A Comprehensive Hygrothermal Investigation of an Unvented Energy-Efficient Roof Assembly in the Pacific Northwest

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ABSTRACT

This paper presents data on the behavior of moisture and temperature in a roof assembly of a western frame constructed, three story high, twelve unit multifamily building in Bellevue, Washington, just outside of Seattle. The data covers a multiyear span and reveals the hygrothermal behavior of two different roof assemblies, first a standard western frame, platform construction vented flat roof assembly, and then a retrofitted unvented and energy efficient roof assembly. The retrofitted roof strategy is only allowed as an exception by the local code authorities, compelling evidence must be presented. This paper provides results from field monitored roof sections and from roof simulations. A state-of-the-art hygrothermal computer program was employed to simulate the complex moisture dynamics, dependent on the specific interior and exterior environments and with the impact of air leakages exchanges in the air cavity. The analysis and measurements were performed for both roof design strategies. Both experimental and advanced modeling provided invaluable insight on the complex hygrothermal transport present in the roof. Results on the moisture accumulation in the roof assemblies, temperatures and relative humidity within the roof envelope systems are presented to quantify the merit of the two different roof assemblies.

INTRODUCTION

Flat roof apartment buildings are common in American housing stock constructed in the building boom of the 1960's and 1970's. These buildings are relatively inexpensive to build, but present a long-term problem with roof's service life. As a provider of low income housing in Suburban Seattle, King County Housing Authority owns and manages several large multifamily housing complexes that have flat roofs. King County Housing Authority is profoundly interested in a long-term solution to this issue. The buildings may have been originally constructed with a slight pitch in the roof, but over the time and for a myriad of reasons, i.e. building settling, failing roof assemblies, the roof pitch is modified greater than the original pitch and essentially flat; ponding of water on the roof membrane is endemic. Many of the existing roofs upon a forensic visit are found to have rotted roof sheathing at a roof tear off of the flat roof multifamily buildings.

King County Housing Authority, on the advice of local and national roofing contractors, experimented with additional passive attic ventilation in the roof assembly. Soffit vent openings were increased, ridge events were devised and installed, and turbine vents were installed. Experience with additional ventilation is mixed. Drainage of the roof is made more problematic; roof maintenance became a significant management burden. Roof service life did not increase substantially. The additional attic ventilation suggested a building with substantial air leakage of warm heated air. King County Housing Authority is concerned about the energy cost burden on its residents. Clearly an alternative solution was needed.

Cascadian Apartments in Bellevue Washington is a scattered site multifamily housing complex. There are sixteen three story buildings and they all have flat roofs. The flat roofs have a life expectancy less than seven years. The roof assembly is typical of this style housing stock and shown in Figure 1. When the scientific hygrothermal investigation was initiated,

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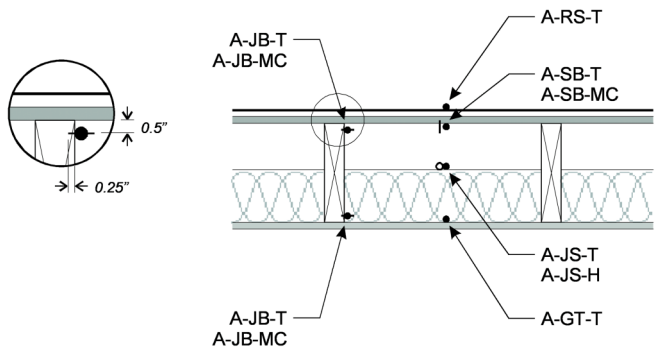

Figure 1 *Existing roof instrumentation layout.*

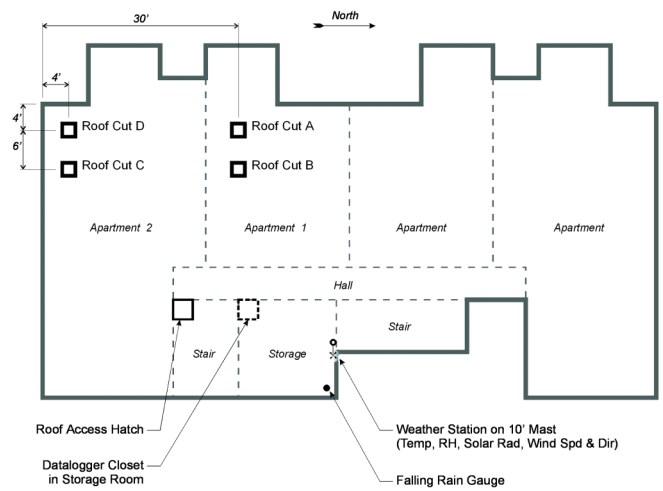

Figure 2 *Existing roof layout.*

King County Housing Authority was in the process of reroofing four of the buildings at Cascadian Apartments. It was proposed that one of the buildings scheduled for reroofing be postponed and investigated for hygrothermal behavior for one year and then reroofed with an alternate roof assembly. The investigation would include field measurements and computer simulations of the moisture and thermal behavior within the roof assembly. The computer simulations could be compared to real world conditions and used to suggest alternative roof assemblies.

One promising alternative approach was to install the insulation on the exterior side of the exterior side of the sheathing, directly under the roof membrane. This assembly would keep the wood sheathing warm and free of condensation. This assembly would render passive attic ventilation irrelevant. Passive attic ventilation could be sealed and insulated and improve the energy efficiency of the building.

INSTRUMENTATION

Existing Roof

To understand the hygric loads involved in the short service life performance of the existing roofs, four sections of the roof were cut-out and instrumented by Straube et al (2003) in November of 2001. One of the apartment complexes in Bellevue, WA was set aside for experimental analysis. This one building would have moisture and temperature sensing equipment installed within the traditional roof assembly to capture the environmental conditions. The following summer this building would be reroofed and the instrumentation would remain.

In Figure 2, details are provided for the existing roof assembly and construction that were in the apartment complex building.

In Figure 1 the experimentation layout is given for the existing roof system. The footprint includes 6 thermistor (defined as (T) and were Fenwall type with accuracy of +/- 0.2 Celsius), three moisture content pins (defined as (MC) with uncertainty of ±2% Moisture Content (MC) within 8-30% MC range) and one RH sensor (defined as (H) manufactured by Omega, with RH: 3 to 95%, Range:-20 to 75°C, ±2.5% RH from 20 to 80% RH; ±3.1% RH below 20 and above 80% RH") placed on the rock wool insulation batt for each of the four roof sections. A complete weather station (temperature, relative humidity, wind speed, wind orientation, and total horizontal solar) was installed on the roof and measurements on an hourly basis were recorded. Additionally sensors were installed in the apartment complexes and the temperature and relative humidity were also recorded.

Roof cut B had high water entry occurrence from the first day and Roof cut D exhibited very high moisture contents in the top and bottom of the joist as well as the sheathing. Overall, similar performance was observed among the roof sections in the existing roof system.

In Figure 3, the hourly temperature and moisture content is shown for the existing roof in section C. The time period is starts between Nov. 3, 2001 until April 5, 2002. The temperature and moisture content at the top of the wooden joist are plotted out. It is obvious that a high moisture accumulation is present in the existing roof system. This accumulation exceeds the fiber saturation of the wood and moisture induced damage is expected to occur with such high levels of moisture contents. Indeed, moisture contents exceeding 20% should be avoided especially for such prolonged periods of time (6 months or more). It is clear why the existing roof needed to be replaced every few years.

In the next section information is presented on the hygrothermal model MOISTURE-EXPERT developed by Karagiozis (2001, 2003, 2005) used to analyze the performance of the existing roof.

COMPUTER SIMULATION

Moisture Modeling

The MOISTURE-EXPERT V1.2, developed by Karagiozis (2003) hygrothermal model, was employed in developing a parametric analysis of the hygrothermal performance of

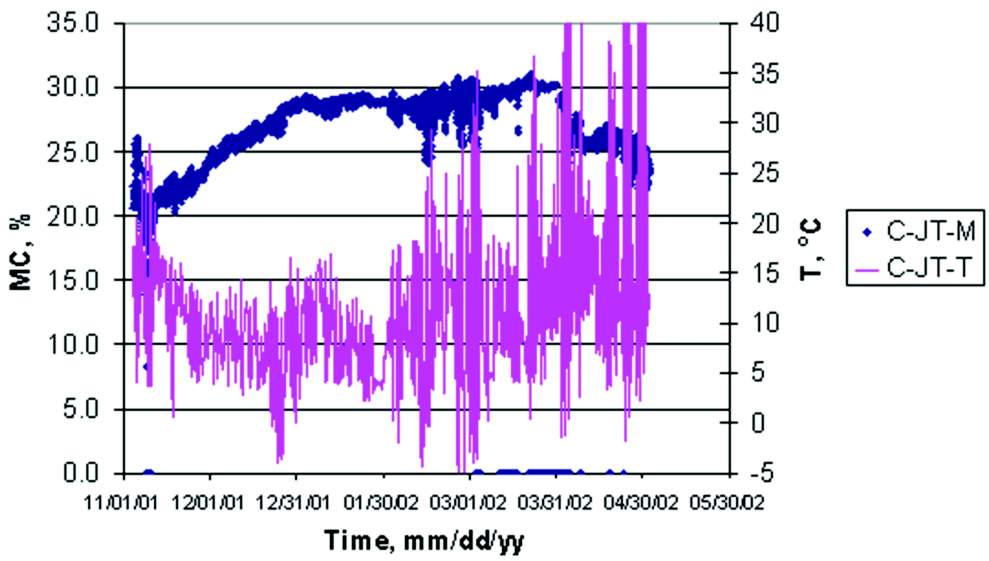

Figure 3 *Field results for top joist temperature and moisture content in existing roof case.*

the selected walls as a function of various climatic conditions, vapor control strategies and interior conditions.

The model was developed to predict the dynamic 1-dimensional and 2-dimensional heat, air and moisture transport in building envelope geometries. The model treats vapor and liquid transport separately. The moisture transport potentials are vapor pressure and relative humidity, with temperature for energy transport. The model includes the capability of handling temperature dependent sorption isotherms and liquid transport properties as a function of drying or wetting processes.

The model has been extensively validated for a number of proprietary wall systems, as well as the 40 odd walls in the test facilities in Charleston, SC and Puyallup WA. In addition, a comprehensive validation was performed for ASHRAE TRP 1091 project on Rainscreen walls and membranes research.

GOVERNING EQUATIONS

Moisture Balance

The moisture transport balance is given as:

$$\frac{\partial(\rho_m u)}{\partial t} = \nabla(-D_\phi \nabla\phi - \delta_p \nabla P_v + \rho_v V_a) \qquad (1)$$

where

ρ_m = dry density of porous material, kg/m^3
D_ϕ = liquid moisture transport coefficient, kg/s
u = moisture content, kg_{wet}/kg_{dry}
T = temperature, °C
ϕ = relative humidity
δ_p = vapor permeability, kg/s·m·Pa
P_v = vapor pressure, Pa
V_a = velocity of air, m/s
ρ_v = density of vapor in the air, kg/m^3
t = time in seconds

Air Balance

The air mass balance is given as:

$$\frac{\partial \rho_a}{\partial t} + \nabla(\rho_a V_a) = 0 \qquad (2)$$

where

ρ_a = dry density of air, kg/m^3

Momentum Balance

The momentum balance (Navier Stokes equation) is given as:

$$\frac{\partial(\rho_a V_a)}{\partial t} + \nabla(\rho_a V_a \cdot V_a) = -\nabla P_a + (\nabla^2)\frac{\mu_a}{K_a} V_a + \rho_a g \qquad (3)$$

where

P_a = air pressure, Pa
K_a = air permeability, s/m
μ_a = dynamic viscosity, m/s^2
g = gravity m/s^2

Energy Balance

Heat transfer in a porous media is complex. Present in the material are conduction, convection, evaporation/condensation sources and radiation heat transfer. The equation governing this scalar quantity is given below as:

$$\rho_m C_p \frac{\partial T}{\partial t} = -\nabla(\rho_a C_p V_a T) + \nabla(k\nabla T) + L_v(\delta_p \nabla P_v) + L_{ice}\rho_m u \frac{\partial f_1}{\partial t} \qquad (4)$$

where

C_p = heat capacity, J/kg·K
k = thermal conductivity, W/m·K
L_v = enthalpy of evaporation, J/kg
L_{ice} = enthalpy of freezing, J/kg
f_1 = liquid fraction (dimensionless)

Boundary Conditions

Vapor mass flow at the faces of the geometry:

$$m_v = \beta(P_{va} - P_{vsurf}) + V_a \rho_v \quad (5)$$

where

m_v = vapor mass flow, kg/m^{2}s

β = convective mass transfer coefficient, s/m

Liquid flow at the faces of the geometry:

$$m_{liquid} = m_{driving\ rain} \quad (6)$$

where

m_{liquid} = liquid flow, kg/m^{2}s

with a maximum moisture content equal to capillary moisture content of the exterior surface. The maximum flow rate is given by the predetermined wind-driven rain flux. The wind-driven rain mass flow $m_{driving\ rain}$ available at the face of the geometry is predicted using the proposed SPC 160P standard. The method takes into account various exposure factors, height, wind speed and orientations.

Heat flux at surface including solar radiation:

$$q_{surf} = h_{eff}(T_{eq} - T_{surf}) + V_a \rho_a T + m_{liquid} C_{p,w} T_a + m_v L_v \quad (7)$$

$$h_{eff} = h_r + h_c \quad (8)$$

where

T_{eq} = equivalent temperature (including shortwave solar and longwave radiation with environment)

$C_{p,w}$ = heat capacity of liquid water, J/kg·K

h_c = convective heat transfer coefficient,W/m^2·K

h_r = radiative heat transfer coefficient,W/m^2·K

In the formulation of the above equation, thermodynamic equilibrium was assumed.

The model accounts for the coupling between heat and moisture transport via diffusion and natural and forced convective air transport. Phase change mechanisms such as evaporation/condensation and freezing/thawing are incorporated in the model. The model includes the capability of handling internal heat and moisture sources, gravity driven liquid moisture, and surface drainage capabilities. The model also captures experimentally determined system and sub-system performances and anomalies of the building envelope.

While data was being collected from the existing roof assembly, a computer simulation of the building was modeled with the goal of simulating the moisture content of the roof sheathing of the two different roof assemblies under different air leakage rates: air leakage from the building interior into the cavity and air leakage from the exterior into the cavity.

Simulation Results

A series of simulations were performed that imposed interior and exterior hygrothermal loads representative of Seattle WA. Hourly simulations were performed for a period of a year that encompassed the 10 percentile coldest year determined from 30 years of US national climatic weather data (1961-1990). Initially a series of preliminary simulations was performed to determine the experimental instrumentation plan. Figures 4 and 5 depict the control volume distribution used in the modeling for both roof systems.

The analysis of the results allowed the placement of the relative humidity, temperature, and moisture content sensor in strategic locations. Once these locations were identified, the existing roof (old) was instrumented accordingly. Next a parametric investigation was performed on both the existing roof and the proposed retrofit one. Several performance attributes were investigated. The contributions of air leakage from either the interior or the exterior was investigated to determine the relative influence on the hygrothermal performance of roof. The effect of ventilation blocking of the roof was studied. The effect of adding additional insulation, thus reducing the drying

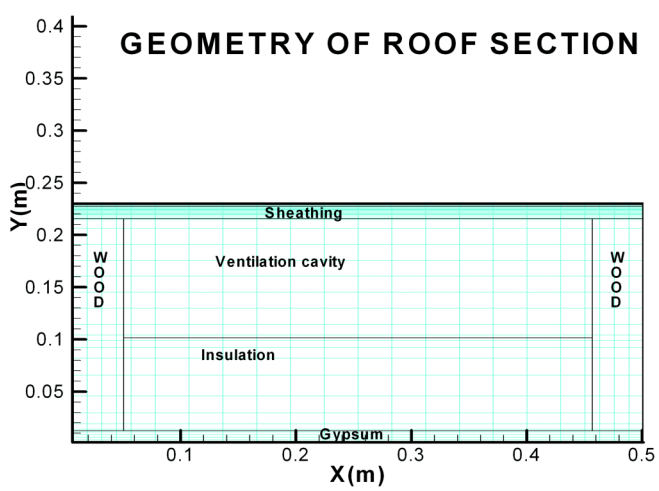

Figure 4 *Numerical grid for simulation of existing roof.*

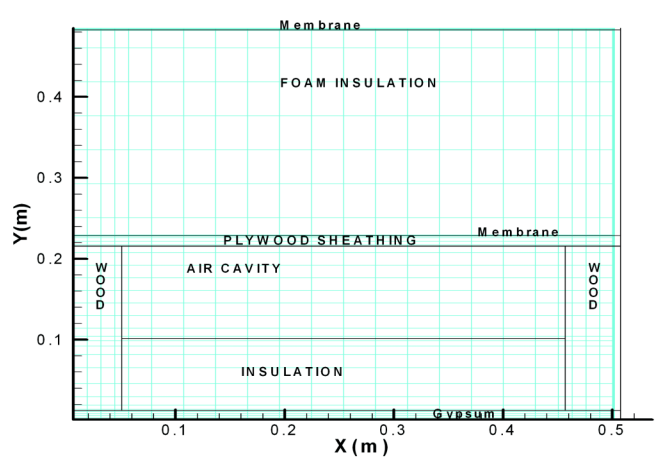

Figure 5 *Numerical grid for simulation of retrofitted roof system.*

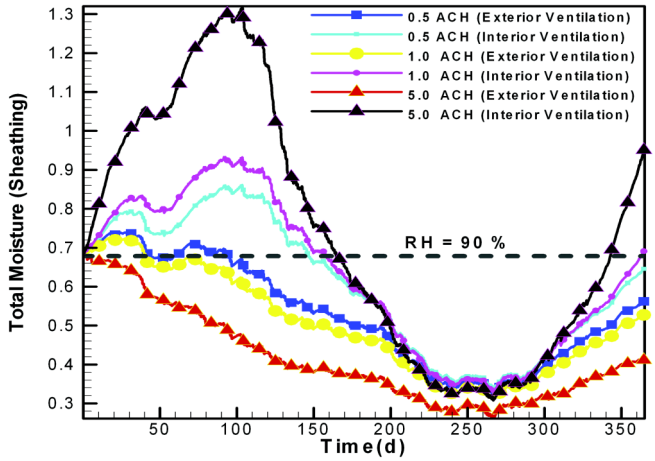

Figure 6 *Performance of existing roof sheathing as a function of interior or exterior ventilation (0.5, 1, and 5.0) (total moisture in kg/m (depth)).*

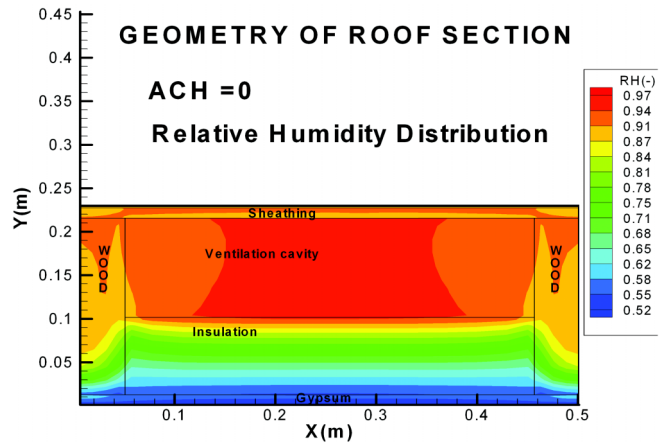

Figure 7 *Relative humidity distribution at week 8 with ACH = 0 from the interior.*

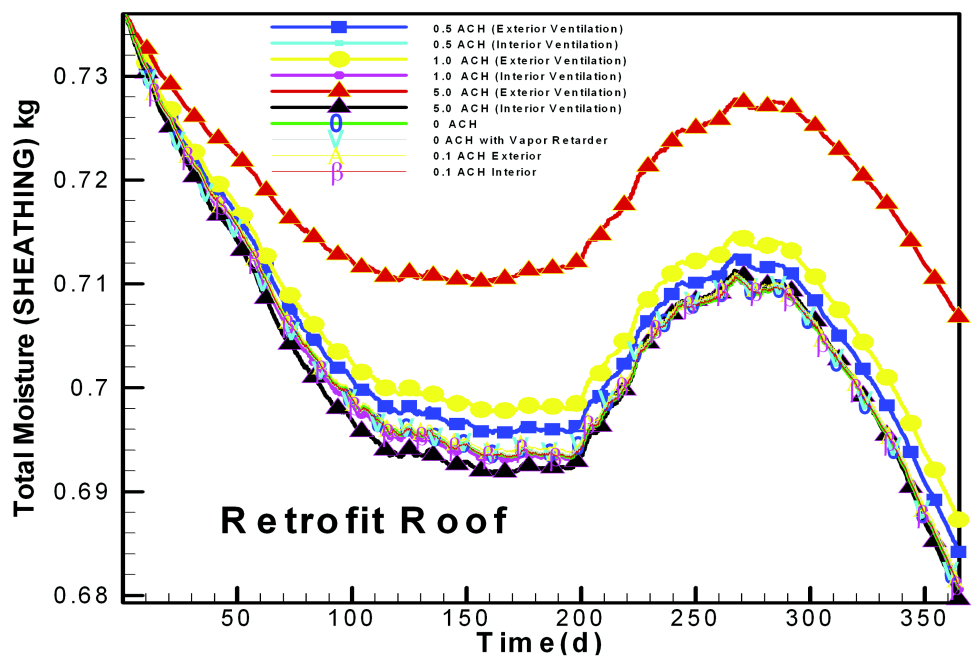

Figure 8 *Results for the retrofitted roof system (total moisture in kg/m (depth)).*

potential of the roof, was also examined. Figure 6 shows the hygrothermal impact of interior leakage and exterior ventilation on the existing roof by plotting the total moisture in the roof sheathing as a function of time. It is clear that even a small amount of interior leakage causes very large increases in moisture in the exterior roof sheathing.

Figure 7 shows a 2-D relative humidity spatial distribution of the existing roof with no air exchange from either the inside or the outside at week 8. High relative humidity were found in the sheathing board.

Figure 8 shows the hygrothermal impact of interior and exterior ventilation on the retrofitted roof by plotting the total moisture in the roof sheathing as a function of time. It is clear that this roof is very dry and the hygric performance is not influenced by interior or exterior ventilation leakage rates causing previously very large increases in moisture in the exterior roof sheathing.

Figure 9 shows a 2-D relative humidity spatial distribution of the proposed roof assembly with the cavity ventilation at 5 air exchanges per hour from exterior at week 8. Low relative humidities were found in the sheathing board indicating good hygric performance.

Results were processed to develop a relative ranking of the roofs heat and moisture performance. The existing roof

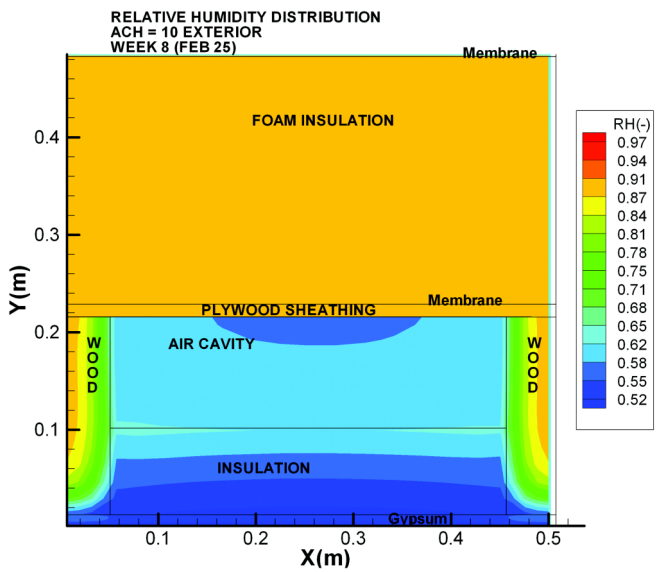

Figure 9 *Retrofitted roof RH distribution week 8 at ACH = 10 from the exterior.*

system was found to be very sensitive to interior moisture loads especially air leakage. Net yearly accumulation in the sheathing board was found for the existing roof suggesting that the performance of such a roof should not be employed in climatic conditions as found in the Bellevue, WA area. The proposed retrofit roof was found to be less sensitive to climatic loads and interior load and provided enhanced drying potential. The proposed roof was found to be both more energy efficient and had a lower risk for moisture problems. Interior and exterior air ventilation did not display a strong dominating impact as found in the existing roof. However exterior ventilation for the retrofitted system did increase diurnal moisture accumulation and soffit ventilation should be blocked. Elimination of (old) roof membrane during the retrofit action was found not to increase the drying performance of the roof.

Retrofit Measured Data for Warm Roof

In Figure 10 the instrumentation layout is given for the retrofitted roof system.

In Figures 11 and 12, the measured time dependent temperature and moisture contents are plotted out for the retrofitted roof system. From the measured moisture contents, the values remain very low never exceeding 18.25%. If one compares these values with those measured with the existing roof which exceeded 20% for a period more than 6-months with a maximum of 35%. These low moisture contents clearly indicate the positive impact when the roof sheathing is maintained warm.

CONCLUSIONS

This project is one of the few projects that moisture engineering principles (material, field and modeling principles) have been applied to solve a real building problem.

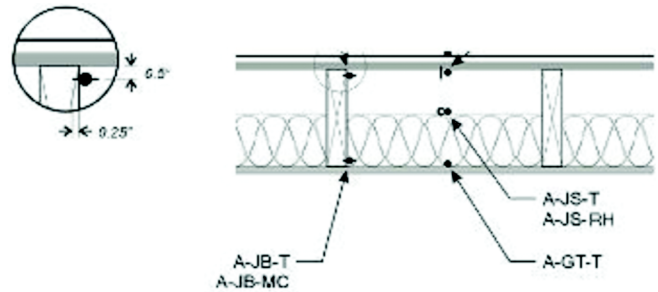

Figure 10 *Instrumentation of new retrofitted roof system (plywood sheathing sealed at edges).*

Good agreement was found between the hygrothermal model and field monitored performances.

From the measured data, the moisture content observed in the sheathing board and the top wood joist were found to be acceptable for the retrofitted roof system. The retrofitted unvented insulated roof system did not perform badly in terms of hygrothermal performance. No net yearly accumulation was found in the retrofitted roof systems and a strong drying performance was displayed in all of the four roof segments.

Sealing of the roof cavity openings along with the addition of foam insulation have reduced the impact of interior and exterior loads on the hygrothermal performance of the roof. This allows the roof to naturally dry towards the interior when conditions permit it to do so, and eliminates the drying towards to exterior. This allows the exterior sheathing boards to be dry all year round. As the moisture contents in the wooden members never exceeded 25%, no rot is expected to occur in these roof systems.

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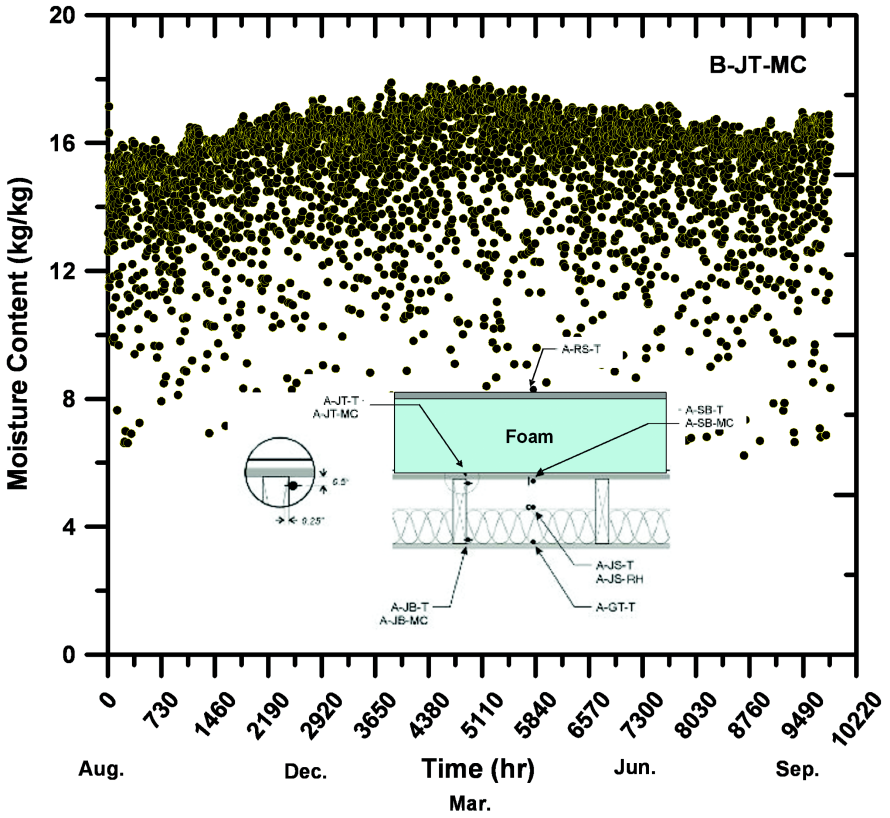

Figure 11 *Measured moisture contents in top joist (sensor locations for sections A and B are the same).*

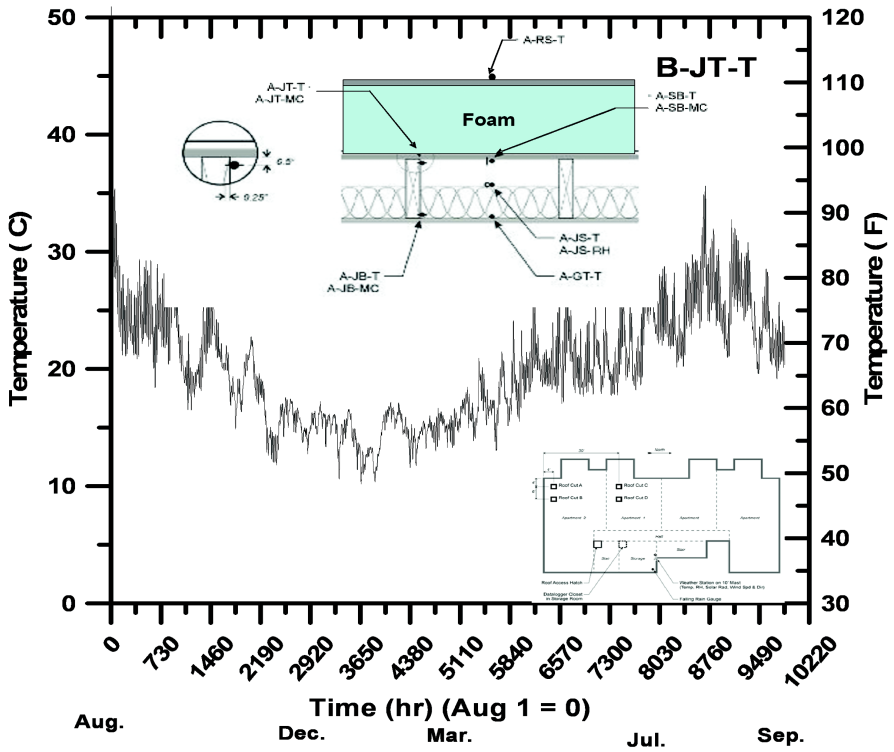

Figure 12 *Retrofitted roof temperature as a function of time .*