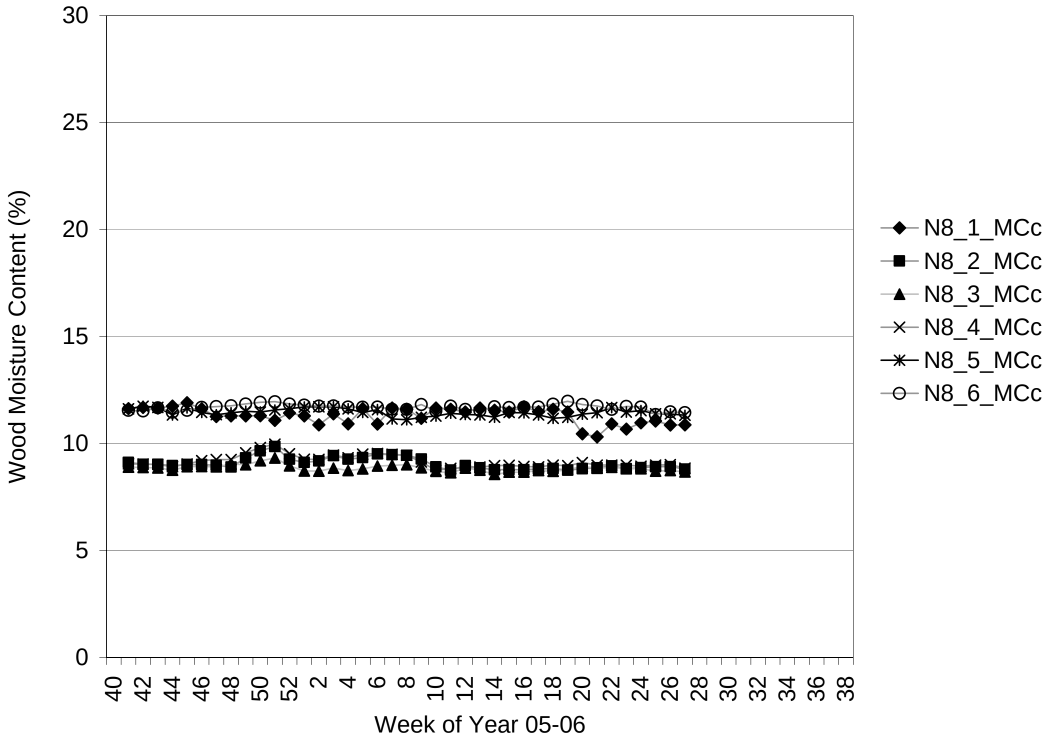


Figure C N8-2 **N8 – Cavity Relative Humidity**

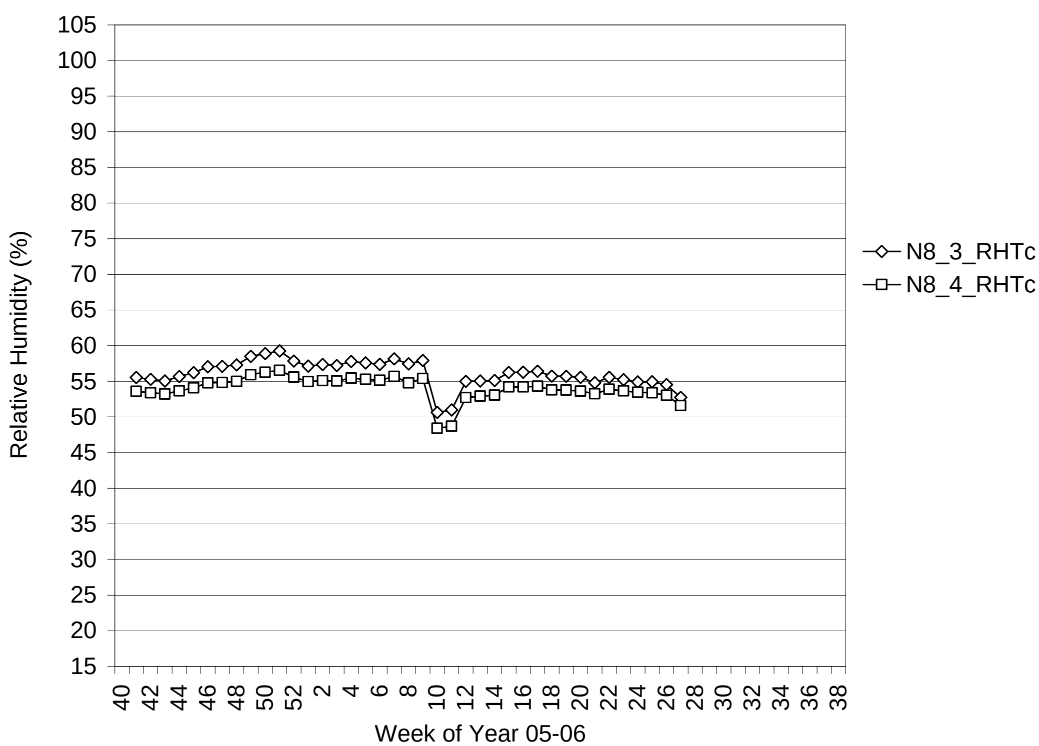


Figure C N8-3 **N8 - Temperature**

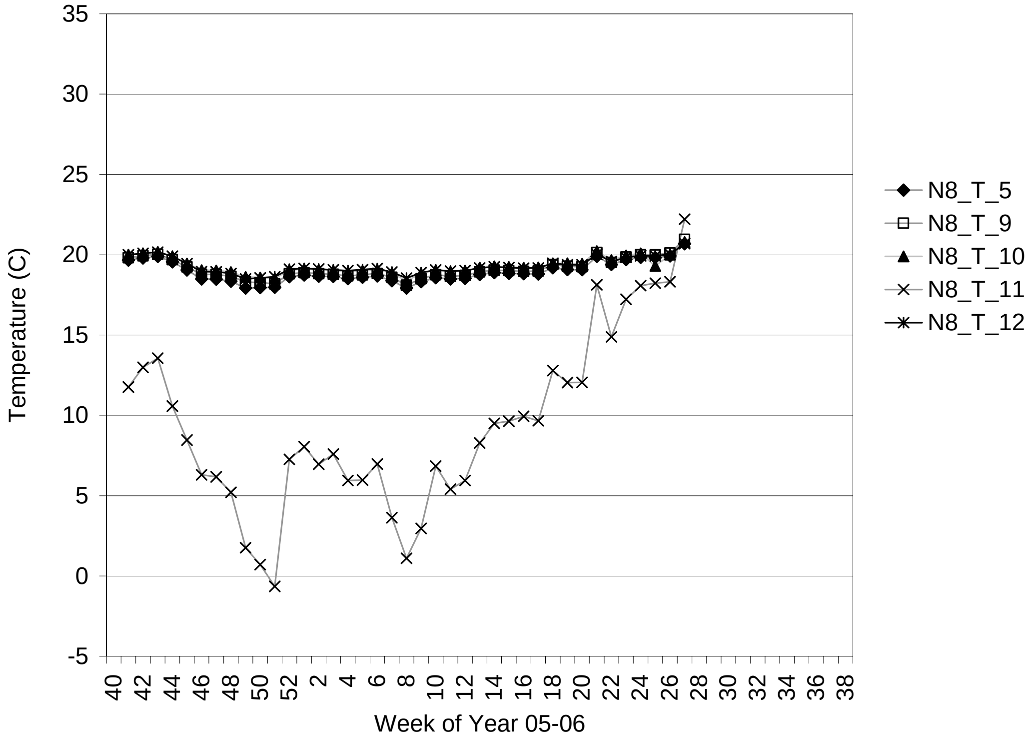
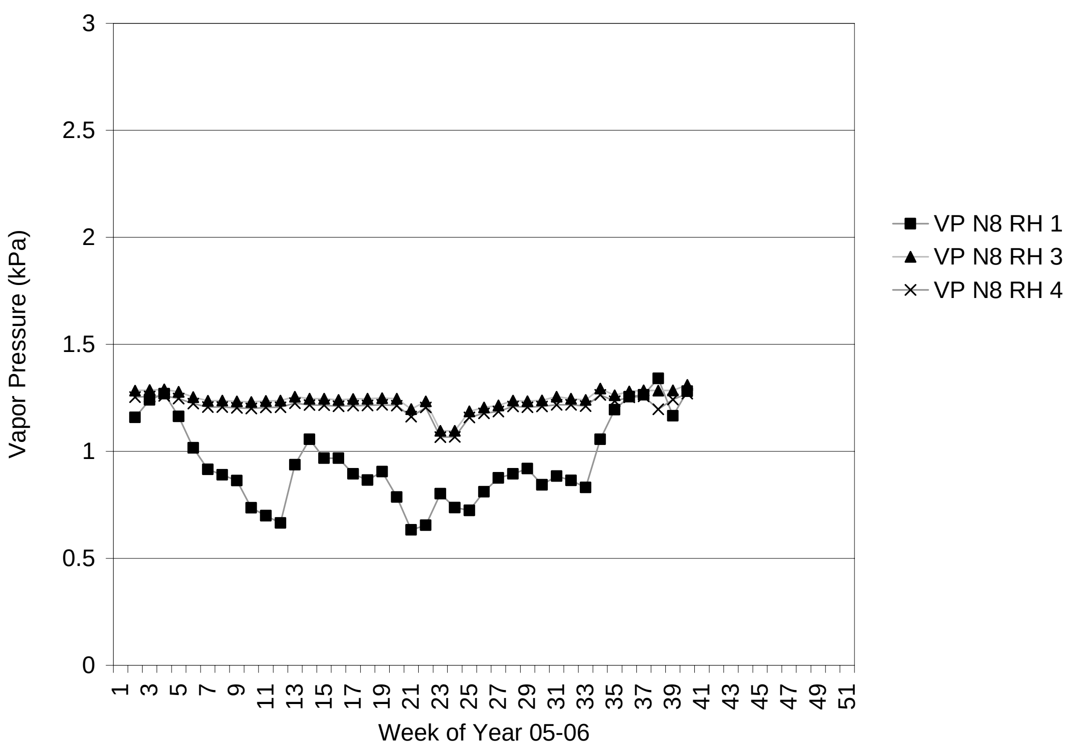


Figure C N8-4 **N8 – Vapor Pressure**



Appendix D

Indoor and Outdoor Environmental Conditions

October 2003 to June 2006

Figure D1 **Outdoor Temperature (C)**

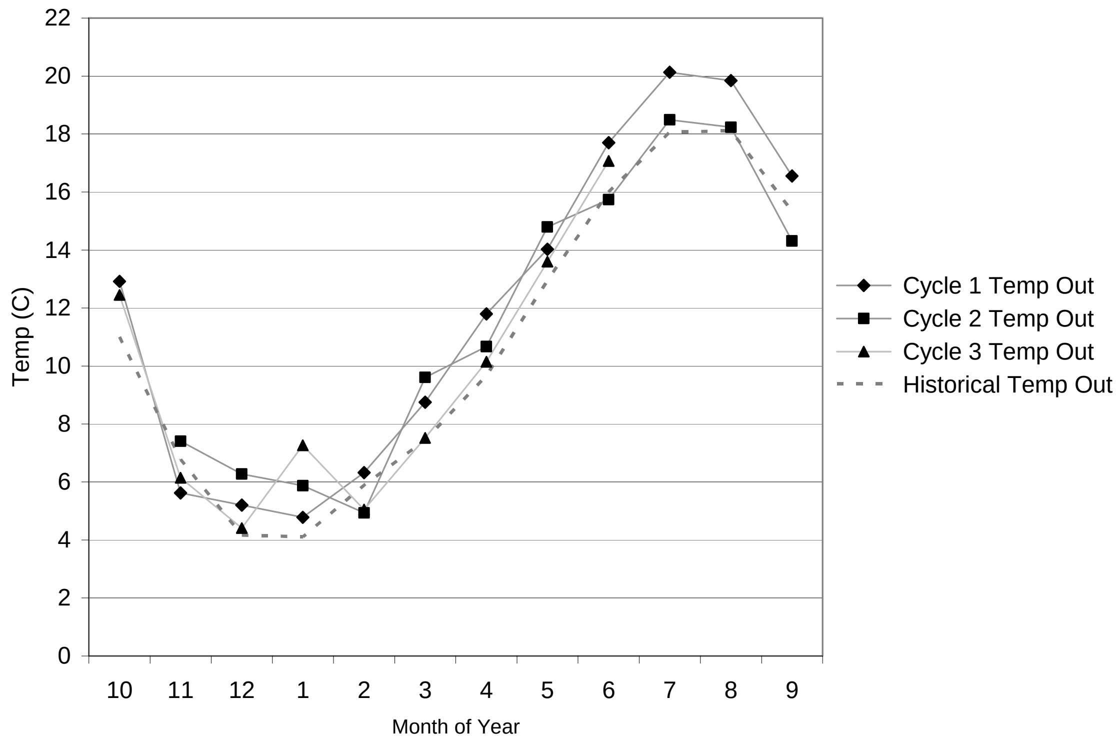


Figure D2 **Indoor Temperature (C)**

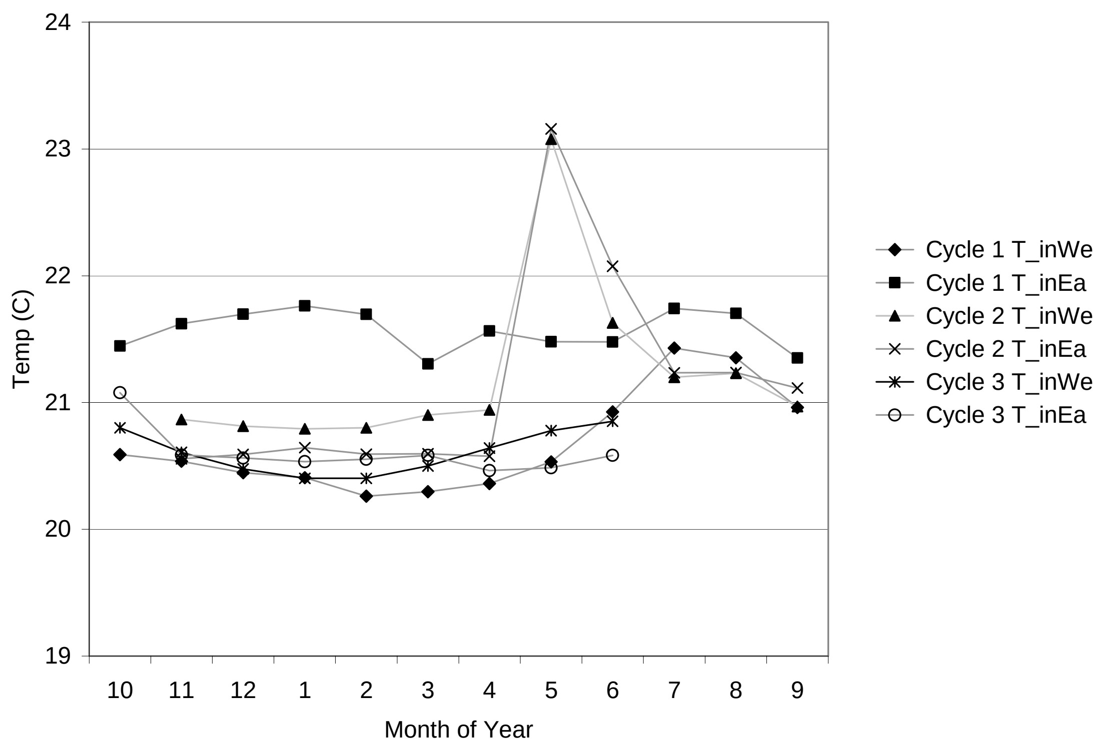


Figure D3 **Outdoor Relative Humidity (%)**

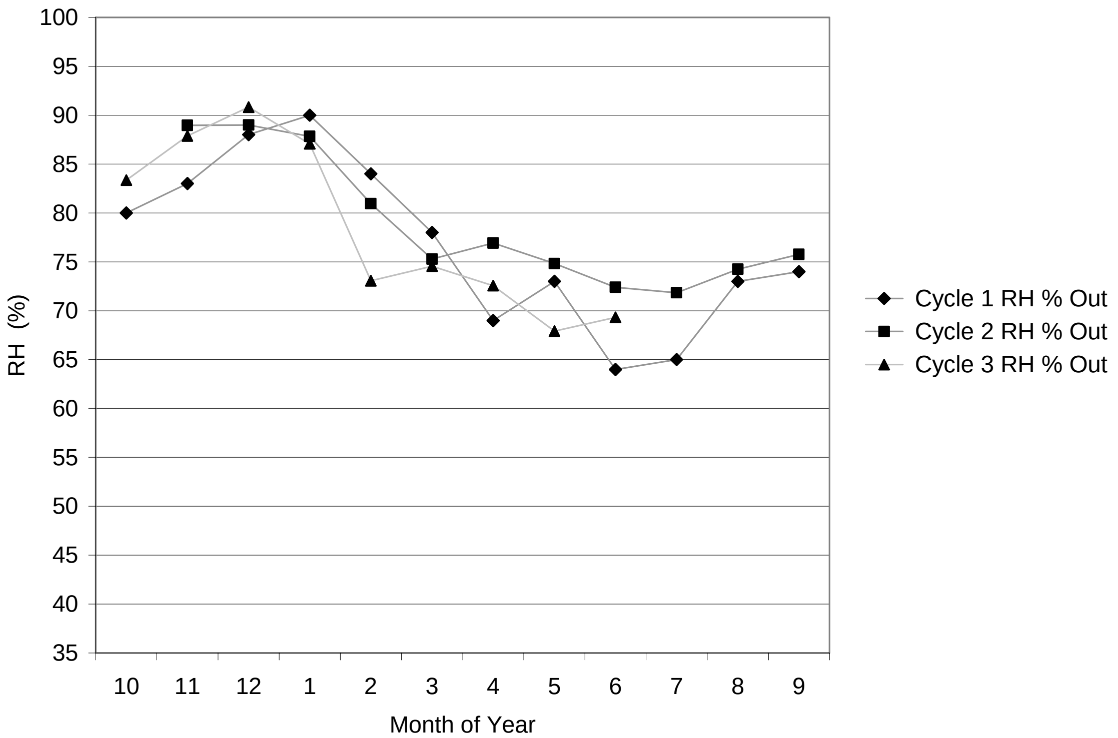


Figure D4 **Indoor Relative Humidity**

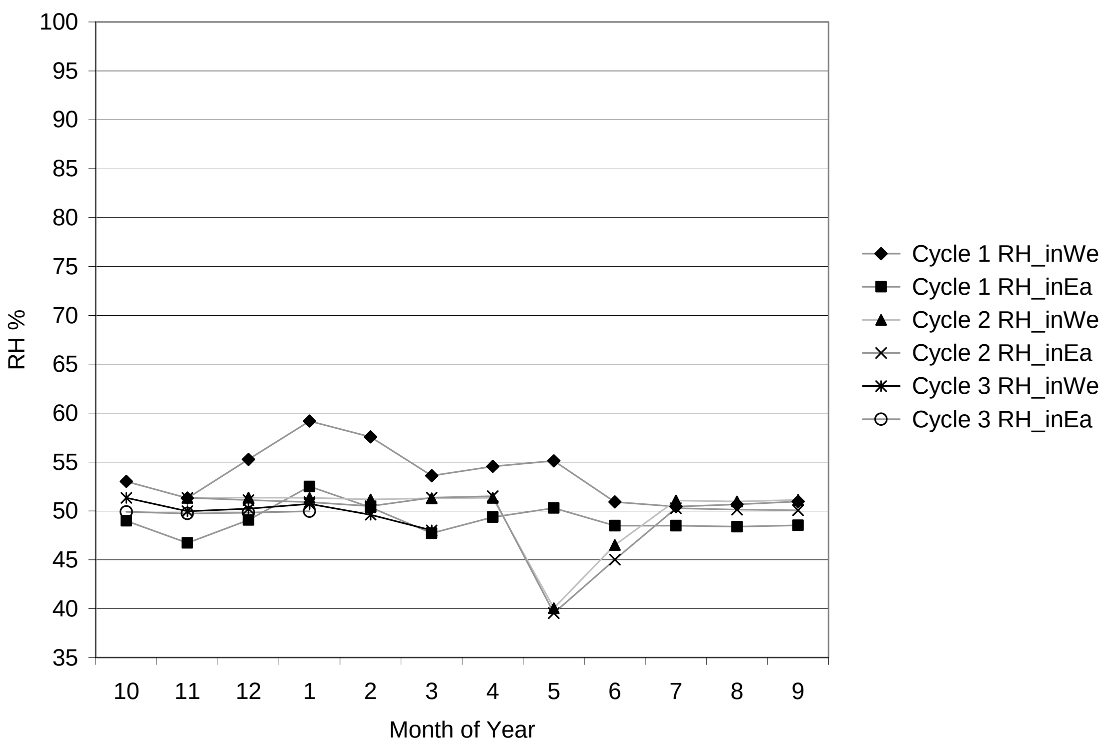


Figure D5 **Vapor Pressure Outdoors (kPA)**

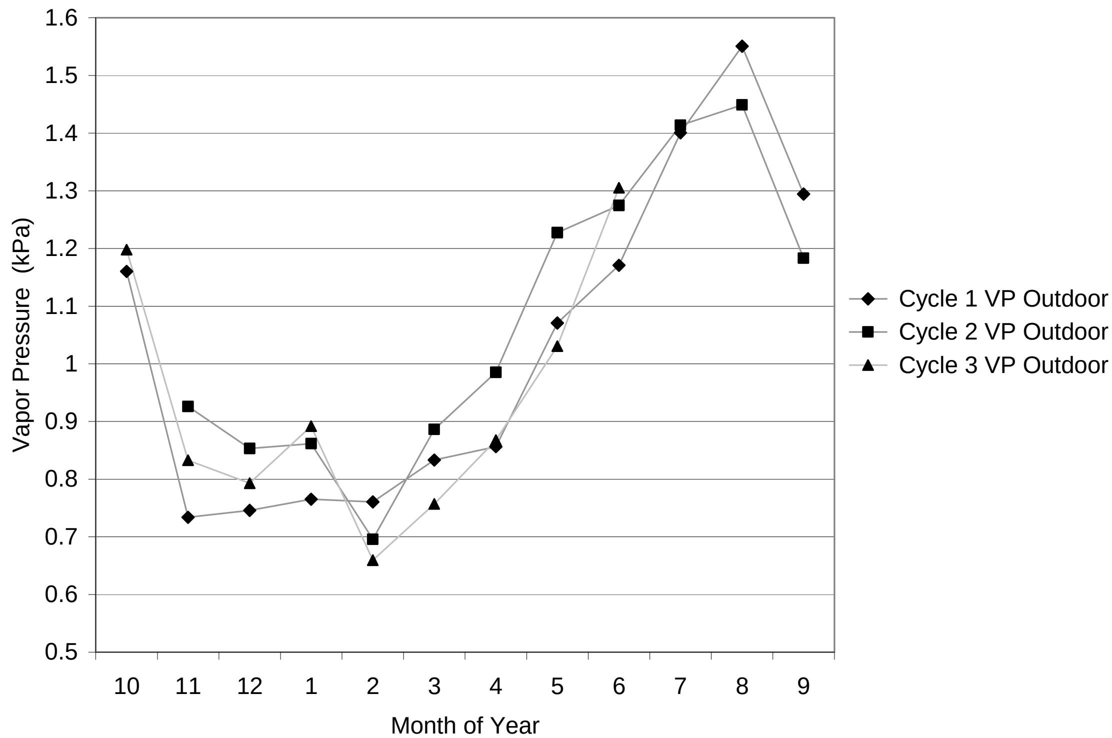


Figure D6 **Vapor Pressure Indoors (kPa)**

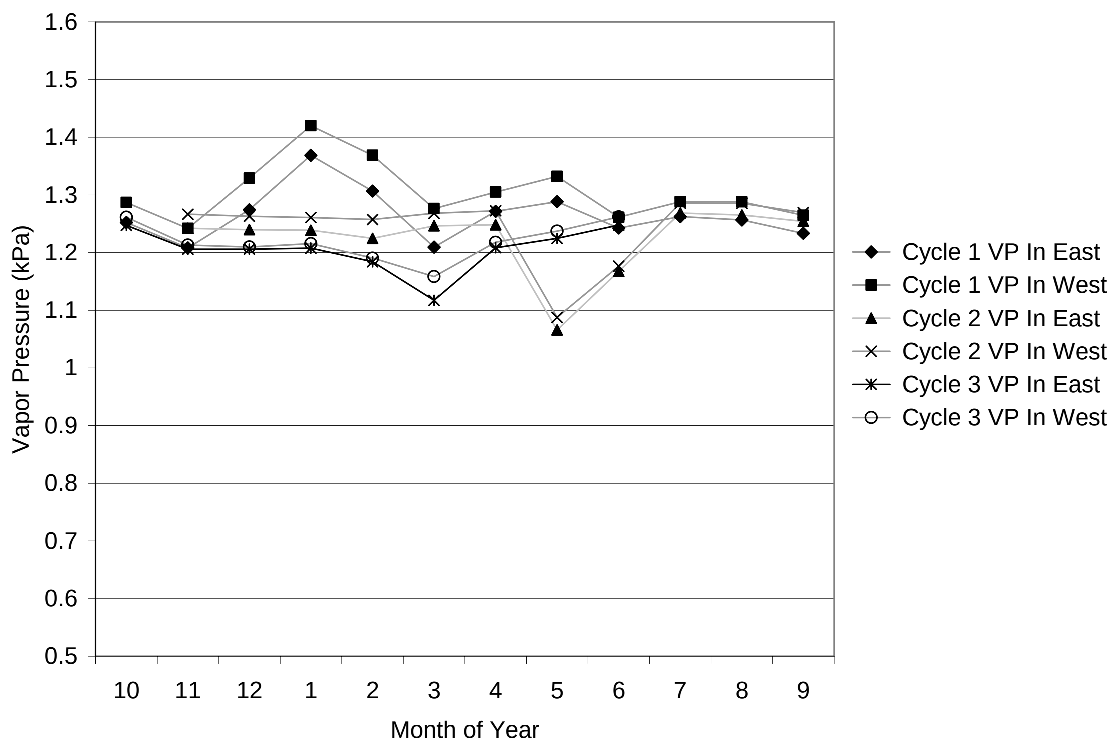


Figure D7 Vapor Pressure Difference (Outdoors – Indoors)

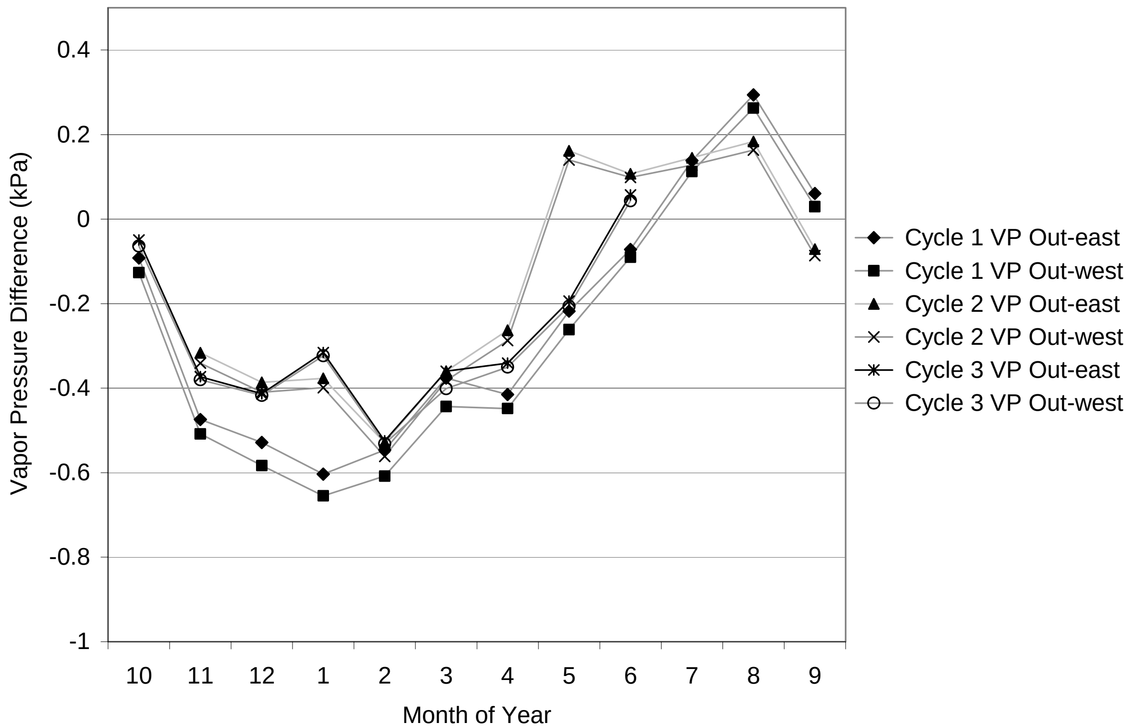


Figure D8 Sum of Precipitation

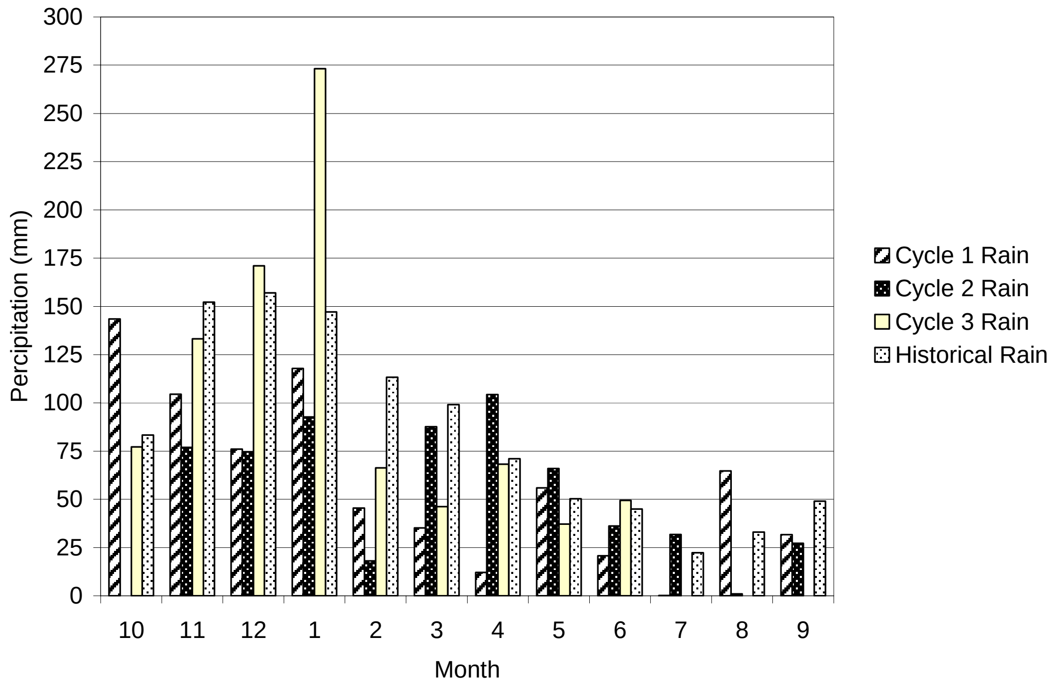


Figure D9 Cumulative Precipitation

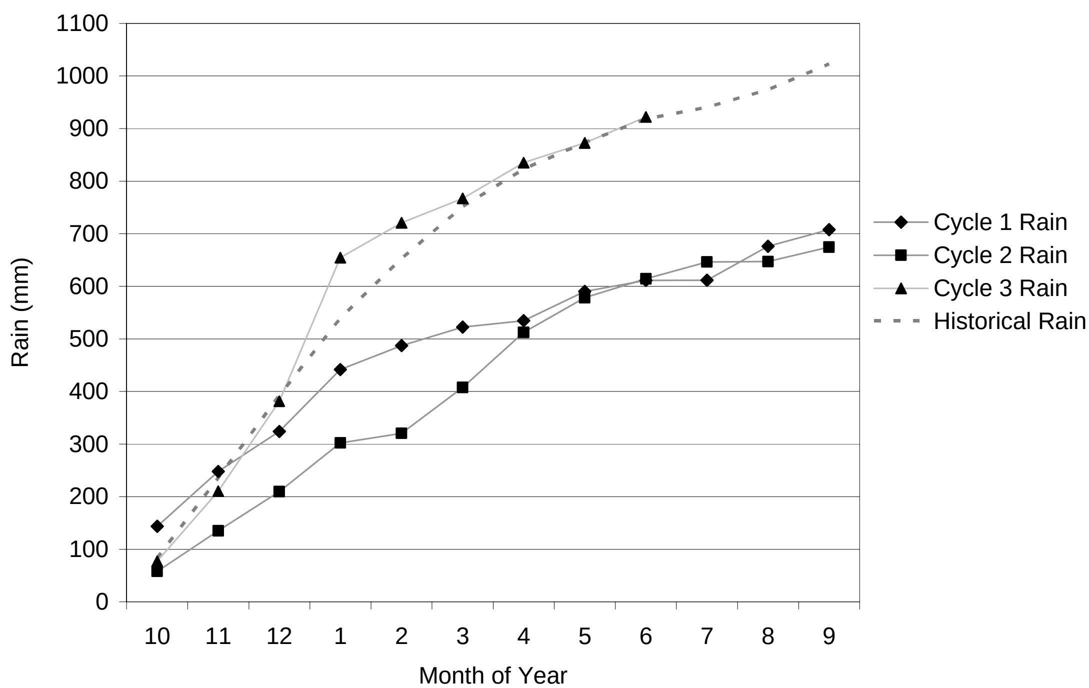


Figure D10 Sum of Vertical Solar Radiation (W/m2)

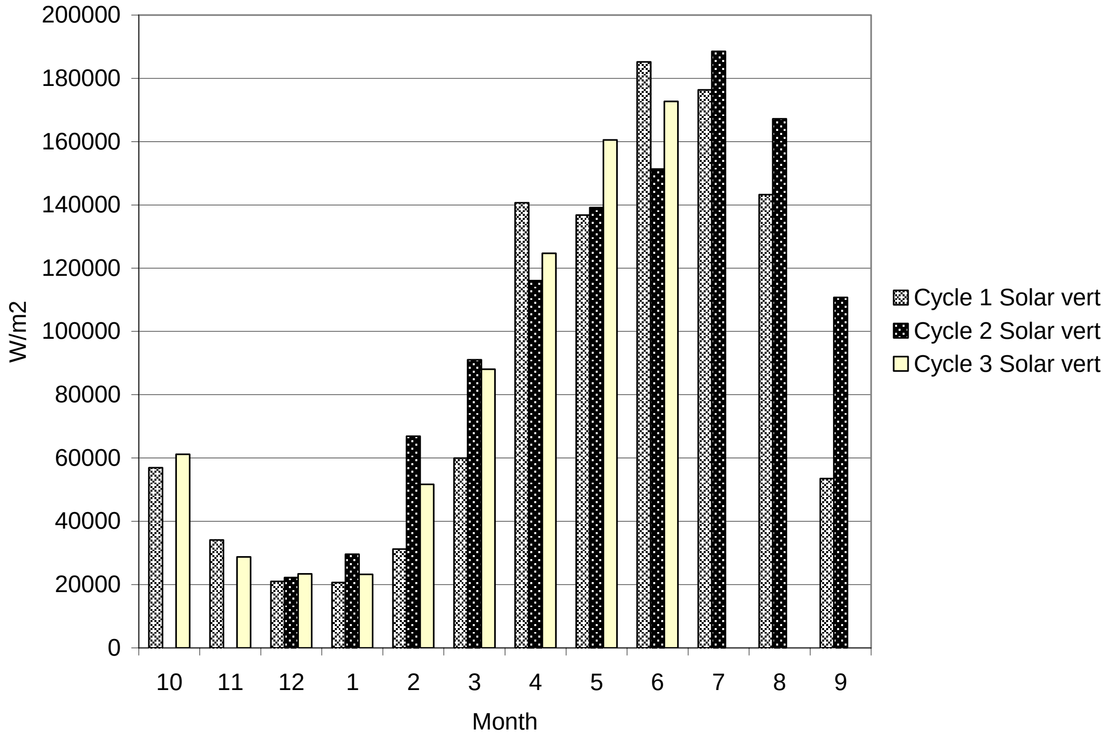


Figure D11 Sum of Horizontal Solar Radiation (W/m2)

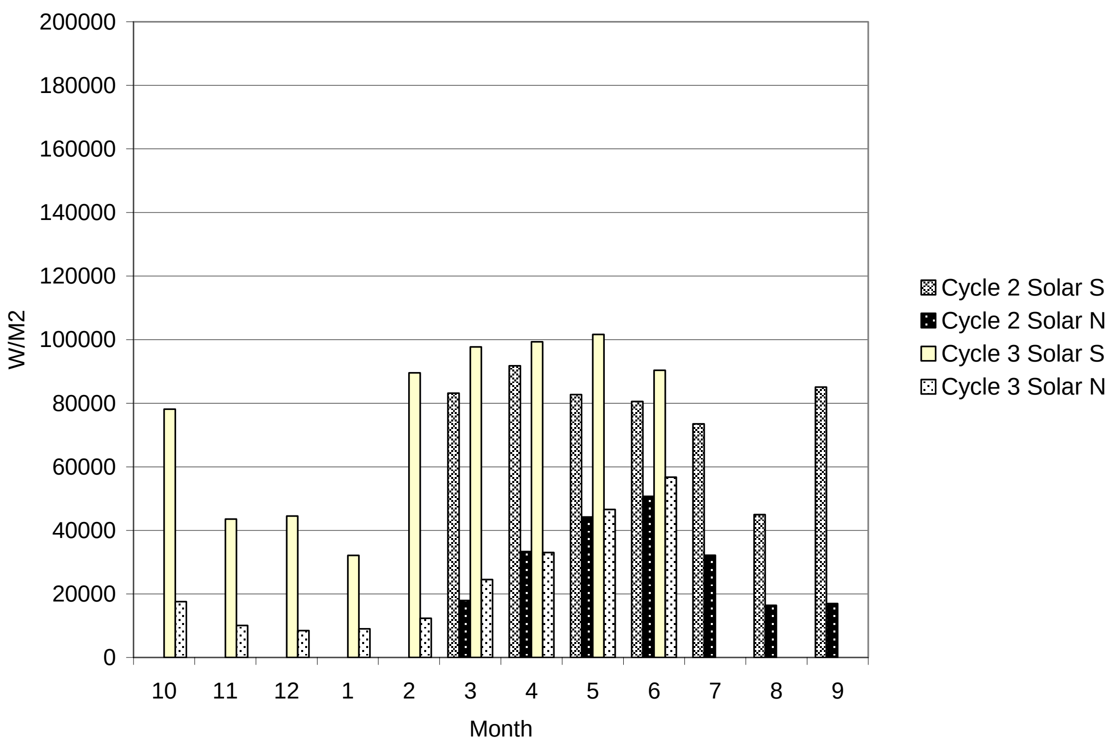


Figure D12 **Cycle 1 - Wind Speed by Wind Direction**

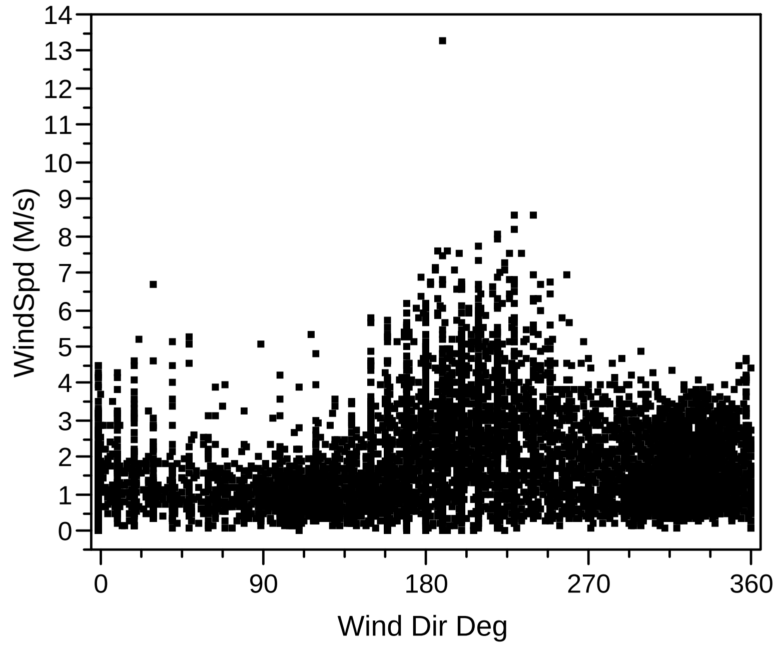


Figure D13 **Cycle 1 – Precipitation by Wind Direction**

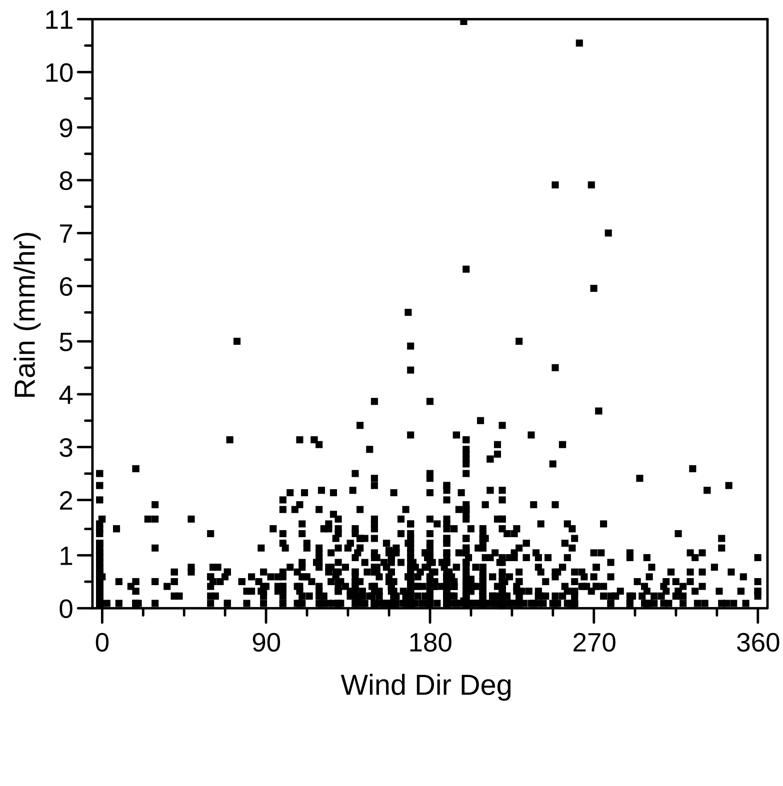


Figure D14 Cycle 2 - Wind Speed by Direction

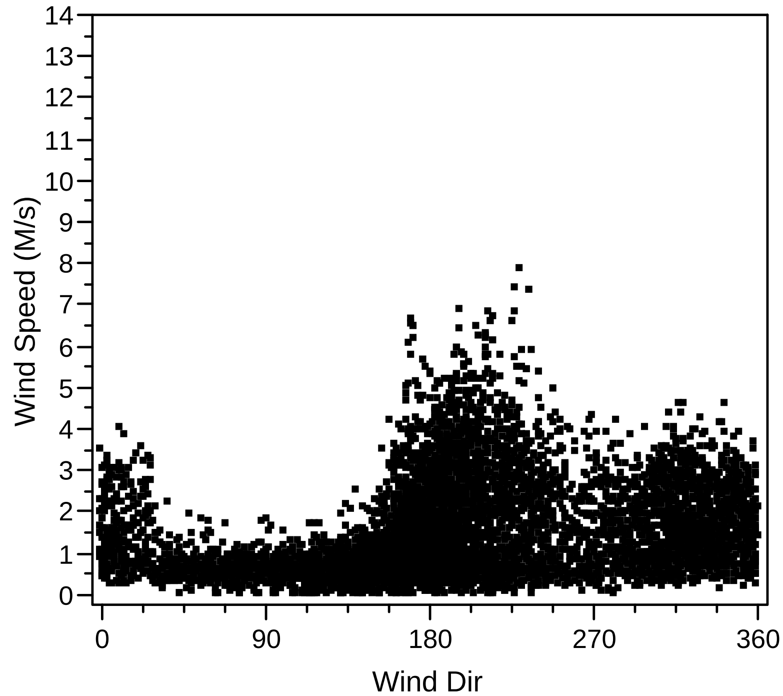


Figure D15 Cycle 2 - Precipitation by Wind Direction

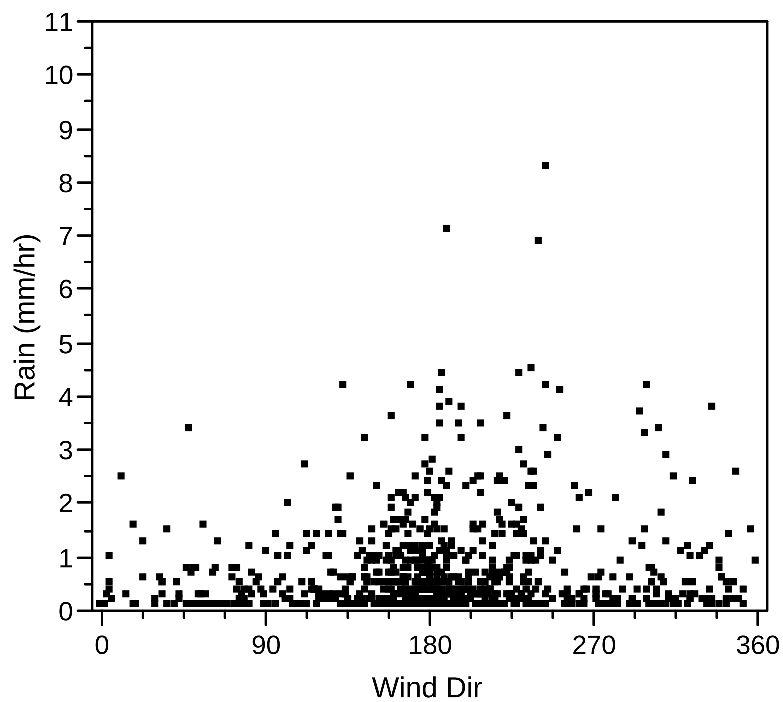


Figure D16 Cycle 3 - Wind Speed by Wind Direction

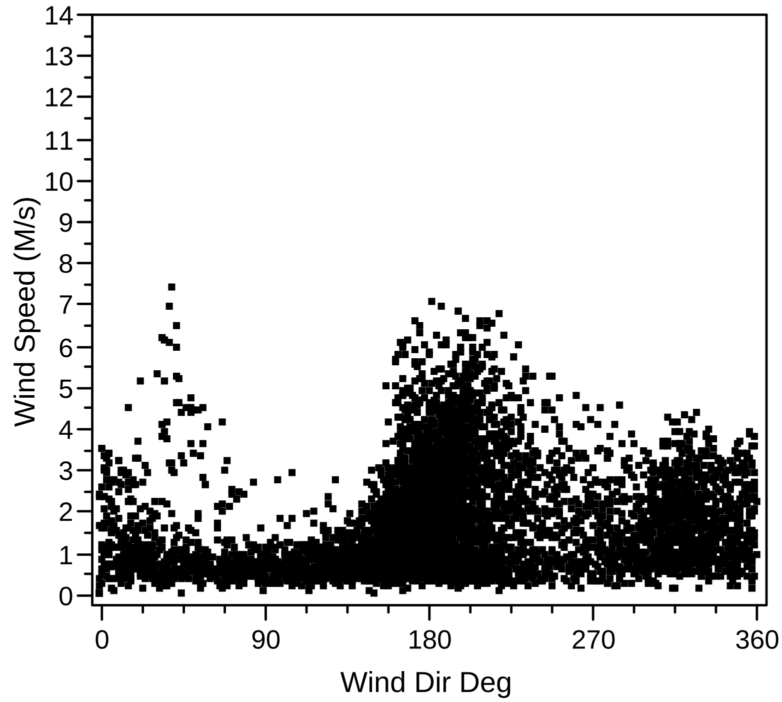


Figure D17 Cycle 3 – Precipitation by Wind Direction