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Hygrothermal Modeling of Building Wall Assemblies

Task 3.4 Report

December 2005

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Table of Contents

List of Tables iv
List of Figures v
Glossary vi
Executive Summary 1
Background 2
Baseline Wall Systems Studied 3
Variations Studied in Baseline Wall Systems 3
California Climate Zones (CZs) 4
WUFI® Wall System Evaluations for Mt. Shasta 6
  Mt. Shasta Moisture Content (MC) of OSB 7
  Mt. Shasta Relative Humidity (RH) of OSB 11
  Mt. Shasta Housewrap Permeance Variations and %MC of Wall 1 11
WUFI® Wall System Evaluations for the Other 15 CZs 15
ORNL MOISTURE-EXPERT Research Implications 22
Conclusions and Research Recommendations 25
References 27
Appendix A Wall Material Properties and Definitions 28
Appendix B Wall Layer Materials and Properties for the 3 Wall Types 31
Appendix C WUFI® Analysis Files 34
  WUFI®-Pro 4.0 (e) Project Data Input Files 34
  METENORM® Generated WUFI® Weather Data Input Files 35
  WUFI® Generated Output Data in Excel® Spreadsheet Files 35

List of Tables

Table 1. Building Paper and Housewrap Properties 4
Table 2. Summary of 16 Climate Zones (CZs).....6
Table 3. Annual %MC for OSB for Mt. Shasta 8
Table 4. Annual Number of Hours OSB > 20%MC for Mt. Shasta 8
Table 5. Annual Hours that RH > 70%for OSB Surface in Mt. Shasta 12
Table 6. Average %RH for OSB Surfaces in Mt. Shasta.....12
Table 7. Annual %MC for OSB for Wall 1-3A4A5B for All 16 Climate Zones.....16
Table 8. Annual %MC for OSB for Wall 1-3C4A5A for All 16 Climate Zones.....16
Table 9. Wall 1-3A4A5B %RH of OSB Surfaces.....19
Table 10. Wall 1-3C4A5A % RH for OSB Surfaces 19

List of Figures

Figure 1. %MC of OSB for All Wall Cases in Mt. Shasta 9
Figure 2. Comparison of %MC for Both Insulation Types in Mt. Shasta 10
Figure 3. %RH of Exterior OSB Surface for All Walls in Mt. Shasta.....13
Figure 4. Wall 1 Stucco & OSB %MC vs. Housewrap Permeance in Mt. Shasta14
Figure 5. %MC of OSB for Wall 1-3A4A5B in All 16 CZ Cities.....17
Figure 6. %MC of OSB for Wall 1-3C4A5A in All 16 CZ Cities 18
Figure 7. %RH of Exterior OSB Surface for Wall 1-3A4A5B in All 16 CZ Cities .20
Figure 8. % RH of Exterior OSB Surface for Wall 1-3C4A5A in All 16 CZ Cities 21
Figure 9. Wall MC at Different Wind Driven Rain Penetration Levels 23
Figure 10. OSB MC with and without Water Penetration Around Window.....23
Figure 11. Building Paper Layering Effect on Water Drainage and OSB MC.....24
Figure 12. Air Movement Effect on OSB MC 24

Glossary

ACH	Air Changes per Hour
Commission	California Energy Commission
ERC	Energy Resources Center
GTI	Gas Technology Institute
IBP	Fraunhofer Institute of Building Physics
MC	Moisture Content
ORNL	Oak Ridge National Laboratory
OSB	Oriented Stand Board
RH	Relative Humidity
UIC	University of Illinois at Chicago

Executive Summary

With mounting concerns about moisture levels, and the resulting potential for decay and mold, inside energy efficient wall systems, the annual hygrothermal performance of three state-of the-art stucco clad wall systems was evaluated in the 16 California Energy Commission climate zones (CZs) using the WUFI® Pro 4.0 building envelope simulation program and the METEONORM® 5.1 weather data generation program. The oriented strand board (OSB) sheathing, and its moisture content (MC) and surface relative humidity (RH), were used to gauge the performance of each wall system since this building layer is vulnerable to both decay and mold problems. Based solely on the current one-dimensional water vapor diffusion and building material liquid water transport analysis capabilities of this WUFI® program, the wall systems in 15 of the 16 CZs generally showed little potential for OSB decay, but somewhat greater, although still limited potential for mold. Except for CZ 1 (Arcata), only modest annual hours, if any, with OSB MC over 20% were exhibited by the wall systems, thus curtailing the prospect of significant wood decay that requires MC levels on the order of 30%. For many more CZs, and larger numbers of hours per year, OSB surface RH was above 70%, a level at which slow growth of certain molds can occur. There was no evidence of condensation on the OSB though, and except for CZ 1 (Arcata), the number of hours were very modest above 90%RH, a level at which surface water activity and growth increase dramatically for many molds.

However, further research is needed to encompass multi-dimensional analyses and other additional hygrothermal phenomena that can ultimately play the dominant role in wall system performance. These additional, potentially dominant effects, such as convective heat and moisture transfer and bulk water intrusion, are not yet in the public domain programs such as WUFI® tools. Oak Ridge National Laboratory (ORNL) has developed MOISTURE-EXPERT, an emerging multi-dimensional heat and moisture transfer research computer program with expanded hygrothermal modeling capabilities including:

- bulk water penetration directly into wall system sublayers;
- sublayer surface drainage of bulk water out of the wall system; and
- air movement over sublayers and in to and out of wall system cavities.

Literature published from ORNL MOISTURE-EXPERT research referenced in this report shows the dramatic effect on hygrothermal performance of varying levels of water penetration and drainage, as well as air movement, in stucco clad wall systems similar to those studied in this analysis. This research by ORNL shows a complex set of interactions in which water penetration can increase OSB MC twofold or more, while drainage and air movement can each decrease the OSB MC by a factor of two or more. The ORNL researchers note that such phenomena as water penetration and drainage, and air movement, could be directly related to design and construction issues, including the “level of complexity” or “level of workmanship” associated with making the wall air and water tight. This more complex hygrothermal modeling coupled with field (or lab) measured and verified performance is needed to gain a more thorough understanding of actual wall system moisture management issues.

Background

As advances are being made in the energy efficiency of residential exterior wall construction through lowered thermal conduction and air infiltration, concerns are being raised about the resulting moisture levels inside these walls and the potential for decay and mold. The relatively new field of hygrothermal modeling, or the modeling of coupled moisture and heat transfer, is making significant strides in our understanding of these emerging moisture management issues through the use of early generation computer programs despite their limited capabilities. WUFI® Pro 4.0 is one such public domain computer program that models one-dimensional water vapor diffusion between wall components and liquid water transport inside the building materials, and then calculates both the moisture content in the individual components of the wall systems and the psychrometric conditions at the wall component surfaces. The program has been developed by Germany's Fraunhofer Institute of Building Physics (IBP) that has teamed with the Oak Ridge National Laboratory (ORNL) to introduce the hygrothermal modeling tool to North America. The tool models the transient behavior of the wall system as it is exposed to hourly weather conditions, especially wind driven rain. The modeling results display moisture content of wall materials indicating potential for organic decay, as well as surface temperature and relative humidity indicating potential for mold formation. As part of research recently completed for the Gas Technology Institute (GTI) and the California Energy Commission (Commission) under the project entitled *Investigation of Mold-Resistant Building Assemblies and Construction Practices for California Homes*, WUFI® Pro 4.0 was employed by the Energy Resources Center (ERC) of the University of Illinois at Chicago (UIC) to evaluate the hygrothermal performance of three stucco clad wall types, including conventional three and “one” (actually two) coat cement stucco constructions and a thin acrylic stucco coated exterior insulation finishing system (EIFS), in 16 Commission designated climate zones in California. This report documents findings from this study of the three wall types, first in detail for a single climate zone to establish a basis for a more focused and limited analysis then on the balance of the California climate zones.

This report cites that the current public domain WUFI®-Pro 4.0 program is limited to one-dimensional water vapor diffusion between wall components and liquid water transport inside the building materials. Obviously, further research is needed encompassing two and eventually three dimensional analyses. Although a two dimensional version, WUFI-2D, is now available, it currently lacks some of the originally modeled phenomena, such as driving rain. However, it is other additional hygrothermal phenomena that can ultimately play the dominant role in the performance of these wall systems. These additional, potentially dominant effects, such as convective heat and moisture transfer and bulk water intrusion, need to be modeled in wall systems. Toward that end, this report also cites the possible implications of such advanced hygrothermal modeling capabilities not yet in the public domain programs such as the WUFI simulation tools. ORNL has

developed MOISTURE-EXPERT, an emerging multi-dimensional heat and moisture transfer research computer program with expanded hygrothermal modeling capabilities including:

- bulk water penetration directly into wall system sublayers;
- sublayer surface drainage of bulk water out of the wall system; and
- air movement over sublayers and in to and out of wall system cavities.

Literature published from ORNL MOISTURE-EXPERT research to date is referenced in this report and shows the effect of varying magnitudes of water penetration and drainage, as well as air movement, in stucco clad wall systems similar to those studied in this analysis. Those published MOISTURE-EXPERT results are contrasted to the findings from this WUFI®-Pro 4.0 analysis to establish a basis for the anticipated order of magnitude impact of these additional hygorthermal effects on potential wall system performance. The ORNL researchers note that such phenomena as water penetration and drainage, and air movement, can be directly related to design and construction issues, including the "level of complexity" or "level of workmanship" in attempting to make the wall air and water tight.

Baseline Wall Systems Studied

Three Coat Stucco (Wall 1)

This wall system has traditional 3-coat, 7/8th inch thick stucco, followed by two layers of building paper, OSB sheathing, insulation, gypsum board and latex paint as the interior finish. This traditional stucco finish is relatively massive, allowing for significant moisture sorption and capacitance effects.

One Coat Stucco (Wall 2)

The so-called 1-coat stucco wall is really a two-coat system with a 1/8th inch thick finish coat with a 3/8th inch thick base coat on metal mesh over a rigid expanded polystyrene (EPS) insulation board. This is followed by one layer of building paper, OSB sheathing, insulation, gypsum board, and latex paint as the interior finish. This wall system has a thinner layer of stucco than the traditional 3-coat stucco wall.

EIFS Wall System (Wall 3)

The exterior insulation and finish system (EIFS) wall type is comprised of a 1/8th inch thick finishing coat of acrylic stucco applied over a resin coated, fiberglass mesh on top of rigid expanded polystyrene (EPS) insulation board. The EIFS is followed by one layer of building paper, OSB sheathing, insulation, gypsum board, and latex paint as the interior finish. The EIFS wall system has a thin, but low permeance stucco coating, which influences the transport of moisture into and out of the wall system.

Variations Studied in Baseline Wall Systems

For each wall system studied, the main variation was the type of building paper or housewrap that was used over the OSB sheathing. In Wall 1, two such layers were applied over the OSB sheathing with the outer layer always a typical building paper (0.04 inch thick, 17.48 lb/ft3 bulk density, 23.075 perm permeance). Three options were available for the second layer: another layer of

the typical building paper (3A), high permeance housewrap (3B), or low permeance housewrap (3C). In Wall 2 and Wall 3, only one layer of either building paper or housewrap was used.

Table 1. Building Paper and Housewrap Properties

Properties/Materials	Units	Building Paper	High Permeance Housewrap	Low Permeance Housewrap
Thickness	(inches)	0.0400	0.0055	0.0140
Bulk Density	(lb/ft3)	17.48	4.058	4.058
Porosity	(ft3/ft3)	0.001	0.001	0.001
Heat Capacity	(Btu/lb*F)	0.358	0.358	0.358
Heat Conductivity	(Btu/hr*ft*F)	6.94	1.387	1.387
Permeability (@ RH=0%)	(perm*in)	0.9230	0.3190	0.0938
Permeance	(perms)	23.0750	58.0000	6.7000
Varies w/%RH (Y=Yes, N=No)		Y	N	N

The property definitions in Table 1 are detailed in Appendix A. Appendix B details the 3 wall systems in spreadsheets showing the complete wall arrangements with sets of properties for all the material layers and the alphanumerical coding to identify the baseline wall systems and their variations.

California Climate Zones (CZs)

The WUFI® software comes with a set of hourly weather data for a full year for 49 US cities and provides the option for the user to import weather data. Unfortunately, it only has 4 California weather locations (San Diego, Los Angeles, San Francisco, and Fresno) of which 3 are the so-called representative cities for 3 of the 16 CZs. The production of those annual hourly weather data sets is a tedious process utilizing 30 year NCDC weather data sets provided by ASHRAE from their 1997 Handbook of Fundamentals design weather data project. Even with access to all those original NCDC/ASHRAE weather data files, still only 10 of the 16 CZ representative cities would be encompassed. It is also uncertain whether these files even contain all the necessary solar radiation and precipitation data required by WUFI, since it was not needed by ASHRAE.

According to the Commission (Meada 2005), the present Title 24 annual hourly weather data files used to represent the 16 CZs are the result of a fairly complex CZ wide statistical compilation of weather data to establish heating and cooling energy requirements in a given CZ. As a result of this data manipulation, the Commission indicates that the concept of a representative city for a CZ is no longer very appropriate and as far as Title 24 residential compliance, the major impact of the representative city is the latitude and longitude of that city's location used in the compliance simulation. As was the case with the ASHRAE files, these CZ files do not contain critical data, such as precipitation, and it is doubtful that coincident data such as precipitation could even be merged successfully into such existing weather data compilations.

Given the tedious generation process and incomplete CZ coverage of the ASHRAE weather data, as well as the impractical nature of integrating additional weather data parameters into the CZ weather data files, an alternative source was located for annual sets of hourly weather data for the 16 CZs to be used in WUFI's hygrothermal modeling.

METEONORM® 5.1 (METEOTEST 2005) is a software tool that consists of a set of meteorological databases, and a series of conversion utilities that prepare and format weather data for use with major modeling software packages including WUFI. METEONORM® comes with an extensive database of nearly 2000 weather data stations from North America, most of which are located in the US, including about 100 California stations. The software can also interpolate the values of weather parameters based on a desired location's latitude and longitude to provide complete coverage of the CZs. A preliminary review of the software showed that METEONORM® contained weather data sets for the representative cities of 14 of the 16 CZs. Only CZs 4 and 14 and their respective representative cities, Sunnyvale and China Lake, would require this interpolation.

The METEONORM® weather databases consist of World Meteorological Organization (WMO) sanctioned monthly climatological normals that for the US were derived from 30 year NCDC weather data sets. From the monthly normals, METEONORM® calculates hourly values of all parameters using a stochastic model. Resulting weather data files are outputted in a variety of formats, including the IBP formatted Test Reference Year (TRY) format that can be directly read by the WUFI program.

METEONORM® provides a very cost effective and expeditious means to generate the necessary weather data files that are representative of the CZs and are ready for use by WUFI®. Even though the METEONORM® hourly weather data sets are synthesized, this approach at least provides a transparent, consistent, and defensible methodology for the creation of the required 16 CZ weather data files. Table 2 lists the CZs used in this analysis, including their representative cities and key geographical data, along with a key weather parameter, the wind driven rain amount and dominant direction. The wall systems simulated in WUFI® were oriented toward the dominant wind driven rain direction.

Table 2. Summary of 16 Climate Zones (CZs)

CZ	Representative City	County	Latitude	Longitude	Altitude (ft)	Precip (inches)	Wind Rain
1	Arcata	Humboldt	40.98	-124.10	216.5	36.83	S
2	Santa Rosa	Sonoma	38.52	-122.82	124.7	23.93	W
3	Oakland	Alameda	37.73	-122.22	9.8	20.93	W
4	Sunnyvale	Santa Clara	37.37	-122.03	102.0	19.95	SE
5	Santa Maria	Santa Barbara	34.90	-120.45	252.6	12.07	W
6	Los Angeles	Los Angeles	33.93	-118.40	105.0	12.07	W
7	San Diego	San Diego	32.73	-117.17	29.5	9.59	NW
8	El Toro	Orange	33.67	-117.73	380.9	11.36	SE
9	Pasadena	Los Angeles	34.09	-118.09	863.8	11.41	E
10	Riverside	Riverside	33.97	-117.33	1049.9	9.69	SE
11	Red Bluff	Tehama	40.15	-122.25	354.3	21.61	W
12	Sacramento	Sacramento	38.70	-121.58	23.0	17.85	E
13	Fresno	Fresno	36.77	-119.72	334.6	10.34	SE
14	China Lake	Kern/San Bernardino	35.68	-117.70	2230.0	5.58	SE
15	El Centro	Imperial	32.80	-115.67	13.1	1.69	SW
16	Mount Shasta	Siskiyou	41.32	-122.32	3543.3	16.96	S

WUFI® Wall System Evaluations for Mt. Shasta

Of the 16 California climate zones, Mt. Shasta was selected as the most adverse climatic location for managing moisture in these wall systems based on preliminary evaluations. Ten simulations were carried out for the Mt. Shasta location on these 3 wall types:

Wall 1:
Building Paper/House Wrap Variations
- 2 layers of building paper (3A)
- 1 layer of building paper and 1 layer of high perm housewrap (3B)
- 1 layer of building paper and 1 layer of low perm housewrap (3C)

Insulation Variations
- Fiberglass insulation (standard) (5A)
- Cellulose insulation (5B)

Wall 2:
Building Paper/House Wrap Variations
- 1 layer of building paper (3A)
- 1 layer of high perm housewrap (3B)
- 1 layer of low perm housewrap (3C)

Wall 3:
Building Paper/House Wrap Variations
- 1 layer of building paper (3A)
- 1 layer of high perm housewrap (3B)
- 1 layer of low perm housewrap (3C)

Note that in all walls the OSB is the layer coded as 4A. Referring to Appendix B for the coding of the wall layers, a 3 coat stucco wall on 2 layers of building paper over OSB in front of fiberglass insulation would be coded as Wall 1-3A4A5A.

The OSB building layer was used to gauge the performance of the wall system, as it is the most vulnerable to decay and mold problems. Using the WUFI® modeling software, the moisture content of the OSB and its surface conditions (temperature and relative humidity) were modeled for a two-year period of time. Only the steady-state data from year two was used in evaluating the performance of the OSB.

Mt. Shasta Moisture Content (MC) of OSB

Per Figure 1, the wall system with the most variation (highest moisture content of the OSB during the winter/spring and lowest moisture content during the summer/fall) was Wall 1 with the layer of low perm housewrap (3C) behind the layer of the building paper. Per Table 3, the percent moisture content (%MC) reached a high of 21.34%. Per Table 4, the OSB remained at a %MC above 20% for 1,311 hours annually. Significant wood decay does not occur until wood fiber reaches saturation, which is typically around 30%MC (Sherwood 1994). However, the moisture content readings from WUFI® represent average readings across the OSB and do not necessarily represent the maximum levels reached in particular sections of the OSB, so readings over 20% are of concern with regards to potential wood decay. Wall 1 with standard building paper (3A) and cellulose insulation had the least variation (lowest moisture content in the OSB during the winter/spring and highest moisture content during the summer/fall). Per Table 3, the percent moisture content peaked at 19.92% for a short period of time. Per Table 4, there were no hours that the OSB for Wall 1 with the cellulose insulation had a %MC above 20%

From Table 4, it appears that for each wall type (Wall 1, 2, and 3) the variation in OSB %MC due to type of building paper or housewrap used is modest. A more significant influence on OSB %MC appears to be the exterior stucco and insulation type. The thicker and more massive exterior stucco layer of Wall 1 results in somewhat higher OSB %MC than the other two walls. The cellulose insulation (5B), with its higher bulk density and % moisture uptake than the fiberglass insulation (5A), yields a lower %MC in the adjacent OSB. In Figure 2, the insulation moisture content in Wall 1 with the two layers of the standard building paper (3A) is almost 11%MC (65%RH) for the cellulose insulation (5B) and only 3%MC for the fiberglass insulation (5A with 3A, 3B or 3C).

Table 3. Annual %MC for OSB for Mt. Shasta

OSB % Moisture Content	Minimum Value	Maximum Value	Average Value
Wall 1-3A4A5A	8.83%	21.23%	15.15%
Wall 1-3A4A5B	8.92%	19.92%	14.67%
Wall 1-3B4A5A	8.83%	21.25%	15.16%
Wall 1-3C4A5A	8.98%	21.34%	15.35%
Wall 2-3A4A5A	9.37%	20.31%	15.10%
Wall 2-3B4A5A	9.36%	20.31%	15.11%
Wall 2-3C4A5A	9.40%	20.35%	15.14%
Wall 3-3A4A5A	9.58%	20.54%	15.26%
Wall 3-3B4A5A	9.57%	20.55%	15.26%
Wall 3-3C4A5A	9.59%	20.56%	15.28%

Table 4. Annual Number of Hours OSB > 20%MC for Mt. Shasta

OSB Moisture Content >20%	Annual Number of Hours
Wall 1-3A4A5A	998
Wall 1-3A4A5B	0
Wall 1-3B4A5A	1001
Wall 1-3C4A5A	1311
Wall 2-3A4A5A	465
Wall 2-3B4A5A	472
Wall 2-3C4A5A	513
Wall 3-3A4A5A	685
Wall 3-3B4A5A	690
Wall 3-3C4A5A	716

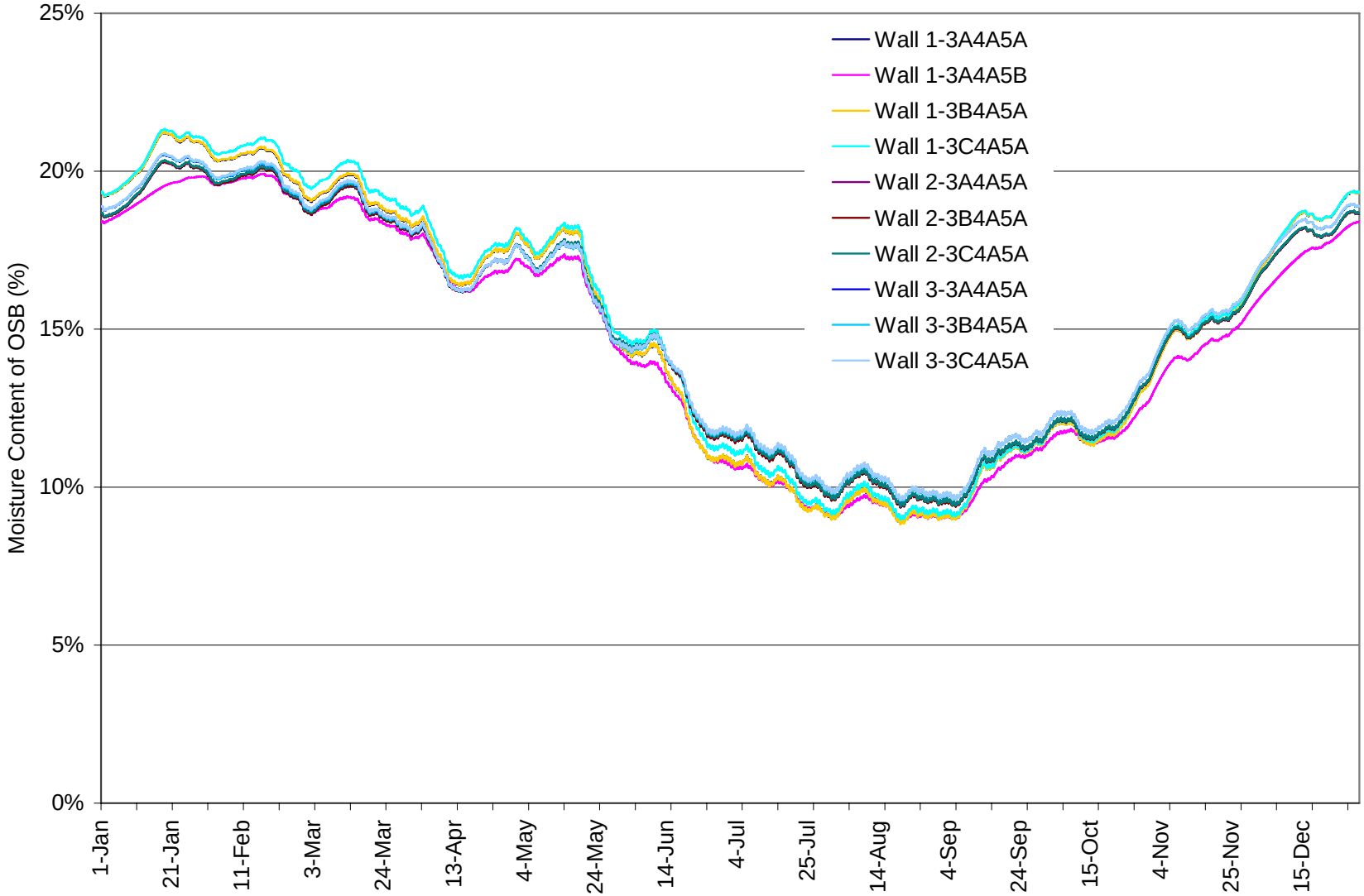


Figure 1. %MC of OSB for All Wall Cases in Mt. Shasta

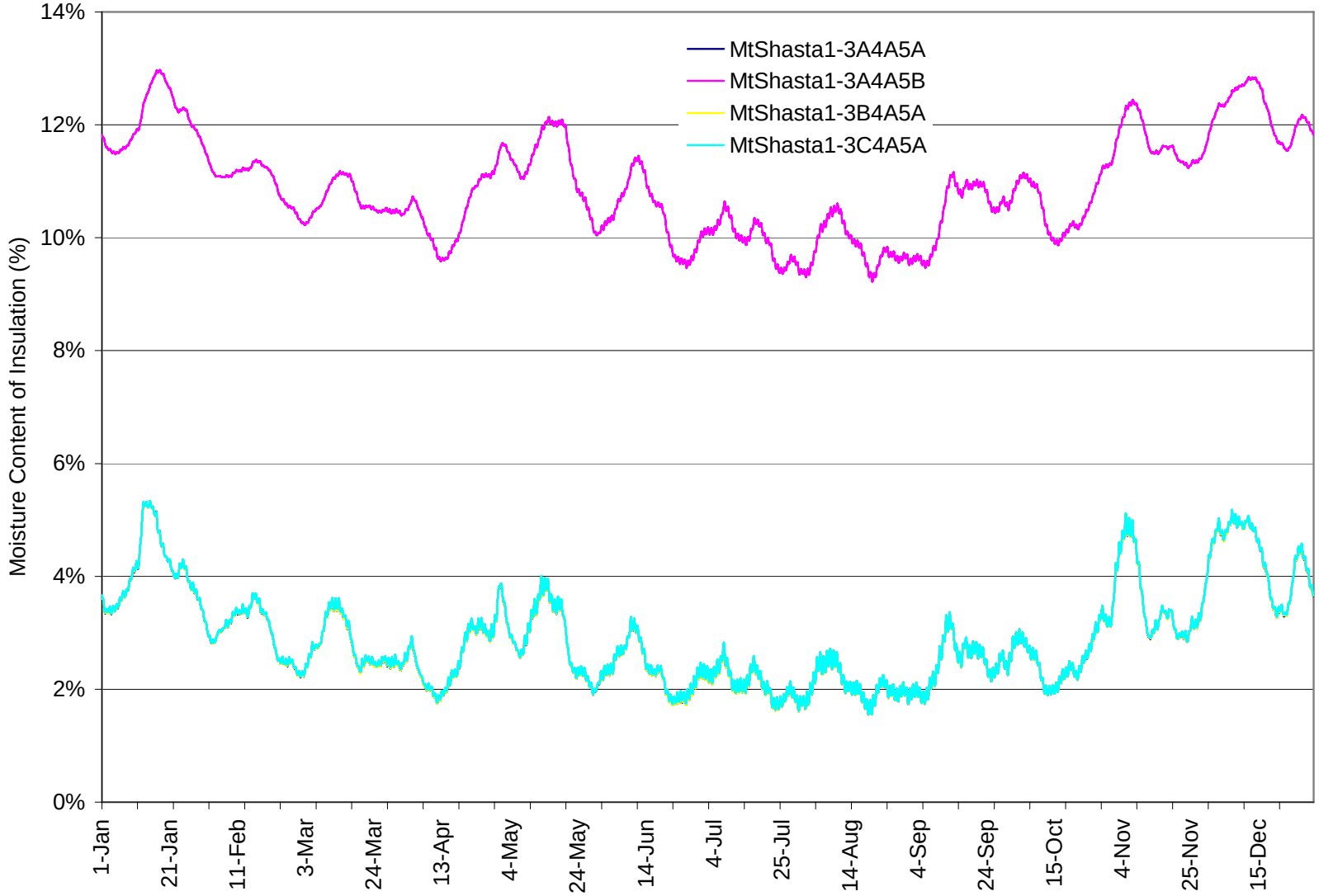


Figure 2. Comparison of %MC for Both Insulation Types in Mt. Shasta

Mt. Shasta Relative Humidity (RH) of OSB

The relative humidity (RH) of the OSB was evaluated on both the interior and exterior facing surfaces of the OSB. The percent relative humidity (%RH) can indicate potential conditions for mold growth. When the RH adjacent to the surface under consideration is above 70%, the conditions are sufficient for mold growth (Lstiburek and Carmody 1994). Per Figure 3 showing the exterior facing OSB surface %RH, there was no evidence of condensation and hours were very modest above 90%RH, a level at which surface water activity and growth increase dramatically for many molds (Harriman 2001). Although, there are large numbers of hours above 70%RH shown in Table 5, a level at which slow growth of certain molds can occur.

Of the three wall systems, Wall 3 had the fastest response to moisture in the wall system. Wall 1 and Wall 2 retained the moisture in the wall for a longer period of time (dampening and extending the peaks/troughs of the RH curve). In Table 6, when examining both the interior and exterior surface RH measurements provided by WUFI®, the walls with the low perm housewrap (3C) had the least variation from exterior to interior surfaces (lowest permeance) and the high perm housewrap (3B) had the greatest variation (highest permeance). However, the high perm housewrap (3B) was not substantially higher in %RH variation than the standard building paper (3A). Both the high perm housewrap (3B) and the standard building paper (3A) had higher permeance than the low perm housewrap (3C). In Table 5, the effect of the stucco finish is seen on the exterior OSB surface, with a smaller number of hours over 70%RH for the traditional 3 coat stucco (Wall 1) that has a greater amount of moisture capacity. The one-coat resin stucco (Wall 3) with a lesser amount of moisture capacity had a larger number of hours over 70%RH.

Mt. Shasta Housewrap Permeance Variations and %MC of Wall 1

To help in determining the effect of housewrap permeance on the moisture content of the OSB the permeance of the housewrap was varied in a separate sensitivity analysis. This was done by altering the permeability input in WUFI® and leaving the thickness of the housewrap (3C) constant for Wall 1-3C4A5A. The housewrap permeance was simulated in six increments from the baseline 6.7 perms to 64.3 perms. As shown in Figure 4, it was found that with an increased housewrap perm value, the average moisture content of the OSB was reduced. At the same time, with the increased housewrap perm value the average moisture content of the exterior stucco layer increased. This analysis indicates that the higher permeance housewrap not only allows moisture into the wall system, but also allows the moisture to dry to the exterior, with the traditional 3 coat stucco and its moisture capacity also helping to draw moisture to the exterior.

Table 5. Annual Hours that RH > 70%for OSB Surface in Mt. Shasta

Annual Hours >70% RH	OSB Exterior Surface	OSB Interior Surface
Wall 1-3A4A5A	5632	6771
Wall 1-3A4A5B	5567	6742
Wall 1-3B4A5A	5632	6771
Wall 1-3C4A5A	5804	6830
Wall 2-3A4A5A	6418	6729
Wall 2-3B4A5A	6417	6728
Wall 2-3C4A5A	6473	6746
Wall 3-3A4A5A	6812	6734
Wall 3-3B4A5A	6808	6734
Wall 3-3C4A5A	6833	6738

Table 6. Average %RH for OSB Surfaces in Mt. Shasta

	Average Exterior RH	Average Interior RH	RH Difference
Wall 1-3A4A5A	76.92	81.12	4.19
Wall 1-3A4A5B	76.34	79.93	3.59
Wall 1-3B4A5A	76.93	81.13	4.20
Wall 1-3C4A5A	77.88	81.29	3.41
Wall 2-3A4A5A	78.67	80.25	1.58
Wall 2-3B4A5A	78.67	80.26	1.59
Wall 2-3C4A5A	78.85	80.29	1.44
Wall 3-3A4A5A	79.61	80.33	0.72
Wall 3-3B4A5A	79.60	80.33	0.73
Wall 3-3C4A5A	79.69	80.35	0.65

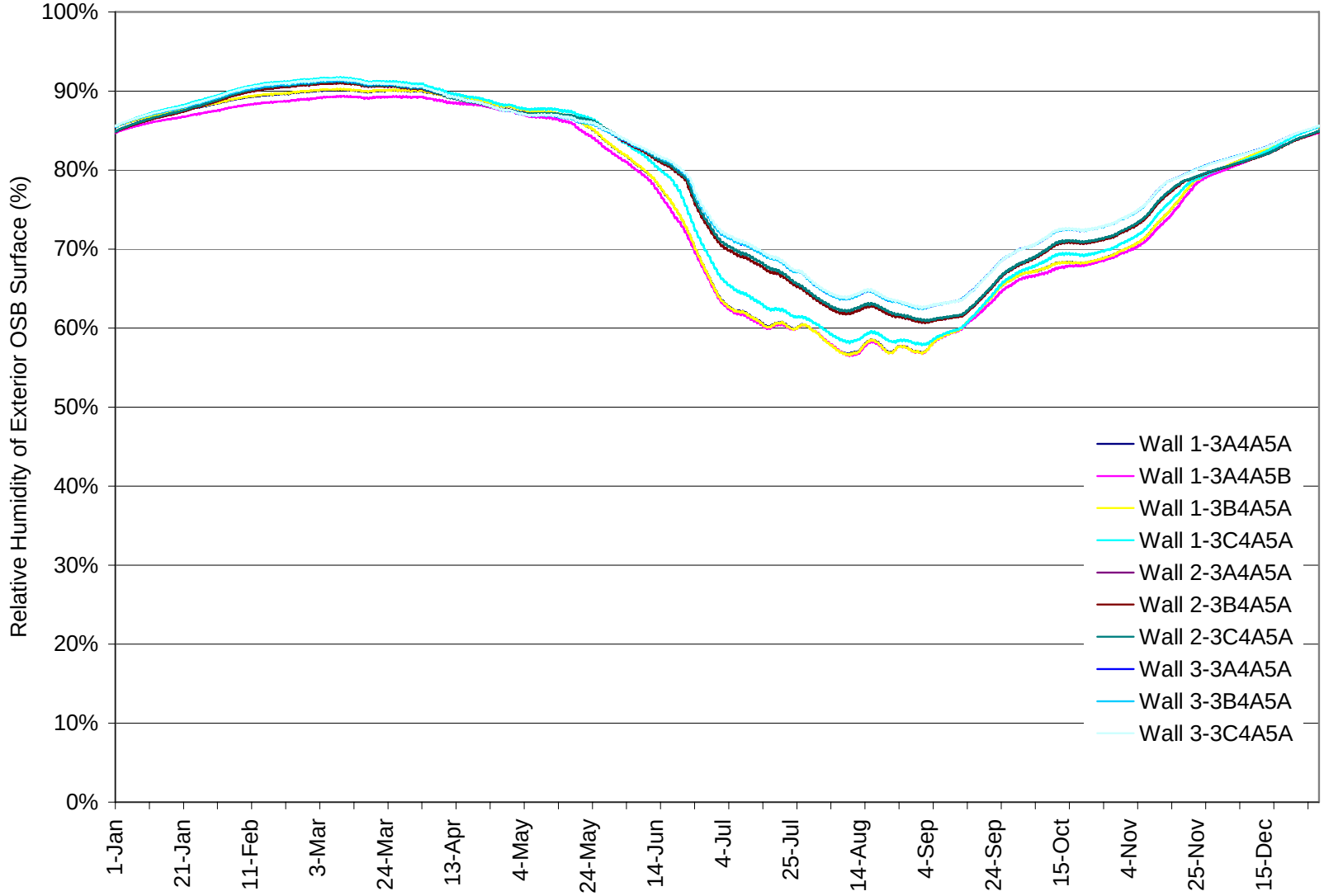


Figure 3. %RH of Exterior OSB Surface for All Walls in Mt. Shasta

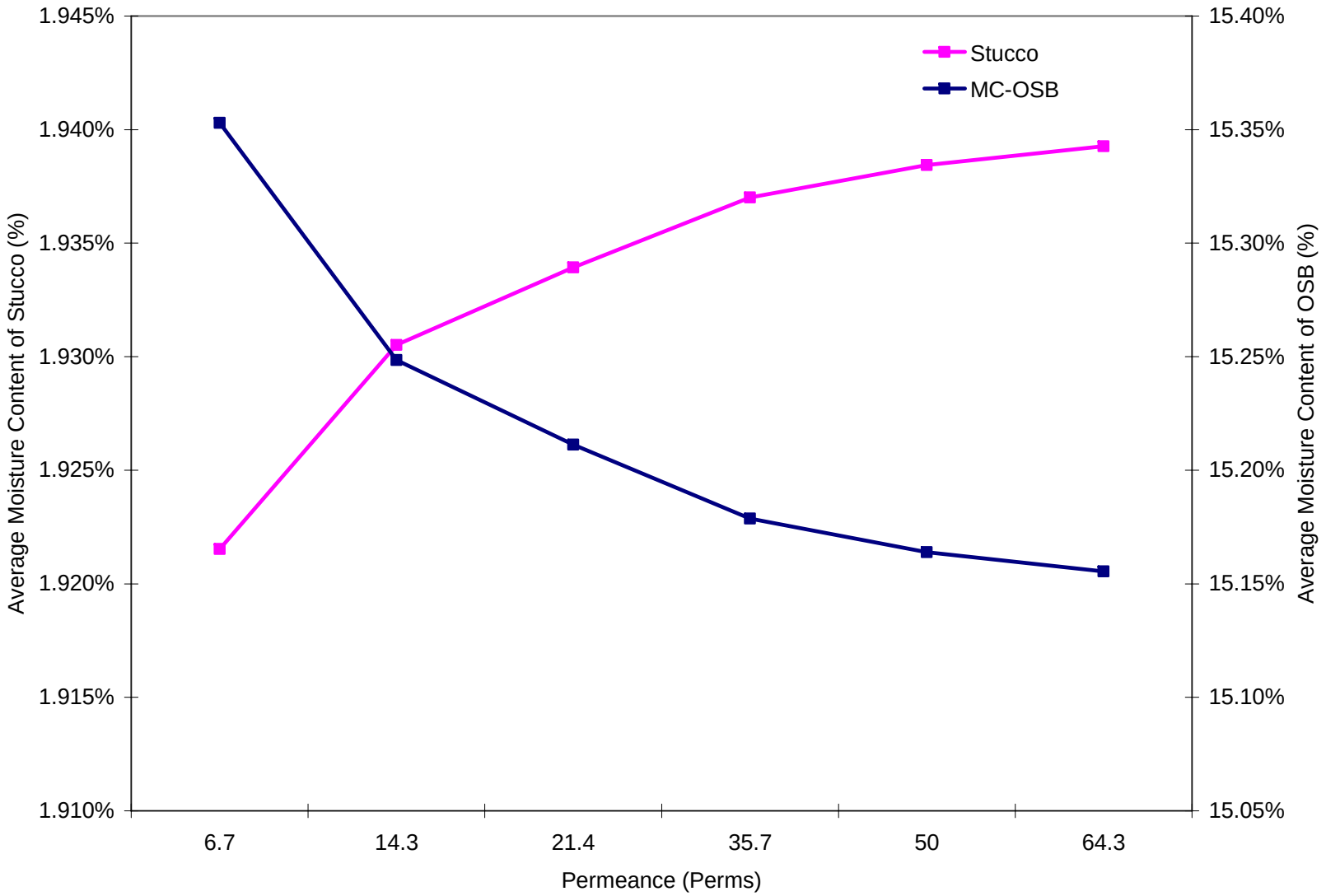


Figure 4. Wall 1 Stucco & OSB %MC vs. Housewrap Permeance in Mt. Shasta

WUFI® Wall System Evaluations for the Other 15 CZs

Refering back to Table 3, based on the performance criteria of annual average OSB %MC, Wall 1-3A4A5B (with 3 coat stucco on 2 layers of building paper over OSB in front of cellulose insulation) and Wall 1-3C4A5A (with 3 coat stucco on 1 layer of building paper/1 layer of low permeance housewrap over OSB in front of fiberglass insulation) represented the respective "best" (lowest average OSB %MC) and "worst" (highest average OSB %MC) performance of all the wall systems evaluated in Mt. Shasta. To keep the number of additional WUFI® simulations and resulting annual 8760 hour datasets to a reasonable minimum, only these two wall systems, representing the performance extremes in Mt. Shasta, were analyzed in the other 15 CZ cities.

Figures 5 and 6 show the hourly OSB %MC over the course of a year for Wall 1-3A4A5B and Wall 1-3C4A5A, respectively, for all 16 CZ cities. The companion Tables 7 and 8, detail the minimum MC, maximum MC, average MC of the OSB of Wall 1-3A4A5B and Wall 1-3C4A5A, respectively. For Wall 1-3A4A5B, the only location that has moisture content of the OSB above 20% for any hours is Arcata, which is above 20%MC for 6,810 hours of the year. For Wall 1-3C4A5B, only Arcata and Mt. Shasta have any hours above 20% moisture content for the OSB. The number of hours for Arcata is 7,450 and for Mt. Shasta it is 1,311 hours of the year.

Figures 7 and 8 show the hourly %RH of the exterior facing OSB surface over the course of a year for Wall 1-3A4A5B and Wall 1-3C4A5A, respectively, for all 16 CZ cities. The companion Tables 9 and 10, detail the minimum RH, maximum RH, and average # hours over 70%RH for the exterior and interior facing OSB surface of Wall 1-3A4A5B and Wall 1-3C4A5A, respectively. Two coastal cities – Oakland and Arcata -- exhibit %RH levels and # hours over 70%RH that are greater than Mt. Shasta.

Table 7. Annual %MC for OSB for Wall 1-3A4A5B for All 16 Climate Zones

OSB % Moisture Content	Minimum Value	Maximum Value	Average Value
Arcata	19.01%	22.02%	20.58%
China Lake	5.07%	15.19%	9.69%
El Centro	5.06%	8.08%	6.29%
El Toro	8.34%	10.82%	9.23%
Fresno	5.67%	14.74%	9.56%
Los Angeles	9.70%	12.48%	11.11%
Mt. Shasta	8.92%	19.92%	14.67%
Oakland	11.26%	15.91%	13.48%
Pasadena	5.96%	13.03%	9.52%
Red Bluff	5.28%	13.97%	9.25%
Riverside	7.35%	10.17%	9.10%
Sacramento	6.73%	15.87%	10.89%
San Diego	10.05%	11.98%	10.87%
Santa Maria	10.76%	12.57%	11.59%
Santa Rosa	7.71%	15.71%	11.28%
Sunnyvale	8.48%	14.12%	11.17%

Table 8. Annual %MC for OSB for Wall 1-3C4A5A for All 16 Climate Zones

OSB % Moisture Content	Minimum Value	Maximum Value	Average Value
Arcata	18.60%	22.32%	20.93%
China Lake	5.05%	15.87%	9.91%
El Centro	5.04%	8.22%	6.34%
El Toro	8.30%	11.04%	9.33%
Fresno	5.67%	15.38%	9.71%
Los Angeles	9.75%	12.73%	11.19%
Mt. Shasta	8.98%	21.34%	15.35%
Oakland	11.18%	16.23%	13.61%
Pasadena	5.94%	13.41%	9.62%
Red Bluff	5.27%	14.21%	9.32%
Riverside	7.25%	10.49%	9.23%
Sacramento	6.69%	16.41%	11.01%
San Diego	10.09%	12.21%	10.93%
Santa Maria	10.81%	13.02%	11.73%
Santa Rosa	7.65%	16.47%	11.52%
Sunnyvale	8.46%	14.51%	11.28%

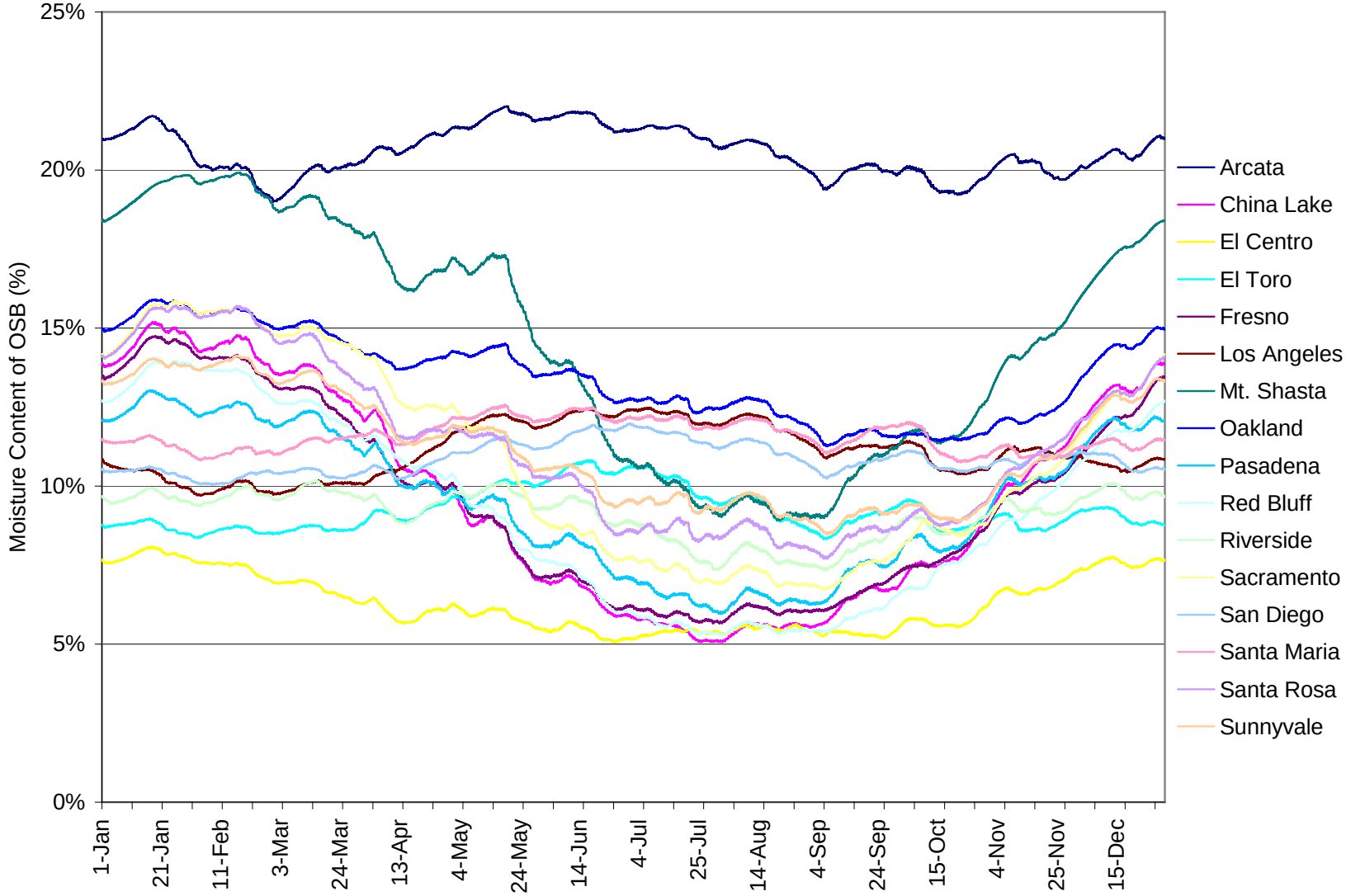


Figure 5. %MC of OSB for Wall 1-3A4A5B in All 16 CZ Cities

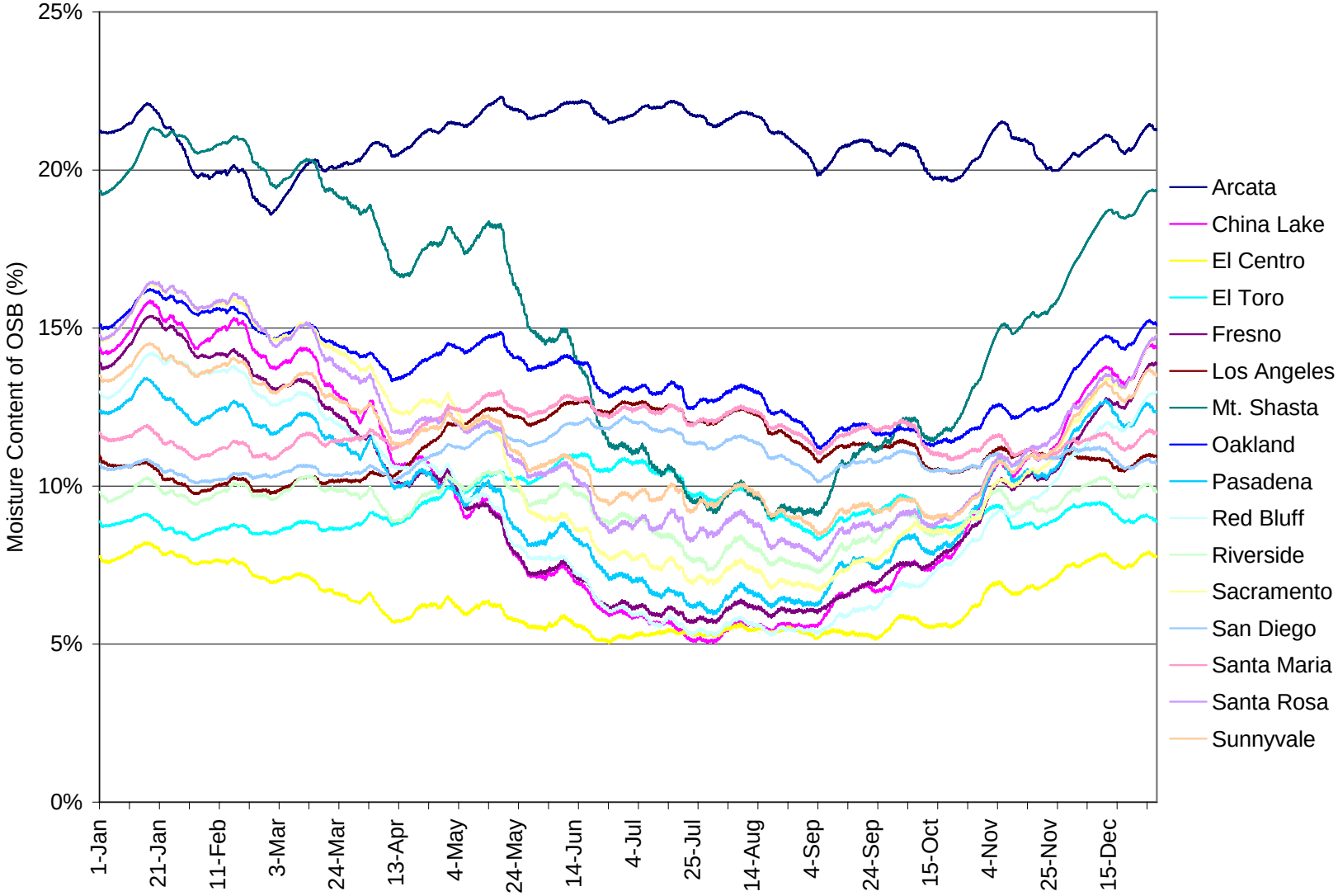


Figure 6. %MC of OSB for Wall 1-3C4A5A in All 16 CZ Cities

Table 9. Wall 1-3A4A5B %RH of OSB Surfaces

	RH Exterior Surface OSB				RH Interior Surface OSB			
City	Mini	Max	Avg	Hrs >70%	Min	Max	Avg	Hrs >70%
Arcata	90.41	95.30	93.18	8760	80.91	94.79	90.68	8760
China Lake	31.08	80.91	57.38	2993	32.29	89.93	61.43	3380
El Centro	29.08	50.89	39.15	0	30.35	61.51	44.53	0
El Toro	50.79	65.81	58.48	0	47.96	72.71	61.06	250
Fresno	35.24	81.76	57.45	2737	35.29	89.33	61.07	2910
Los Angeles	61.38	73.56	68.35	3700	56.03	77.83	68.43	3209
Mt. Shasta	56.49	89.36	76.34	5567	53.16	95.96	79.93	6742
Oakland	68.99	86.11	77.87	8057	62.69	87.16	76.77	8068
Pasadena	37.00	79.47	59.23	2325	36.87	82.97	60.81	2283
Red Bluff	32.66	80.98	56.91	2866	32.43	84.57	58.80	2453
Riverside	48.07	66.39	56.89	0	43.33	73.81	60.98	410
Sacramento	43.10	85.71	64.46	3787	39.89	91.62	66.28	3916
San Diego	62.37	71.61	67.36	1666	57.55	75.35	67.26	2237
Santa Maria	65.21	74.95	70.23	4943	59.21	79.65	70.95	5302
Santa Rosa	51.71	84.08	66.57	3449	45.33	91.81	69.50	4414
Sunnyvale	54.51	83.18	67.86	3515	50.12	84.92	69.02	3787

Table 10. Wall 1-3C4A5A % RH for OSB Surfaces

	RH Exterior Surface OSB				RH Interior Surface OSB			
	Min	Maxi	Avg	Hrs >70%	Min	Max	Avg	Hrs >70%
Arcata	91.44	95.03	93.42	8760	79.00	97.38	91.56	8760
China Lake	31.63	81.83	58.11	3034	29.78	93.12	62.21	3537
El Centro	30.43	51.09	39.61	0	27.86	64.57	44.79	0
El Toro	52.82	65.73	59.06	0	45.14	76.31	61.48	645
Fresno	36.09	81.80	58.03	2745	32.45	92.59	61.69	2928
Los Angeles	62.98	74.39	68.68	3216	53.21	80.46	68.85	3583
Mt. Shasta	57.86	91.73	77.88	5804	50.00	98.11	81.29	6830
Oakland	69.80	85.01	78.08	8663	60.07	89.44	77.38	7940
Pasadena	37.63	78.45	59.53	2679	34.13	85.82	61.41	2566
Red Bluff	33.21	80.70	57.11	2870	29.56	87.60	59.36	2706
Riverside	48.73	65.38	57.68	0	40.01	78.90	61.54	1142
Sacramento	43.83	84.41	64.75	3818	36.16	94.29	66.88	3905
San Diego	63.84	72.19	67.61	1351	55.53	78.01	67.61	2714
Santa Maria	66.29	74.01	70.87	5371	55.81	82.37	71.60	5494
Santa Rosa	52.05	84.10	67.36	3869	42.79	94.57	70.26	4419
Sunnyvale	55.79	81.92	68.24	3680	47.75	87.66	69.59	3982

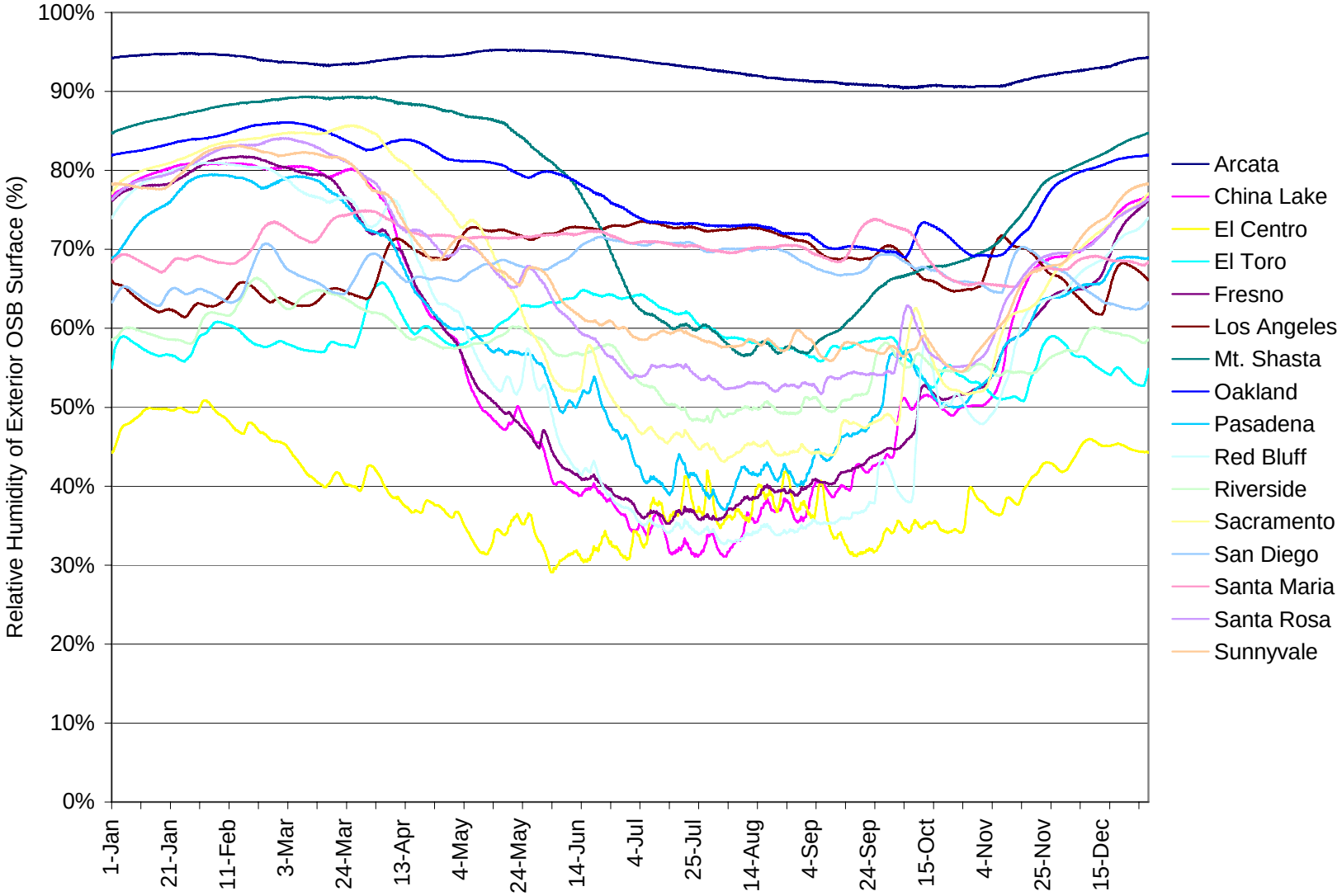


Figure 7. %RH of Exterior OSB Surface for Wall 1-3A4A5B in All 16 CZ Cities

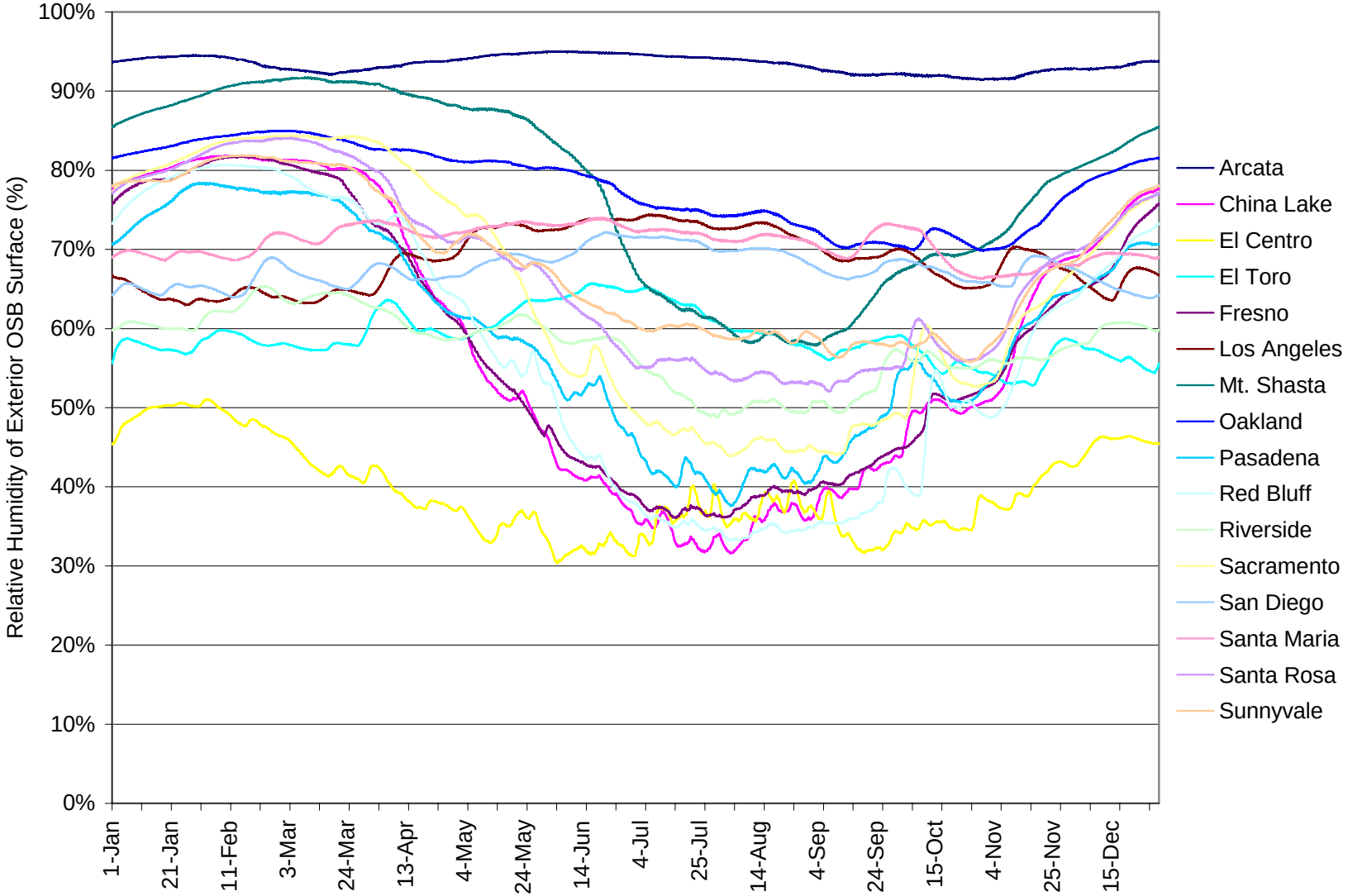


Figure 8. % RH of Exterior OSB Surface for Wall 1-3C4A5A in All 16 CZ Cities

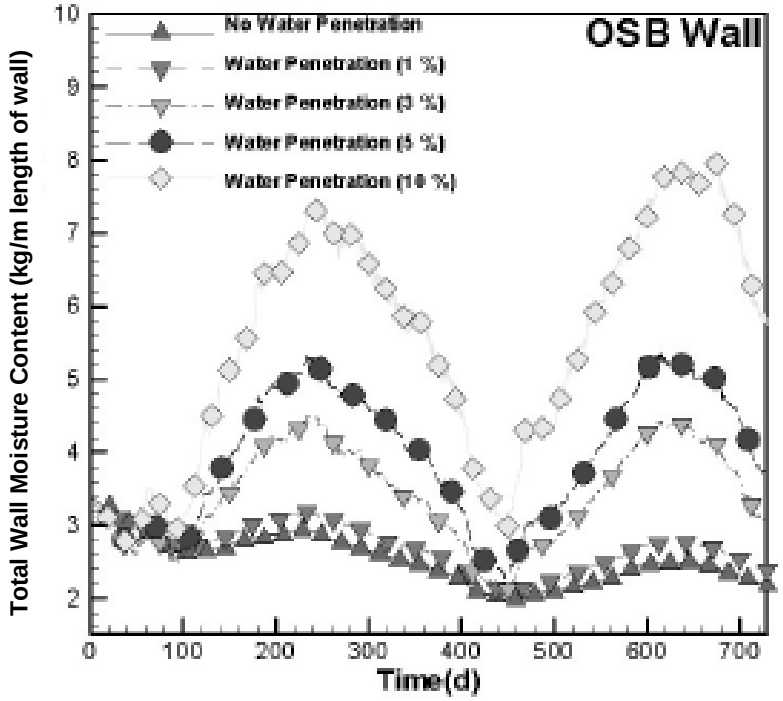
ORNL MOISTURE-EXPERT Research Implications

As noted before, the WUFI®-Pro 4.0 program is limited to one-dimensional water vapor diffusion between wall components and liquid water transport inside the building materials. Other additional hygrothermal phenomena can ultimately play the dominant role in the performance of these wall systems. ORNL has developed MOISTURE-EXPERT, an emerging multi-dimensional heat and moisture transfer research computer program with expanded hygrothermal modeling capabilities including:

- bulk water penetration directly into wall system sublayers;
- sublayer surface drainage of bulk water out of the wall system; and
- air movement over sublayers and in to and out of wall system cavities.

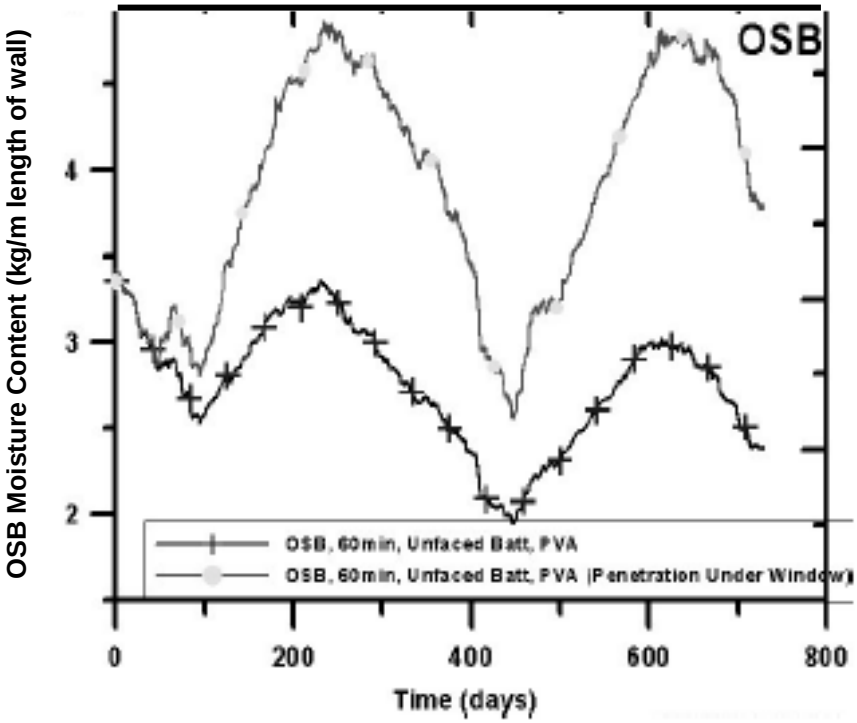
ORNL along with other researchers utilized short term laboratory experiments to establish levels of bulk water penetration and drainage to apply in this preliminary modeling. Literature published from the ORNL MOISTURE-EXPERT research to date provides insight into the effect of varying magnitudes of water penetration and drainage, as well as air movement, in stucco clad wall systems similar to those studied in this report's WUFI® analysis.

As part of a MOISTURE-EXPERT evaluation of stucco clad wall systems in Seattle, ORNL showed the dramatic effect on wall system moisture content when wind driven rain penetrates to the wall system sublayers. In Figure 9 (Karagiozis 2001), the total moisture content of the entire wall system is plotted over time for several different percentages of wind driven rain that penetrates behind the stucco to the papered sheathing (felt paper over OSB) through cracks, joints or around windows. With 5% wind driven rain penetration, the maximum water content doubles over the baseline 0%, or no water penetration. In Figure 10 (Karagiozis 2001), the moisture content of OSB with and without water penetration around a window is shown. Again, with water penetration, increases in maximum OSB moisture content approach twice the level without water penetration. Some of this water penetration can be shed by drainage and gravity effects if the OSB sheathing is covered by adequate layers of weather resistive barriers such as building papers or housewraps. In Figure 11 (Karagiozis 2003), the ability of two layers of building paper to better shed penetrating water than a single layer is illustrated by the nearly halving of the maximum OSB moisture content with the addition of the second building paper layer. In Figure 12 (Karagiozis 2002), the effect of increased air movement over the OSB sheathing can be seen. According to ORNL researchers, in this Seattle stucco clad wall system, 5 ACH provided sufficient drying potential to handle a water penetration load of 2% of the wind driven rain. The ORNL researchers further note that such phenomena as water penetration and drainage, and air movement, can be directly related to design and construction issues, including the "level of complexity" or "level of workmanship" in attempting to make the wall air and water tight.



Starting with July 1 at day 0

Figure 9. Wall MC at Different Wind Driven Rain Penetration Levels
(Reproduced with permission from Achilles Karagiozis/ORNL)



Starting with July 1 at day 0

Figure 10. OSB MC with and without Water Penetration Around Window
(Reproduced with permission from Achilles Karagiozis/ORNL)

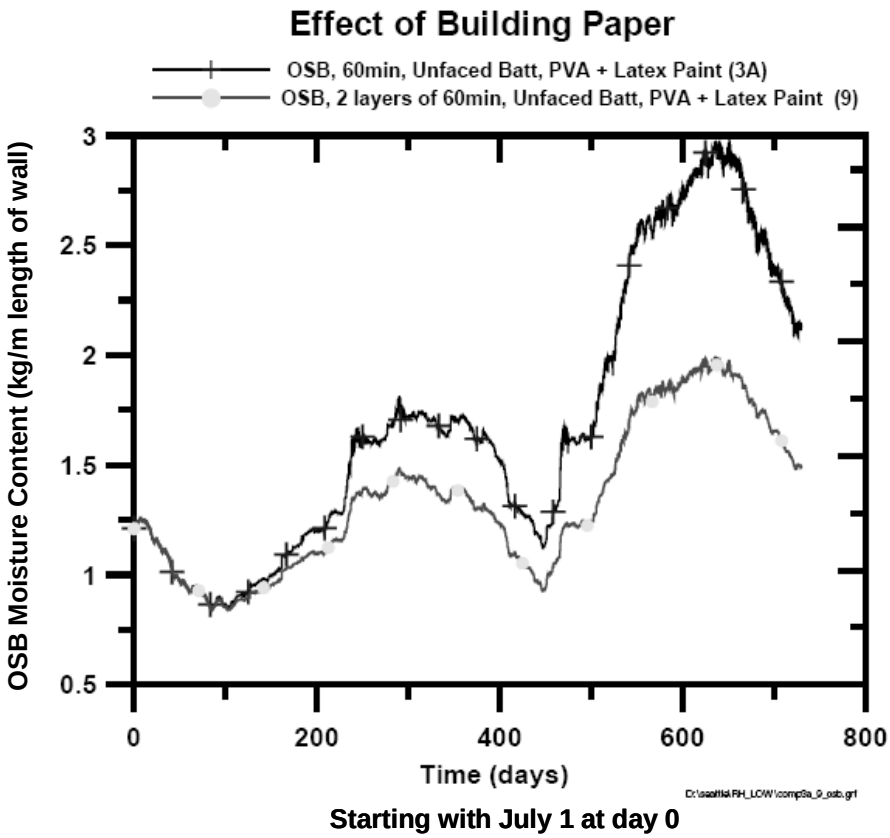


Figure 11. Building Paper Layering Effect on Water Drainage and OSB MC
(Reproduced with permission from Achilles Karagiozis/ORNL)

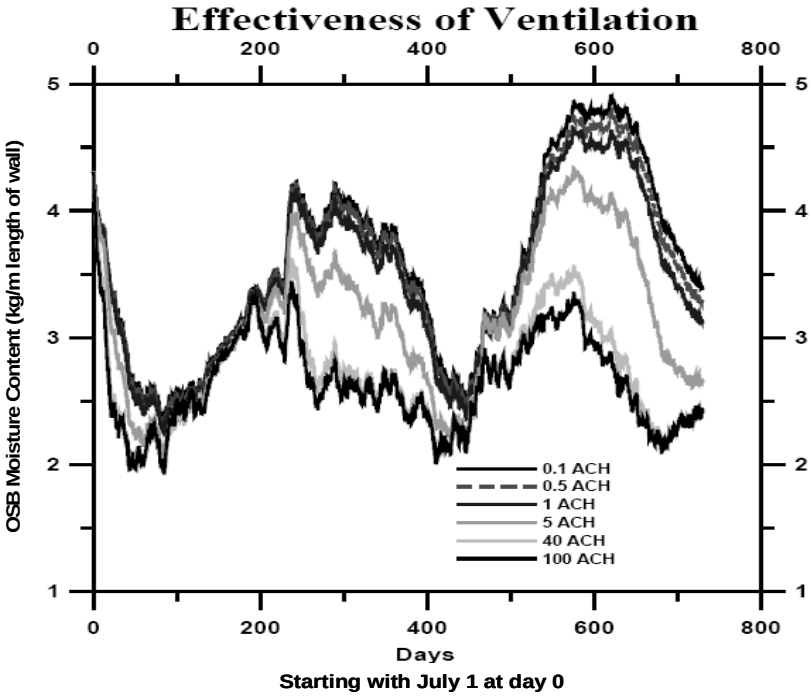


Figure 12. Air Movement Effect on OSB MC
(Reproduced with permission from Achilles Karagiozis/ORNL)

Conclusions and Research Recommendations

The hygrothermal performance of three stucco clad wall systems was evaluated using the WUFI® Pro 4.0 building envelope simulation program and the METEONORM® 5.1 weather data generation program. The evaluation was completed first in detail for a single climate zone (CZ) to establish a basis for a more focused and limited analysis then on the balance of the 16 California CZs. The OSB building layer was used to gauge the performance of the wall system, as it is vulnerable to both decay and mold problems. Using the WUFI® modeling software, the moisture content of the OSB and its surface conditions of temperature and relative humidity were modeled.

Based only on this current WUFI® analysis, which was limited to one-dimensional water vapor diffusion between wall components and liquid water transport inside the building materials, and the 10 different wall system simulations in a single target CZ location of Mt. Shasta (CZ 16), the greater stucco thickness and its larger water uptake lead to the largest increases in the resulting moisture content and surface relative humidity levels of the OSB. A single alternative insulation scenario that used cellulose versus the baseline fiberglass, showed the increased moisture capacitance of the cellulose insulation lead to decreases in the values of those OSB properties. The cellulose insulation appeared to have a mitigating effect on the moisture loading in other wall elements such as the OSB, but other alternative insulation materials should be evaluated, and studied in additional wall systems as well before drawing general conclusions. For each of the 3 stucco clad wall systems, the selection of building paper and housewrap had the least effect on those OSB properties. All of the wall systems demonstrated a winter loading and summer drying moisture profile for the OSB moisture content. However, as illustrated by the tight grouping in the OSB MC plot (refer back to Figure 1), the relative difference between all these wall systems was modest, with less that a 1 percentage point difference in average MC over a year (refer back to Table 3). In general, the wall systems showed modest annual hours, if any (refer back to Table 4), with OSB MC over 20%, thus limiting the possibilities for significant wood decay that requires MC levels on the order of 30%. Similar moisture loading/drying profiles and wall system groupings were exhibited for OSB RH. There was no evidence of condensation and hours were very modest above 90%RH (refer to Figure 3), a level at which surface water activity and growth increase dramatically for many molds. Although, there are large numbers of hours above 70%RH (refer to Table 5), a level at which slow growth of certain molds can occur.

When the two wall systems representing the performance extremes in Mt. Shasta (CZ 16) were analyzed in the other 15 CZ cities, only CZ1, represented by Arcata, demonstrated a more extreme behavior with higher OSB MC and surface RH (refer to Figures 5 and 6). Outside of Arcata (CZ 1), the wall systems in the other 15 CZs generally showed little potential for OSB decay, but still limited potential for mold. Except for CZ 1 (Arcata) and Mt. Shasta (CZ 16), no other CZ exhibited a maximum OSB MC over 20% (refer to Tables 7 and 8), again

curtailing the prospect of significant wood decay that requires MC levels on the order of 30%. By contrast many more CZs exhibited larger numbers of hours per year with OSB surface RH above 70% (refer to Tables 9 and 10), a level at which slow growth of certain molds can occur. There was no evidence of condensation on the OSB though, and again, except for CZ 1 (Arcata), the number of hours were very modest above 90%RH (refer to Figures 7 and 8), a level at which surface water activity and growth increase dramatically for many molds.

All CZ cities exhibited a typical winter loading and summer drying moisture profile, except Arcata (CZ 1) which showed a much flatter and more elevated profile (refer again to Figures 5 – 8). Meteorologically, Arcata shares more in common with the Pacific Northwest and cities like Seattle and Vancouver than it does with its other California CZ cities. Arcata is located in a coastal climate that according to METEONORM® has even more moderate temperatures and higher relative humidity throughout the year than either Seattle or Vancouver. This curtails the summer drying potential for wall systems in Arcata (CZ 1).

<u>However, based on the implications of the ORNL MOISTURE-EXPERT research cited in this report, it is clear that these WUFI® results will be radically altered with the introduction of additional hygrothermal effects. Continued funding of these more advanced computer models and further envelope modeling research with these higher level tools is needed to fully encompass the necessary multi-dimensional analyses and other hygrothermal phenomena, such as convective heat and moisture transfer and bulk water intrusion, that can ultimately have the determining role in wall system performance.</u> Convective heat and moisture transfer, either via natural buoyancy or wind induced, can provide the primary mechanism, as opposed to diffusion, for moisture movement in wall systems, especially those with higher ventilation rates. Bulk water intrusion from wall/roof penetrations, plumbing leaks, etc. can be a major cause of decay and mold in wall systems. Modeling the introduction of liquid water directly into sublayers of wall systems and analyzing the wall systems hygrothermal response is essential to linking the computer simulations to the “real world” performance. In real world stucco clad wall systems, cracking of the stucco layers and inadequate drainage planes underneath, can lead to liquid water penetrating through seams, joints, and other openings in building paper/housewrap/sheathing and deep into the wall system. This water intrusion can compromise the energy efficiency of the insulation and lead to wood decay and mold formation.

These additional, potentially dominant hygrothermal effects, are not yet in the public domain programs such as the WUFI® simulation tools. The emerging multi-dimensional heat and moisture transfer research computer program developed at Oak Ridge National Laboratory (ORNL) called MOISTURE-EXPERT, has expanded hygrothermal modeling capabilities including:

- bulk water penetration directly into wall system sublayers;
- sublayer surface drainage of bulk water out of the wall system; and
- air movement over sublayers and in to and out of wall system cavities.

The referenced literature published from ORNL MOISTURE-EXPERT research shows the dramatic effect on hygrothermal performance of varying levels of water penetration and drainage, as well as air movement, in stucco clad wall systems similar to those studied in this analysis. This research by ORNL shows a complex set of interactions in which water penetration can increase OSB MC twofold or more, while drainage and air movement can each decrease the OSB MC by a factor of two or more. The ORNL researchers note that such phenomena as water penetration and drainage, and air movement, could be directly related to design and construction issues, including the "level of complexity" or "level of workmanship" associated with making the wall air and water tight. This more complex hygrothermal modeling coupled with field (or lab) measured and verified performance is needed to gain a more thorough understanding of actual wall system moisture management issues.

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Appendix A Wall Material Properties and Definitions

(Excerpted from WUFI®-Pro 4.0 (e) Online Help)

- **Bulk density** [kg/m³],
  serves to convert the specific heat by mass to the specific heat by volume.

  The bulk density ρ_{bulk} is the ratio of the mass m of the sample and the total volume V_{tot} of the sample: $\rho_{bulk} = m / V_{tot}$.
  The true density ρ_{true}, by contrast, is the ratio of the mass of the sample and the volume taken up by the material matrix only: $\rho_{true} = m / (V_{tot} - V_{pores}) = m / V_{true}$.

  The bulk density should be available for virtually every building material. If not, it can be measured very easily. Since it only affects the specific heat value entering into the calculation, and hygrothermal simulations usually don't depend very sensitively on this value, it need not be known with great precision.

- **Porosity** [m³/m³],
  determines the maximum water content w_{max} (by multiplication by ρ_{water} = 1000 kg/m³).

  Since most calculations are not sensitive to the exact value of the maximum water content (you'll rarely encounter water contents above free saturation), it is usually sufficient to estimate it if no value is available for the material in question.
  The porosity can be estimated from the true density ρ_{true} and the bulk density ρ_{bulk}:
  $\rho_{bulk} = m / V_{tot} = m / (V_{true} + V_{pores}) = \rho_{true} / (1 + V_{pores}/V_{true}) = \rho_{true} * V_{true}/V_{tot} = \rho_{true} * (1 - V_{pores}/V_{tot}) = \rho_{true} * (1 - \text{porosity})$, therefore

  $$\text{porosity} = 1 - \rho_{bulk} / \rho_{true}.$$

  ρ_{true} can in turn be estimated from other materials which have the same composition but different bulk density, if their bulk density and porosity are known. Example: a cellular concrete brick with ρ_{bulk} = 600 kg/m³ and porosity = 0.72 has ρ_{true} = 600 / (1 – 0.72) kg/m³ = 2140 kg/m³. The porosity of a cellular concrete brick with ρ_{bulk} = 400 kg/m³ can then be estimated as porosity = 1 – 400/2140 = 0.81.

- **Heat capacity** [J/kgK],
  the specific heat capacity by mass of the dry material.

  Using the specific heat capacity *by mass* has the advantage that this value only depends on the chemical composition of the material, but not on its porosity. For example, cellular concrete bricks with bulk densities of 400 kg/m³ and 600 kg/m³ have the same specific heat capacity by mass.

  To convert into heat capacity by volume (which enters into the transport equations), WUFI multiplies the mass-specific heat capacity by the bulk density.

  Rough values are 850 J/kgK for mineral materials and 1500 J/kgK for organic materials. In most cases, these estimates will be sufficient since hygrothermal simulations usually don't depend very sensitively on this value.

  WUFI automatically allows for the additional heat capacity of the water content, if any.

- **Heat conductivity dry** [W/mK],
  the heat conductivity of the material in dry condition. A moisture-dependent heat conductivity is optional.

  Please note that experimentally measured heat conductivities of vapor-permeable materials may include the effect of vapor transport with phase change (i.e. water evaporating at one side of the specimen and condensing at the other side, thus in effect transporting latent heat without a corresponding heat flow being *conducted* across the specimen). Since WUFI explicitly computes this thermal effect of vapor flow, it should *not* be included in the heat conductivity, if possible. However, it is usually difficult or impossible to separate this effect out of the measured data.

- **Diffusion resistance factor dry** [-]
  the diffusion resistance factor (μ-value) of the material in dry condition. The μ-value states by how much the diffusion resistance of the material in question is higher than that of stagnant air. A moisture-dependent μ-value is optional.

  The definition of the μ-value and its relation to permeability are discussed in Details / Water Vapor Diffusion.

  Please note that even if you do not explicitly use a moisture-dependent μ-value, WUFI will treat it as moisture-dependent for moisture contents above free saturation w_f. WUFI will reduce it in proportion to the moisture excess over w_f, until it reaches μ=0 at w_{max}. This reflects – in a first approximation - the fact that at very high moisture contents even the larger capillaries become clogged with water and can't contribute to vapor transport any more.

Water vapor diffusion resistance factor, μ-value

Diffusion of water vapor in air can be described by the equation

$g_v = -\delta * dp/dx$ (in air),

g_v	[kg/m²s]	:	water vapor flux density
p	[Pa]	:	water vapor partial pressure
δ	[kg/(msPa)]	:	water vapor diffusion coefficient in air,

where

$\delta = 2.0 \cdot 10^{-7} \; T^{0.81} / P_L$ [1]

T	[K]	:	absolute ambient temperature
P_L	[Pa]	:	ambient atmospheric pressure.

In porous building materials, diffusion likewise takes place in air (in the pore spaces), but it is impeded by the reduction of the accessible cross-section, adsorption effects at the pore walls and the tortuosity of the pore paths. In the context of building physics, it is admissible to allow for this by simply introducing a **diffusion resistance factor** μ:

$g_v = -(\delta/\mu) * dp/dx$ (in porous material),

μ	[-]	:	water vapor diffusion resistance factor.

Retaining δ as a separate coefficient in the above equation has the advantage that it already describes the temperature and pressure dependence of water vapor diffusion and μ is therefore practically independent of temperature and pressure, i.e. it is a constant which only depends on the material in question.

However, measurements of μ which are performed at different levels of relative humidity (dry-cup and wet-cup) may result in different values for one and the same material. This is due to surface diffusion which becomes noticeable at higher humidities but is more properly treated as liquid transport [2]. This additional moisture transport is usually not separated out in the analysis of the measurements and, lumped together with vapor diffusion, reduces the apparent diffusion resistance, resulting in a lower μ-value. In these cases, it is more appropriate to use a constant μ-value and to adjust the liquid transport coefficients to include surface diffusion. However, WUFI also allows to use a moisture-dependent μ-value to simplify the treatment of cases where this distinction can be neglected.

The μ-value represents the ratio of the diffusion coefficients of water vapor in air and in the building material and has therefore a simple interpretation: it is the factor by which the vapor diffusion in the material is impeded, as compared to diffusion in air. For very permeable materials, such as mineral wool, the μ-value is thus close to 1, whereas it increases for materials with greater diffusion resistance.

Vapor diffusion thickness, s_d-value

Assuming constant temperature and μ-value, the diffusion flow through a material layer with thickness $\Delta x = s$ is

$g_{v_mat} = -\delta/\mu * \Delta p/\Delta x = -\delta/(\mu * s) * \Delta p$,

whereas the diffusion flow through an air layer (μ=1) with thickness s_d is

$g_{v_air} = -\delta/\mu * \Delta p/\Delta x = -\delta/(1 * s_d) * \Delta p = -\delta / s_d * \Delta p$.

Dividing the former equation by the latter yields

$g_{v_mat} / g_{v_air} = s_d / (\mu * s)$.

If the air layer is to be chosen so that its vapor diffusion resistance is the same as that of the material layer of thickness s (and therefore $g_{v_mat} = g_{v_air}$), then its thickness s_d must be

$s_d = \mu * s$.

For a material layer with diffusion resistance factor μ and thickness s, the product $\mu * s$ thus gives the thickness which an air layer would need in order to have the same diffusion resistance. This **"s_d-value"** or **"vapor diffusion thickness"** expresses the diffusion resistance of a layer in a form which is easily understood and applied.

For some building components, only their diffusion resistance is of importance but not their μ-value and their thickness separately. They may then simply be specified in terms of their s_d-value. Also, measuring the s_d-value does not require to determine the thickness of the sample.
In particular, the s_d-value is used to characterise vapor retarders (s_d >= 10 m), vapor barriers (s_d >= 1000 m) and surface coatings (mineral paints: $s_d \approx 0.04$ m, oil paints: s_d = 1.0 .. 2.6 m), where it can be difficult to determine their thickness properly.

Permeance, Permeability

Rearranging

$g_v = -\delta/\mu * \Delta p/\Delta x$

and taking absolute values yields

$g_v/\Delta p = \delta/\mu * 1/\Delta x = \delta/s_d$ [kg/(m²sPa)].

The leftmost term is the **permeance Δ** of the layer. In Inch-Pound units the permeance is measured in **perm**. One perm is one grain (avoirdupois) of water vapor per hour flowing through one square foot of a layer, induced by a vapor pressure difference of one inch of mercury across the two surfaces. In SI units, this corresponds to 57.45e-12 kg/(m²sPa) [4]. Therefore, with Δ expressed in perm:

$57.45e\text{-}12*\Delta = \delta/s_d$ [kg/(m²sPa)], or
$s_d = \delta/(57.45e\text{-}12*\Delta)$ [m].

For a reference temperature of 5°C and a barometric pressure of 1013.25 hPa, δ has the value 1.884e-10 kg/(msPa) (see above), and we obtain

$s_d = 3.28/\Delta$,

where Δ is expressed in perm and s_d in m.

The permeance describes a property of a specific construction layer with a given thickness. Multiplying the permeance by the layer thickness Δx yields the **permeability Π** [perm in] of the layer material:

$g_v*\Delta x/\Delta p = \delta/\mu$.

The conversion factor for the left side is now 57.45e-12 [kg/(m²sPa)]/[perm] * 0.0254 [m]/[in] = 1.459e-12 [kg/(msPa)]/[perm in]:

$1.459e\text{-}12*\Pi = \delta/\mu$ [kg/(msPa)],

and with the same reference value for δ as above:

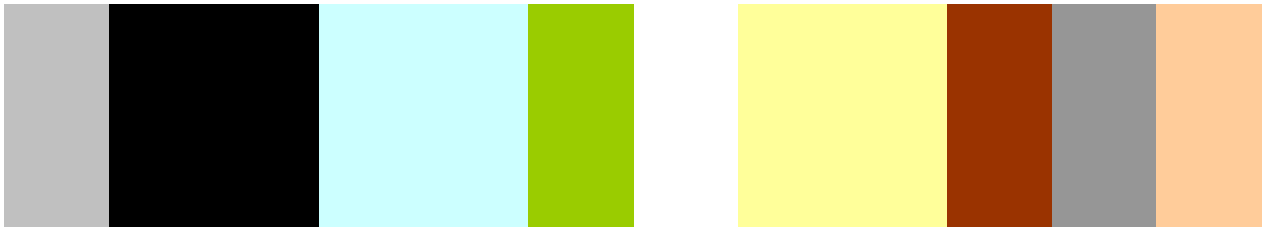
$7.744e\text{-}3*\Pi = 1/\mu$ [-], or

$\mu = 129 / \Pi$ [-],

where Π is expressed in perm inch and μ is dimensionless.

Appendix B Wall Layer Materials and Properties for the 3 Wall Types

Wall #1 -- 3 Coat Stucco
Note: material layers are not to scale (realtive or absolute)



Layer #		**1**	**2**	**3A or**	**3B or**	**3C**	**4A or**	**4B**	**5A or**	**5B or**	**5C**	**6**	**7**
Properties/Materials		conventional 3 coat stucco	building paper	building paper	higher permeance housewrap	lower permeance housewrap	OSB sheathing	without OSB sheathing	fiberglass insulation	cellulose insulation	2x4 pine	gypsum panel	paint
WUFI Data (Y=Yes, N=No)	Units	Y	Y	Y	Y/N	Y/N	Y		Y	Y	Y	Y	Y/N
Thickness	(inches)	0.8750	0.0400	0.0400	0.0055	0.0140	0.5000		3.5000	3.5000	3.5000	0.5000	0.0030
Bulk Density	(lb/ft3)	124.856	17.48	17.48	4.058	4.058	37.457		1.873	4.37	24.971	53.064	53.064
Porosity	(ft3/ft3)	0.3	0.001	0.001	0.001	0.001	0.6		0.99	0.95	0.73	0.65	0.65
Heat Capacity	(Btu/lb*F)	0.203	0.358	0.358	0.358	0.358	0.449		0.201	0.597	0.358	0.208	0.208
Heat Conductivity	(Btu/hr*ft*F)	0.693	6.94	6.94	1.387	1.387	0.058		0.02	0.023	0.052	0.094	0.094
Permeance	(perms)	5.888	23.075	23.075	58.000	6.700	0.396		28.308	24.533	0.184	42.934	7.000
Permeability (@ RH=0%)	(perm*in)	5.1520	0.9230	0.9230	0.3190	0.0938	0.1980		99.0770	85.8670	0.6440	21.4670	0.0210
Varies w/%RH (Y=Yes, N=No)		Y	Y	Y	N	N	Y		N	N	Y	Y	N

Material Modeling Variations
(1, 2 and 3) 3A, 3B, or 3C with different second layers for drainage plane
(4 and 5) 4A and 4B with and without OSB sheathing
(6, 7 and 8) 5A and 5B with different insulations, and 5C with stud

Additonal Notes on Layers
(1) Cement Plaster (stucco) from WUFI database
applied in 3 coats totaling 7/8":
3/8" scratch coat on metal mesh
3/8" brown coat
1/8" finish coat
(2) 60 Minute Building Paper from WUFI database (asphalt saturated)
(3A) 2nd layer of building paper (same as 2)
(3B) incomplete data on higher permeance housewrap (58 perms -- measured 5.5 mils)/other properties assumed for Spun Bonded Polyolefin from WUFI database-- awaiting validation
(3C) incomplete data on lower permeance housewrap (6.7 perms -- measured 14 mils)/other properties assumed for Spun Bonded Polyolefin from WUFI database-- awaiting validation
(4A) Oriented Strand Board (density 600 kg/m3 -- 37.457 lb/ft3) also available in 34.468 and 39.330 lb/ft3 densities in WUFI material database
(5A) Fibre Glass from WUFI database (open face insulation in wall cavity formed by 2x4 studs 16 inch on center in actual wall)
(5B) Cellulose Fiber (heat cond 0.04 W/mK) from WUFI database
(5C) Softwood from WUFI database
(6) Gypsum Board from WUFI database (paper faced)
(7) WUFI documentation states that there is no applicable material properties for paint itself, but rather painted surfaces
WUFI developers suggest using a thin, lower perm layer along with other gypsum drywall properties
3 mil one coat primer/two coats latex paint with 6.96 perm at 50%RH per ASHRAE Handbook of Fundamentals 2005

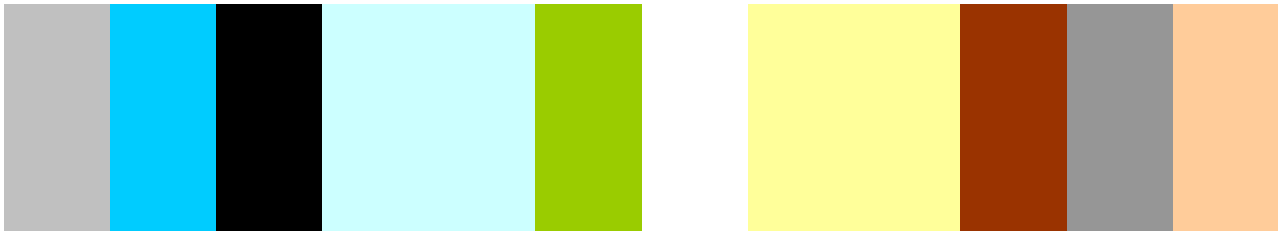
Wall #2 -- 1 Coat Stucco
Note: material layers are not to scale (realtive or absolute)

Layer #		1	2	3A or	3B or	3C	4A or	4B	5A or	5B or	5C	6	7
Properties/Materials		one (two) coat stucco	EPS	building paper	higher permeance housewrap	lower permeance housewrap	OSB sheathing	without OSB sheathing	fiberglass insulation	cellulose insulation	2x4 pine stud	gypsum panel	paint
WUFI Data (Y=Yes, N=No)	Units	Y		Y	Y/N	Y/N	Y/N		Y	Y	Y	Y	Y/N
Thickness	(inches)	0.500	1.000	0.040	0.0055	0.0140	0.500		3.500	3.500	3.5000	0.500	0.003
Bulk Density	(lb/ft3)	124.856	1.6	17.48	4.058	4.058	37.457		1.873	4.37	24.971	53.064	53.064
Porosity	(ft3/ft3)	0.3	0.95	0.001	0.001	0.001	0.6		0.99	0.95	0.73	0.65	0.65
Heat Capacity	(Btu/lb*F)	0.203	0.29	0.358	0.358	0.358	0.449		0.201	0.597	0.358	0.208	0.208
Heat Conductivity	(Btu/hr*ft*F)	0.693	0.2	6.94	1.387	1.387	0.058		0.02	0.023	0.052	0.094	0.094
Permeance	(perms)	10.304	1.000	23.075	58.000	6.700	0.396		28.308	24.533	0.184	42.934	7.000
Permeability (@ RH=0%)	(perm*in)	5.1520	1.0000	0.9230	0.3190	0.0938	0.1980		99.0770	85.8670	0.6440	21.4670	0.0210
Varies w/%RH (Y=Yes, N=No)		N	N	Y	N	N	Y		N	N	Y	Y	N

Material Modeling Variations
(1, 2 and 3) 3A, 3B, or 3C with different second layers for drainage plane
(4 and 5) 4A and 4B with and without OSB sheathing
(6, 7 and 8) 5A and 5B with different insulations, and 5C with stud

Additonal Notes on Layers
(1) Cement Plaster (stucco) from WUFI database
applied in 2 coats totaling 1/2":
3/8" base coat on metal mesh
1/8" finish coat
(2) incomplete EPS data (perm-in = 1.0, density 1.6 lb/ft3, conductivity 0.2 Btu/hr-ft2-F)/heat capacity from ASHRAE HOF/porosity for XPS Core in WUFI database -- awaiting validation
(3A) 60 Minute Building Paper from WUFI database (asphalt saturated)
(3B) incomplete data on higher permeance housewrap (58 perms -- measured 5.5 mils)/other properties assumed for Spun Bonded Polyolefin from WUFI database-- awaiting validation
(3C) incomplete data on lower permeance housewrap (6.7 perms -- measured 14 mils)/other properties assumed for Spun Bonded Polyolefin from WUFI database-- awaiting validation
(4A) Oriented Strand Board (density 600 kg/m3 -- 37.457 lb/ft3) also available in 34.468 and 39.330 lb/ft3 densities in WUFI material database
(5A) Fibre Glass from WUFI database (open face insulation in wall cavity formed by 2x4 studs 16 inch on center in actual wall)
(5B) Cellulose Fiber (heat cond 0.04 W/mK) from WUFI database
(5C) Softwood from WUFI database
(6) Gypsum Board from WUFI database (paper faced)
(7) WUFI documentation states that there is no applicable material properties for paint itself, but rather painted surfaces
WUFI developers suggest using a thin, lower perm layer along with other gypsum drywall properties
3 mil one coat primer/two coats latex paint with 6.96 perm at 50%RH per ASHRAE Handbook of Fundamentals 2005

Wall #3 -- EIFS
Note: material layers are not to scale (realtive or absolute)



Layer #		1	2	3A or	3B or	3C	4A or	4B	5A or	5B or	5C	6	7
Properties/Materials		top coat acrylic resin stucco	EPS	building paper	higher permeance housewrap	lower permeance housewrap	OSB sheathing	without OSB sheathing	fiberglass insulation	cellulose insulation	2x4 pine	gypsum panel	paint
WUFI Data (Y=Yes, N=No)	Units	Y		Y	Y/N	Y/N	Y/N		Y	Y	Y	Y	Y/N
Thickness	(inches)	0.125	1.000	0.040	0.0055	0.0140	0.500		3.500	3.500	3.5000	0.500	0.003
Bulk Density	(lb/ft3)	68.671	1.6	17.48	4.058	4.058	37.457		1.873	4.37	24.971	53.064	53.064
Porosity	(ft3/ft3)	0.12	0.95	0.001	0.001	0.001	0.6		0.99	0.95	0.73	0.65	0.65
Heat Capacity	(Btu/lb*F)	0.203	0.29	0.358	0.358	0.358	0.449		0.201	0.597	0.358	0.208	0.208
Heat Conductivity	(Btu/hr*ft*F)	0.404	0.2	6.94	1.387	1.387	0.058		0.02	0.023	0.052	0.094	0.094
Permeance	(perms)	1.032	1.000	23.075	58.000	6.700	0.396		28.308	24.533	0.184	42.934	7.000
Permeability (@ RH=0%)	(perm*in)	0.1290	1.0000	0.9230	0.3190	0.0938	0.1980		99.0770	85.8670	0.6440	21.4670	0.0210
Varies w/%RH (Y=Yes, N=No)		Y	N	Y	N	N	Y/N		N	N	Y	Y	N

Material Modeling Variations
(1, 2 and 3) 4A, 4B, or 4C with different second layers for drainage plane
(4 and 5) 4A and 4B with and without OSB sheathing
(6, 7 and 8) 5A and 5B with different insulations, and 5C with stud

Additonal Notes on Layers
(1) Resin Finishing Coat (acrylic stucco) from WUFI database
applied over a resin coated, fiberglass mesh
(2) incomplete EPS data (perm-in = 1.0, density 1.6 lb/ft3, conductivity 0.2 Btu/hr-ft2-F)/heat capacity from ASHRAE HOF/porosity for XPS Core in WUFI database -- awaiting validation
(3A) 2nd layer of building paper (same as 2)
(3B) incomplete data on higher permeance housewrap (58 perms -- measured 5.5 mils)/other properties assumed for Spun Bonded Polyolefin from WUFI database-- awaiting validation
(3C) incomplete data on lower permeance housewrap (6.7 perms -- measured 14 mils)/other properties assumed for Spun Bonded Polyolefin from WUFI database-- awaiting validation
(4A) Oriented Strand Board (density 600 kg/m3 -- 37.457 lb/ft3) also available in 34.468 and 39.330 lb/ft3 densities in WUFI material database
(5A) Fibre Glass from WUFI database (open face insulation in wall cavity formed by 2x4 studs 16 inch on center in actual wall)
(5B) Cellulose Fiber (heat cond 0.04 W/mK) from WUFI database
(5C) Softwood from WUFI database
(6) Gypsum Board from WUFI database (paper faced)
(7) WUFI documentation states that there is no applicable material properties for paint itself, but rather painted surfaces
WUFI developers suggest using a thin, lower perm layer along with other gypsum drywall properties
3 mil one coat primer/two coats latex paint with 6.96 perm at 50%RH per ASHRAE Handbook of Fundamentals 2005

Appendix C WUFI® Analysis Files

These groups of electronic files are contained in a companion CD.

WUFI®-Pro 4.0 (e) Project Data Input Files

Name	Size	Type
MtShasta Wall1-3A4A5A.W4P	22,672 KB	WUFI® 4-Project
MtShasta Wall1-3A4A5B.W4P	22,672 KB	WUFI® 4-Project
MtShasta Wall1-3B4A5A.W4P	22,810 KB	WUFI® 4-Project
MtShasta Wall1-3C4A5A.W4P	22,810 KB	WUFI® 4-Project
MtShasta Wall2-3A4A5A.W4P	22,672 KB	WUFI® 4-Project
MtShasta Wall2-3B4A5A.W4P	22,672 KB	WUFI® 4-Project
MtShasta Wall2-3C4A5A.W4P	22,810 KB	WUFI® 4-Project
MtShasta Wall3-3A4A5A.W4P	21,843 KB	WUFI® 4-Project
MtShasta Wall3-3B4A5A.W4P	21,843 KB	WUFI® 4-Project
MtShasta Wall3-3C4A5A.W4P	21,982 KB	WUFI® 4-Project

To recreate any of the runs from this analysis, use the corresponding wall system project file above for Mt. Shasta. For runs in the other 15 cities, simply substitute one of the other weather data input files (both the .try and .agd files) listed on the next page. Also adjust the interior relative humidity conditions for the Indoor Climate Sine Curve per the table below with the Day of Maximum on 8/1.

CZ	City	Mean RH Value (%)	+/- Amplitude
1	Arcata	46.2	4.4
2	Santa Rosa	46.1	5.1
3	Oakland	47.8	6.4
4	Sunnyvale	48.3	6.9
5	Santa Maria	43.9	7.4
6	Los Angeles	50.3	9.7
7	San Diego	51.3	8.7
8	El Toro	46.8	11.4
9	Pasadena	44.5	12.0
10	Riverside	45.6	11.6
11	Red Bluff	42.1	6.1
12	Sacramento	46.7	7.3
13	Fresno	44.6	6.9
14	China Lake	43.7	6.7
15	El Centro	47.1	12.9
16	Mount Shasta	37.6	9.7

The interior temperature conditions for all the cities are 73 ^{o}F +/- 3 ^{o}F and peaks at 76 ^{o}F on 8/1. The RH values in the table are based on an ambient climate analysis for each city and resulting interior RH levels when the interior temperature is 70 ^{o}F October through March and 76 ^{o}F April through September, with 5 additional RH percentage points added form internal moisture generation. Interior RH was limited to 60 %RH. **Note that interior RH assumptions have a major bearing on the resulting wall MC and surface RH results.**

METENORM® Generated WUFI® Weather Data Input Files

Name	Size	Type
Arcata.try	703 KB	TRY File
Arcata.try.agd	1 KB	AGD File
ChinaLake.try	703 KB	TRY File
ChinaLake.try.agd	1 KB	AGD File
ElCentro.try	703 KB	TRY File
ElCentro.try.agd	1 KB	AGD File
ElToro.try	703 KB	TRY File
ElToro.try.agd	1 KB	AGD File
Fresno.try	703 KB	TRY File
Fresno.try.agd	1 KB	AGD File
LosAngeles.try	703 KB	TRY File
LosAngeles.try.agd	1 KB	AGD File
MountShasta.try	703 KB	TRY File
MountShasta.try.agd	1 KB	AGD File
Oakland.try	703 KB	TRY File
Oakland.try.agd	1 KB	AGD File
Pasadena.try	703 KB	TRY File
Pasadena.try.agd	1 KB	AGD File
RedBluff.try	703 KB	TRY File
RedBluff.try.agd	1 KB	AGD File
Riverside.try	703 KB	TRY File
Riverside.try.agd	1 KB	AGD File
Sacramento.try	703 KB	TRY File
Sacramento.try.agd	1 KB	AGD File
SanDiego.try	703 KB	TRY File
SanDiego.try.agd	1 KB	AGD File
SantaMaria.try	703 KB	TRY File
SantaMaria.try.agd	1 KB	AGD File
SantaRosa.try	703 KB	TRY File
SantaRosa.try.agd	1 KB	AGD File
Sunnyvale.try	703 KB	TRY File
Sunnyvale.try.agd	1 KB	AGD File

WUFI® Generated Output Data in Excel® Spreadsheet Files

Name	Size	Type
All CZ Cities for Wall 1-3A4A5B.xls	85,329 KB	Microsoft Excel Worksheet
All CZ Cities for Wall 1-3C4A5A.xls	85,331 KB	Microsoft Excel Worksheet
Mt Shasta for All Walls.xls	53,548 KB	Microsoft Excel Worksheet

These files contain the 8760 hour datasets used to produce the tables and figures in this report, plus more much wall system data not reported here.