RESEARCH REPORT

COMPARISON OF MODELED AND MONITORED PERFORMANCE OF A WALL INSULATION RETROFIT IN A SOLID MASONRY BUILDING

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Comparison of Modeled and Monitored Performance of a Wall Insulation Retrofit in a Solid Masonry Building

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Executive Summary

In 1996, CMHC participated in the renovation of a four storey, solid masonry building located in Prince Albert, Saskatchewan. As CMHC was asked to invest heavily in the building renovation under the Rental Repair Assistance Program, the Corporation initiated a research project to determine whether or not the renovation strategy, which involved the addition of insulation on the interior of the solid masonry walls, represented technically sound practice. Many architects, renovators and building owners are wary of interior insulation retrofits within solid masonry structures as the practice is thought to increase the likelihood of wall failures due to freeze thaw cycles, structural stresses and interstitial condensation.

In order to assess the degree to which these concerns were valid, the performance of the building envelope was monitored over the first year of operation upon completion of the building envelope retrofit. Temperature, relative humidity, thermal flux, and air pressures were monitored in several locations through the building envelope in order to provide sufficient data to allow for an assessment of the heat, air and moisture performance of the exterior walls. By all indications, the walls are performing well with none of the aforementioned concerned realized.

Another motivation of the collection of the wall monitoring data was to use the data to test the predictive capability of computerized hygrothermal models. Furthermore, once the model(s) were reconciled with the monitoring data, CMHC was interested in undertaking an evaluation of the renovation strategy under different outdoor environmental conditions and to study the performance of the wall system given different boundary conditions. In this way, an indication of the advisability of the interior application of insulation in solid masonry structures could be assessed for other climate situations.

The following research project was undertaken to assess the predictive capability of a computerized hygrothermal model given the extensive monitoring of heat, air and moisture and environmental conditions in an actual building retrofit and to assess the risk associated with the application of insulation on the interior of solid masonry structures under various outdoor environmental conditions. The simulation program WUFI was used in conjunction with the monitored site weather and indoor environmental conditions, in a blind assessment to predict the heat, air and moisture conditions in the wall assembly over the course of a year. The output of the model was compared to the actual monitoring data. Reasons for any significant derivations were assessed in terms of both the capabilities of the model and the strengths and weaknesses of the monitoring protocol.

The simulation model was reconciled with the monitoring data. The model was then used to assess the hygrothermal performance of the wall sections. This information was used to determine whether or not the resultant heat, air and moisture conditions in the walls could be of concern over the longer term. After some adjustments were made to account for air movement, uncertainty of the permeance of the stucco, and the amount of hygric mass provided by the wood lath, a reasonable agreement between the modeled and the monitored results was reached.

In the cases considered, the results of the modeling suggested that the moisture in the walls was trending towards an annual equilibrium (i.e. there was no net gain or loss in moisture over the course of a year). These trends seem to be confirmed by the results of the monitoring. In those cases where the wall is subjected to brief wetting periods, it

does dry out and hence no long-term moisture accumulation is predicted. A number of important lessons were also learned regarding future monitoring/modelling projects that can serve to guide the development and execution of heat, air and moisture evaluation projects.

At this stage in the development of hygrothermal modelling, the quality of the predictions are highly dependent on the experience and expertise of the analysts. This project, for example, required certain derived material properties, the generation of detailed exterior boundary conditions, an understanding of interior conditions and a practical appreciation of the effects of building flaws (such as air leakage and rain penetration).

Résumé

En 1996, la SCHL a participé à la rénovation d'un bâtiment de quatre étages en maçonnerie massive situé à Prince Albert, en Saskatchewan. Comme on a demandé à la SCHL de procéder à une injection massive de fonds en application du Programme d'aide à la remise en état des logements, la Société a décidé de procéder à une étude devant permettre de déterminer si la stratégie de rénovation envisagée, qui comportait l'ajout d'isolant sur l'intérieur des murs en maçonnerie massive, constituait une pratique recommandable sur le plan technique. Il faut savoir que bien des architectes, rénovateurs et propriétaires d'immeubles hésitent à refaire l'isolation des structures en maçonnerie massive par l'intérieur, car on croit que ce procédé peut favoriser les défaillances murales résultant des cycles de gel et de dégel, des contraintes structurales et de la condensation interstitielle.

Afin d'évaluer dans quelle mesure ces préoccupations étaient justifiées, nous avons observé la performance de l'enveloppe du bâtiment au cours de la première année suivant la rénovation de l'enveloppe. Les paramètres de température, d'humidité relative, de flux de chaleur et de pression d'air ont été contrôlés à divers points dans l'enveloppe du bâtiment en vue de produire suffisamment de données pour permettre d'évaluer la performance des murs extérieurs relativement à la chaleur, à l'air et à l'humidité. Selon toute vraisemblance, les murs se comportent bien et ne présentent aucun des problèmes que l'on appréhendait.

Les données faisant suite au contrôle des murs ont aussi été recueillies pour déterminer le pouvoir de prédiction de certains modèles hygrothermiques informatisés. De plus, une fois que les données issues des modèles ont été rapprochées avec les données de contrôle, la SCHL a voulu procéder à une évaluation, dans diverses conditions climatiques, de la stratégie de rénovation employée et étudier la performance des murs dans différentes conditions aux limites. Elle espérait ainsi pouvoir établir si l'application par l'intérieur d'un isolant dans des structures de maçonnerie massive était recommandable dans d'autres contextes climatiques.

L'étude dont il est ici question a été entreprise pour évaluer le pouvoir de prédiction d'un modèle hygrothermique informatisé dans un contexte de surveillance étendue de la chaleur, de l'air et de l'humidité de même que des conditions environnementales en situation de rénovation réelle, puis pour évaluer le risque associé à l'application d'isolant sur l'intérieur des structures de maçonnerie massive dans diverses conditions climatiques. Le programme de simulation appelé WUFI a été utilisé en concomitance avec la mesure des conditions climatiques et de l'ambiance intérieure propres au bâtiment à l'étude, lors d'une évaluation à l'aveugle visant à prédire les conditions de chaleur, d'air et d'humidité dans l'assemblage mural au cours d'une année. Les résultats obtenus par le modèle ont été comparés aux données de contrôle réelles. Tout écart important a été expliqué en fonction des capacités du modèle ainsi que des forces et des faiblesses du protocole de contrôle.

On a effectué un rapprochement entre les résultats obtenus avec le modèle de simulation et les données de contrôle. On a ensuite utilisé le modèle pour évaluer la performance

hygrothermique de sections murales. Cette information a servi à déterminer si les conditions résultantes de chaleur, d'air et d'humidité dans les murs pouvaient être préoccupantes à long terme. Après quelques réglages effectués pour tenir compte du mouvement de l'air, de l'incertitude quant à la perméance du stucco et de la masse hygrique des lattes en bois, on a pu obtenir une correspondance raisonnable entre les résultats obtenus avec le modèle et ceux recueillis lors de la surveillance des conditions réelles.

Dans les cas qui ont été observés, les résultats de la modélisation portent à croire que l'humidité dans les murs avait tendance à s'équilibrer sur un an (c'est-à-dire qu'on ne constatait ni gain net ni perte nette d'humidité durant l'année). Ces tendances semblent être confirmées par les résultats du contrôle. Dans les cas où le mur est soumis à de brèves périodes de mouillage, il parvient à sécher et aucune accumulation d'humidité n'est à prévoir à long terme. On a pu tirer des leçons importantes de l'expérience en ce qui concerne les futurs projets de contrôle et de modélisation qui pourraient servir à guider la conception et la réalisation d'études d'évaluation de la chaleur, de l'air et de l'humidité.

À ce stade de la mise au point de la modélisation hygrothermique, la qualité des prédictions dépend dans une large mesure de l'expérience et de l'expertise des analystes. La présente étude, par exemple, a exigé de ceux-ci qu'ils établissent les propriétés de certains matériaux sur la base de mesures publiées pour des matériaux similaires, qu'ils produisent des conditions aux limites extérieures détaillées, qu'ils soient à même de bien saisir les conditions intérieures et qu'ils puissent comprendre concrètement les effets des vices de construction (tels que les fuites d'air et les infiltrations de pluie).

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Table of Contents

Table of Figures

1. Introduction

CMHC awarded a contract to compare the heat and moisture performance of an upgraded solid masonry wall as predicted by a computer model with the results of a previous field measurement project. The intent was not to benchmark the computer model, but to determine whether or not computer modelling/simulations can be useful in the design and analysis of building enclosures. In this project results from computer simulations are compared to monitored hygrothermal data from a real building retrofit to demonstrate the benefits and limitations of computer modelling. Where the modelling was unable to predict the measured trends, potential reasons were sought to explain the disagreement. This report summarises the project, the results, and provides conclusions and recommendations for future computer modelling work.

1.1 Background

The Building Performance Section of the Saskatchewan Research Council (SRC) monitored temperature, moisture and heat flow conditions within the walls of a retrofit apartment building located in Prince Albert Saskatchewan. The four-storey building was constructed in 1910 with solid exposed clay brick masonry walls and an interior finish of wood lath and plaster. As part of the 1996/97 retrofit, the exterior walls were modified: a 2x4 frame was added and filled with batt insulation and a polyethylene-drywall air barrier assembly was added to the interior. A lime-cement stucco was applied to the exterior of all but the north street-facing side (for aesthetic / historical preservation reasons).

A total of 96 temperature, Relative Humidity (RH), wood moisture content, air pressure, and heat flow sensors were frequently measured and averages were stored at ½ hour intervals for 15 months starting in August 1997. A weather station recorded wind speed, direction, rainfall, temperature, RH, and solar radiation on a horizontal surface.

Most of the information used in the present project was based on the reports generated by the Saskatchewan Research Council. These reports, along with part of the appendices of the report titled *The Renovation of an Apartment Building with Solid Masonry Walls*, dated October 1999 are collectively called the monitoring reports in the rest of this document. Additional information was provided by Mr Snodgrass of the SRC, via email and phone responses to the authors' questions. This assistance is gratefully acknowledged.

This report begins with a review of computer modelling and the specific data input requirements for this project. The modelling results and their interpretation are discussed in the following section, followed by recommendations and conclusions.

2. Modelling

Hygrothermal modelling, like most building simulations, is an iterative process that comprises a problem definition (in this case, to predict the performance of a specific wall assembly under specific conditions), a model, and interpretation of the results (Figure 2.1). The Physics and Numerics are typically provided as part of a computer model. The Topology, or arrangement and relationship of each of the material layers, the material properties, and the boundary conditions are all input by the analyst, although the accuracy of this input may be limited by the design of the computer model. The accuracy of a model (the major interest of this project) can be limited by any of the elements, but in modern models is typically limited by the Material Property, Topology, and Boundary Condition inputs to the model. The physics are not a serious issue in most for cases for most modern models, and the numerical solution technique affects speed or ability to find a solution more than accuracy.

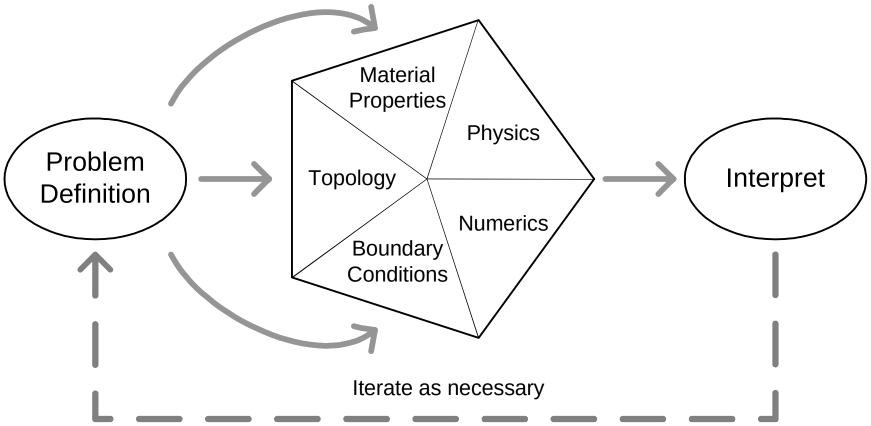


Figure 2.1: Modelling Process

A one-dimensional WUFI Pro 3.2 model was employed for most of the modelling. This is one of the most advanced commercially available hygrothermal moisture programs in use today. Its accuracy has been verified (by the Fraunhofer Institut Bauphysik in Holzkirchen, Germany – www.wufi.de) against numerous full-scale field studies of enclosure performance (roofs, walls, foundations, parking garage decks, etc.) over a number of years. Much of the field verification work supporting the model has been solid masonry and stone wall systems. It is also one of the few models that can properly account for rain absorption.

To provide a comparison, a second model, DELPHIN, was used. This model allows for a wider range of choices in the form of the physics, boundary conditions, and material properties used. It is, however, essentially a research tool and as such is less user-friendly than WUFI Pro. The model has the major advantage that airflow can be modelled in two-dimensions, although we found it almost impossible to find reliable air permeance material properties or to identify a limited but reasonable number of possible air flow paths or air pressure boundary conditions. Hence, for this project, the one-dimensional version was used.

An assembly is “built” in a model by defining each layer, the number of elements per layer (more elements typically means greater accuracy and slower calculation), its thickness, and the appropriate material data (density, porosity, thermal conductivity, moisture storage, vapour permeability, and liquid/ adsorbate permeability). The interior and exterior boundary conditions (temperature, RH, solar radiation, and rain) are identified, and the starting hygrothermal conditions are entered. Finally, the model (WUFI or DELPHIN) calculates heat and moisture flow for each time step (typically hourly) under the influence of sun, rain, temperature and humidity. Both of the one-D models assume a perfectly airtight building enclosure.

In general, most of the modelling effort was expended collecting and synthesising the input data required for modelling, i.e., defining the building sections, interpreting the monitored data, creating boundary condition files, and entering appropriate material property data. Less effort was required to actually model the wall assemblies. This is typical of the authors’ experience in computer modelling building assemblies.

The building sections, boundary conditions, and material property data used for the simulations are described in the following sections.

2.1 Building Sections

The results presented here are based on a one-dimensional model. This is a major simplification. Although the one-dimensional model provides a good representation of the field of a solid masonry wall, it is not capable of predicting the conditions at irregularities such as beam pockets and floor or roof intersections.

The authors chose to focus on the wall section at location NW4 – a west-facing wall on the fourth floor, near the North corner. This location is exposed to the street, seemed to have reliable measured data, and is the most exposed part of the building (according to the photographs and commentary in the monitoring report).

Initial attempts were made to model location NW4 using only the information provided in the monitoring report. This “blind” analysis was intended to examine how well a typical well-informed analyst would proceed. The SRC was subsequently contacted, and additional information was sought. Drawings in the monitoring report suggested that the space behind the wood lath was filled with insulation. Discussions with SRC confirmed that this was not the case and modelling proceeded with an air gap between the masonry and the new insulated wall. This assembly is shown in Figure 2.2. Note that there is no plaster attached to the wood lath in the assembly on the fourth floor. There is also no paint on the parge coat.

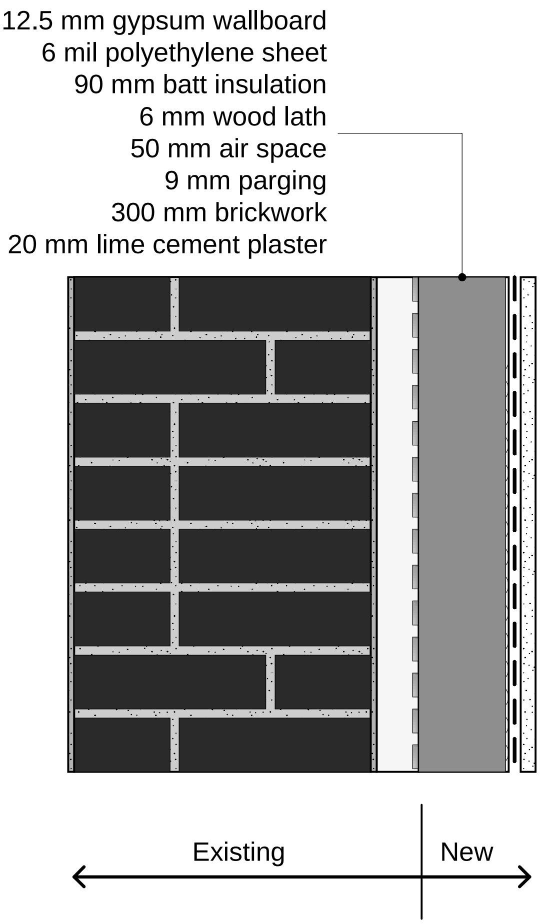


Figure 2.2:Typical Retrofit Wall System (NW4)

Most of the simulation results presented here are based on the revised information.

Clearly, the air space between the masonry and the insulated wood frame allows air leaks that may occur through the polyethylene-drywall air barrier assembly (or exterior masonry) to move freely around the building within the plane of the wall. This could be especially important at corners (due to the large exterior pressure gradients) and may, in fact, allow stack pressures to drive air from below upward through the building.

Later, the response of NW4 was compared to data for NW1, which is lower on the building (and hence much more sheltered) has thicker masonry, and according to SRC, had the inner plaster layer still intact (Figure 2.3). Monitoring location N4, a north-facing wall without an exterior stucco-coating, allowed for another set of simulations and comparisons. Note that the east wall (typically the worst orientation for driving rain in Prince Albert) is protected for the first two floors by an abutting building, and the neighbouring buildings also provide shelter. For this reason east-facing walls were not modelled.

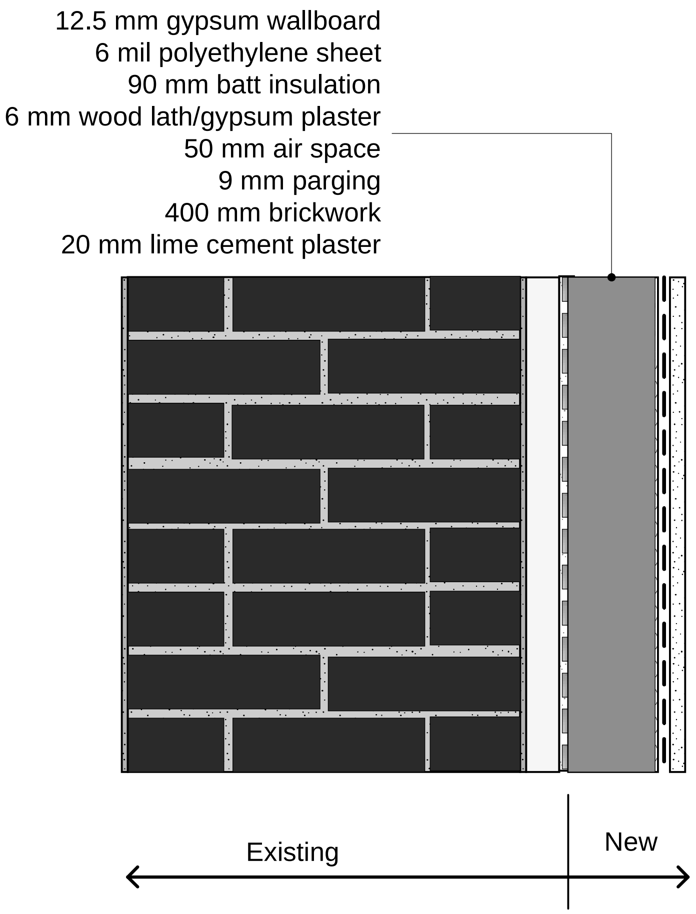


Figure 2.3: Wall NW1 (note plaster and thicker masonry)

2.2 Boundary Conditions

For the majority of building simulations, the analyst must find a year-long hourly weather record which contains sufficient information and is collected at a location similar to that of the subject building. In this case, the weather conditions were recorded at ½ hr records for 15 months. The monitored data provided on CD by CMHC was comprehensive and fairly complete. A map of the surrounding 1 km and many photographs of the exterior facades, of the approaches to each face, and of instrument location would be preferred in the future.

No standard set of moisture design weather files has been developed; hence none are available to practitioners. Energy files are widely available for many locations and, with the use of long-term or average rainfall data, can be adapted for use in moisture calculations. To consider the impact of choosing a weather record from publicly available files, the Canadian Weather year for Energy Calculations (CWEC) file for an available location most similar to Prince Albert (North Battleford, SK) was investigated. This is the approach that would likely be currently taken in the design of a similar building.

2.2.1 Temperature and Humidity

Air temperature and humidity have long been measured at many locations around the world. These variables also do not change significantly around most buildings. Therefore, the conditions measured at the roof weather station were directly entered into the weather file.

Figure 2.4 plots the temperature and relative humidity of the measured Prince Albert site. Figure 2.5 plots the same information for the synthetic CWEC data file. It can be seen that the data are different although quite similar in trends.

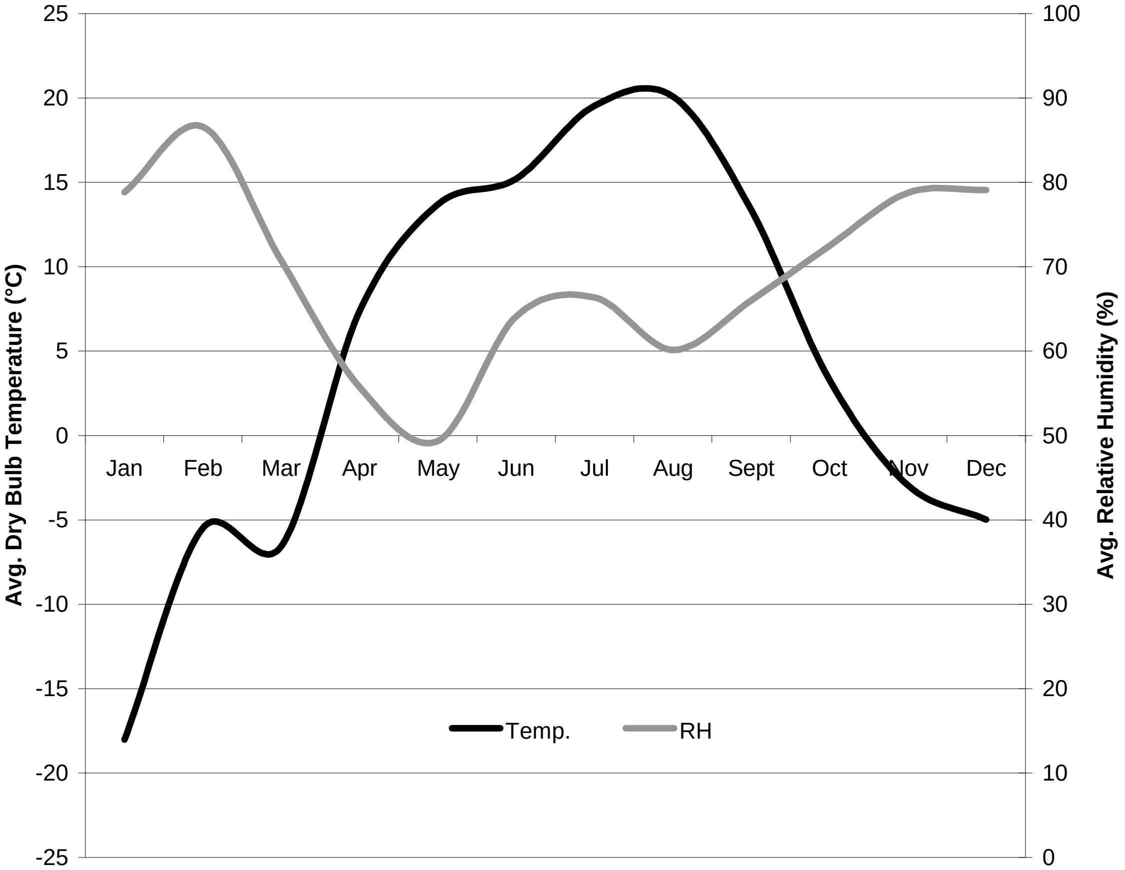


Figure 2.4: Monitored Prince Albert Data

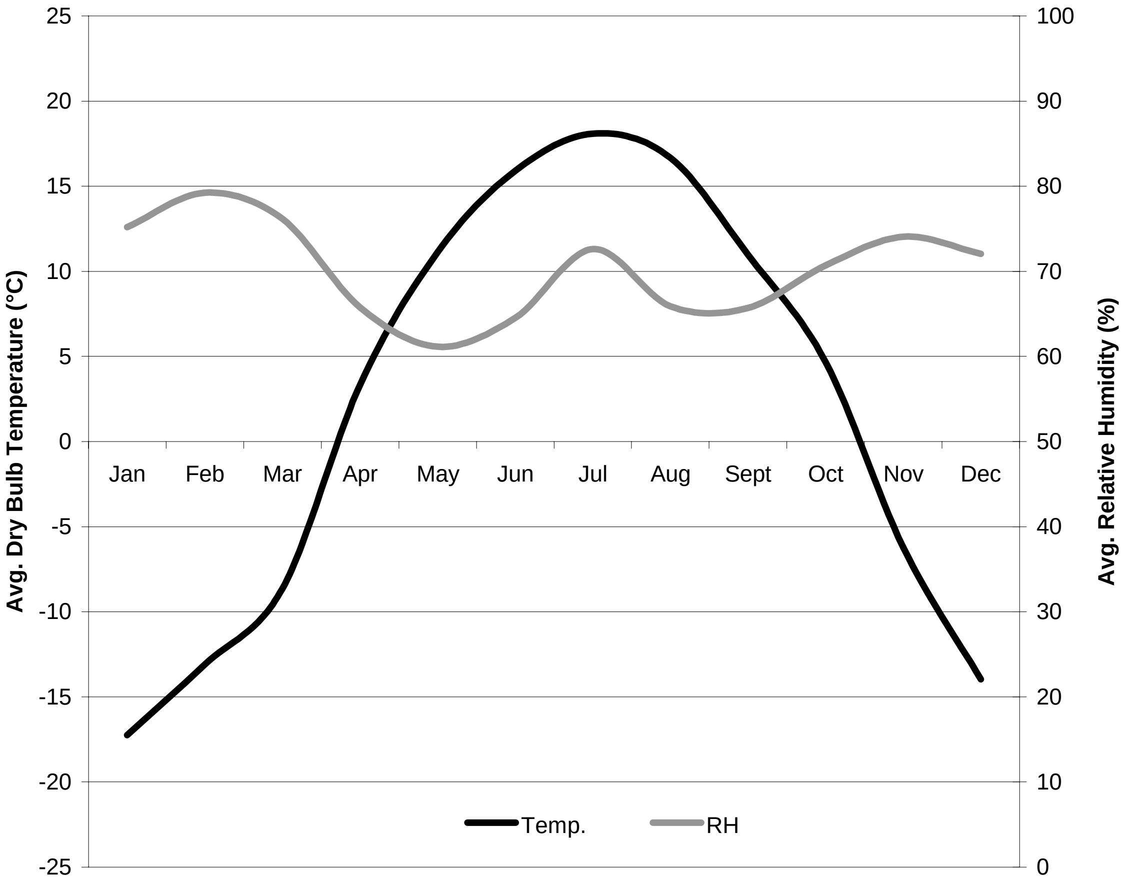


Figure 2.5: CWEC Data for North Battleford, SK

All detailed computer models require boundary conditions on the surface of the enclosure. This means that weather data and monitored data (other than temperature and RH) must be converted from the plane of the weather station to that of the enclosure element being modelled. Some models perform these transformations internally (e.g. WUFI 3.0 ORNL/IBP) but in doing so they must make certain assumptions. In this case, to improve accuracy, weather files were generated specifically for each face of the building.

The ½ hourly temperature and relative humidity used for all of the simulations are shown in Figure 2.6 and Figure 2.7. The daily cycles of temperature can be seen in these figures along with the general trends.

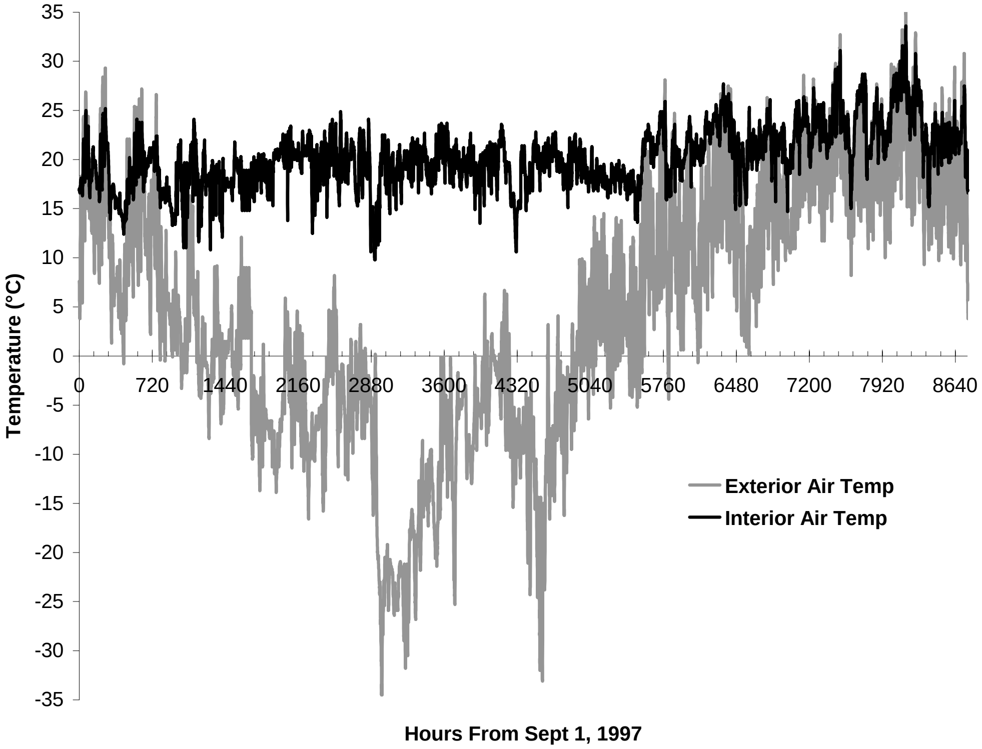


Figure 2.6: Temperatures Measured and Used as Boundary Conditions

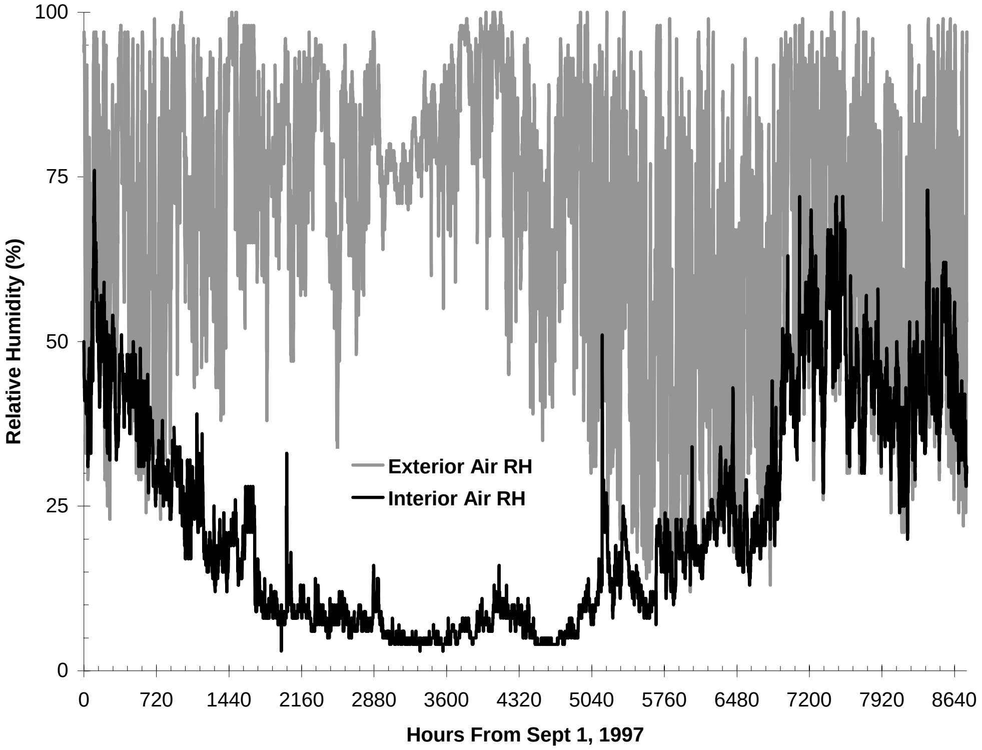


Figure 2.7: Relative Humidities Measured and Used as Boundary Conditions (NW4)

2.2.2 Surface Transfer Coefficients

The transfer of heat and mass from the air adjacent to an enclosure element is not perfect. Equivalent surface transfer coefficients are used to account for the combined conduction, convection and radiation effects. In all of the simulations, interior and exterior heat transfer coefficients of 7.7 W/m^2K and 17.8 W/m^2K respectively were used. Both of these coefficients are valid for average, (not extreme) conditions. The mass transfer coefficients are generally very high relative to the resistance of the materials (e.g. a permeance of 15 000 -75 000 metric perms). In this case they were set to infinity.

2.2.3 Solar Radiation

Solar radiation plays a significant role in the performance of most assemblies. The daily heating created by the sun can reduce the potential for exfiltration wetting, increase drying, and cause inward vapour drives. As part of the SRC monitoring, the total horizontal solar radiation was measured on the roof. This data needed to be modified for each orientation.

Calculating the radiation that would hit an arbitrary wall surface using only this measured data requires the splitting of the total radiation into direct and diffuse components. The solar radiation was calculated using Hottel’s model and Liu & Jordan's empirical relationship between the transmission coefficient for beam and diffuse radiation (tauD) for clear days. (These models are described in *Solar Engineering of Thermal Processes*, by Duffie and Beckman and the *ASHRAE Handbook of Fundamentals*). It was found that the published correlations (i.e., Stauter and Klein's) do not properly predict the diffuse to total radiation under low angle sun (i.e., during sunrise and sunset). This is an important issue in a northern climate that is exposed to many hours of low altitude sun.

A correction was developed and applied to existing methods to facilitate the generation of realistic solar radiation on the four faces of the building on a ½ hourly basis. For solar altitudes below 10 degrees, the diffuse horizontal radiation on a horizontal surface was found to be equal to Cosine of (7.84 * solar altitude) * Measured Total Radiation on a horizontal. It was assumed that there was no ground reflection of solar radiation, although some reflection always occurs. In this case there was not sufficient information to make estimates of reflection, so it was ignored. The measured total horizontal radiation and the resulting predicted solar radiation for each orientation are plotted in Figure 2.8. Measurement of radiation on the surface being monitored would have dramatically lowered the effort required and reduced the need for assumptions.

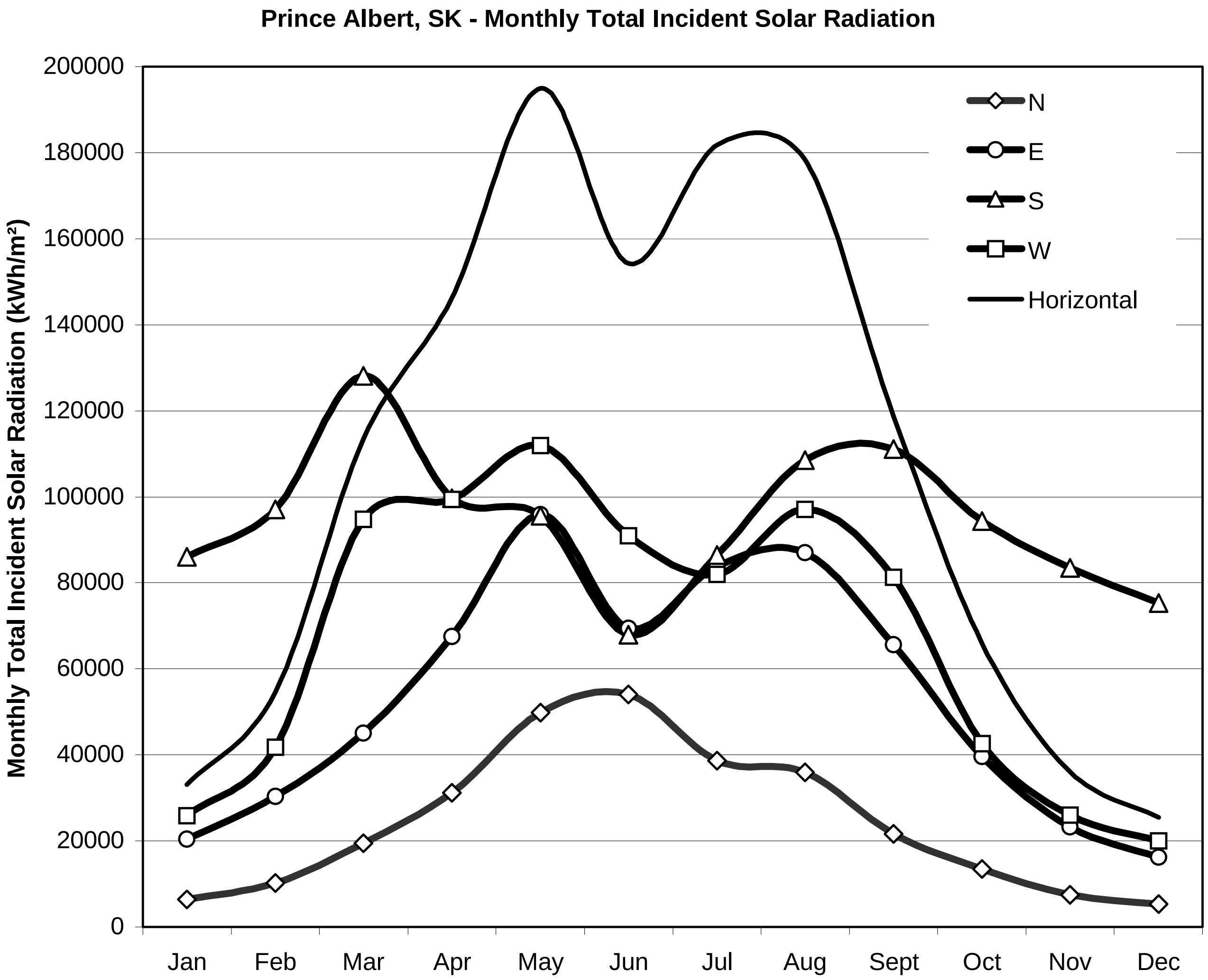


Figure 2.8: Monitored and Calculated Incident Solar Radiation

2.2.4 Driving Rain

Driving rain data was generated from the monitored wind speed, wind direction, and rainfall data. Methods developed earlier by the authors and presently being proposed for ASHRAE SPC 160P were used. Driving rain deposition varies with location on the building, and this is accounted for by a rain deposition factor (RDF). For exposed, blunt-edged buildings a value of around 1.0 is suggested for upper edges of buildings and a value of around 0.3 to 0.5 for middle parts. A RDF equal to one was used for NW4 and N4 and a RDF of 0.3 was used for NW1 and other lower floor locations. The amount of deposition was simply cosine corrected for wind direction.

The driving rain in the free wind was calculated for North Battleford using CWEC files and for Prince Albert using the monitored data. The total quantity of driving rain was not dissimilar, but the peak directions were quite different. The north and southeast faces receive the most rain in the CWEC file, whereas the east face receives the most based on the monitored data.

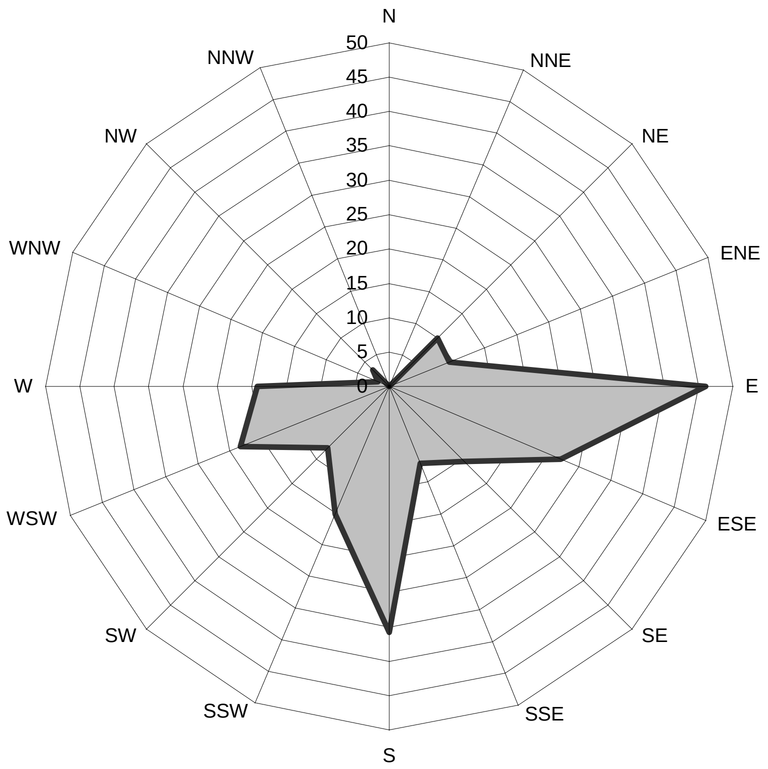


Figure 2.9: Driving Rain Calculated From Monitored Prince Albert Data (mm/yr)

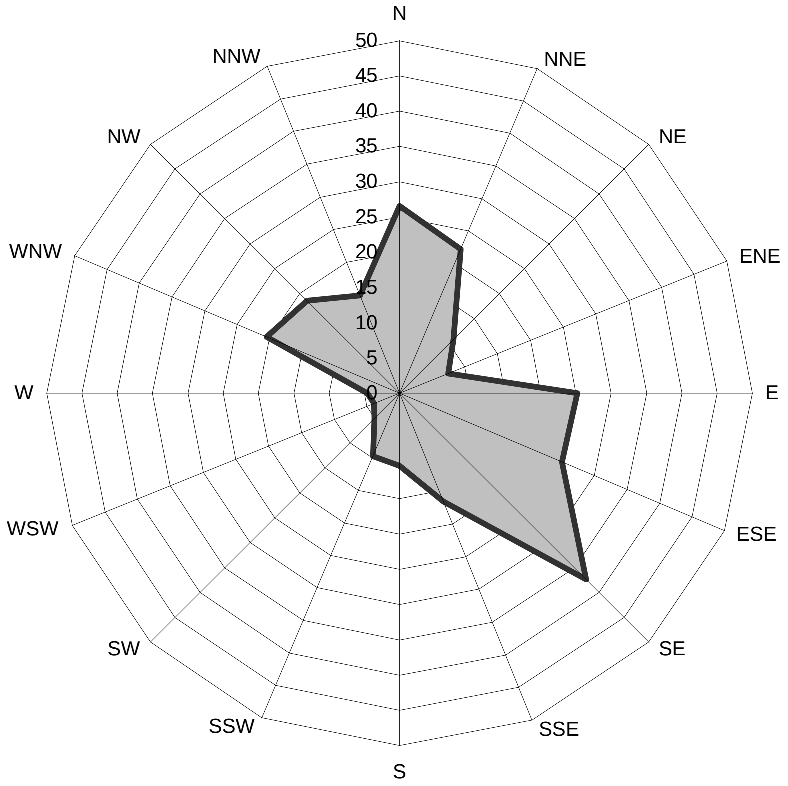


Figure 2.10: Driving Rain Calculated From CWEC Data (N. Battleford)

The deposition of rain on the wall over the year is plotted in Figure 2.11. It can be seen that the peak deposition rates are relatively low. These rates are about ½ of the driving rain deposition rates that has been measured by the authors on similar size buildings in several much wetter (e.g., Waterloo, Vancouver) North American locations.

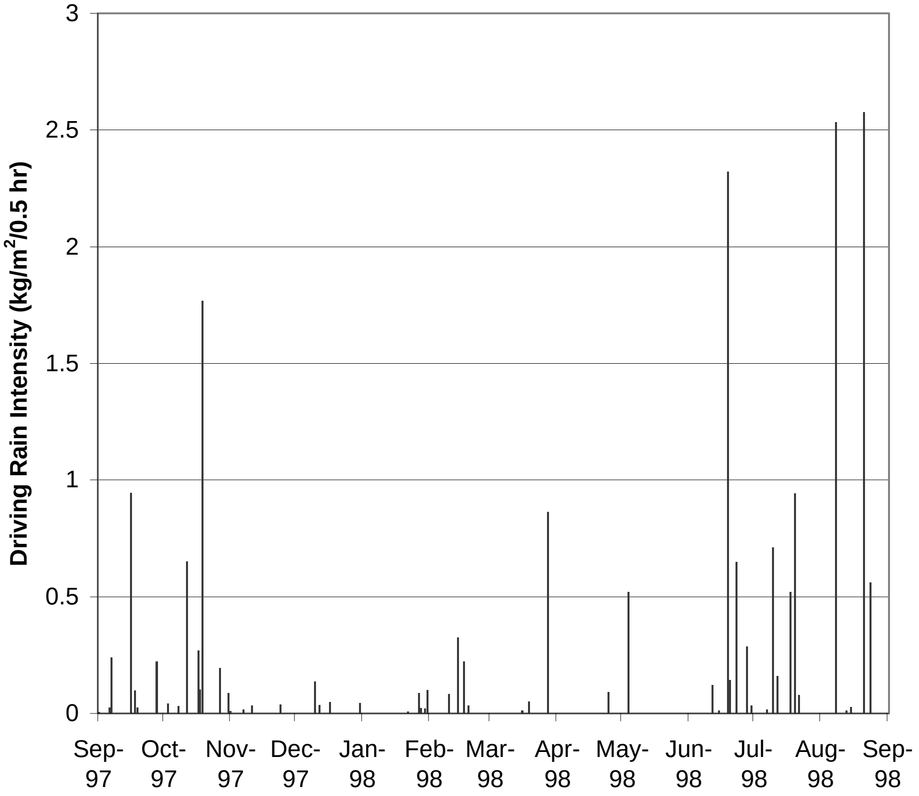


Figure 2.11: Driving Rain Deposition Rates used in Simulation (location NW4)

2.2.5 Missing Data

There are more than 25 periods of between 0.5 to over 100 hours during which data was not stored, and these gaps (unavoidable in most field work) needed to be filled to allow for simulation. As a result, it was necessary to make some assumptions. For short periods (a few hours) the intervening data points were interpolated. For longer periods of missing data (several days), whole 24 hour periods before and after the missing segment were copied into the missing periods and the interfaces between such days interpolated to make a smooth transition.

No suite RH was monitored, although this information is a critical boundary condition for many enclosure systems. For the purposes of the simulation work, this value was generated from the monitored data, using the exhaust temperature and RH values. The absolute humidity of the exhaust air was calculated and, it was assumed that the absolute humidity was the same in all of the suites. Each individual suite RH was then calculated using the measured suite temperature. As mentioned in the monitoring report, the calculated RH within the suites was very low, well below what would be considered comfortable.

The lower than typical average wind speed measured by the roof top wind monitor (2.4 m/s) suggests either that the building was sheltered by the surrounding buildings or that the monitor was partly sheltered by its locations on the building. If the former is the case, then rain deposition can be expected to be lower than other more exposed buildings, and if the latter is the case rain deposition is being under-predicted in the authors' calculations. Figure 2.12 shows the wind speed distribution for the monitored data and the CWEC data for North Battleford. The monitored data is clearly slower.

The information provided (one photograph, Figure 18, in the October 1999 SRC report) indicates that the wind monitor was located about 3 m above the roof, about 6 to 8 m from the parapet. This is an acceptable, but far from ideal, location for monitoring wind speed. From the same photo, the cityscape appears to be equivalent to suburban exposure, i.e., not very sheltered.

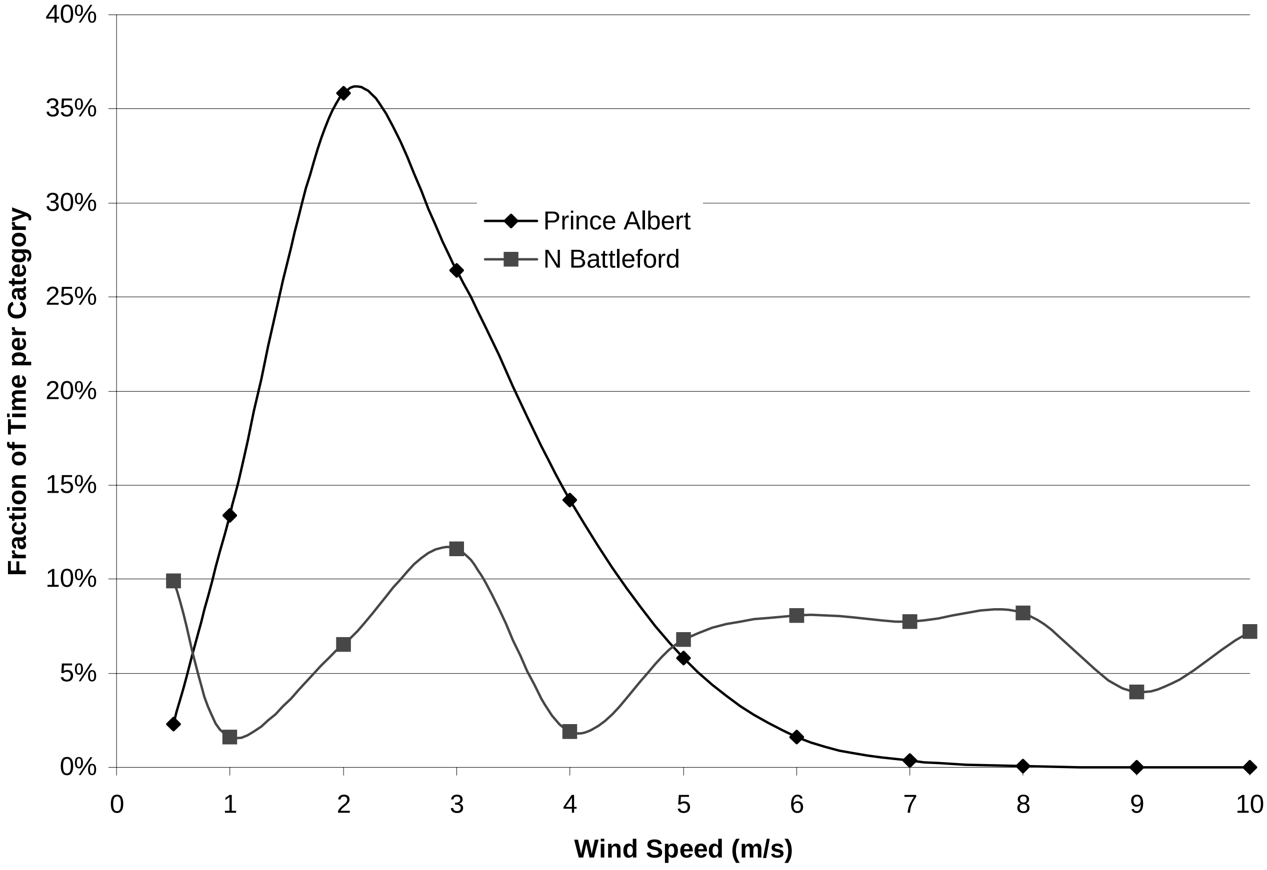


Figure 2.12: Wind Speed Distribution – Measured vs CWEC

2.3 Material Properties

The default material property data from WUFI was used where possible, although some judgement is usually required in this selection. It must also be borne in mind that material properties vary over the building, and the properties at one location will be different than at another. This may or may not be a concern for any given project.

The exterior lime-cement stucco, brick masonry, spruce, batt, and gypsum wallboard were assigned default values. Based on initial simulations, it became clear that some material properties had a greater influence on the predicted hygrothermal behaviour than others. For example, permeance values for the parging, and the effective storage and permeance of the wood and lath required some modification.

The actual material used as a parge coat on the back of the masonry is unknown. The SRC believed the parging was cement-based, although it is unclear if cement plaster was widely available in Prince Albert in 1910. The parge might also be lime plaster. Hence, parametric studies were conducted to assess the impact of the very different vapour permeance properties.

The “old lath and plaster” that was left on the brick walls in the lower floors was assumed to be a gypsum-based plaster. The lath was left on the walls in almost all locations. The effect of the moisture storage capacity of this lath can be important and parametric studies were conducted to quantify its effect.

The Appendix contains the material data used for some of the more important materials.

3. Modelling and Results

The first year's boundary conditions (i.e., 8760 hours from Sept 1, 1997) generated from the measured data were placed into a file format acceptable to WUFI, and used for the simulations.

A model was first "built" for location NW4 with only the information from the monitoring report as guidance. Comparing the results of this "initial guess" simulation to the measured results prompted some adjustments to a few of the material properties and a closer investigation into the actual assembly of the wall (by contacting SRC). The initial guess assembly was stucco over masonry over a lime plaster interior parging, a 50 mm air gap, and 90 mm of batt, poly and drywall. Subsequent parametric investigations focused on the influence of the wood lath, parging permeance, and air leakage impacts.

Several hundred different assemblies with variations in material properties, starting conditions, and boundary conditions were simulated. The results of some of the more important of these models are presented below.

The first section below discusses the fit of temperature data at the exterior and middle of the wall, followed by a comparison of relative humidity results and two-dimensional simulations.

3.1 Temperatures

Temperatures within and heat flow through enclosures can be fairly accurately predicted, since the material properties and boundary conditions are better known than for moisture transport. The predicted and monitored temperatures were compared for two points in the wall assembly: at the exterior surface and at the back of the masonry wall. The measured temperature data is expected to be relatively accurate (better than ±2ºC).

3.1.1 Exterior Surface Temperatures

The exterior surface temperature is strongly affected by solar radiation, stucco solar absorptance, and heat capacity of masonry. Hence, it provides a good test of agreement between simulated and measured. Figure 3.1 to Figure 3.4 plot the measured and predicted temperatures for different time periods. The overall annual plot shows good agreement. A 30-day winter period plot, which allows for more precise comparisons, shows that extreme daily temperatures are not always predicted accurately (e.g., 2-3 degree deviations were common, with occasional excursions of five degrees). It must be noted, however, that measured solar radiation data was not available for many hours, and hence predicted solar radiation was used. The spring period, for which almost all measured data was available, showed excellent agreement. It must be emphasised that the default solar absorption values for stucco were chosen, and no account of solar reflections was taken when generating the boundary conditions. The excellent agreement, therefore, may be fortuitous or indicate that the results are not very sensitive to the variability of the material properties and boundary conditions.

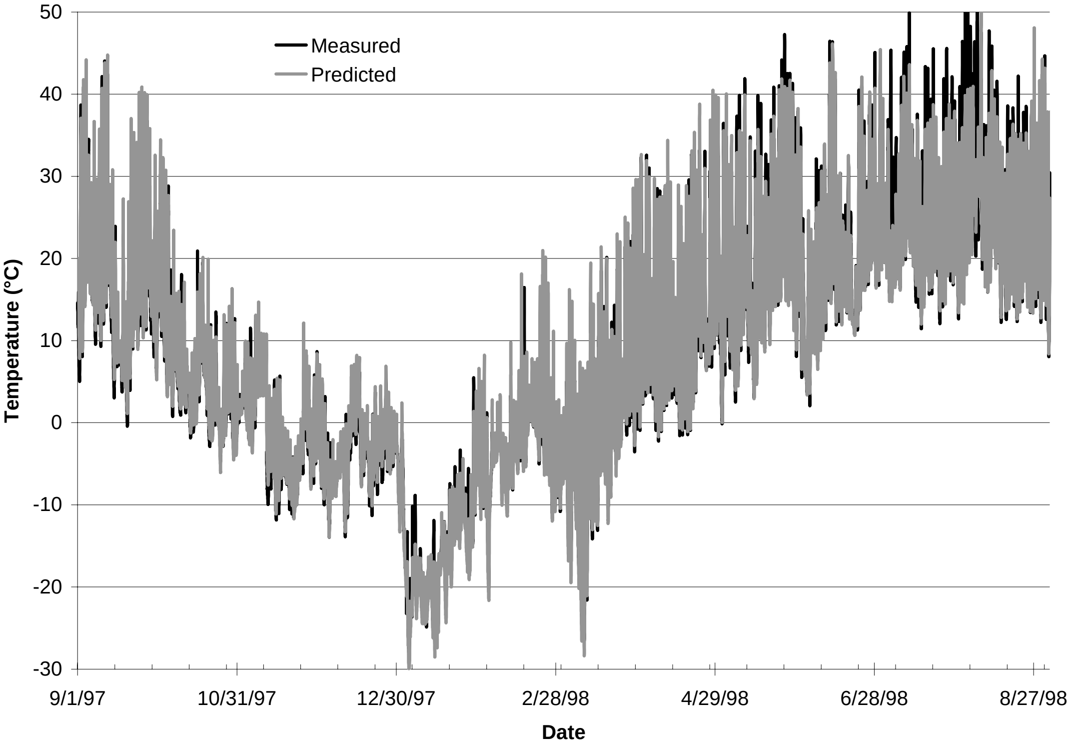
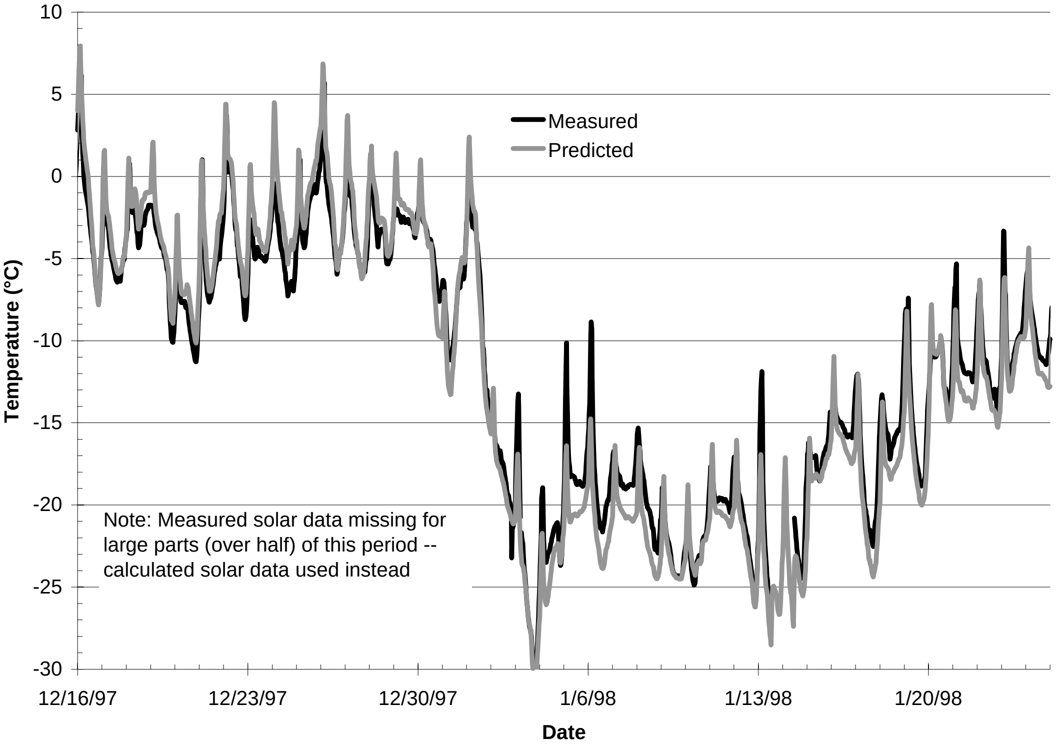


Figure 3.1: Comparison of Stucco Surface Temperature over Year (NW4)



Note: Measured solar data missing for large parts (over half) of this period -- calculated solar data used instead

Figure 3.2: Comparison of Stucco Temperatures – Detail of Winter Period

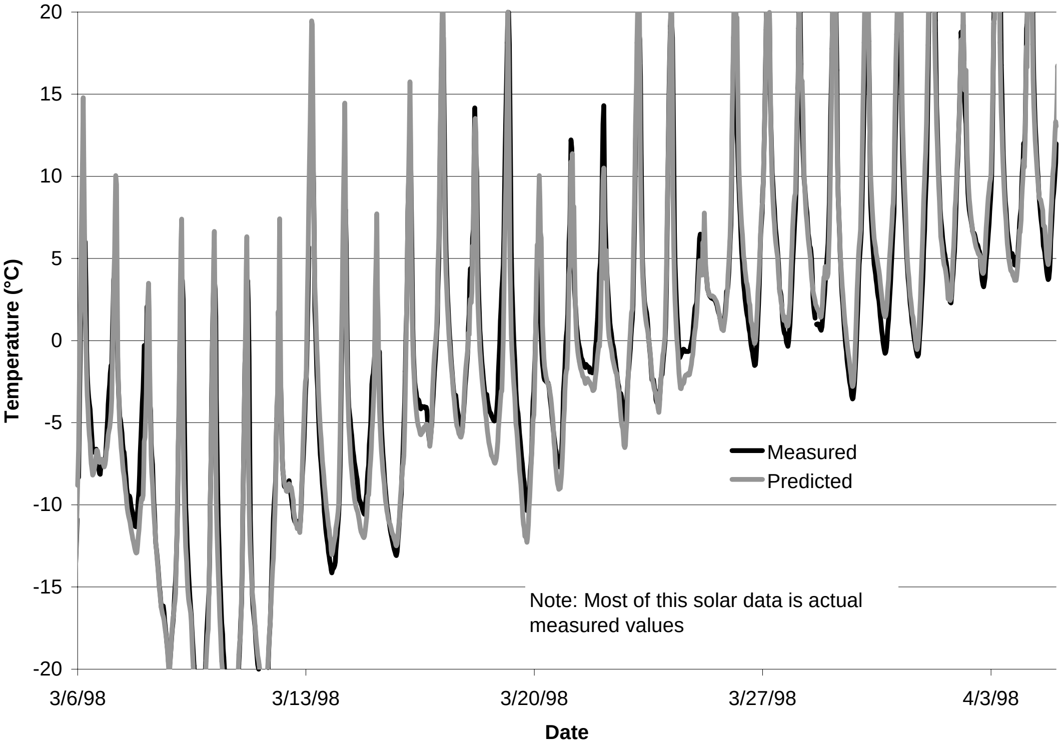


Figure 3.3: Comparison of Stucco Surface Temperatures: Spring Period

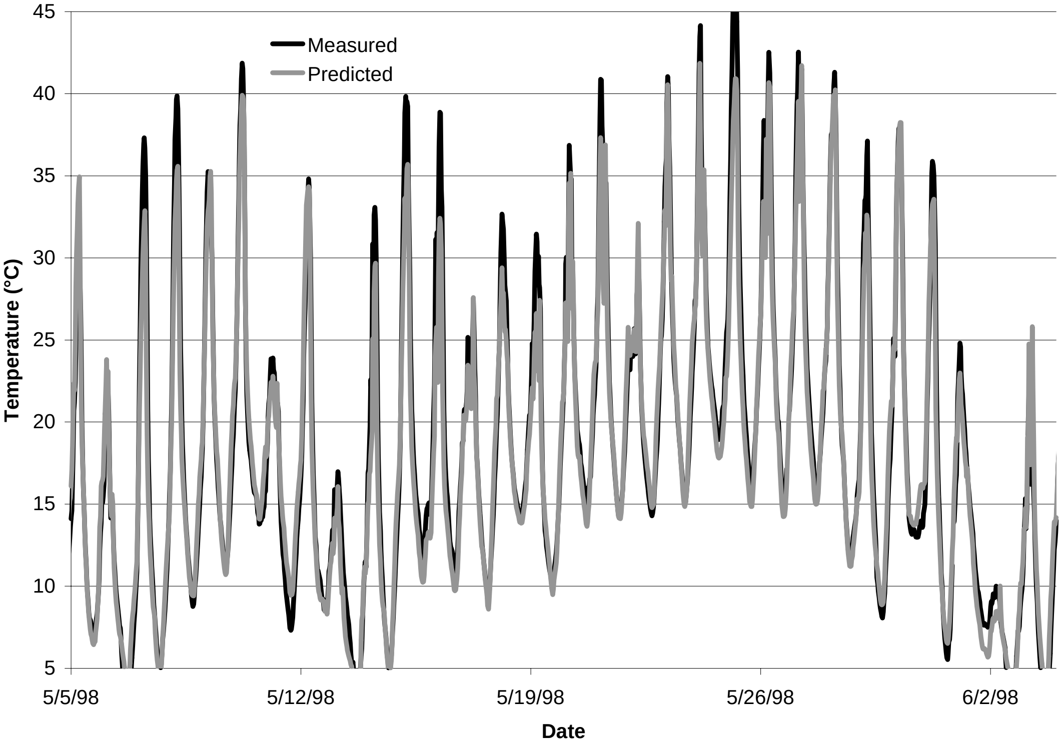


Figure 3.4: Comparison of Stucco Surface Temperatures: Summer Period

3.1.2 Back of Masonry Temperatures

The relative thermal resistance of the retrofit and existing portions of the wall influence the temperature of the back of the masonry. The temperature at the back of the masonry is important for the assessment of exfiltration condensation and freeze-thaw cycling. The predicted and measured temperatures at the back of the masonry are shown in Figure 3.5 to Figure 3.7. The plots all show very good agreement, although the monitored values for N4 are generally warmer, NW4 is sometimes higher and sometimes lower, and NW1 is generally slightly cooler. These deviations, although small, could be due to outward leakage, variable leakage inward or outward, or inward leakage of air. This explanation is not suggested as likely because of the size of the variations (since they are very small) but because of the moisture results presented in the next section.

Hence, it can be concluded that this type of simulation can be used to generate relatively accurate temperature data. This would allow one to assess freeze-thaw cycling and the *potential* for condensation caused by exfiltration air leakage rather accurately.

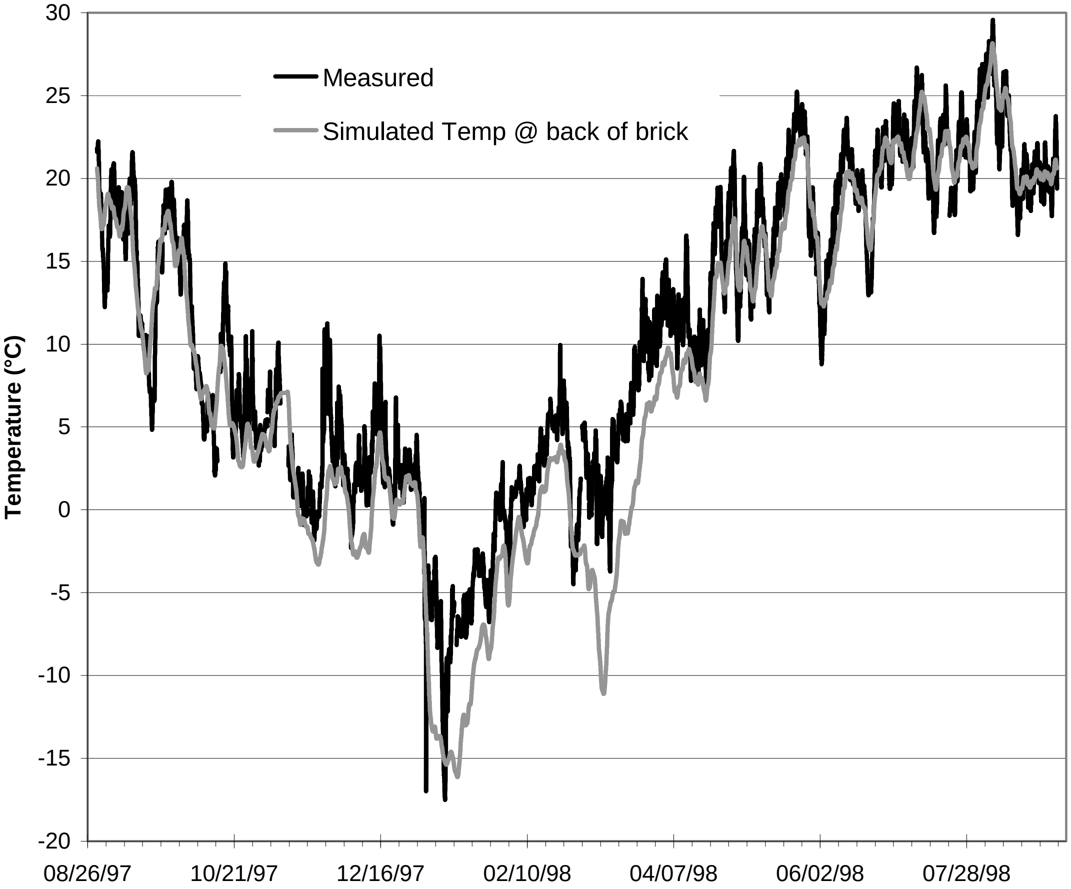


Figure 3.5: Comparison of Back of Masonry Temperature over Year (N4)

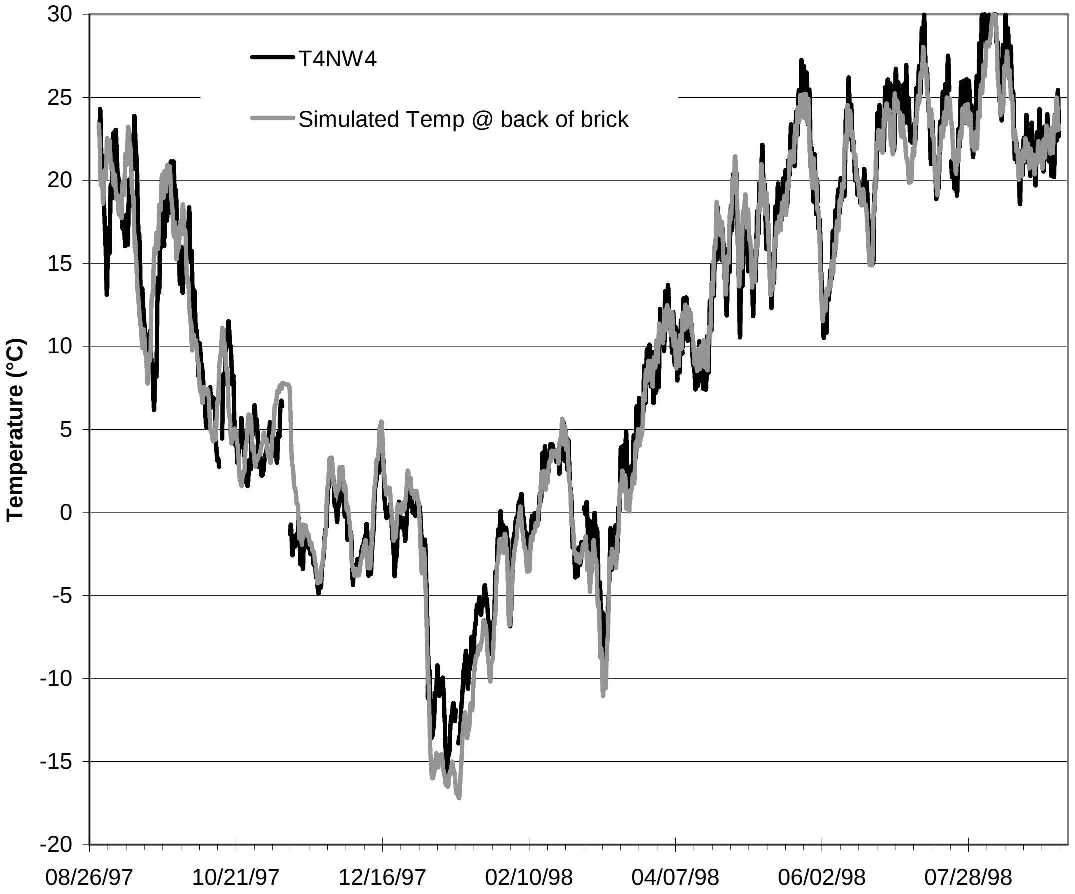


Figure 3.6: Comparison of Back of Masonry Temperature Over Year (NW4)

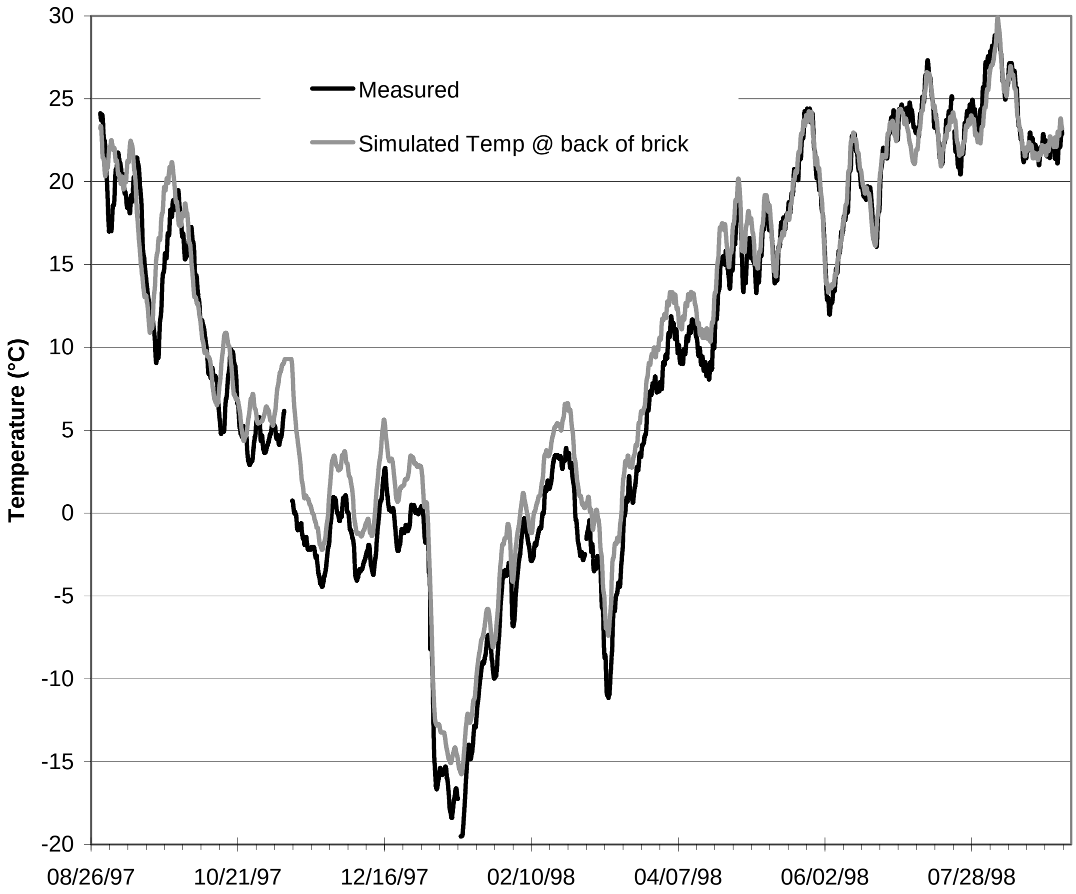


Figure 3.7: Comparison of Back of Masonry Temperature Over Year (NW1)

3.2 Moisture

The relative humidity of the air space between the masonry and the retrofit wall was used to compare predicted to measured moisture performance. This location was chosen since the temperature was reasonably well known (the temperature at the RH sensor was not measured), and this location was important for durability-related performance, i.e. exfiltration condensation and rain penetration problems would be worst at this interface. The accuracy of the measured relative humidity data (which was monitored by high-quality Vaisala sensors) is likely no better than ±3%RH, although this accuracy will be worse at low and high RH levels.

3.2.1 Simulations at NW4

As mentioned previously, most of the simulation involved location NW4. The results of an "initial guess" assembly are compared with the measured results in Figure 3.8. Although the trend appears correct, the RH measured in the space behind the masonry appears to vary much more quickly and dramatically than the WUFI model predicts, and the deviations from measured data become large at some points (e.g. end of December and middle of June).

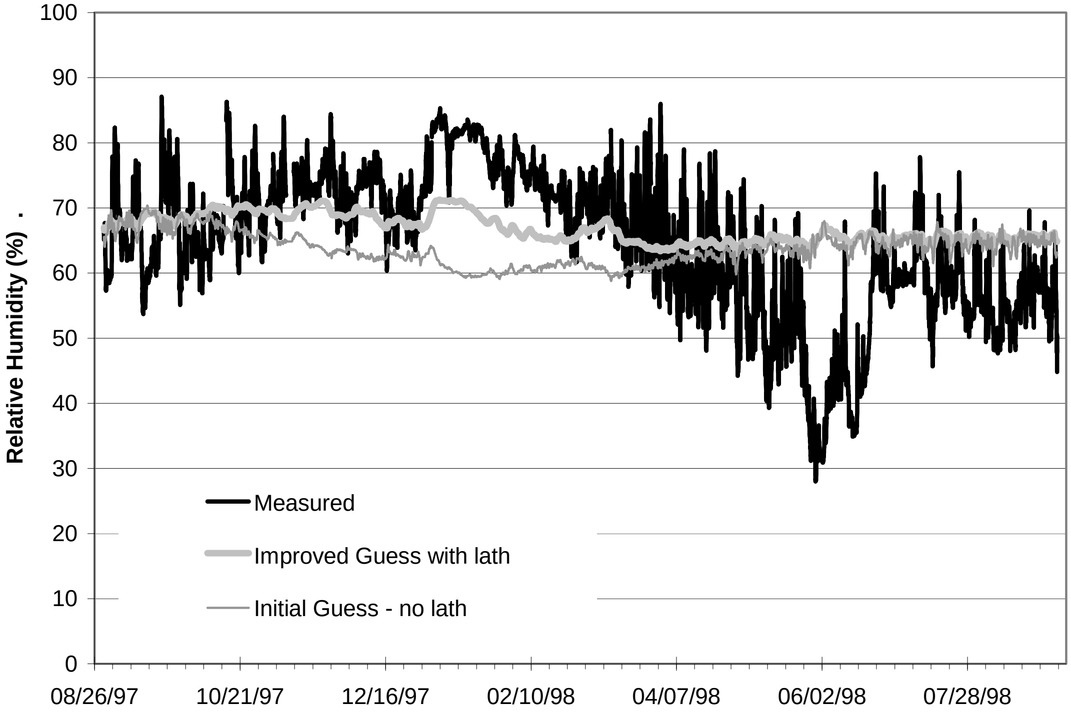


Figure 3.8: Measured and Predicted RH in Stud Cavity for NW4

There are several possible explanations for the much more rapid variations in RH measured versus predicted, both of which involve the sorption isotherm for wood. One possible reason is that the true sorption isotherm is very flat over the range of 60 to 80%RH. This would mean that for a very small change in moisture content (the vertical axis of a plotted sorption isotherm), the RH would change dramatically (the horizontal axis). Another contributor could be wood's unique short-term hysteresis. Most isotherms are measured at equilibrium that requires several weeks to achieve for small slivers of material. Dynamic isotherm measurements show that wood has a different short term sorption isotherm than equilibrium curve. This is assumed to be due to the different nature of moisture adsorption to larger wood pores and the parechyma cells that comprise the cell walls. Finnish researchers of roof assemblies have observed this phenomenon, which leads to deviations in hourly comparisons but results in accurate weekly values.

A comparison was also made between the RH of the outdoor air heated to the temperature of the back of the masonry and the measured results for location N4. This would approximate the effect of outdoor air leaking into this space. A similar comparison was made to assess the effect of indoor air leaking into the space. Figure 3.9 shows that the comparison assuming outdoor air leakage tracks the measured results closely. Hence, location N4 was modelled assuming that outdoor air could pass through the exterior masonry layer by dramatically reducing the vapour resistance of the exterior. The results shown in Figure 3.10 are clearly very good and predict much of the variation. The same comparison was conducted for Wall NW1, with results that showed fairly good fit. Although NW1 experiences large inward pressures, it may be more airtight and hence have less inward airflow than N4.

Therefore, it can be concluded that outdoor air was passing from the exterior behind the masonry, and that this airflow was dominating the performance of the RH in this space for Walls N4 and NW1. Hence, at least for these two locations, it can be assumed that air leakage from the exterior to the space behind the masonry was occurring. By making this assumption, WUFI modelling can predict the measured results. These results underline the importance of air leakage to moisture performance and the importance and assessing the impact of airflow if and when it occurs.

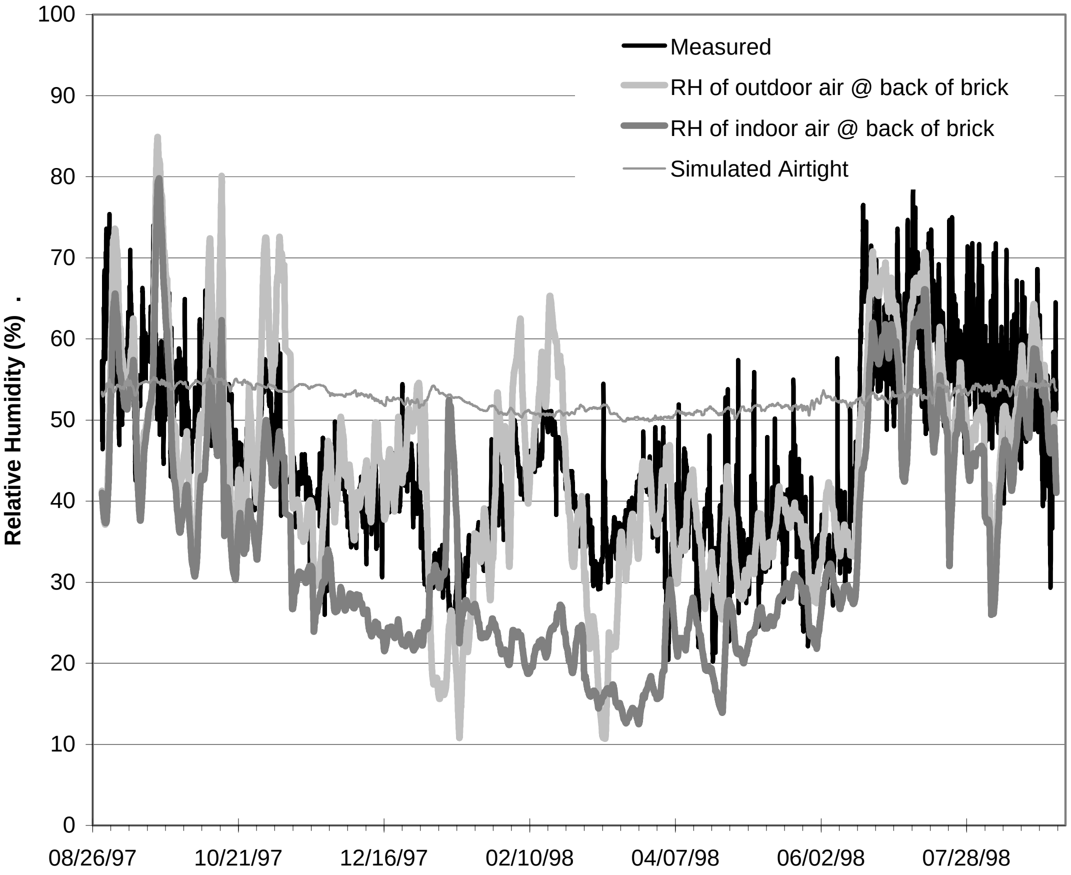


Figure 3.9: RH Behind Masonry for N4

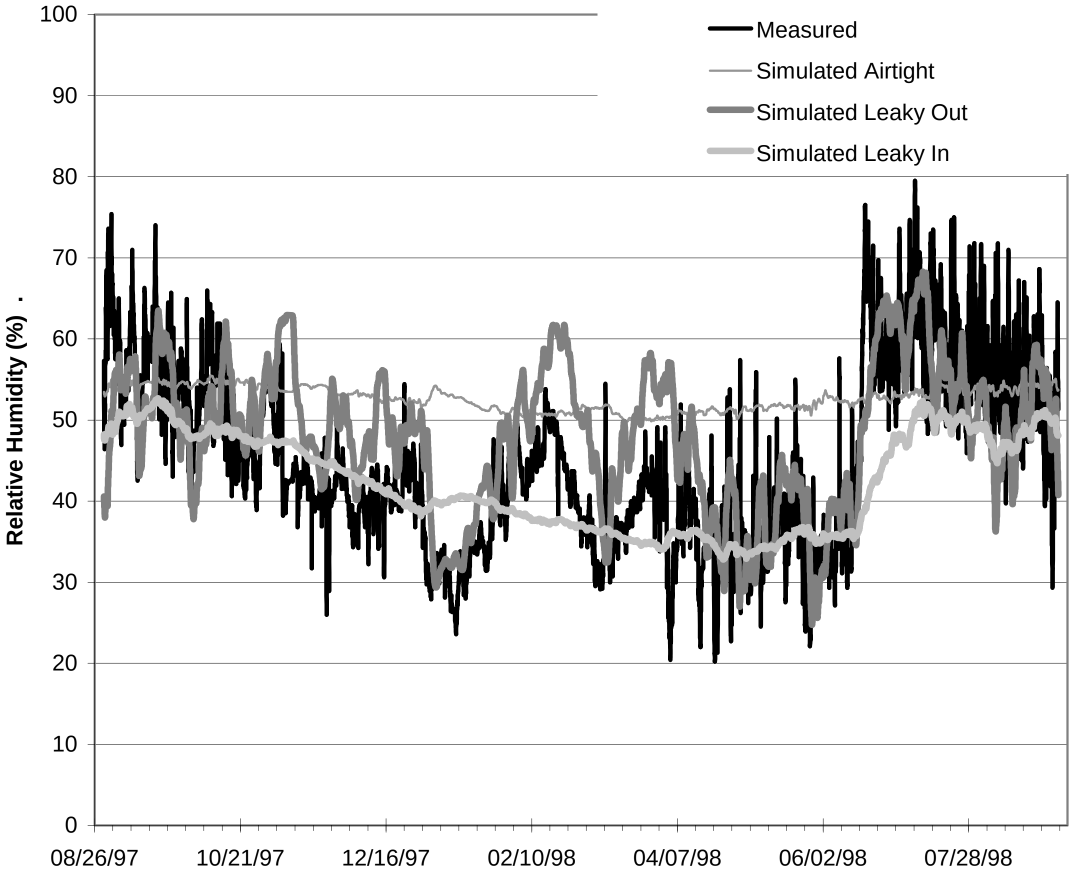


Figure 3.10: Comparison of Measured and Simulated RH Behind Masonry for Various Air Leakage Scenarios (N4)

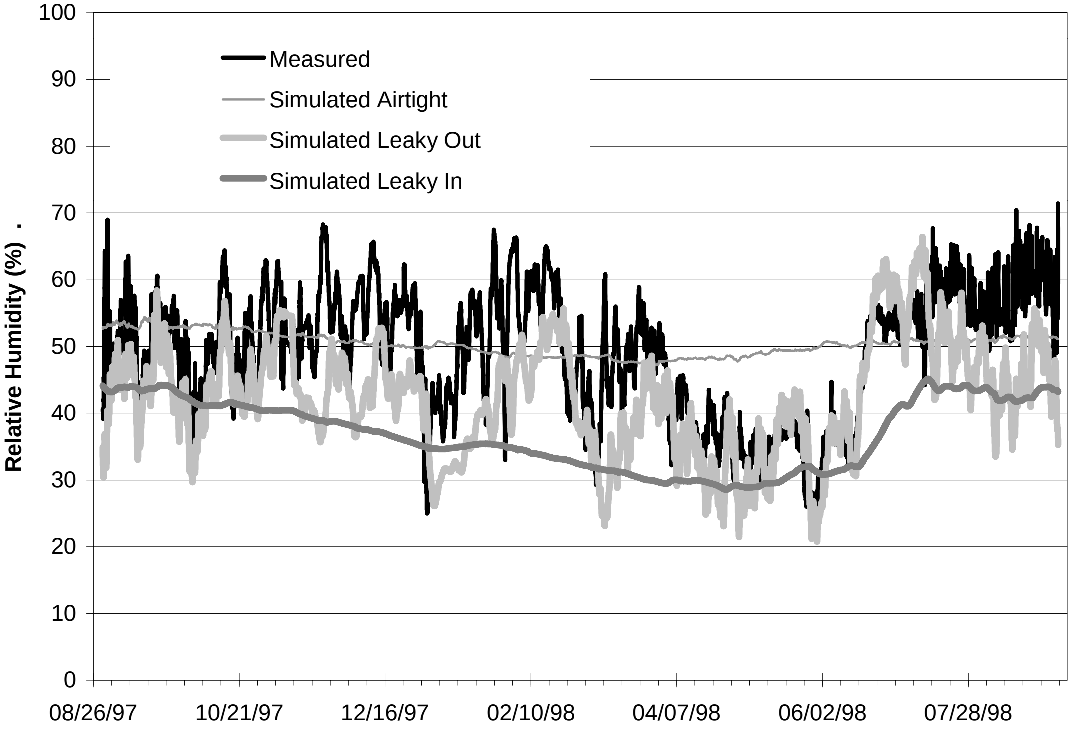


Figure 3.11: Comparison of Measured and Simulated RH Behind Masonry for Various Air Leakage Scenarios (NW1)

While it is not certain where the air entered, the design of the retrofit clearly encouraged airflow behind the masonry. Interestingly, the primary plane of airtightness in the building was measured to be the exterior masonry. Air flowing around the window perimeter into the space would seem to be possible from the drawings. Stack effect pressures (calculated to be about 30 Pa with –30 ºC ambient air temperatures) would encourage outdoor air to enter the lower floors and rise to the top behind the masonry in almost all weather conditions. The monitoring report states (pg. 13) that the entire building was under negative pressure due to unbalanced HVAC equipment and that the neutral pressure plane was above the roof – hence the largest inward pressure undisturbed by wind pressures are on the ground floor. This trend is clearly shown in Figure 3.12 which also shows that NW1 experienced long term net inward pressures whereas the pressure at the top floors (NW4 and N4) was much smaller, often reverse direction and are almost zero on average.

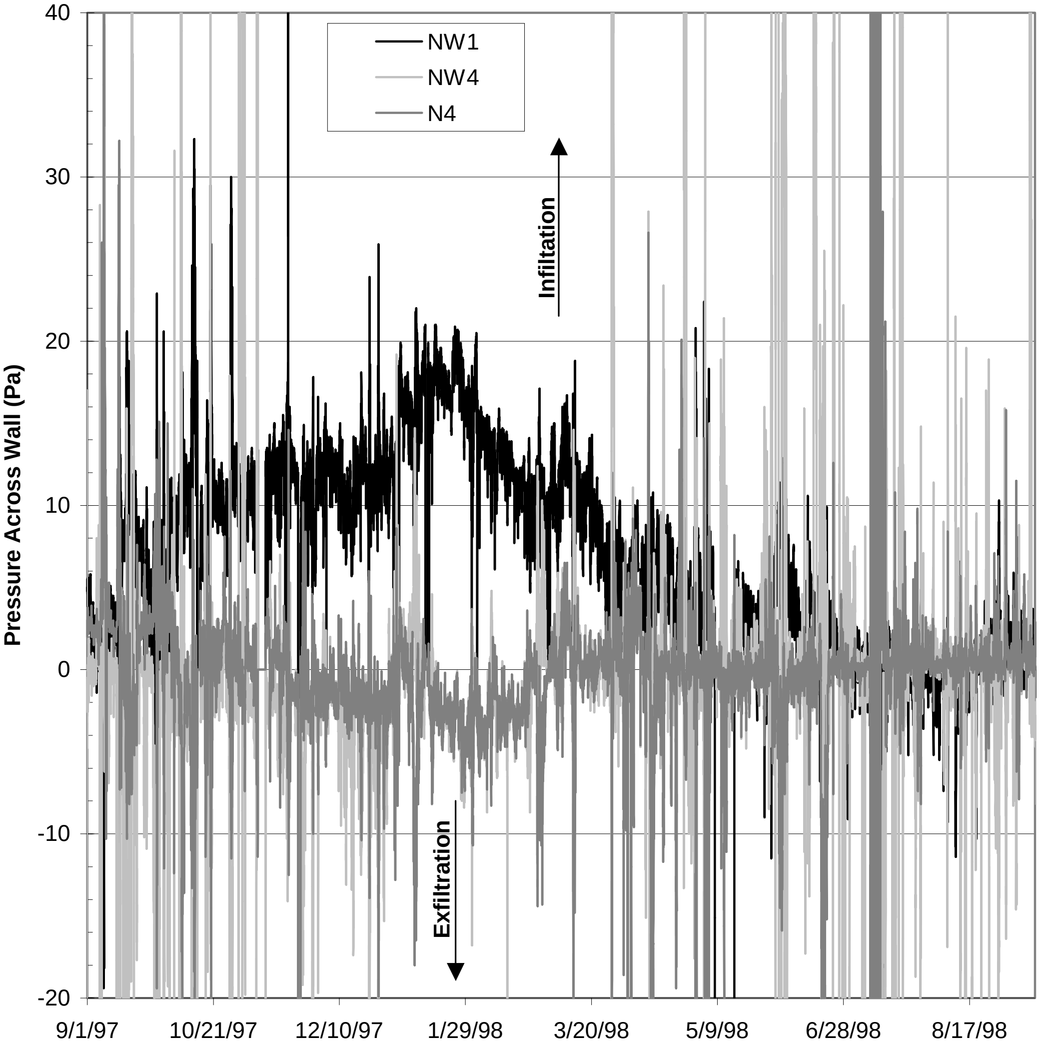


Figure 3.12: Monitored Pressure Across Walls Over One Year

If the foam fill at the joist level was installed properly, little leakage between floors should have been possible and a large chimney would have been avoided, although this is clearly a concern. It is difficult to form a perfect vertical airseal when spraying foam around joint pockets. Spray foam at the joint of the wood floor boards and the wall, however, should provide a good seal.

When the measured results of NW4 were compared to simulations of air leaky interior and exterior wythes, no fit was evident (Figure 3.13). This may be because of the variable airflow direction shown in Figure 3.12. The fit does improve near the end of the simulation period (after the “event” that occurred mid-June). It also appears that the wall was wetter than the other walls during the initial period of simulation, perhaps because of a rain leak.

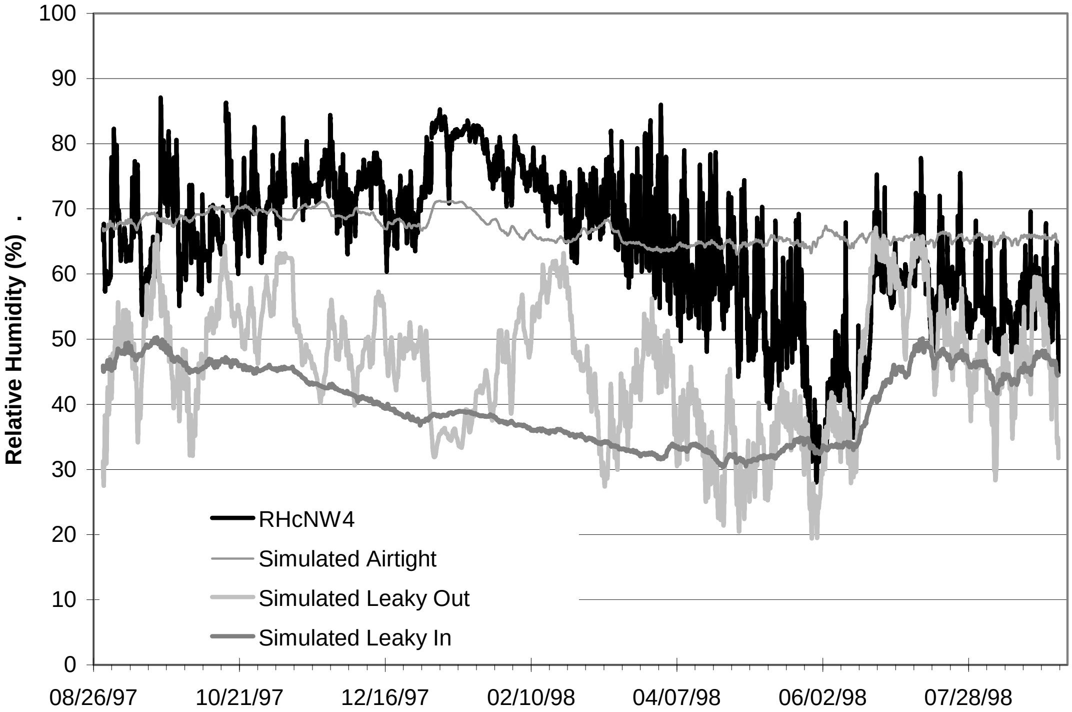


Figure 3.13: Comparison of Measured and Simulated RH Behind Masonry for Various Air Leaky Scenarios (NW4)

3.2.2 Simulations Comparing NW1 and N4

Although much of the work involved the location NW4, locations NW1 and N4 were also considered. As discussed above, the influence of air movement had a large impact on the results. A straight comparison of location NW4 and N4 shows the RH in wall NW4 was significantly higher than wall N4. The simulated values were started at different moisture contents to allow the simulations to match the measured with one year of simulated data. It is interesting to note that the measured RH values for both wall systems converge after the mid-June event, and then behave in a similar manner for the rest of the record. It was expected that the RH of wall N4 might be higher that of west-facing NW4 because N4 did not have a protective stucco layer. However, a review of Figure 2.9 shows that the north face received much less rain than the west facing wall. The difference in rain deposition may be enough to explain the difference in performance, not the stucco.

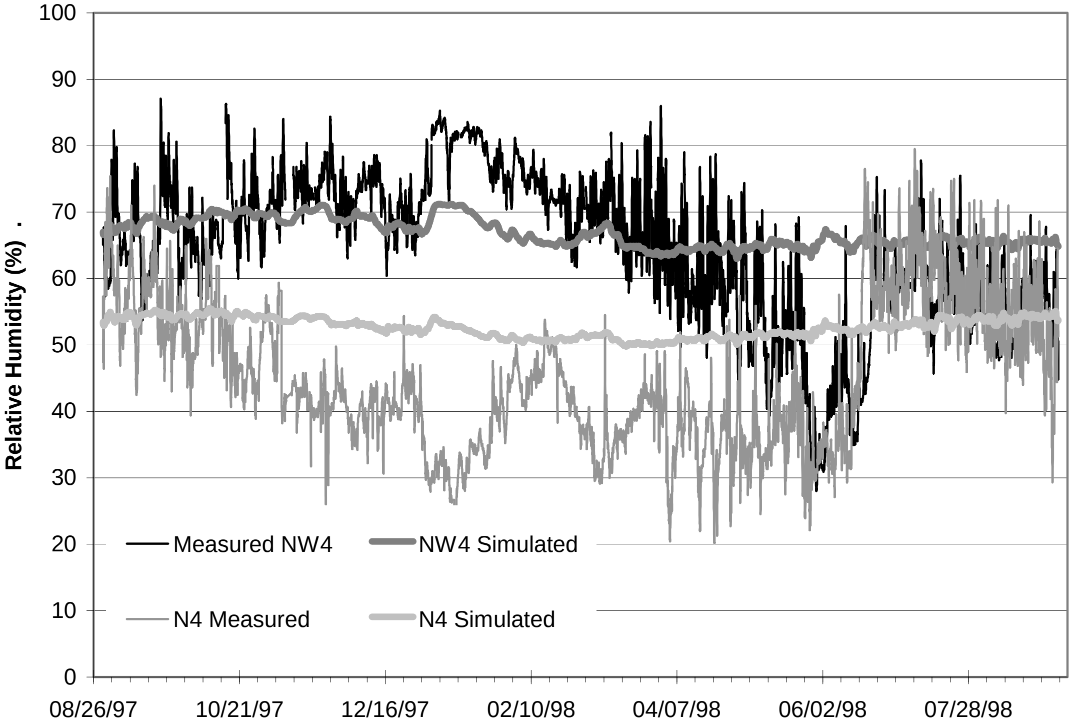


Figure 3.14: Comparison of NW4 and N4 Locations

3.2.3 Summary

In general, reasonable agreement between the modeled and the monitored results was reached by accounting for air movement through the wall. In the cases considered, the results of the modeling suggested that the moisture in the walls was trending towards an annual equilibrium (i.e. there was no net gain or loss in moisture over the course of a year). These trends seem to be confirmed by the results of the monitoring. In those cases where the wall is subjected to brief wetting periods, it does dry out and hence no long-term moisture accumulation is predicted.

3.3 Parametric Investigations

A number of important variables were noted during the analysis. The role of airtightness has already been explored, and is certainly the most important variable. The starting moisture content of the assembly also played a role in this assembly because of the very high hygric mass, and the low drying rates. The vapor permeance of the parging and the inner layer and the method of modelling the lath were also somewhat important to the results. The climate assumed for the simulations obviously also plays a role. These are discussed below

3.3.1 Influence of Starting Moisture Content

The length of time that the starting moisture content influences the performance of a wall depends on the hygric capacity and the permeance of the interior and exterior layers of the assembly. The wall assembly modelled has both a high level of hygric mass and relatively low exterior and interior permeance. As a result the starting moisture content influences the performance of the wall for a long period of time (Figure 3.15). The influence of the sorption isotherm can also be seen in this figure. Simulations started at a higher moisture content undergo fewer short-term changes because a large amount of moisture must be added or removed before the RH is affected.

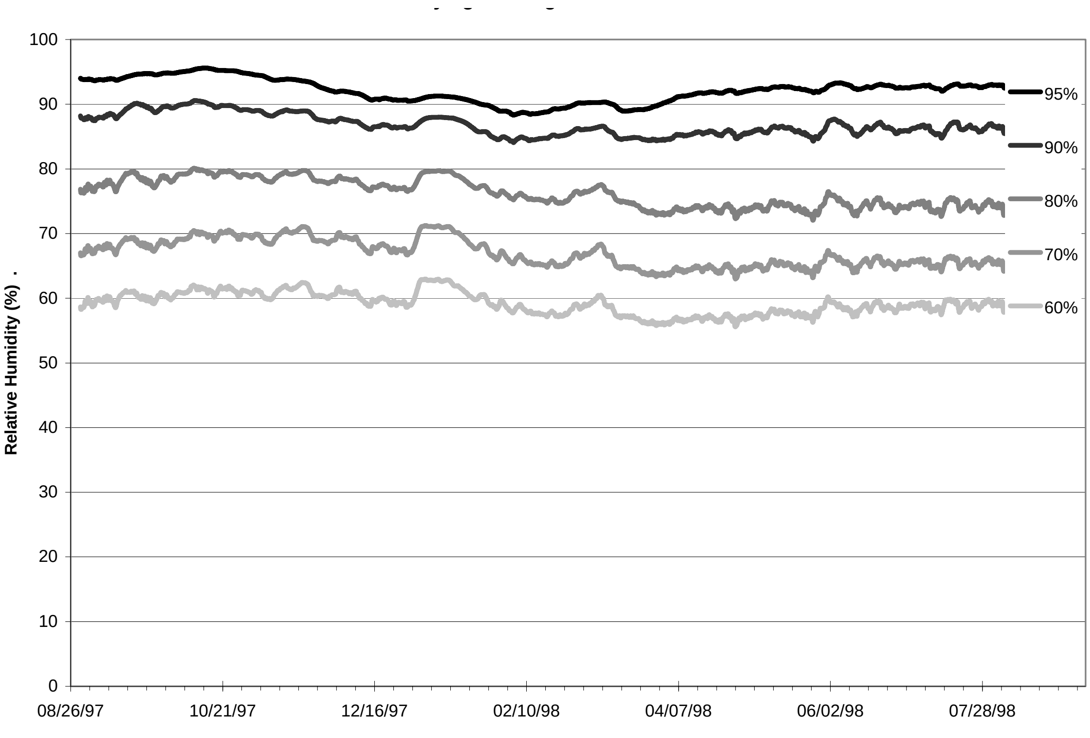


Figure 3.15: Role of Starting Moisture Content on Simulated Behaviour (NW4)

3.3.2 Influence of Parging Permeance

It was not initially clear what properties to assign the inner parging layer. The default permeance value for lime plaster 10 mm thick was 2600 ng/Pa/s/m^2. The impact of this decision was investigated by considering three other parging permeance values. As can be seen from the results plotted in Figure 3.17, the parging permeance does plays a role, although it is not that significant. The less permeable the parging, the more accurately the simulations compare with measured results.

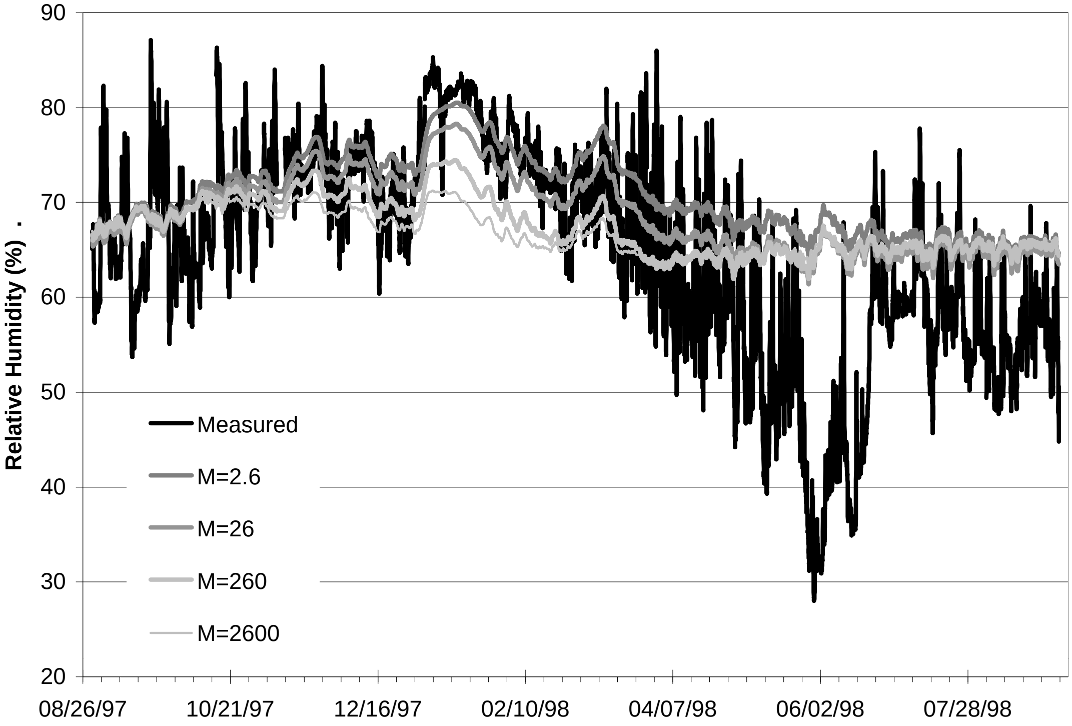


Figure 3.16: Role of Parging Permeance on Simulated Behaviour

3.3.3 Influence of Wood Mass

In this case, the total volume of the wood in the wall (50x50 mm strapping @ 400, 38x89 mm studs @400, and 6x 19 mm @25) contained the equivalent of about 19 mm of solid wood. Hence, this much wood might be available to participate in moisture absorption and release. A parametric study was conducted to assess the impact of the equivalent wood thickness on the results.

It can be seen from Figure 3.17 that increasing the thickness of wood in the system increases the moisture storage capacity and modifies the behaviour. These results encouraged the use of 19 mm of wood for all of the simulations.

Because the wood is not installed in the wall in a single, continuous layer, the permeance of the wood was artificially increased (to 9700 metric perms) to reflect the fact that air and water vapour can freely move around the lath and framing.

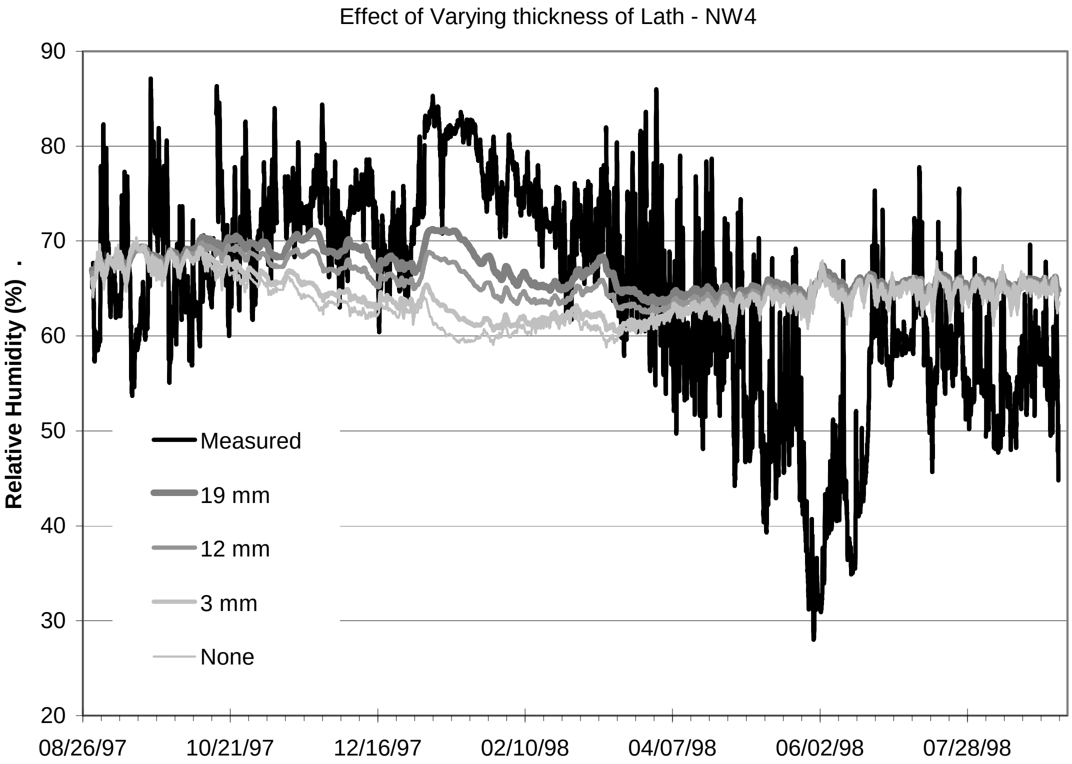


Figure 3.17: Influence of Lath on Simulated Behavior

3.3.4 Influence of Permeance of Inner Layer

The permeance of the interior layer is well known – 6 mille poly has a predictable and constant permeance of around 3.7 metric perms. However, the role of the permeance of the interior wall layers was investigated because of its potential performance.

The permeance of the interior layers of the wall used for most simulations was increased in three steps from 3.7 metric perms (0.15 mm thick poly) to 37 perms (typical of a heavy oil paint), to 370 (a high estimate for latex paint on drywall) to 3700 (a value essentially equal to little or no vapour resistance). The results are shown in Figure 3.18. Even in a very cold climate such as Prince Albert, the RH is predicted to be much lower with little or no interior vapour resistance. This is due to the combination of low interior relative humidity, the insulating value of the masonry, and its moisture storage capacity. It is important to emphasize that these results are only valid for the very dry interior conditions of this particular building. Higher interior relative humidities would obviously change the results.

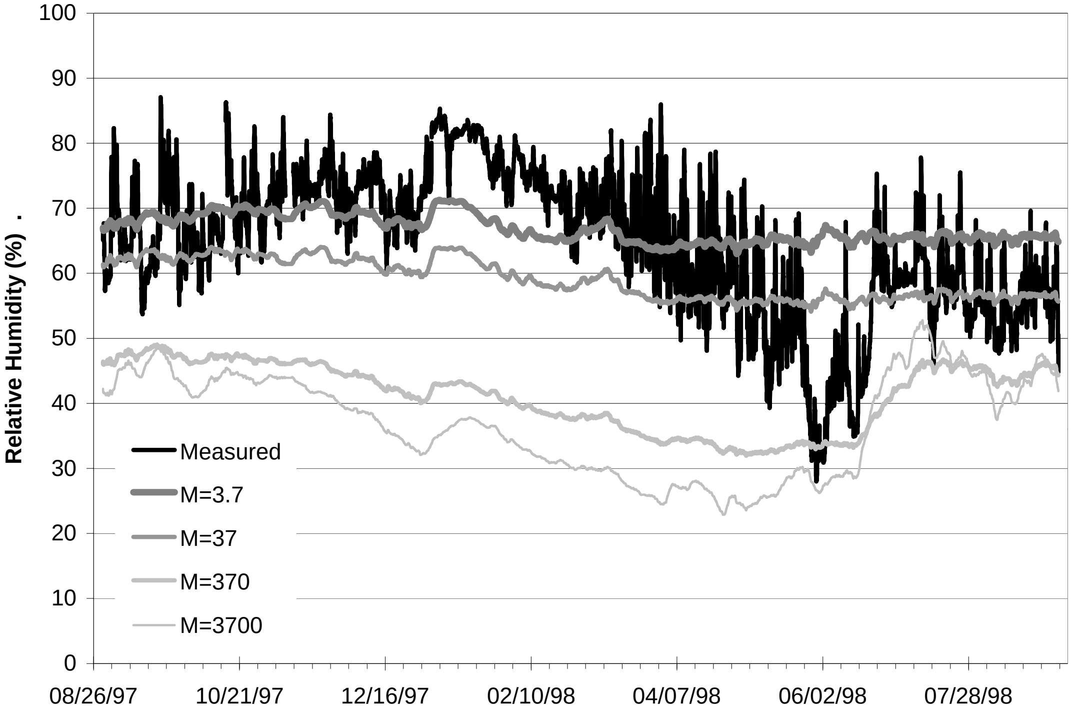


Figure 3.18: Influence of Interior Layer Permeance on Simulated Behavior

3.3.5 Simulations in Different Climates

The best-fit wall NW4 was simulated for an exposed east-facing location in Toronto (this orientation was chosen since it is known to result in the worst performance). The interior conditions were assumed to vary from 40%RH to 60%RH, with a minimum on Feb 21, whereas temperature varied from 20 to 24 C peaking on July 21.

The results, plotted in Figure 3.19, shows that the wall design which performed well in Prince Albert would become much wetter in Toronto. In fact, the relative humidity continued to climb for the first two years. The impact of removing the poly, a possible change to the wall design, was also investigated. Removing the poly did not reduce the RH in the airspace or change the moisture content of the masonry. This shows the impact of higher interior RH conditions.

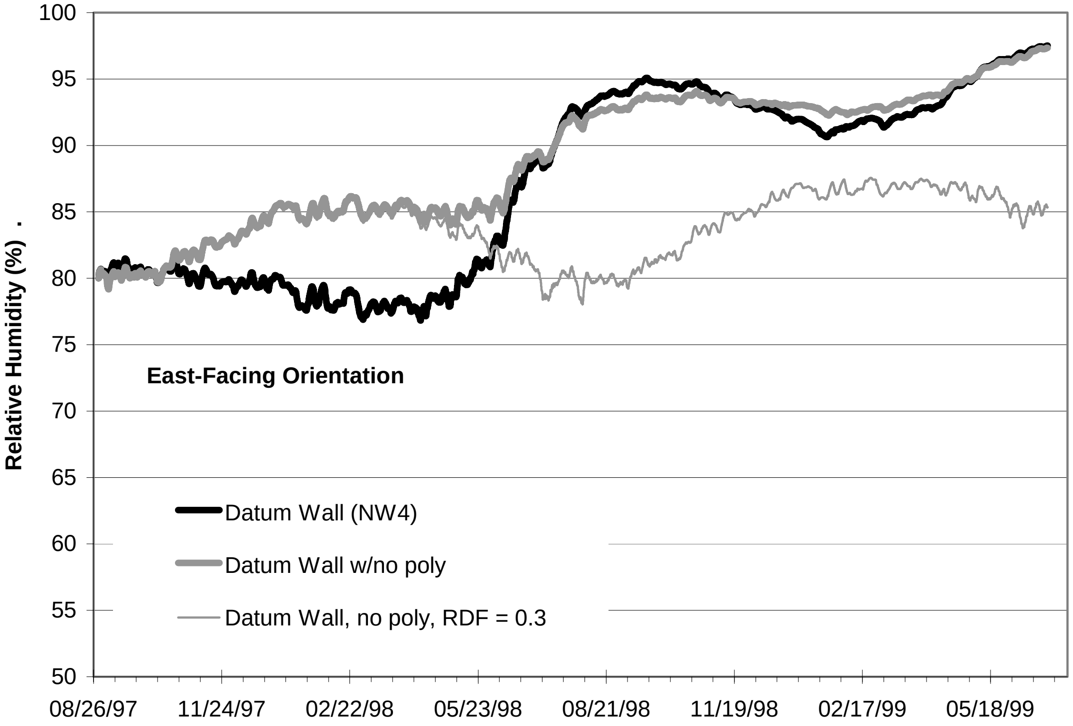


Figure 3.19: Simulated Performance of Wall NW4 in Toronto Climate

Another simulation for the Toronto climate investigated the effect of reducing the driving rain exposure (via the Rain Deposition Factor). A value of RDF=0.30 represents a somewhat sheltered wall, typical of most walls on a three-storey building surrounded by other three storey or higher buildings. The results show that the relative humidity of the space would be maintained around 80 to 90%, rendering the design on the threshold of acceptable. It is important to note that the peak moisture content in the masonry would remain below the freeze-thaw threshold in this case. If the interior RH were reduced to a more reasonable 30% in the winter (via an HRV for example), this wall would be predicted to be acceptable.

Clearly, many important and practical variations are possible, e.g., water repellent stucco, foam insulation, interior vapour resistance, air leakage flaws, etc., but these are beyond the scope of this report.

3.4 Two-Dimensional Simulations

WUFI 2.2 v2.1 was used to model a horizontal section through a beam pocket at a joist. It was not possible to make the model handle driving rain absorption properly. The brickwork would become saturated with even a small amount of rain (this is physically impossible, since, for example, 2 kg of moisture per square meter cannot possibly saturated a 300 mm thick masonry wythe). To trouble shoot this, material properties were adjusted, the size of the finite-element grid was increased and decreased, and the geometry was greatly simplified. We were unable to solve this problem, although we hope that we will soon. We are presently discussing this problem with the authors of WUFI 2D, and will be meeting with them soon.

3.5 DELPHIN Simulations

The DELPHIN model was used in a similar manner as WUFI to predict the performance. Although DELPHIN is very powerful, it is not as user-friendly to use, as easy to install, or as stable in performance. The many different choices describing transport and storage function is impressive and suggests it will be more useful as a research tool than design tool.

To begin, the same boundary conditions as used in the WUFI simulations were applied to default material property data. There are several functions in DELPHIN that allow solar data on a horizontal surface to be converted to a specific vertical orientation, but for reasons mentioned earlier, such standard transforms were not that accurate in this case. The driving rain data can also be calculated by DELPHIN, but the predicted rain data is again quite different than our experience.

The default material property data for each program were initially used. The results of temperature and RH are compared in Figure 3.20. It can be seen that the temperature data is essentially the same, but that the RH data are not matched as well with DELPHIN.

To allow for comparisons between the *computer models* (as opposed to the model input), the same material properties and boundary conditions were then used in the DELPHIN simulations. It can be seem in Figure 3.21 that the models are more consistent in this comparison. The temperature data is identical, and the RH data of DELPHIN varies for part of the year, but not for the other.

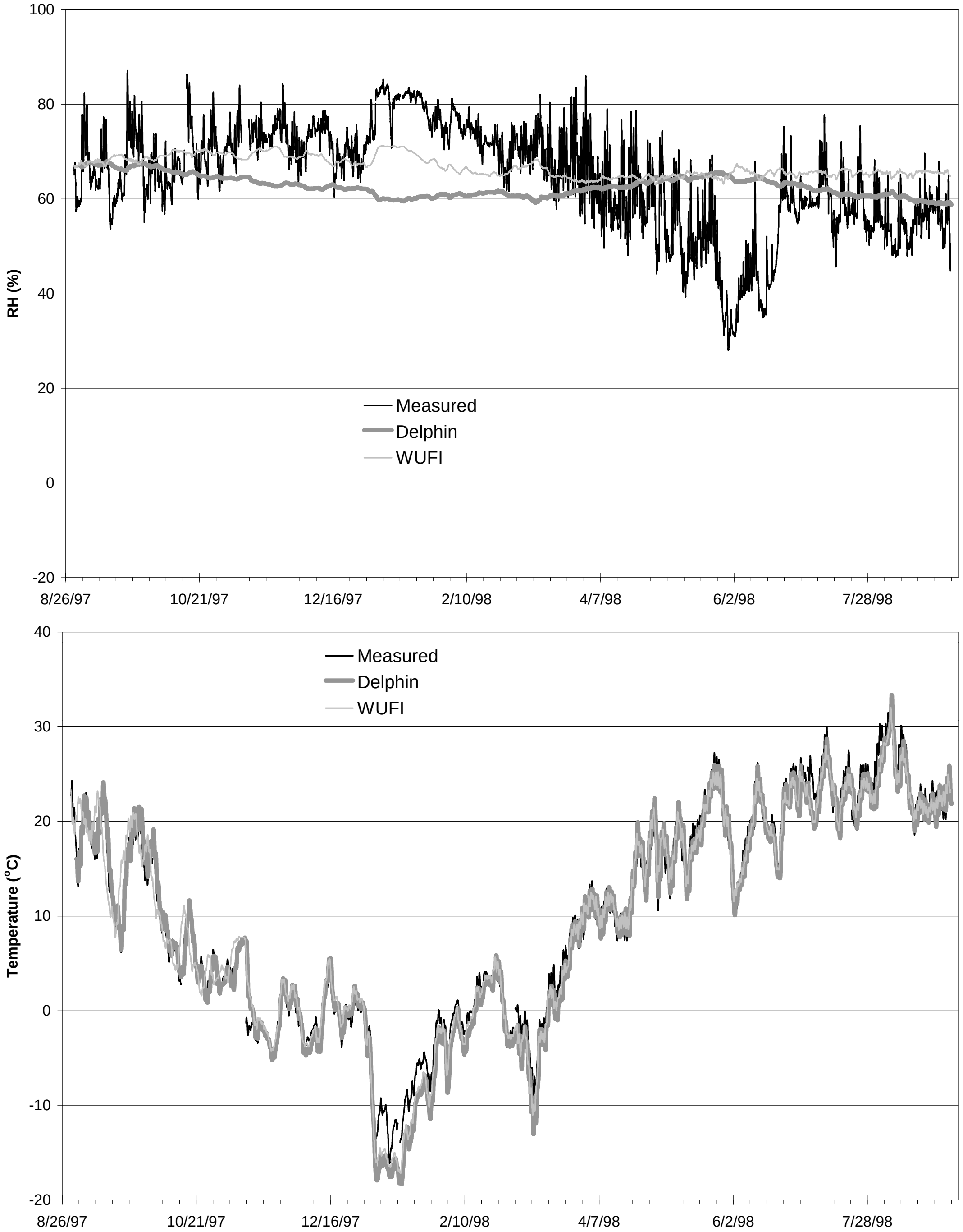


Figure 3.20: DELPHIN and WUFI Results Compared (Program Default Material Properties)

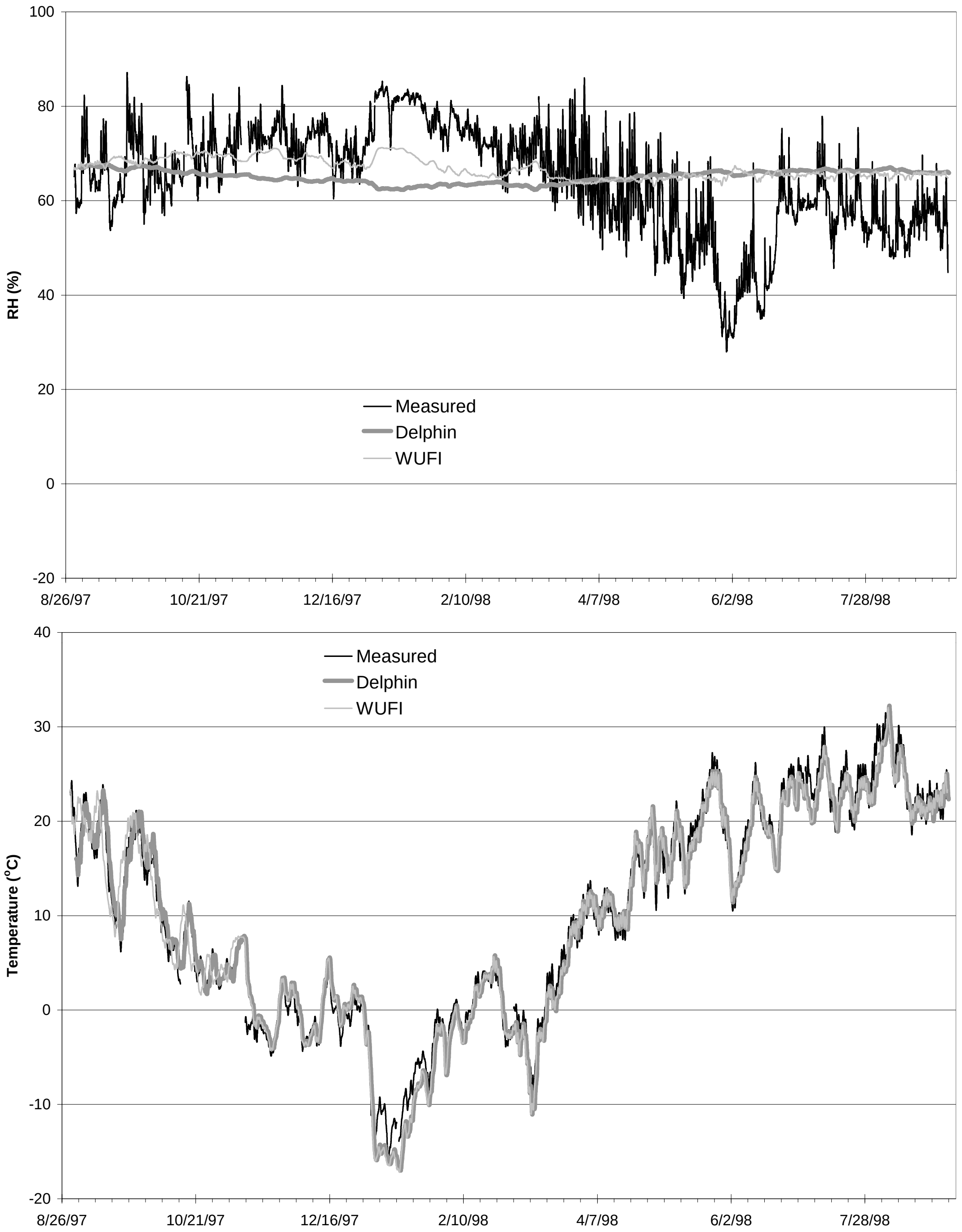


Figure 3.21: DELPHIN and WUFI Results Compared (Using WUFI Material Properties)

4. Conclusions and Recommendations for Future Projects

4.1 Conclusions

After some adjustments were made to account for air movement, uncertainty of the permeance of the stucco, and the amount of hygric mass provided by the wood lath, a reasonable agreement between the modeled and the monitored results was reached.

In the cases considered, the results of the modeling suggested that the moisture in the walls was trending towards an annual equilibrium (i.e. there was no net gain or loss in moisture over the course of a year). These trends seem to be confirmed by the results of the monitoring. In those cases where the wall is subjected to brief wetting periods, it does dry out and hence no long-term moisture accumulation is predicted.

A number of important lessons have been learned, and it was felt that a major goal of this project was to document these for future monitoring/modelling projects.

4.2 Recommendations for Monitoring

The information provided by the SRC monitoring in this case was generally very good. In fact, most data from field monitoring reviewed by this author to date have not been as useful. Several specific recommendations for future monitoring based on this project and several other ongoing projects are listed below.

- A detailed physical description of the subject building and its surroundings should be provided in any similar exercise. For example, the orientation (relative to solar south) of the Karcher building was not provided, although it could be inferred from the drawings. The dimensions of the masonry were not given, neither were floor-to-floor heights, etc. No material properties were given (e.g., a physical description and an IRA and 24 hr cold water absorption of the brick and interior plaster), although the exterior stucco mixture was given as a cement-lime. The photographs provided in the report were useful, although many more photos (especially one from each face of the building looking directly away from the building and one of each face) should be provided in the future. Plan drawings (or at least photos) should always provide the location of the subject building with respect to the size and shape of the adjoining buildings to aid the assessment of exposure conditions.

- Elevation drawings of the sensor locations were quite detailed and useful. However, the location of the sensors through the depth of the wall is at least as important, and no horizontal or vertical sections were provided in the monitoring report.

- RH sensors located within an enclosure system are the most useful measure of moisture performance. Since RH does not measure the moisture content of the air, any RH sensor should always have a temperature sensor located as close as possible to the actual RH sensor pad to allow for an accurate assessment of the air's moisture content. Based on the authors' experience monitoring literally dozens of different types of wall systems in the field, in climate chamber studies, and in test houses, combined RH and T sensors are absolutely critical for an understanding of hygrothermal performance.

- It would be useful to have wall orientation specific solar radiation and driving rain data. Although this is clearly an additional expense, any serious model validation project must measure driving rain and solar radiation at, or near, to the location at which enclosure performance is being measured. This would overcome some of the major assumptions that were required to generate the boundary conditions in this project.

- Measurements of wind speed and direction, and ideally some measure of air pressure across the assembly are useful for the assessment of driving rain and forces driving airflow through enclosures. However, these wind-related measures have little value if they are measured at intervals greater than once every 15 minutes. At least 20, and preferably 50 measurements should be taken to every 15 minutes to result in reliable average values for use in understanding enclosure behaviour.

- The suite RH should be measured along with the suite temperature. In the experience of the authors, the RH between different suites varies quite significantly because of occupant density and behaviour. Although the wall system in question did not have a vapour or air permeable interior finish, the measured performance of any enclosure system that did would be strongly affected by different suite RH values.

- In assemblies that contain a significant amount of moisture storage capacity, at least one set of gravimetrically determined moisture content values would avoid the need to estimate the starting moisture content. The actual moisture content and dry density of masonry, for example, can be easily found using an accurate postal scale and a kitchen oven.

4.3 Recommendations for Modelling

At this stage in the development of hygrothermal modelling, the quality of the predictions is highly dependent on the experience and expertise of the analysts. This project, for example, required certain derived material properties, the generation of detailed exterior boundary conditions, an understanding of interior conditions and a practical appreciation of the effects of building flaws (such as air leakage and rain penetration).

Certain lessons that apply to most modelling projects are summarized below:

- An assessment of the climate data of a site is important. The role of driving rain can be especially important, and differences between standard weather years and monitored data can play a significant role for exposed assemblies with absorbent cladding materials.

- Parametric studies should be used to identify those variables that are important and those that have little influence on the results. Important variable can receive further investigation while less important variables can be estimated.

- The starting moisture contents must be chosen based on measured values (if available) or the model must be calibrated to the measured data for any hope of matching results in systems that store appreciable amounts of water (e.g., masonry and wood systems).

- The actual materials in the monitored building should be carefully identified and the basic material properties measured if possible. Basic material property data includes colour, density, and, for cladding, rate of water uptake.

- The role of air and rain leakage must always be considered. Although all buildings should be designed and built to be airtight, some assemblies are more sensitive than others to air leakage impacts in service and construction flaws. Air and rain leakage will often overwhelm the influence of heat conduction and vapour diffusion on hygrothermal behaviour.

If hygrothermal enclosure simulation is used as an analysis tool in the design process, the absolute accuracy is less important since design decisions are based on discrete variations in assembly and materials. Hence, for design, more emphasis should be made on comparisons of performance between different assemblies and between climate zones and less on absolute values of performance.

Appendix A

Default Material Property Data Used for Hygrothermal Simulations

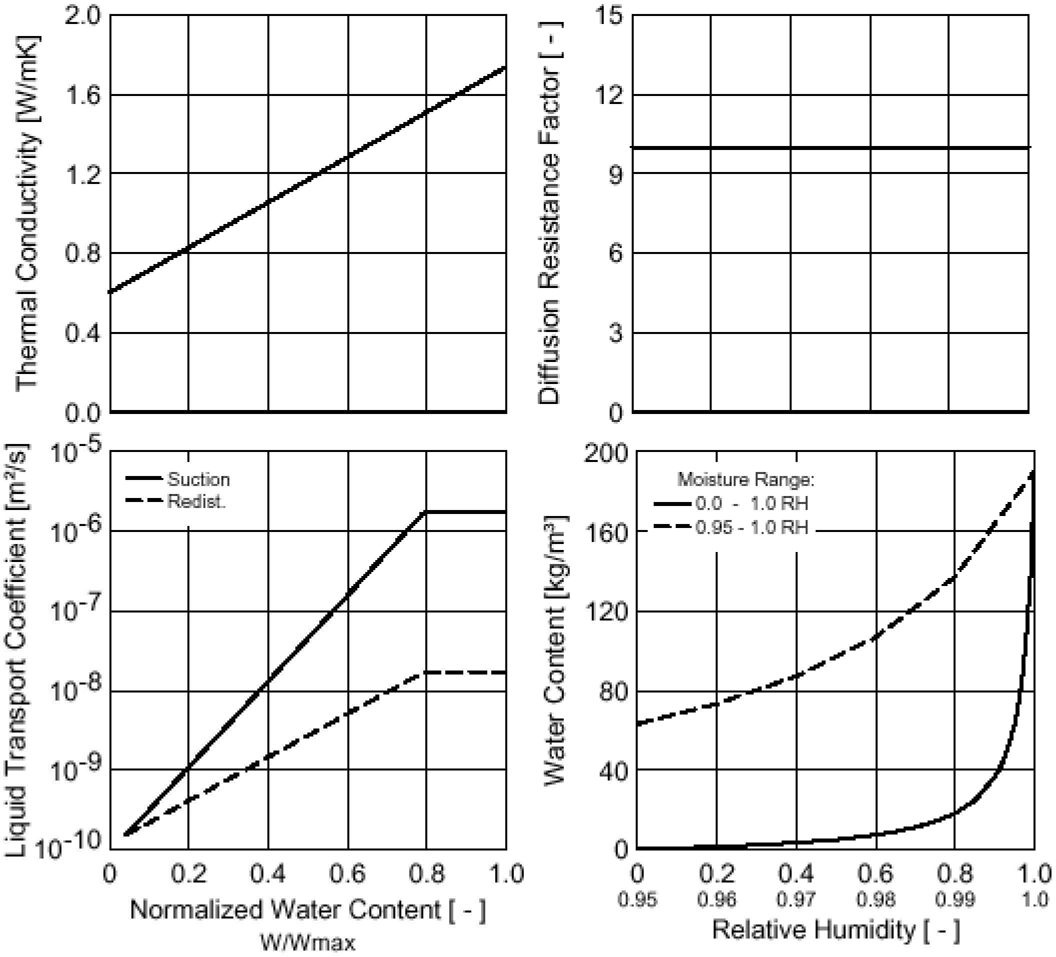
WUFI3.2

IBP

Material : Solid Brick Masonry

Checking Input Data

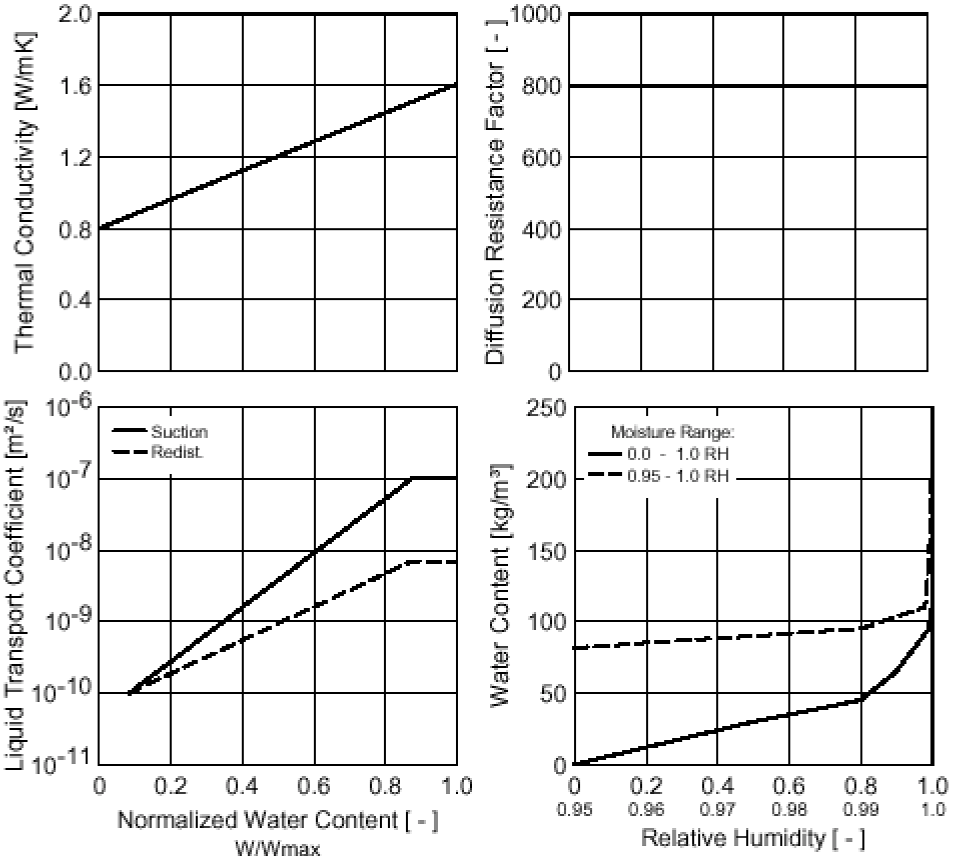
Property	Unit	Value
Bulk density	[kg/m^3]	1900,0
Porosity	[m^3/m^3]	0,24
Specific Heat Capacity, Dry	[J/kgK]	850,0
Thermal Conductivity, Dry	[W/mK]	0,6
Water vapour diffusion resistance factor	[-]	10,0
Reference Water Content	[kg/m^3]	18,0
Free Water Saturation	[kg/m^3]	190,0
Moisture-rel. Thermal Conductivity Supplement	[%/M.-%]	15,0



Material : Cement Lime Plaster

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	1900,0
Porosity	[m³/m³]	0,24
Specific Heat Capacity, Dry	[J/kgK]	850,0
Thermal Conductivity, Dry	[W/mK]	0,8
Water vapour diffusion resistance factor	[-]	800
Moisture-rel. Thermal Conductivity Supplement	[%/M.-%]	8,0

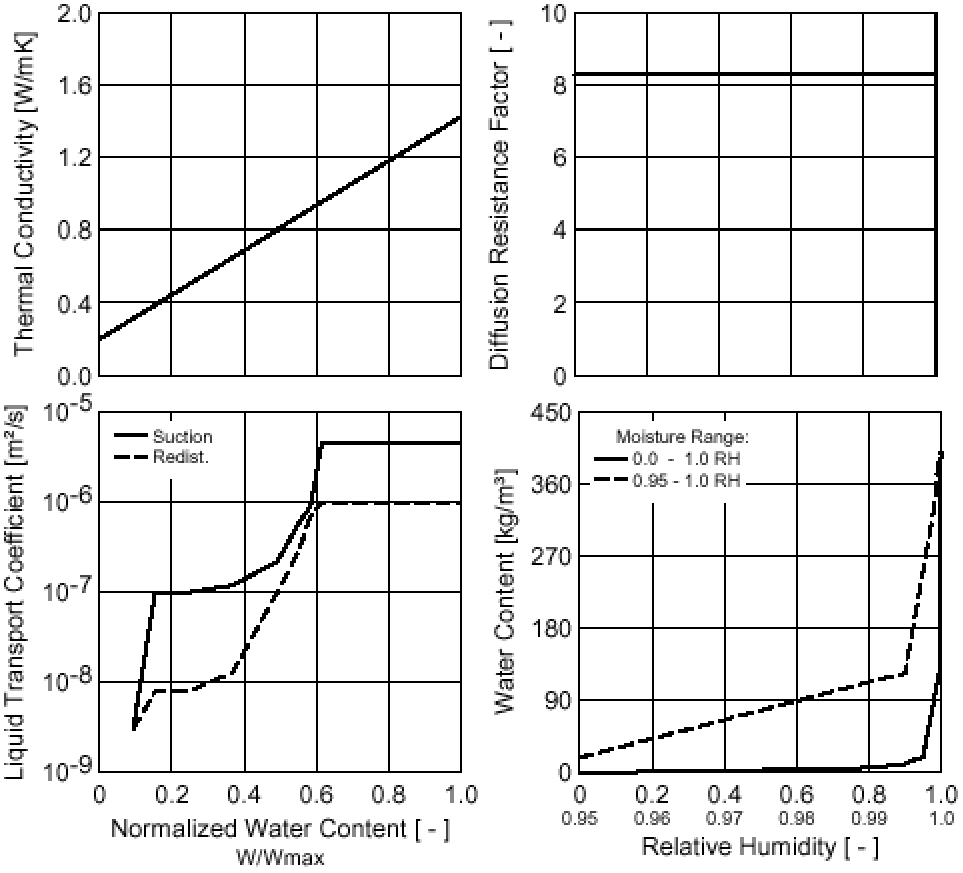


WUFI3.2

Material : Interior Plaster (Gypsum Plaster)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	850,0
Porosity	[m³/m³]	0,65
Specific Heat Capacity, Dry	[J/kgK]	850,0
Thermal Conductivity, Dry	[W/mK]	0,2
Water vapour diffusion resistance factor	[-]	8,3
Moisture-rel. Thermal Conductivity Supplement	[%/M.-%]	8,0

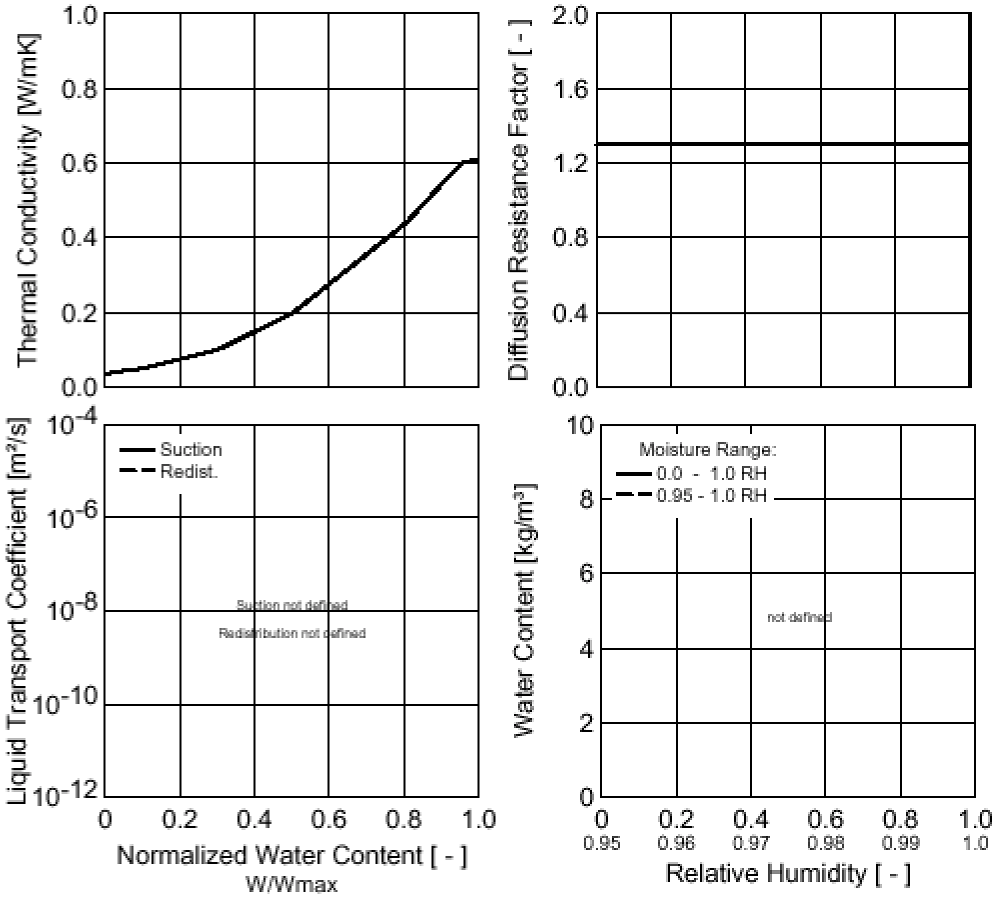


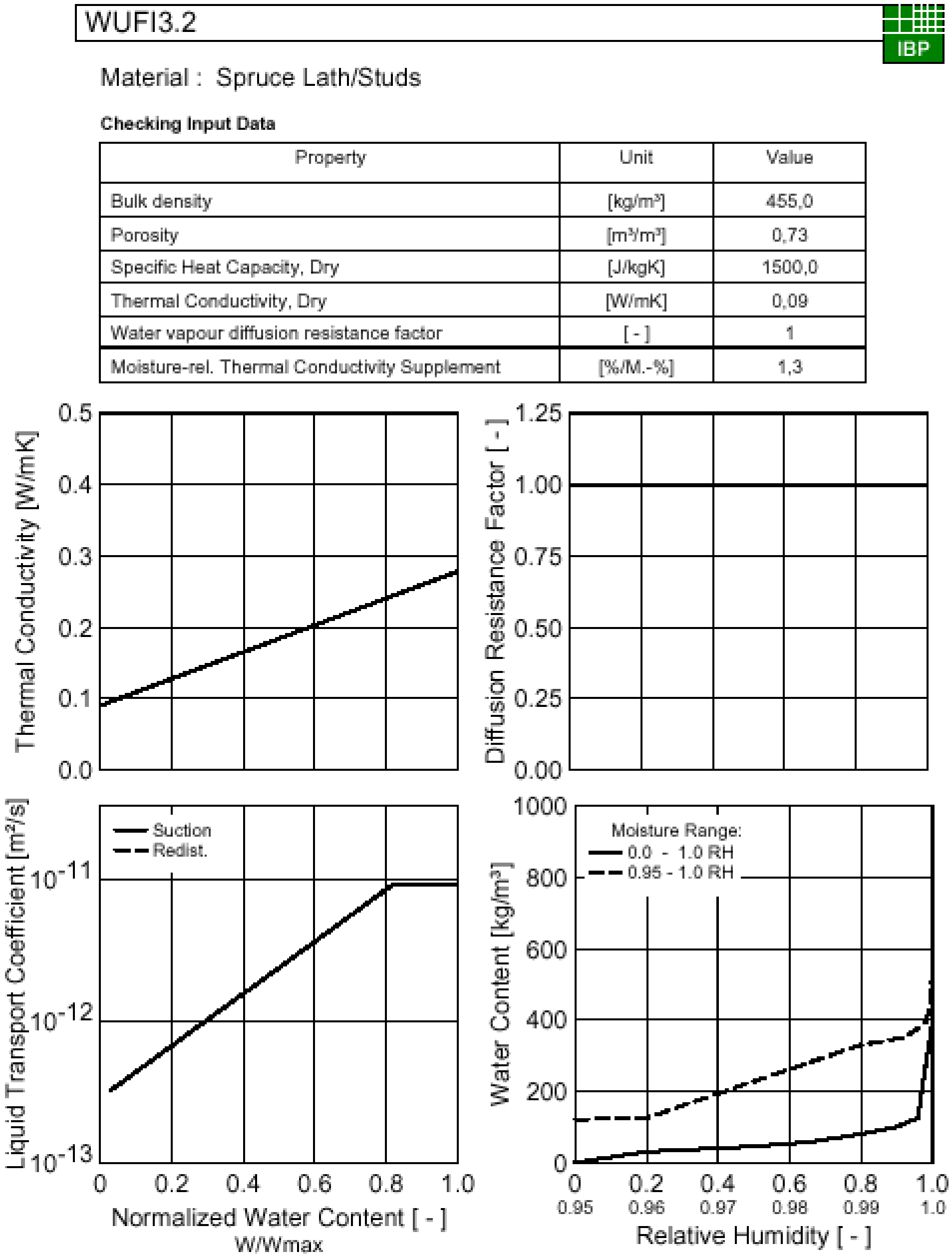
WUFI3.2

Material : Fibre Glass Batt

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	30,0
Porosity	[m³/m³]	0,99
Specific Heat Capacity, Dry	[J/kgK]	840,0
Thermal Conductivity, Dry	[W/mK]	0,035
Water vapour diffusion resistance factor	[-]	1,3





WUFI3.2

IBP

Material : Spruce Lath/Studs

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	455,0
Porosity	[m³/m³]	0,73
Specific Heat Capacity, Dry	[J/kgK]	1500,0
Thermal Conductivity, Dry	[W/mK]	0,09
Water vapour diffusion resistance factor	[-]	1
Moisture-rel. Thermal Conductivity Supplement	[%/M.-%]	1,3

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