A Field Study on Quality of Three First Nation Homes on the Squamish Urban Reserve of West Vancouver

By

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ABSTRACT

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Three new homes in the First Nations Squamish urban reserve were instrumented, tested, and monitored for a period of one year. Performance data was obtained from these homes and analyzed to help assess their quality and improve their performance. From the field study, the houses performed reasonably well. However, there is large room for improvements. Considering construction durability, the built-in moisture in the houses dried well. However, as expected, the moisture in the attics was high and improvements are recommended. The monitoring also confirmed that north facing walls take more time to dry and remain wet in some areas, despite the fact that the monitored year was one of the driest years in record, as reported by Environment Canada. Dangerously high moisture levels were also recorded in a few wall locations, believed to be caused by construction deficiencies at window sills and wall penetrations. In general, wall orientation and obstructions to solar radiation play a major role in the moisture balance of walls. This study confirmed that north-facing walls have higher moisture content, which also takes longer to dry out. South-facing and east-facing walls have lower moisture content (i.e. due to higher solar radiation and higher wall temperature to promote

evaporation). The effect of external obstructions (i.e. large trees) to solar radiation was seen in the high moisture content of the west walls that was close to that of north walls.

However, as reported in this study, poor construction detailing overpowers orientation on impacting wall moisture, and is the major source of concern for rain penetration. Unfortunately, wood-frame construction is unforgiving to construction deficiencies, and maximum care must be exercised to protect all details and wall penetrations from rain.

Considering the indoor environment, in general the conditions were within acceptable limits; however, indoor conditions are greatly affected by occupants' behaviours (e.g. opening windows in cold days). Particular problems arising from tobacco smoking and wood carving could not be measured. From the field study and computer simulations, it is recommended to make the houses more airtight to improve durability, energy efficiency, and possibly indoor air quality. It is also recommended to decouple the ventilation system from the house heating system to improve its ventilation reliability.

Keywords: Monitoring First Nation homes, Indoor air quality and energy efficiency, CO2 contaminant dispersion models, ventilation

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

First Nation communities are more likely to live in poor housing conditions than the general population, owing to usually lower construction quality, low maintenance, lower ventilation rates, high occupancy and environmental tobacco smoke (National Council on Welfare, 2007). These communities are mostly located in remote and colder regions of Canada, where the construction season is shorter. Moreover, unique constraints like shortage of skilled workers, unavailability of building materials, dependence on fossil fuels for heat & electricity, and rising population challenges the construction, indoor air quality and energy efficiency.

Poor housing is related to poor health conditions in these communities (Royal Commission on Aboriginal People, 1996). Increase in life threatening infections, respiratory disorders, mental and chronic illnesses, and higher infant mortality rates are the result of poor living conditions (Health Canada, 2010). Limited information is available on how construction, mechanical equipment, climate, & occupant related factors affect the quality of these homes. There is a need to monitor the actual performance and devise solutions to improve the quality; incorporating the unique constraints, construction & service life conditions.

This research is a pilot project which attempts to study the performance of three First Nation Homes on a Squamish Nation Reserve in West Vancouver. The project originated after discussions with a representative of the Canada Mortgage and

Housing Corporation (CMHC) in Vancouver who transmitted the interest from the local Squamish First Nations band to have their houses monitored and obtain help to improve their quality.

The construction on the Squamish Nation Reserve is typical of local urban reserve homes, which do not require stringent home inspections by city officials. The building codes and best practice guidelines (HPO 2011) for coastal climate of British Columbia are not followed strictly; therefore, they are believed to be more vulnerable to durability issues than a conventional home. Moreover, typical occupant behaviors like smoking inside the house and hobbies like wood carving, adversely affect the indoor air quality in these homes.

In collaboration with the local company, SMT Research Inc., a remote sensing technology was used to monitor these homes. The intent of using remote monitoring system was to investigate if this system is feasible and practical, for its use in the remote regions of Canada.

The underlying premise in this research is that higher value can be gained from a monitoring system that combines different types of monitored data, such as indoor, construction, and energy, in building awareness and enabling better informed decision-making by homeowners and builders. Good housing quality is a result of good design, careful construction, and proper maintenance practices. Housing quality does not only affect property value, but also the use of natural resources, such as energy, and the health and well-being of the occupants.

1.2 SCOPE

The thesis focuses on the performance of three houses on an urban First Nation reserve. It does not attempt to demonstrate that such a small sample of houses is representative of all Canadian or First Nations' homes, or of homes in remote regions. Instead, it attempts to use a sample of typical new homes on a local First Nation Reserve to improve the quality of the existing as well as future homes on the reserve.

1.3 OBJECTIVES

The primary objective of this study is to monitor a group of First Nations homes to obtain durability, indoor air quality, & energy performance data over the period of one year, and use this data to propose cost-effective solutions to optimize the quality & resiliency of existing as well as future homes on the reserve. The second objective is to use knowledge gained from the study to test the feasibility of a remote monitoring system integral to homes and identify the challenges faced in implementing such a system in remote regions.

1.4 LIMITATIONS

This work is mainly limited to three first nation homes situated on a local urban reserve, thus statistical analysis of the data is not applicable. The project was initially planned for a remote First Nation reserve located in Tofino, BC, but due to logistics and project costs, the location was changed and the number of houses was limited to three. These homes are not truly representatives of remotely located, high occupancy houses located in colder climates. But they provide a good experimental setting for testing the feasibility of remote monitoring system and to study the indoor air quality and envelope performance of the houses on the selected reserve; and devise cost effective and practical solutions for future improvements.

As agreed with the homeowners and with the Squamish First Nation, the monitoring took place over a period of one year. However, it would have been convenient to extend the monitoring period to two years to be able to appreciate two cycles of wetting and drying and help better predict the long term performance of these constructions. The results show gaps in the data as well as some incomplete data i.e. not spanning one year. The reasons for missing data were malfunction of some sensors (which were new) and the inability to fix these sensors due to lack of access to some houses.

1.5 STRUCTURE OF THE THESIS

This thesis is presented as a collection of three manuscripts, where, individual manuscripts are interrelated but may be read as separate entities. Together, these manuscripts build on each other through the presentation of data, analysis and conclusions. The list of manuscripts and their objectives are listed in the section 1.6; and the manuscripts are included in APPENDIX A. The rest of the thesis is divided into eight chapters.

- Chapter 1 presents the introduction and background

- Chapter 2: Literature Review – Presents the literature review that serves as the point of departure of the research as a whole. Each manuscript has its own literature review pertaining to its subject.
- Chapter 3: Problem Statement – Describes the problem statement based on the challenges discussed in the literature review.
- Chapter 4: Methodology – Describes the methodology of the whole research work in detail. This methodology is common to all three manuscripts.
- Chapter 5: Analysis and Results – Presents the overview of the results from the data analysis.
- Chapter 6: Discussion and Recommendations – Discuss the research findings based on the data analysis, and energy & air flow models.
- Chapter 7: Conclusions – Presents the conclusions of the research work. Discuss future work and challenges faced in the project
- Chapter 8: References

1.6 MANUSCRIPTS

This research resulted in the following three interrelated manuscripts.

Manuscript 1:

"Sensitive Homes: Remote Sensing and Monitoring Integral to Homes"
In Proceedings from 17th ASHRAE IAQ Conference, 2013, pp: 341-351, Vancouver, BC

Objective: *To study the need and value of a remote health monitoring system integral to homes from preliminary monitoring data of a group of First Nation homes; and based on the* *knowledge gained and challenges faced, set the vision for the conceptual architecture of such a health monitoring system.*

Manuscript 2:

"Indoor air quality and envelope monitoring of First Nation homes on an urban reserve: A pilot study"

Selected for the 14th Canadian Conference on Building Science and Technology

Objective: *Complete data analysis to gain knowledge on the indoor air quality, durability and energy efficiency of three First Nation homes on the reserve. The emphasis was to identify indoor humidity, temperature and air quality patterns in relation to occupancy, occupant behavior and weather; envelope moisture performance in relation to indoor and outdoor conditions, construction and orientation; and weather effects on indoor conditions. Use the knowledge gained to recommend performance improvements in future homes on the reserve.*

Manuscript 3:

"Ventilation for a house as a system: A pilot study on the Squamish Urban reserve"

In Proceedings from the Indoor Air Conference 2014, Hong Kong

Objective: *Building on the knowledge gained in manuscript 2, study the ventilation performance of three homes on the reserve and; investigate energy efficient and cost effective solutions to improve the air quality of the houses on the reserve.*

CHAPTER 2 - LITERATURE REVIEW

2.1 CHALLENGES IN FIRST NATION HOMES

First Nations communities in Canada suffer from a poorer quality of life as compared to non-Aboriginal population (Wilson et. al., 2002). These communities are mostly located in remote and colder regions of Canada, henceforth, more likely to live in poor housing conditions than the general population. Shortage of skilled workers and unavailability of building materials in remote regions, coupled with rising population and shorter building season, challenges the construction, indoor air quality and energy consumption (National Council on Welfare, 2007).

Studies conducted on these communities have related poor housing conditions to poor health outcomes. Lower ventilation rates, high occupancy and low maintenance are found to be responsible for higher infant mortality rates, Sudden Infant Death Syndrome, respiratory deceases (UNICEF 2009), and increase in life threatening infections, injuries, mental illness and chronic illness (Kovesi 2006, Kovesi 2007, CMHC 2003, National Collaborating Centre for Aboriginal Health, 2010).

Mold is a major problem in First Nation homes. Several crises due to mold infestation with damp floors, and sometimes whole walls and ceilings have been reported (Firstnation.ca, 2007). In a field survey of 400 homes in First Nations community in British Columbia, 50% of the houses were found to have excessive mold growth due to moisture intrusion from leaky roofs and crawl spaces, lack of vapor barriers, lack of ventilation, blocked soffits and poor housing design for marine climate in BC. Another survey of 26 houses in Fort Albany found that more than half of these houses had mold growth due to poor grading and construction. Similarly all houses in Dakota plains First Nation Community were found to be infected with mold due to basement flooding as these were built on bog (Kovesi, 2010).

Stringent inspections from city officials are not needed in newly built First Nation Homes. Thus, there is a tendency of ignorance in building these homes on behalf of contractors and tradesmen. The houses tend to be built with low standards; and trade-offs between quality and costs are normal.

Limited information is available on the performance of First Nation homes in the literature. Few studies have been conducted to analyze how the unique challenges of remote locations affect the actual performance of these houses. Recently, efforts have been made to identify exposure pathways to environmental contaminants among First Nation Communities in Canada (AFN 2011, FNFNES 2011). But these studies did not include indoor contaminant exposures. There is a need to monitor and characterize the performance of these homes; and find solutions to improve their resiliency and indoor air quality.

A good communication at local councils, housing authorities and Government levels is needed to improve the construction standards and most importantly educate First Nation communities about the indoor air quality and subsequent health problems. This research is based on the premise that monitoring the actual performance of a home is an effective way for homeowners to understand the performance of their own homes and get a general perspective how a house is affected by the indoor and outdoor conditions.

2.2 NEED TO CONSIDER A HOUSE AS A SYSTEM

This section reviews previous work on the key interrelated factors that need to be considered to understand the performance of a house. House is a system and its performance depends upon many components which are interrelated and vary with time. Changing one component of a house without considering how it influences other components, often results in unintended negative consequences to the related systems. For example, improved envelope airtightness is advantageous for energy, comfort and durability; but it can also lead to increased indoor pollutants that are harmful and often trigger ailments, asthma and other respiratory illnesses among occupants (Wray, Matson, & Sherman, 2000,U.S. EPA,2009). Several epidemiological studies have established relationship between increased indoor air pollutants and adverse effects on the health of occupants (Butz et. al. 2011, Gale et. al. 2012, Zhu et. al. 2012).

The major sources of air pollutants in housing are: combustion by-products from boilers, furnaces, or gas stoves; chemicals stored or used regularly inside homes (e.g. cleaning detergents, paints, perfumes, etc.); occupants' habits such as cooking, hobbies producing chemicals or dust, and smoking; and microbial growth at the envelope and indoors. Addressing the first three sources is out of the scope of this project because they are safety related for the former one (which deserves a separate study), or habits related for the latter two (which cannot be controlled by construction). Therefore, this study focuses on microbial pollutants, which are prevalent in houses. A Wealth of microbial pollutants can be found in the indoor air, such as dust mites, air borne bacteria, and mould spores. The presence of all of these is promoted by dampness and moisture (WHO 2009), and by poor cleaning habits. Measure of humidity in the air is the relative humidity (RH). Ideally, indoor RH as indicated in Figure 1 (Sterling 1985) should range between 30% and 55%. Higher RH levels lead to dampness and microbial growth. Lower RH levels produce discomfort and respiratory problems from air dryness.

Relative humidity (RH) levels above 80% sustained over a certain period of time will certainly lead to mould growth on wood; and RH levels above 90% will certainly lead to wood decay. The severity of the growth and subsequent decay depends on how high the RH is, the type of wood, and the amount of time in which such high RH levels are sustained.

Two solutions to control indoor air pollutants are offered from a construction perspective. 1) Source control, which involves eliminating or minimizing the presence of source of air pollutants: chemicals in construction materials and microbial pollutants; and 2) ventilation, which involves diluting polluted indoor air with make-up fresh outdoor air. In the past, house ventilation was leakage-based, by natural air movement through the envelope cracks; nowadays, an active mechanism (i.e. a fan) to draw fresh outdoor air into a house is required.

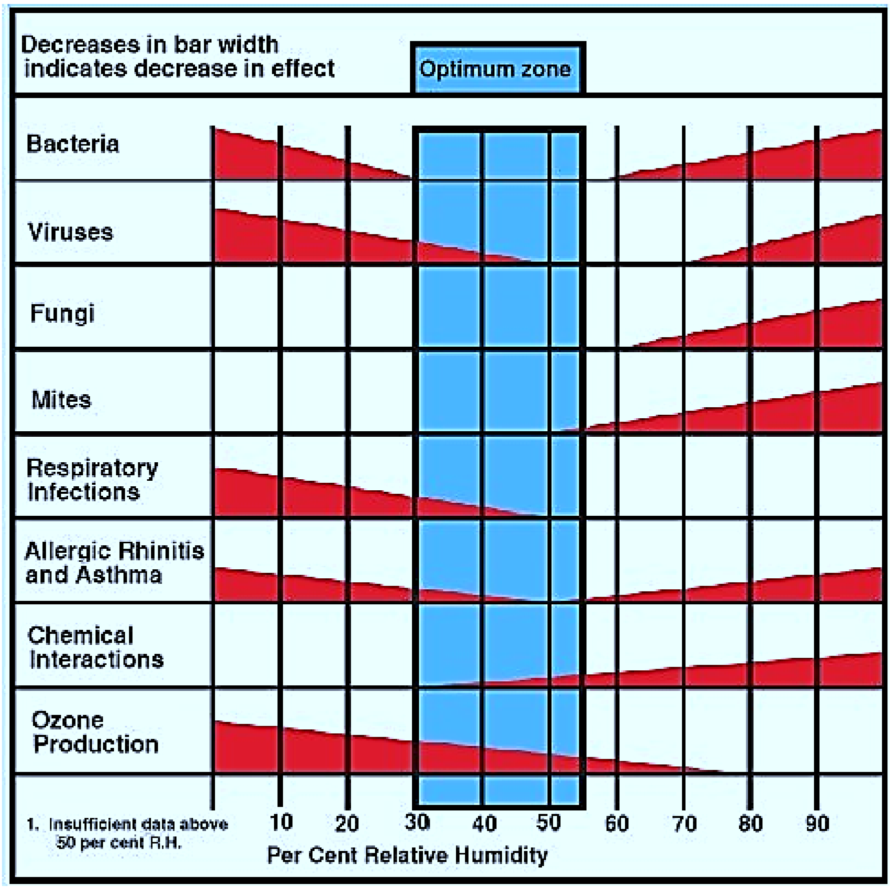

Figure 1 Indoor humidity and the presence of microorganisms in the indoor air (Sterling 1985)

The amount of fresh air that needs to be brought into a house depends on the number of occupants expected to live in and on its size. The CAN/CSA-F326-M91 Residential Ventilation Systems standard (CAN 2010) specifies the minimum ventilation rates indicated in Table 1.

Table 1. Minimum Ventilation Requirements, CAN/CSA-F326-M91 (2010)

Space classification	Minimum ventilation capacity (L/s)
Category A	
Master bedroom	10
Basement	10

Single bedrooms	5
Living room	5
Dining room	5
Family room	5
Recreation room	5
Other habitable rooms	5
Category B	
Kitchen	5
Bathroom	5
Laundry	5
Utility room	5

According to the standard, ventilation should be provided continuously but can be provided intermittently provided that the total time of no ventilation air supply does not exceed 1 h within any 2 h period and the average flow rate of ventilation air in any 24 period is no less than the minimum ventilation capacity calculated according to Table 1. In this study, the ventilation rates for each house were measured, as well as the rates on each main room.

Ventilation improves perceived indoor air quality (Fanger 1998, Wargocki et. al. 2005) and productivity (Fisk et. al 2012, Satish et. al. 2012); and is negatively correlated with the prevalence of inflammation, respiratory infections, asthma symptoms and allergic manifestations (Wargocki et. al. 2002); but with regards to the relation between ventilation and the presence of microbiological contaminants, the results are conflicting.

While controlled ventilation helps control indoor humidity levels and dilute indoor contaminants, uncontrolled air leakage, possibly driven by exhaust ventilation, can potentially bring moisture laden contaminants from damp envelope locations and from out-of-the-envelope crawl spaces and attics (Airaksinen et al 2004b, Rao et al 2006). Lawton et al. (1998) monitored a group of houses in southern Ontario, and found that houses with higher levels of microbiological indoor contaminants had, on average, higher leakage-based air change rates.

For many years, large amounts of air leakage were acceptable in construction, and even used as a means for ventilation. However, this practice is no longer acceptable due to its negatives effects on durability, health, and energy efficiency. In cold climates, uncontrolled air leakage brings large amounts of indoor moisture into the envelope, which typically condenses in the first coldest surface in its path just behind the insulation, which for walls is typically the interior of the plywood sheathing. Over time, such moisture accumulation (or dampness) leads to microbial growth and the deterioration of the plywood sheathing. Under the right pressure conditions, air leakage in turn transports microbial spores inside the house causing negative health effects on occupants, such as allergies and other respiratory problems. Furthermore, air leakage takes away heat (energy) from the house in an uncontrolled, wasteful manner.

House air leakage is typically measured using a blower door pressurization test. The test pressurizes or depressurizes a house up to 50 Pascals and measures the air flow through the blower door at that pressure differential between the house and the outdoor ambient air. The principle behind this test is that the air that leaves through the door enters through the house cracks. Air leakage results are reported as air changes per house at 50 Pascals (ACH50). Figure 2 (Parekh et al, 2007) demonstrates how Canadian houses have become less leaky (i.e. more air tight) over the years.

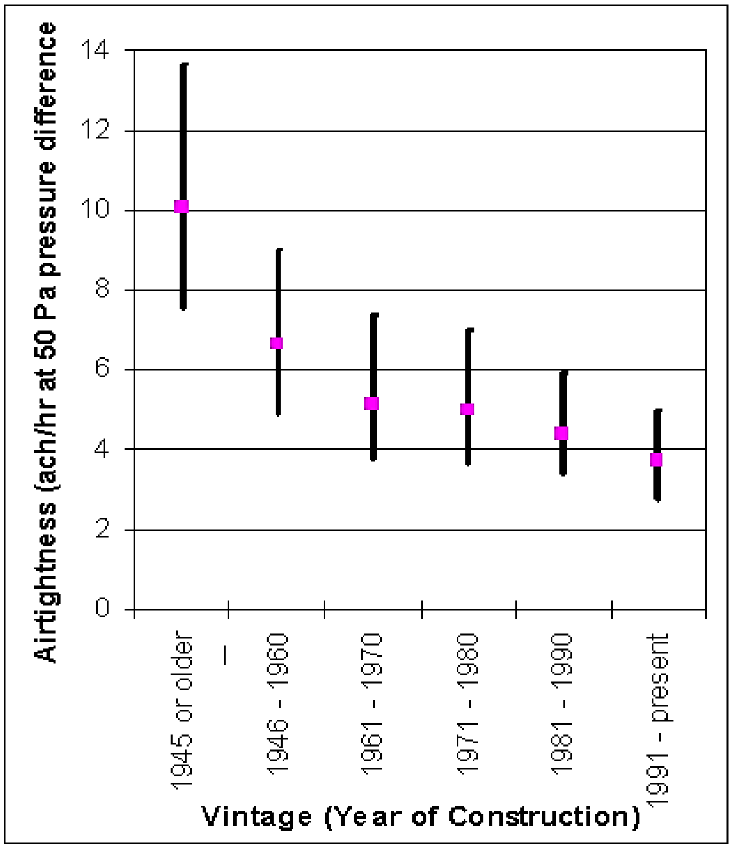

Figure 2 Air tightness evolution of Canadian houses (Parekh et al., 2007)

Figure 3 (Parekh et al, 2007) presents a comparison of housing air tightness across Canadian provinces, both pre and post air tightness retrofits; typically, the colder the region, the higher the need for air tightness for energy efficiency and envelope durability.

In this study, blower door tests were conducted in two houses; their tightness is reported in Section 4. 3.

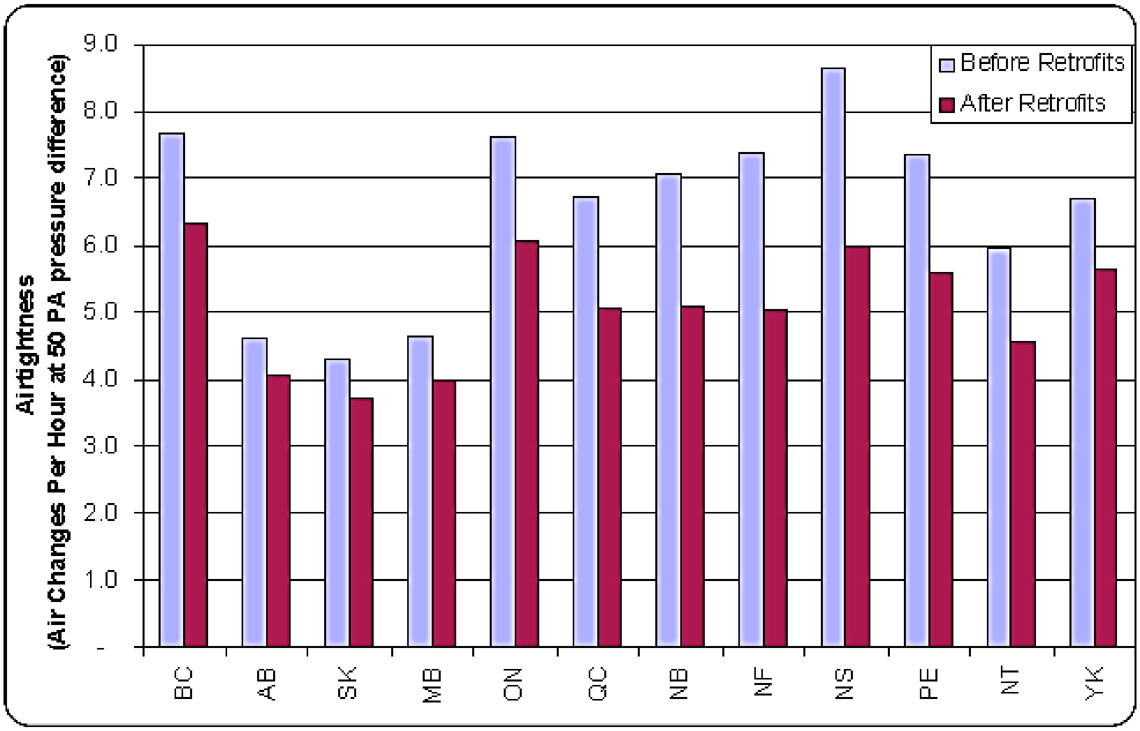

Figure 3 Average air tightness characteristics of dwellings in Canada (Parekh et al, 2007)

Associations between persistent dampness and adverse health effects have been acknowledged in the literature. A series of epidemiological studies in Scandinavian countries established a link between signs of dampness, water problems and mold in buildings and the prevalence of asthma and other respiratory and allergic symptoms (Bornehag et.al 2001-2005, Daisey et. al. 2003). However, relationships between persistent dampness, microbial exposure, and health effects cannot be quantified precisely at the moment (WHO 2009). As a consequence, no quantitative health-based exposure guideline or thresholds are recommended for acceptable levels of microbial contamination (IOM 2004). In light of this, ASHRAE (2012) and AIHA (2013) recommend keeping buildings and their systems as dry as possible, given their normal functions, to limit the potential for microbial growth and reduce dampness-related health risks.

The moisture content (MC) of materials is the key parameter for assessing the risk of microbial growth on surfaces leading to deterioration. As indicated in Figure 4 (CMHC 1999), acceptable MC levels in wood should remain below 19%. In some extreme situations MC levels may reach higher values for short periods of time but eventually stabilize down to less than 19%. Durability problems arise when MC levels remain above 19% for long periods of the year.

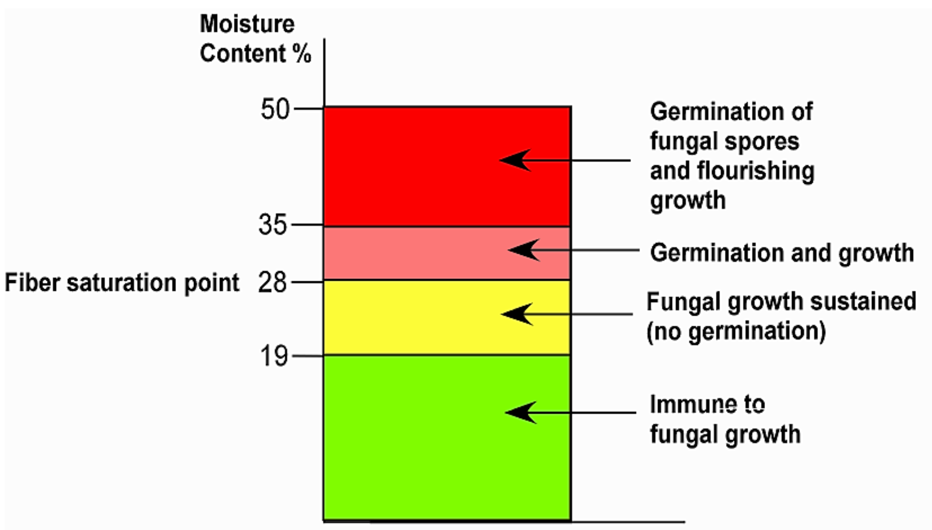

Figure 4 Moisture contents (MC) and fungal growth in wood (CMHC 1999)

MC between 20% to 30% indicates probable exposure to liquid water, and represents a MC at which fungal growth can be sustained. MC greater than 30% indicates exposure to liquid water and conditions under which decay fungi can grow.

A limitation of the MC as a universal indicator of dampness risk is its extreme spatial variation over short distance (a few centimeters), and its dependence on the materials and the quality of the construction (ASHRAE 2012). Errors can also be introduced by poor contact of the pins with the material being measured. Aware of this limitation, in this project MC sensors were placed in carefully selected envelope wall locations to attempt to represent the moisture conditions in these locations. The MC sensors were attached to the inside of the plywood sheathing, behind the insulation.

Occupants play an important role in the energy performance; and also, their behavior has a profound effect on indoor air quality of a house (Lai et. L. 2013, Kabiret. Al 2011, Nazaroffet.al. 2004). Recently, many studies have focused on the effects of occupant behavior on energy performance and indoor air quality in residential buildings (Peng et.al. 2012, Santin et.al. 2011, Fabi et. al 2012); and efforts have been made to include occupant behavior as an integrated part of energy simulations (Clevenger et. al. 2006).

A premise in indoor air quality and ventilation is that occupants and their activities, either directly or indirectly, are the main factors leading to poor indoor air quality (i.e. bath, cook, smoke, clean, etc.). Therefore, the presence of indoor air pollutants is directly related to the amount of occupants in the house. Occupants produce carbon dioxide (CO_2) when breathing. Therefore, an indirect measure of the amount of fresh air in the indoor environment is the concentration of carbon dioxide (CO_2) in the indoor air (i.e. the higher the CO_2 level in the indoor air, the more likely the air is polluted). CO2 concentration in the air is measured in part per million (PPM). As indicated in Table 2 (Health Canada 1987), preliminary research evidence indicates that high CO_2 level can potentially result in negative health consequences to occupants.

Table 2. CO2 levels and their impacts of people (Health Canada 1987)

Outdoor air	350 – 500 PPM
Acceptable indoor air	< 1200 PPM
Discomfort (odours) & impaired performance	1200 < CO2 < 5000
Can pose a health risk	> 5000 PPM

As indicated in Table 2, in general CO_2 levels below 1200 PPM are considered acceptable. However, levels reaching up to 1500 to 2000 PPM are still permissible. In recent years, CO2 sensors and recording devices are becoming more accurate and inexpensive and are often used to monitor indoor air quality in commercial buildings.

Building on the reviewed literature and the premise that house should be considered as a system, this research attempts a holistic assessment of residential performance that combines monitored data from: the indoor environment, the construction, the occupants' behaviors, and the energy system to provide a more informed view of performance for homeowners and builders.

2.3. RESIDENTIAL MONITORING AND SENSING TECHNOLOGIES

There is a little research on sensor technologies integral to homes with the exception of heating thermostats and humidistats (Gao et. al. 2009, Lu et. al. 2010). Occupancy sensors are being used in bathroom ventilation, for example a bathroom exhaust fan starts as the occupant enters and stops after a set time interval when the occupant leaves. These sensors are also used to control ventilation in a house by providing fresh air only when the house is occupied.

Deploying long-lived sensing systems for IAQ and enclosure monitoring in residential settings pose significant challenges. In particular, recent studies have highlighted the unique and often overlooked challenges of designing in situ residential sensing deployments, which must blend into the home without compromising household aesthetics (Hnat et. al. 2011, Barker et. al. 2012). As a result, in many cases, researchers collect only the data they require for a specific project using a temporary, short-lived deployment. A disadvantage of the approach is that it may fail to capture aspects of the home that only reveal themselves over long periods.

This project attempts to use a remote monitoring system integral to homes to monitor houses for one year and look into the feasibility and challenges in deploying such a system in individual homes which could be a promising tool for the future long term monitoring of remote aboriginal communities.

Although remote sensing technologies have matured over the years, and are affordable (Jaman et. al. 2007); there are no previous attempts to develop formal mechanisms to enable a permanent monitoring of the indoor building environment coupled with the envelope in the residential setting. Despite having advantages of enabling the monitoring of private areas of house without annoying occupants and without visiting sites regularly, the main concern of deploying these technologies is the bridging of the data to knowledge gap, i.e. how to streamline the processing of vast amounts of continuous data while inferring meaningful performance knowledge from it. This pilot study attempts to study these challenges.

CHAPTER – 3 PROBLEM STATEMENT

There is an urgent need to develop First Nations homes that are resilient and responsive to the unique constraints of location, construction, occupancy, and service life conditions. Three interrelated aspects of housing performance need to be addressed: indoor air quality, durability, and energy efficiency; and three related systems need to be studied ventilation, construction, and heating system. However, considering that occupants are a main driver of poor housing performance, dealing with the human aspect is indeed one of the main challenges in attempting to develop resilient housing in remote regions.

As a first step, monitoring data from these homes is needed to help better understand the factors that drive poor housing performance. However, accessing performance data, particularly for remote communities is difficult. A Remote sensing and monitoring system could help make monitoring in remote regions more accessible. However, these systems still suffer from technological reliability issues and their widespread use is still questionable.

This pilot study is a first step to monitor a small sample of homes holistically, from a local reserve and attempt to improve their performance; and investigate the practicality & functionality of a remote monitoring system.

CHAPTER – 4 METHODOLOGY

4.1 DESCRIPTION OF THE HOUSES MONITORED

Three new houses were made available for this study by the Squamish First Nations band in agreement with the homeowners. These houses are typical 2-storey, wood-frame construction single family houses. The attic is ventilated. Table 3 describes the overall characteristics of the houses. The houses are located near waterfront exposure and are surrounded with large trees on the west elevation. The construction of the three houses ended between May and August of 2013, and the monitoring began in September, shortly after the houses were occupied.

Table 3. Characteristics of the houses studied

Characteristics	**House#1**	**House#2**	**House#3 (lower zone only, see notes)**
Area	2,500 ft^2 (232 m^2)	2,000 ft^2(186 m^2)	1,000 ft2 (93 m^2)
Number of bedrooms	6	3	2
Number of bathrooms	3	2	2
Garage	Yes	No	No
Crawl space	Yes (heated/ventilated)	No	Yes (heated/ventilated)
No Occupants	5	2	1
Required ventilation rate (L/s)	ASHRAE 62.2-2010: 77 CFM (37 L/s)	ASHRAE 62.2-2010: 57 CFM (27 L/s)	ASHRAE 62.2-2010 33 CFM (16 L/s)
Ventilation system	Distributed supply only system Make-up air on return Coupled with furnace operation	Distributed supply only system Make-up air on return Coupled with furnace operation	Distributed supply only system Make-up air on return Coupled with furnace operation

Heating	Natural gas furnace Passive combustion air	Natural gas furnace Passive combustion air	Natural gas furnace Passive combustion air
Notes	• House is divided into two semi-independent living zones, one in the first floor and one in the second floor. They are only separated by an interior door. • Both zones were monitored.	• First floor was unfinished • First floor used for wood carving work	• House is divided into two completely independent living zones, one in the first floor and crawl, and one in the second floor. They have separate entrance doors. • Only the lower zone was studied, first floor and crawl space.

The Research was carried out in two phases. In the first phase, monitoring system was developed and the houses were instrumented with sensors; and in the second phase, the monitored data was analyzed, energy and airflow models were developed; and options for recommendations for improvements in future homes were explored. The detailed methodology used is described as follows:

The houses have typical wood stud construction with vinyl cladding, plywood sheathing, batt insulation within the stud space, an interior polyethylene vapor retarder and gypsum board, as shown in Figure 5. These wall assemblies with non-absorptive cladding are able to prevent the penetration of rain water, however, moisture can still enter the building enclosure due to rain water leakage through small flaws especially at vulnerable locations like wall-window interfaces, balcony-wall interfaces and wall penetrations; via vapor diffusion or air leakage (from humid interiors); or be built in during construction.

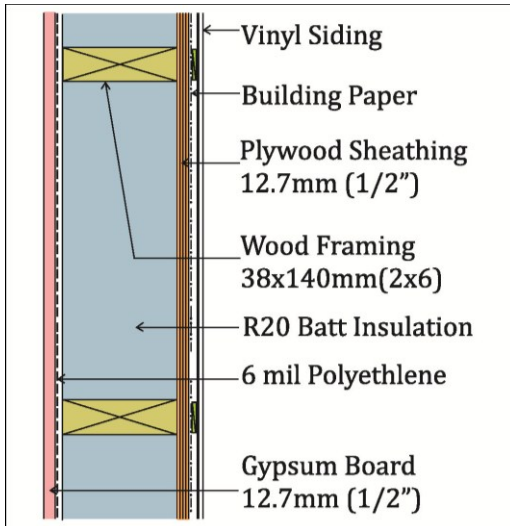

Figure 5: The Wall Assembly

4.2 SENSING SYSTEM LAYOUT PLANNING AND INSTRUMENTATION

A moisture content (MC) sensing system was designed to monitor envelope moisture as a function of dynamic indoor and outdoor conditions. It should be noted that MC sensors have limitation of being spatially variable over short distances. The measurements depend on the material and the quality of construction. Thus, critical envelope locations were identified and the sensors were installed. These locations included the underside of the roof sheathing; the walls underneath the windows, particularly close to the corners and the bottom plate; the envelope bathroom walls; and the floor joists at the crawl in all the three houses. The majority of MC sensors were placed on North facing walls as these walls have lowest drying potential due to limited exposure to sun. APPENDIX B presents the specification and calibration of MC and other sensors used in this project and APPENDIX C present photographs of the sensors installed at various critical locations.

The houses were instrumented with Relative Humidity-temperature (RH/T) and carbon-dioxide (CO_2) sensors for indoor environment monitoring. These sensors were installed at strategic locations like common areas of the houses e.g. kitchens, family rooms and master bedrooms. Figure 6 shows a schematic of the sensor placement in House #1.

MC and RH/T sensors were also installed in attics. Attics are not part of the envelope in these houses, but they are unintentionally connected to the living space through cracks in the ceiling, as observed during blower door tests discussed later in this chapter.

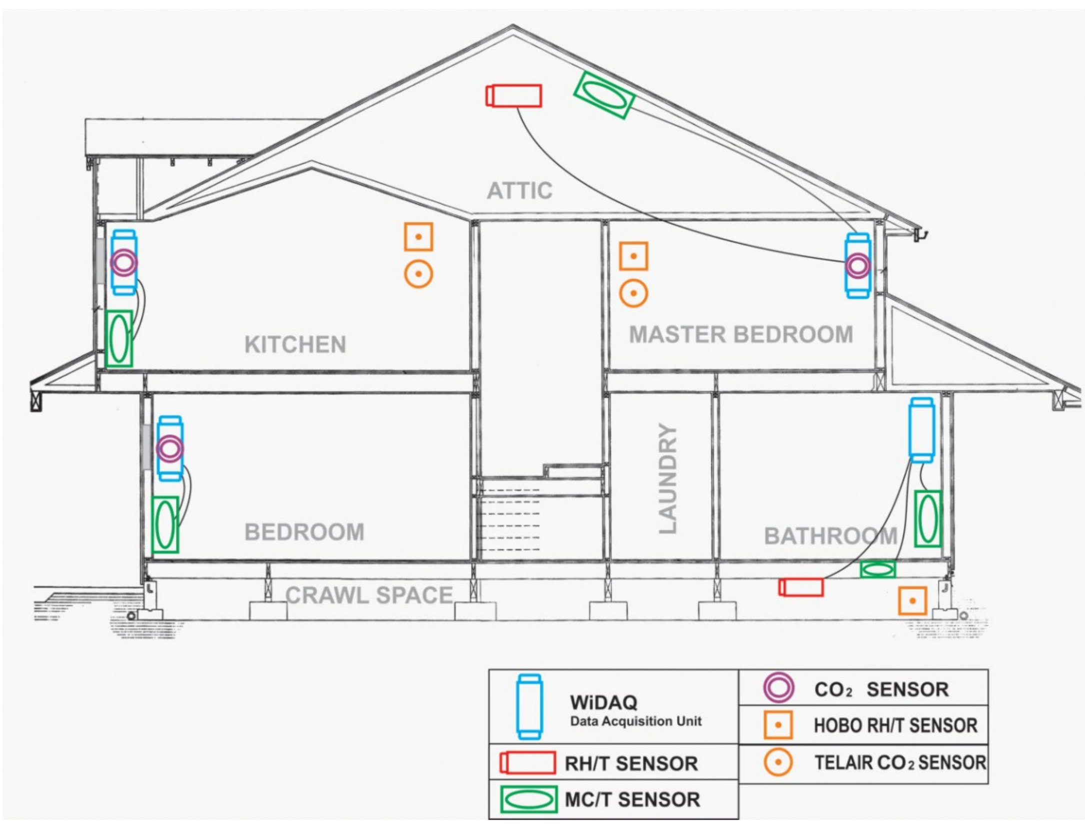

Figure 6: MC, RH/T, CO2 and HOBO RH/T Sensor placement in House #1

An ON/OFF switch type sensor was placed in the air handling unit in two houses (House #1 AND #2) to monitor operation of the HVAC system. A weather station was installed on the roof of the nearby community center to measure ambient temperature, outdoor relative humidity, rainfall, wind speed, wind direction and solar radiation. All sensors used in the project are commercially available and a brief description of each is given in Appendix C. To validate remotely collected data, ONSET HOBO RH/T sensors and Telair CO2 data loggers were also installed in kitchens and master bedrooms.

4.3 MONITORING SYSTEM

A distributed data acquisition monitoring system was used with the battery-powered data loggers (WiDAQ), deployed in strategic locations, to acquire data from cabled nearby groups of sensors. Sensors were deployed in groups of 8 or less in order to minimize sensor cabling and number of data loggers used (each data logger support 8 channels of either resistance or voltage inputs). The data loggers transmitted the data wirelessly to a central gateway computer placed in house#2, which, in turn, used Internet to transmit data to a central platform combining a repository and analytical tools. An overview of the monitoring and control system is shown in Figure 7.

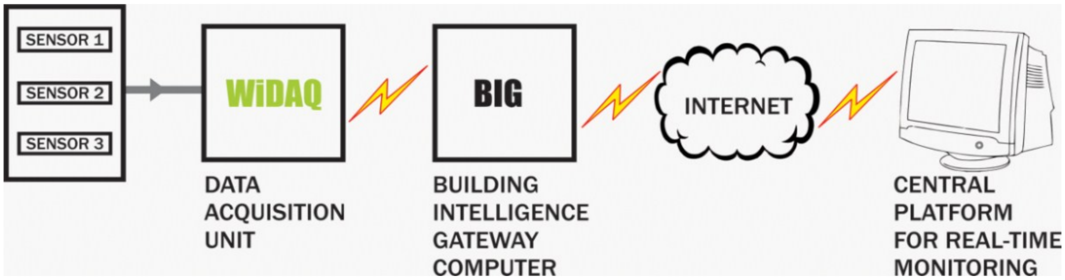

Figure 7: Schematic of the Monitoring and control system

4.4 TESTING, MEASURING, AND QUESTIONNAIRES

Multi-point blower-door de-pressurization tests were conducted in two houses (House #1 & 2) for building envelope airtightness and construction quality characterization. From the tests, a power-law (pressure versus volume flow rate) curve was obtained. Figure 8 shows the Power Law curve for House #1 and Table 4, shows the test results for both houses.

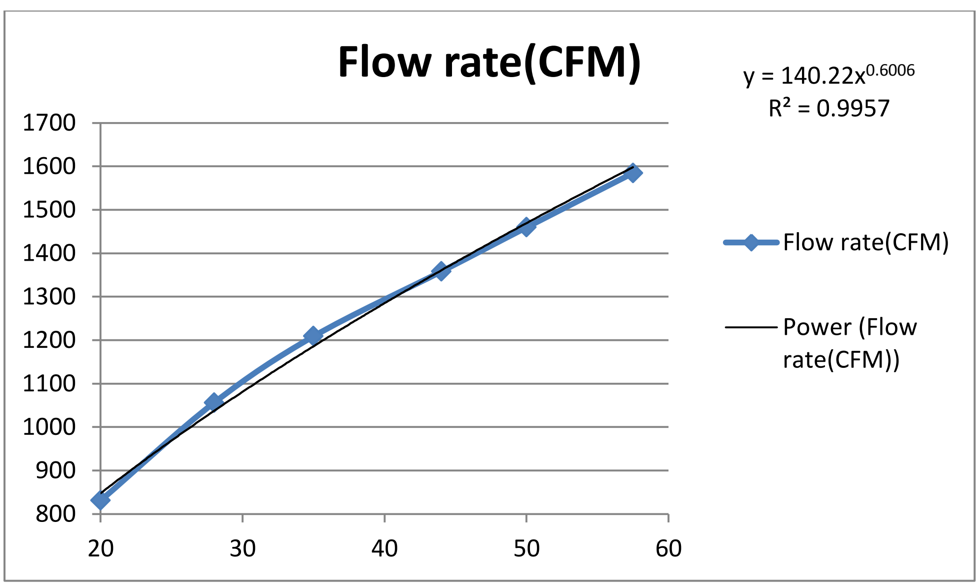

Figure 8: Power Law curve for House #1

Table 4: Blower Door Test Results for House #1 and #2

Blower Door Test Results	
House #	**ACH50**
1	4.41
2	5.65

These tests indicate that these homes are leaky. A typical home in Fraser Valley has airtightness between 4-5 ach50. Thus, the test-bed homes are not very different from a conventional local home. As expected, these tests indicated that the air leakage was mainly through wall and ceiling penetrations and around the exterior doors, mainly under the door leading to the garage. Leakage from the attic through recessed lights at ceiling at the top floor was also significant.

Air flows at the supply and return grilles, and at the make-up air vent of the forced air heating system were also measured with Digital Thermo-Anemometer described in Appendix B. Table 5 presents airflow measurements at various heat registers in House #1. These measurements were used to calibrate air flow models discussed in Section 4.6.

Table 5: Airflow measurements in different heat registers

HEATING REGISTER	AIRFLOW(FT/MIN)	SIZE(sq.ft)	TEMP(F)	CFM
FIRST FLOOR				
ENTRY	681.14	0.21	133.8	143.04
LAUNDRY	468.38	0.21	107.4	98.36
BDRM(BESIDES LAUNDRY)	650.67	0.21	105.9	136.64
BDRM	547.80	0.21	101.8	115.04

BATH	547.80	0.21	101.8	115.04
FAMRM	654.63	0.21	108.3	137.47
KITCHEN	450.00	0.21	88.8	94.50
RETURN (Assumption)	840.09			
SECOND FLOOR				
GREATRM #1(RHS)	535.38	0.21	101	112.43
GREATRM#2 (LHS)	555.71	0.21	97.2	116.70
NOOK #1 (NEAR DOOR)	485.00	0.21	93.4	101.85
NOOK#2	525.25	0.21	83.3	110.30
KITCHEN	321.33	0.21	86.5	67.48
BDRM#2	659.20	0.21	112.1	138.43
BATH	714.78	0.21	140	150.10
BDRM#3				138.43
M.BDRM#1	672.00	0.21	122.6	141.12
M.BDRM#2 (RHS)	595.67	0.21	132.5	125.09
ENSUITE	323.29	0.21	107.7	67.89
RETURN (Assumption)	1269.83			
CRAWLSPACE				
REGISTER#1 (NEAR ENTRY)	367.20	0.21	98.3	77.11
REGISTER#2	463.67	0.21	100.9	97.37
REGISTER#3(FAR END)	416.88	0.21	99.5	87.54
REGISTER#4	503.63	0.21	108.4	105.76
RETURN (Assumption)	367.79			
Outdoor air intake	477.44	3.5"*3.5"	64.1	40.00

Information on house operation was obtained by an administered occupant-survey and by direct inspection on regular site visits. A questionnaire was designed for homeowners to capture occupancy loads, occupant lifestyle and uses of the house.

The detailed questionnaire is included in Appendix D. Table 6 presents the approximate occupancy schedule for House #1.

Table 6: Approximate Occupancy Schedule in House #1

Time	No. of Occupants
12:00am-7:00am	5
7:00am-8:00am	4
8:00am-9:00am	3
9:00am-12:00pm	2
12:00pm-1:00pm	3
1:00pm-5:00pm	2
5:00pm-7:00pm	4
7:00pm-12:00am	5

The knowledge gained from the questionnaires was used to correlate indoor relative humidity and carbon dioxide patterns with the occupancy and occupant behaviors (e.g. opening and closing of windows, cooking and shower times).

4.5 MONITORING

The houses were monitored for one year starting in September of 2012, when occupancy started, till October 2013. Data was collected hourly from remote monitoring system whereas indoor relative humidity, temperature and CO2 were measured every 30 minutes using standalone HOBO sensors. Weather station data was also collected every 30 minutes.

4.6 DATA ANALYSIS

The monitoring data was analyzed to identify environmental loads (both indoor and outdoor) and infer knowledge by correlating data from different sensors as follows:

- **Identify predominant loads:**
  - Indoor humidity, temperature, & air quality patterns in relation to occupancy & weather, as affected by construction
  - Envelope moisture performance in relation to outdoor boundary conditions, construction, & orientation
  - Indoor humidity & air quality performance thresholds based on effects on people & construction.
  - Weather effects on indoor condition
- **Infer knowledge by correlating data from multiple sensors:**
  - Envelope moisture content at critical orientation
  - Indoor humidity & CO_2 levels
  - Indoor humidity and CO_2 levels at different locations in the house
  - Indoor Humidity with Outdoor conditions

4.7 MODELING AND ANALYSIS

Energy and multi-zone airflow models were created to evaluate energy and ventilation performance of the houses respectively. These models were fine-tuned with air tightness tests, air flow measurements at the forced air system's supply and return grilles, questionnaires to occupants and readings on the air handling unit on/off operation.

The energy model was developed in HOT2000 software tool which is an energy analysis and design software for low-rise residential buildings. Utilizing current heat loss/gain and system performance models, the program aids in the simulation and design of buildings for thermal effectiveness, passive solar heating and the operation and performance of heating and cooling systems. It performs whole-house energy analysis which can be used to determine annual energy use and help to determine cost effectiveness of energy efficiency upgrades. It takes into account thermal bridging through studs in assemblies, has a detailed air infiltration model and foundation heat loss model.

Figures 9 to 11 and Table 7 presents data inputs in the HOT2000 energy model for House #1. The model was validated by comparing simulated energy use with utility bills data collected from the homeowners. The validated energy model was then used to assess the impact of the occupants' behaviors on energy performance, and to compare the energy performance of the current heating/ventilation system with other potentially better systems as discussed in the next chapter.

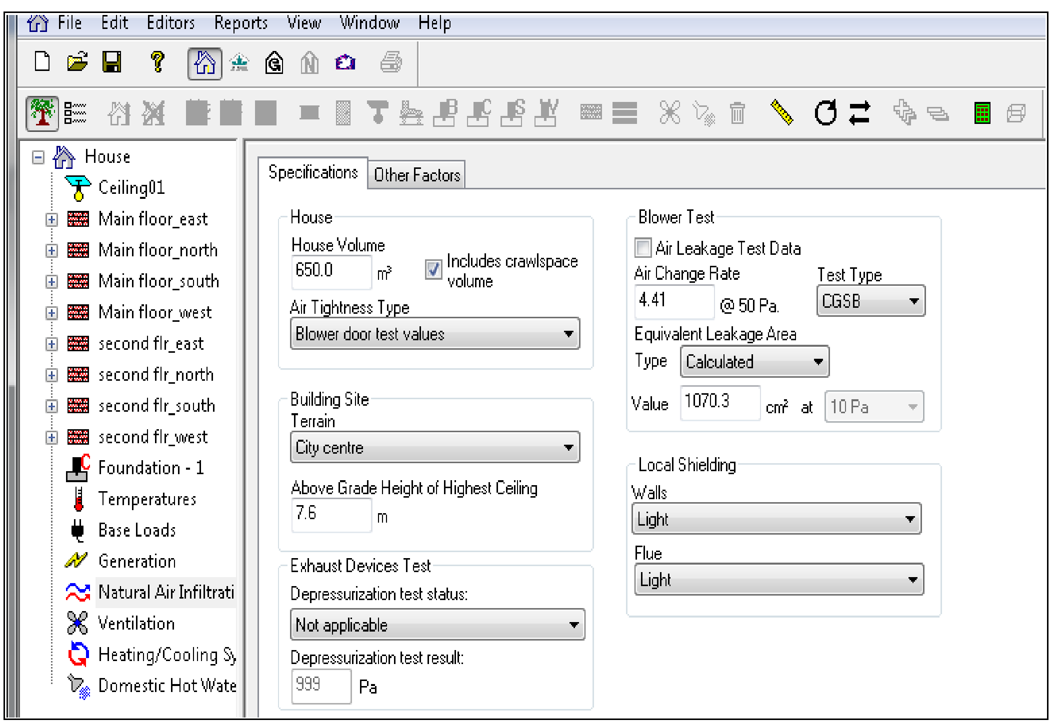

Figure 9: House specifications in HOT2000 software tool

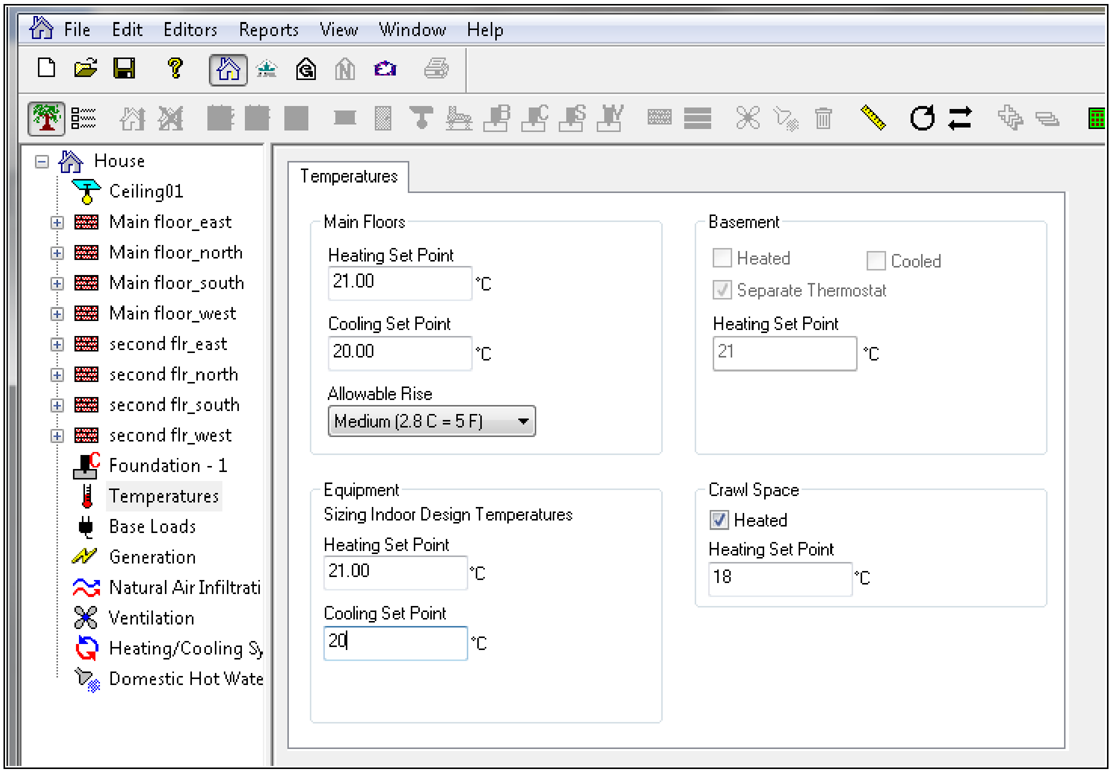

Figure 10: Temperature settings throughout the house

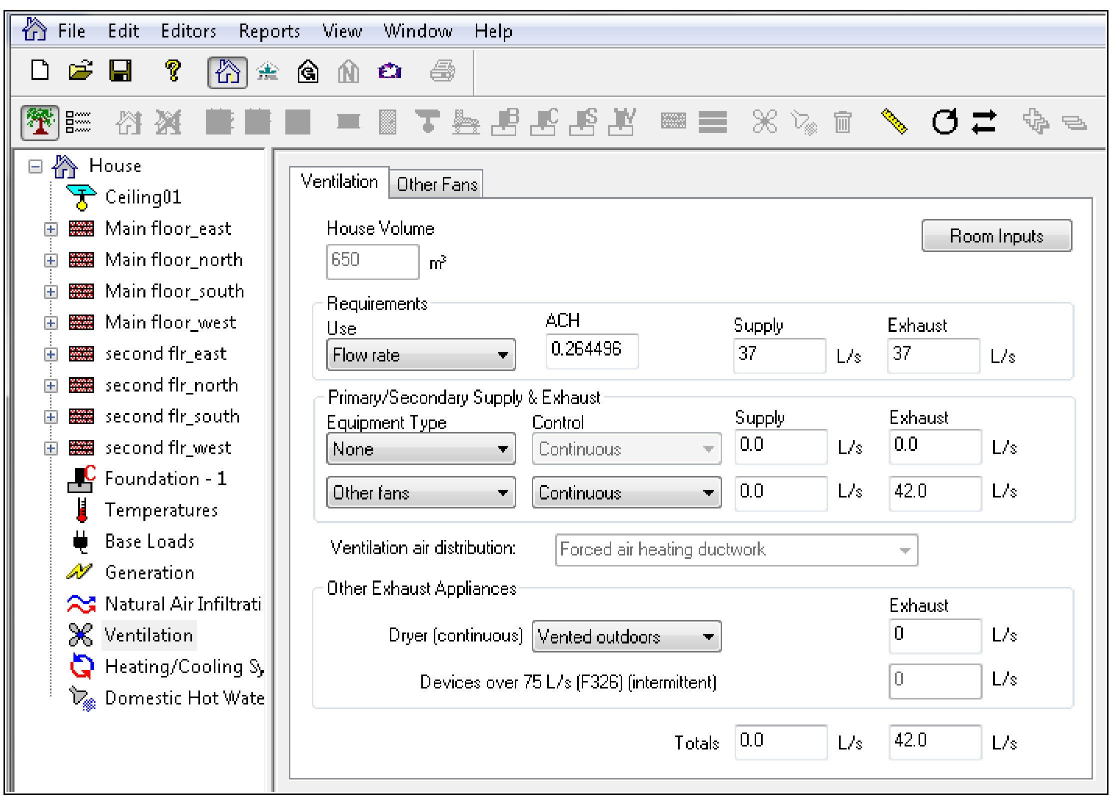

Figure 11: Assumptions for continuous exhaust ventilation

Table 7 Mechanical Equipment in House #1

Name	House#1
Heating	Armstrong G91BU75 condensing boiler @ 91 % AFUE
Primary DHW	RHEEM 40US Gal Direct Vent
DHW Load	225L/day
Air Change Rate (Blower Door test)	4.41 @ 50Pa
House Volume	650 m3
Base Load	16 KWh/day
HRV	Lifebreath HRV Sensible Recovery Efficiency of 71%
Control	Continuous, 37 L/s , Supply and Exhaust

Similarly, an airflow model was developed for House #1 to evaluate performance of the existing ventilation system. The model was developed in CONTAM, a multi-zone airflow modeling software developed by the National Institute of Standards and Technology (Walton 2005; Emmerich 2003; Emmerich 2001), which is commonly used in ventilation research to model buildings, ventilation systems and contaminants in indoor and outdoor air (Emmerich 1995; Persily 1998).

The house has two floors, with attic and crawlspace. Each room in the model was considered as a separate zone. The airflow paths in the model and their leakage values are listed in Table 8. There are five occupants in the house. Two occupants were modeled for Master bedroom and other bedrooms had one occupant.

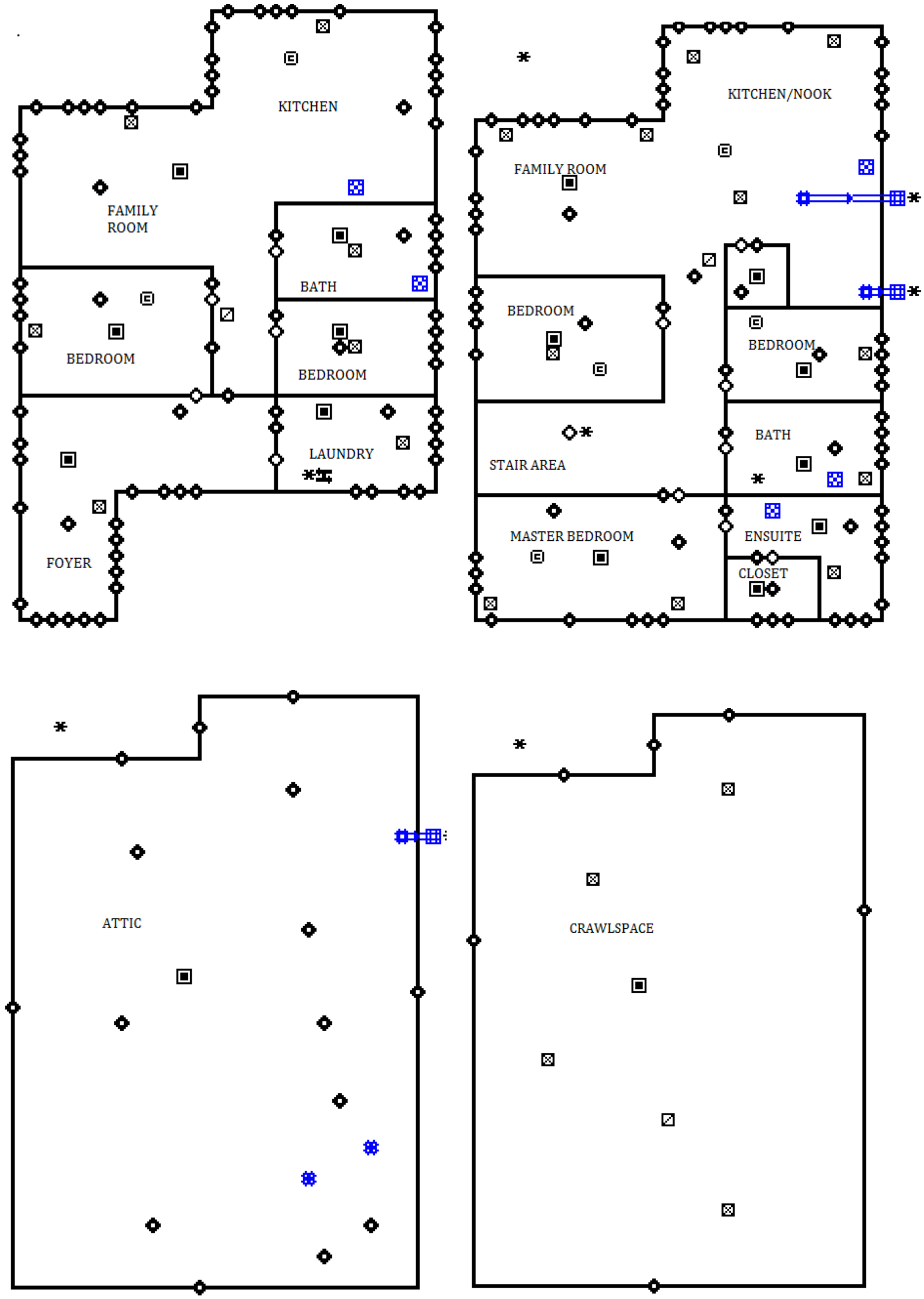

Figure 12: CONTAM model for House #1

The CONTAM model was fine-tuned and validated with air tightness tests, air flow measurements at the forced air system's supply and return grilles as presented in Table 5, and questionnaires to occupants. The occupancy schedule used in the model is presented in Table 6 and Figure 13.

Table 8: Leakage values of the airflow paths used in CONTAM Model

FLOW ELEMENT NAME	DESCRIPTION	VALUE
attic_floor	upper floor ceiling(attic floor)	2 cm2/m2
bath_exh_vent	bathroom exhaust	20 cm2/item
bath_window	bathroom window (small)	2 cm2/item
bedroom_window	bedrooms window (medium)	2 cm2/item
ceil_wall_intef	ceiling wall interface	1.5 cm2/m
closet_door	closet door	2.1 m2/item
closet_doorfram	closet door frame	25 cm2/item
corner_intf	wall to wall corner interface	1.5 cm2/m
craw_expos_wall	exposed walls of crawlspace (3/4')	8 cm2/m2
crawl_atticdoor	access door to attic/crawlspace	30 cm2/m2
dryer_vent	dryer vent	15 cm2
eave_vent	eave vents	106 cm2/m
exterior_door	exterior door/ door to garage/door to balcony	21 cm2/item
exterior_wall	exterior walls	0.14 cm2/m2
famrm_window	family rooms window (large)	5 cm2/item
floorabov_crawl	ground floor	2.25 cm2/m2
flr_wall_intrf	floor to wall interface	4 cm2/m
int_door_frame	interior door frame	400 cm2/item
interior_wall	interior wall	2 cm2/m2
intr_floor	upper level floor	3.65 cm2/m2
kitchen_vent	kitchen vents	40 cm2
open_int_door	interior doors	2.1 m2/item
roof_vent	roof vents	0.135 cm2
slide_patiodoor	sliding patio doors	22 cm2/m2

HVAC_pentration	furnace B-vent on roof	5 cm2/item
plumb_outlets	plumbing penetration from the roof (from baths)	2 cm2/item

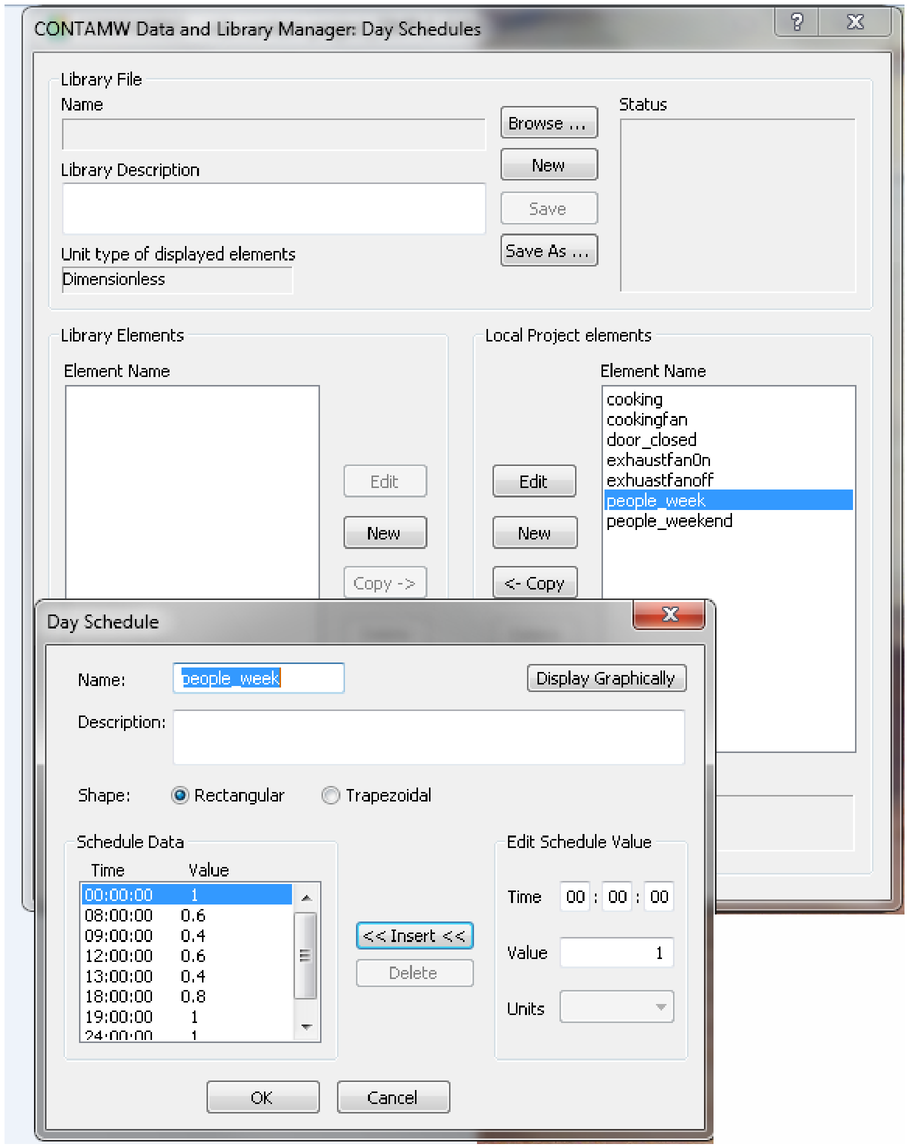

Figure 13 Occupancy schedule during week days

The occupants in this house open windows for almost eight months in a year. This makes it difficult to know the effectiveness of the mechanical system. Thus, to eliminate the open-windows factor from the analysis, the model was calibrated by comparing predicted CO_2 versus measurements for the duration when the windows were closed (October-December). This period is critical for IAQ and was used for assessing the effectiveness of alternative ventilation systems. The calibrated model was then used to evaluate existing ventilation system in the house; and its performance was compared to other kinds of ventilation systems.

Based on the data analysis, combined with the airflow and energy models, feedback was given to the homeowners and builders; and recommendations were proposed for improvements in future homes on the reserve as discussed in the next chapter.

CHAPTER – 5 DATA ANALYSIS AND RESULTS

This chapter presents the monitoring data from the pilot study. The data has not been statistically analyzed as it has no statistical significance given the size of the sample of houses. The main emphasis of this analysis is to infer knowledge from the monitored data collected from different kinds of sensors. Before analyzing the data, construction of these houses needs to be discussed. Next section discusses the main assemblies and the related deficiencies noted during various site reviews.

5.1 CONSTRUCTION

All three houses were built with the same construction crew and hence the quality is similar. It was noted that the architectural plans were very generic. The plans included the floor plans and elevations only. They did not include different transition details e.g. below grade to wood frame wall, wall to roof transition, windows and door details etc. which are critical for any construction. Below subsections describe the main assemblies used, as seen during the site reviews:

5.1.1 EXTERIOR WALLS

As discussed in Section 4.1 (Figure 5), walls of these houses have horizontal lapped vinyl cladding which act as the primary layer of protection against water ingress. The vinyl cladding is fastened to plywood sheathing and is generally designed with a 10mm (7/16”) space at the bottom of each horizontal strip to provide capillary break (rainscreen). The second layer of protection is provided by the sheathing membrane, which functions to drain any incidental water that penetrates through the cladding.

Figure 14 Exterior walls with sheathing membrane and vinyl cladding

A breathable building wrap (Simplex) is used as the main sheathing membrane. A combination of 30 minute building paper and self-adhered membrane (Blueskin) is used for pre-stripping and waterproofing the window and door rough openings respectively. The sheathing membrane is mostly positively lapped with sufficient vertical and horizontal laps. The laps are sealed with tape.

During site reviews, it was noted that window and door rough openings were pre-stripped and waterproofed as discussed in next section, but other penetrations like exhaust vents, hose bibs and exterior electrical boxes were not waterproofed. They were pre-stripped with sheathing membrane only. Electrical meters of House #3 are not pre-stripped at all. The best construction practice is to waterproof these penetrations with self-adhered membrane and seal the leading edges with mastic. This waterproofing detail prevents water ingress into the wall assembly.

Figure 15- Photo 1 shows the exhaust penetration pre-stripped with sheathing membrane
Photo 2 shows the pipe penetration stripped and sealed with red tape only

As shown in the Figure 16 photo (#2) below, balcony in House #1 has a vinyl membrane. Membrane has approx. 8” upturn at the saddle joint and building paper is positively lapped with the balcony membrane which is a good practice to prevent water penetration at this critical location. Usually, a diverter/cricket is installed at the saddle joint to divert water away from the joint and drain water at the balcony front edges. The diverter was missing at the balcony.

Figure 16: Photo1 shows the meters are neither pre-stripped with membrane nor waterproofed
Photo 2 presents the balcony saddle detail

Below grade foundation walls of House #1 and #3 are dampproofed with liquid-applied asphalt material and the concrete slab on grade is formed over 6-mil poly sheet with drainage rock below to prevent moisture penetration from the ground below. But, at the foundation wall to wood frame wall transition, there is no capillary break installed. A gasket is usually installed to prevent moisture ingress from concrete foundation wall to wood (bottom plate of wall).

Figure 17: Capillary break missing at the concrete to wood transition

The houses use 6-mil poly as both air and vapour barriers. This strategy makes the detailing at the penetrations like electrical boxes and exhaust vents more critical. The air barrier continuity is critical for durability of wood frame buildings. A discontinuity in air barrier brings the moisture-laden air into the assembly and cause condensation on the inner face of plywood sheathing, which in turn causes deterioration of sheathing. It was noted that the poly was prestripped at the wall corners and between different floor levels in the houses. But, details around the penetrations were not up to mark. Holes in the poly were noted which were later fixed with the tape. The electrical boxes were detailed with polypans for air barrier continuity. But, blower door tests showed that there is noticeable air leakage at the electrical outlets.

The air barrier at the roof is provided with the poly and drywall. The penetrations at the ceilings were detailed with poly. Similar to walls penetrations, noticeable air leakage was noted at the ceiling pot lights.

Figure 18: Polypan at electrical outlet and poly pre-stripping at the wall.

5.1.2 WINDOWS

Windows in all three houses are double glazed flanged vinyl windows. Window sills have self-adhered membrane (SAM) flashing. SAM is installed along the sill and another piece of SAM is installed with approx. 4” upturn on jamb and makes a lap joint over the sill SAM on both sides of windows. This is not a good practice. There should be no lap joint at the sill since if water penetrates through the window, it will penetrate through this joint and reach the wood framing.

Figure 19: Installation of SAM at window sills.

Figure 20: Window sill detail deficiency as there is no weatherproofing (SAM) installed at the sill on three windows

Figure 20 shows that at some windows, there was no waterproofing installed. Windows are directly installed in the rough openings and sealed from outside. It should be noted that these are just few windows which were reviewed during the site visits. There is a possibility that more windows are installed in this manner.

5.1.3 ROOFS

All three houses have sloped roofs and they are covered with asphalt shingles. Roofs have valley flashings to drain water at the intersection of different roof planes. Also, flashing is installed at wall to roof transitions. We noted at one location at the front elevation of House #2 (below the window), flashing is negatively lapped with the sheathing membrane. This is not a good construction practice, since it may lead to water ingress behind the flashing.

Figure 21: Roof details

5.1.4 CRAWLSPACES

House #1 and House #3 have heated crawlspaces. During construction, large puddles of water were noted on crawlspace floors. The water was evaporated due to the forced air heating in house #3, but House #1 had ponding water after 2-3 months of occupancy. The occupants used extra heaters to get rid of water.

Figure 22: Construction moisture on crawlspace floors

Above discussion indicates that overall construction practices at the reserve are fairly good, but few details and workmanship could be improved to prevent any future water ingress issues and hence improve the durability of these houses.

Next sections discuss the analysis of monitoring data from different sensors.

5.2 WEATHER DATA ANALYSIS

As expected, the weather station data indicates a typical moderate marine climate, with high relative humidity and moderate temperatures. The average dry bulb temperature and relative humidity during monitoring period were 11.4 ˚C and 81% respectively. Figure 23 presents the daily average temperatures and relative humidity over the course of monitoring. The temperature typically varied between 0 ˚C and 25 ˚C; it rarely came below -5.0 ˚C and above 30 ˚C. Similarly, the relative humidity varied between 50% (comfortable) and 97% (very humid). It rarely dropped below 50%, but it reached as high as 98 % in winter months.

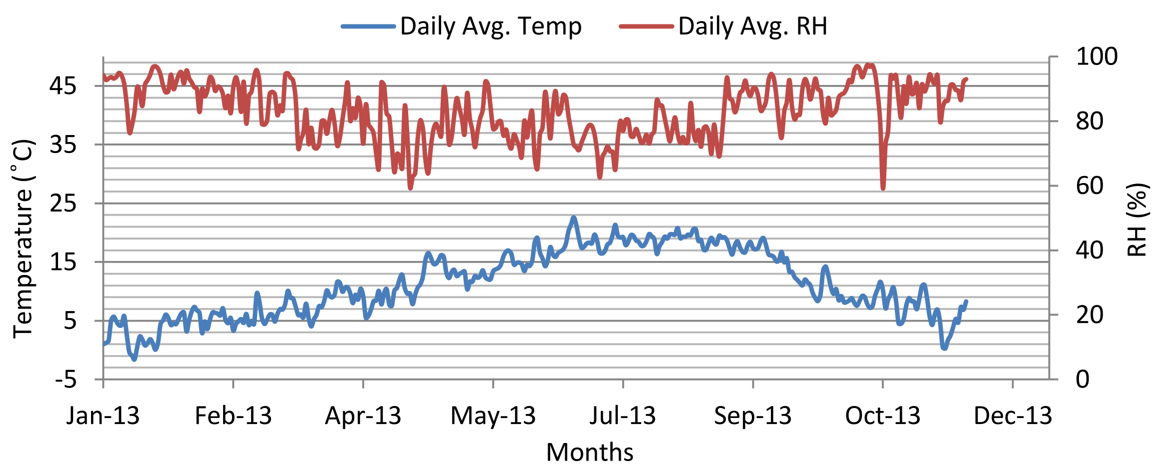

Figure 23: Annual daily average temperature and relative humidity

Over the course of the year typical wind speeds varied from 0 mph to 10 mph (calm to gentle breeze), rarely exceeded14 mph (moderate breeze). The wind was coming mostly from the North-East (16% of the time), South-East (14% of the time) and South (11% of the time) directions as shown in Figure below.

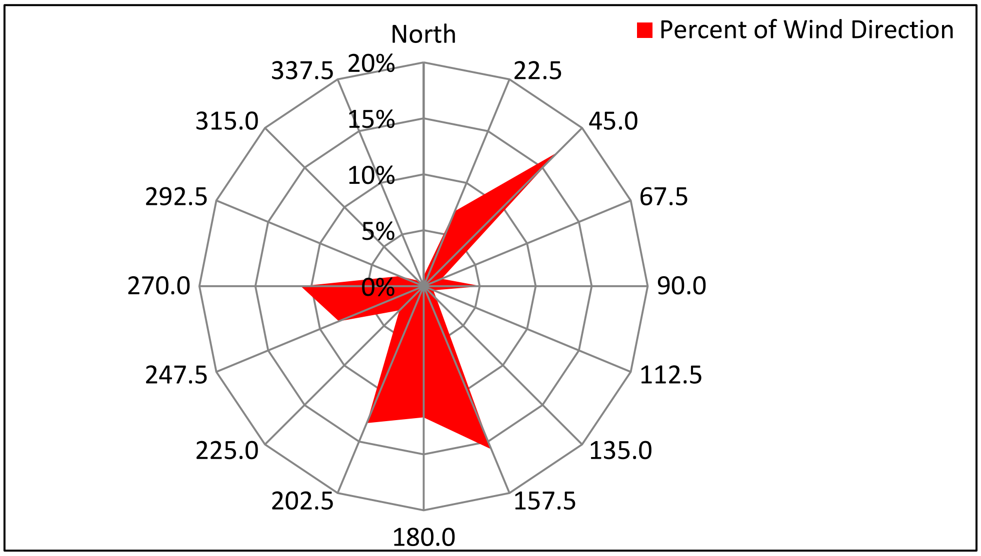

Figure 24: Annual Wind Direction

Figure 25 presents monthly rainfall for the monitoring period. The majority of the rain occurred from September to March months; whereas the summer months were comparatively dry. Figures 23 and 25 show the typical mismatch between the monthly wetting and drying potentials in the marine climate of BC. However, it is important to mention that the monitored year was a typical one. In fact it was one of the driest years in recorded history, with about 30 percent less than the average annual precipitation in the city of Vancouver, according to Environment Canada.

The wind driven rose (Figure 26) for the reserve location shows that the direction of wind driven rain is predominantly from the South. Thus, the south elevations are critical from envelope durability point of view.

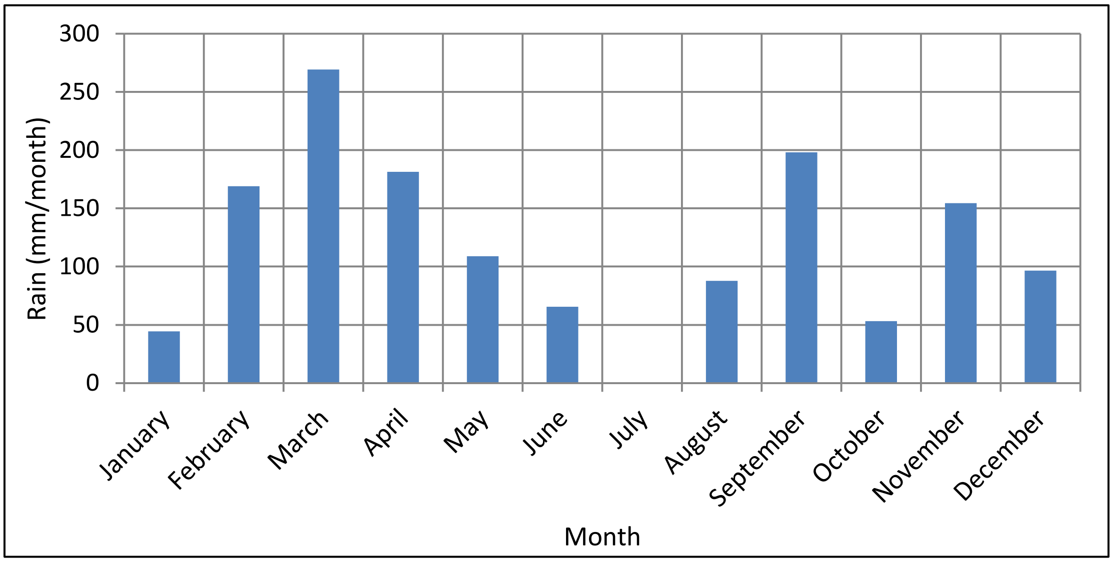

Figure 25: Annual monthly rain

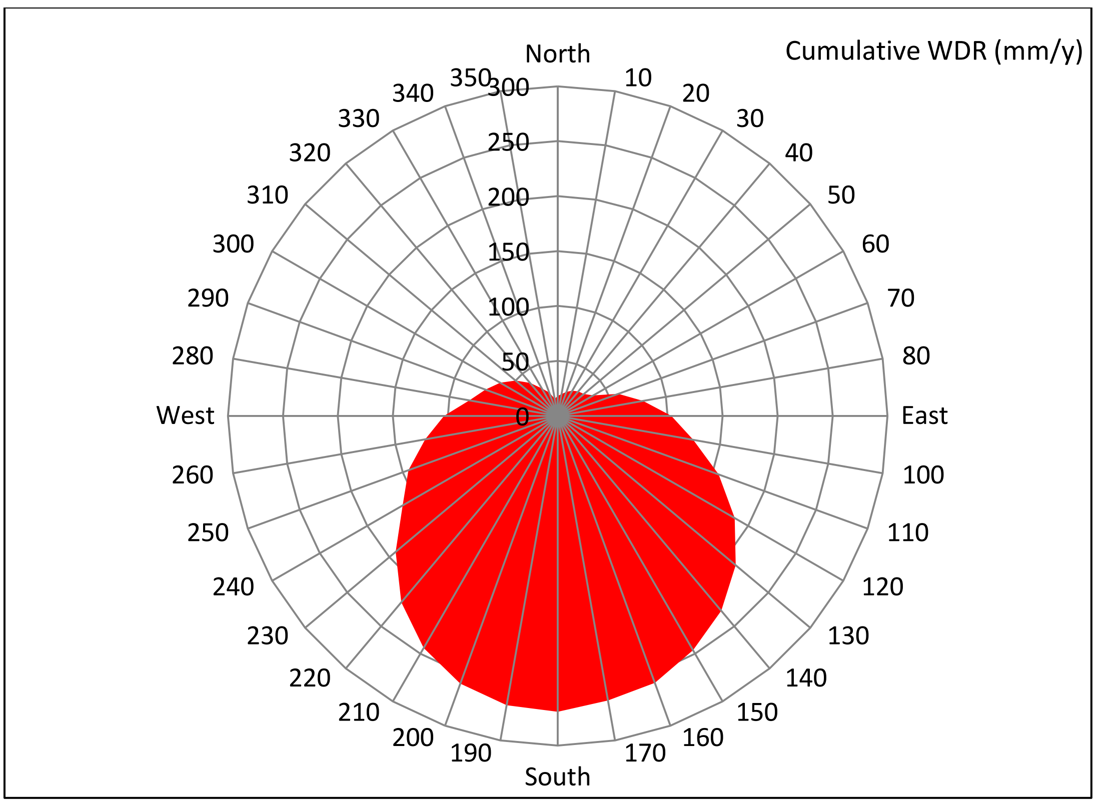

Figure 26: Wind direction distribution

Figure 27 presents the average daily solar radiation during the monitoring period. The solar radiation was not intense, as expected in this climate, during winter when skies were mostly covered with clouds.

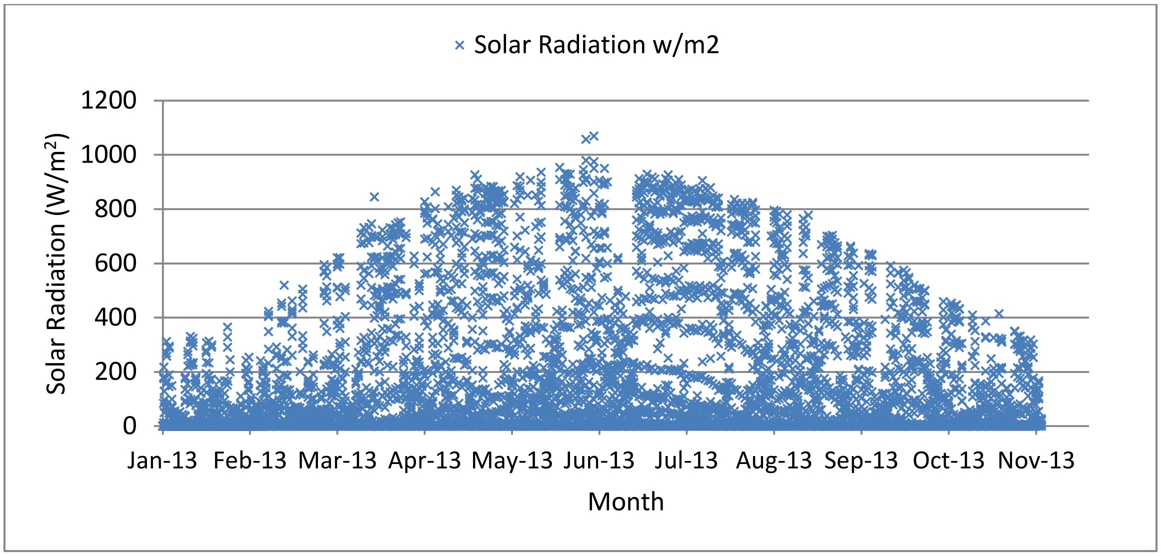

Figure 27: Average hourly solar radiation

The typical wet and mild winter conditions in BC challenge the building envelop durability as they reduce the potential for exterior walls to dry. Historically, building envelope failures in pacific coast marine climate have been attributed to rain penetration due to wind-driven rain at vulnerable locations like window edges, balcony-wall interfaces, electrical and other wall penetrations; and its inability to dry in wet winter months (CMHC 1998).

5.2 BUILDING ENVELOPE PERFORMANCE ANALYSIS

The moisture content of the plywood sheathing is used as the building envelope performance measure in this study. The strategically placed MC sensors at critical locations showed that moisture fluctuations did not correlate with the rainwater leakage into the wall cavity (Manuscript#2, Figure 3) except at two locations discussed later in this section; it rather followed the exterior temperature and humidity, solar radiation and building orientation.

Figure 28 presents moisture content measurements at the north elevations in all three houses. Seasonal wetting and drying trends are noticeable during the monitoring period. During winter, the MC levels were the highest; and in the late spring & early summer months, plywood sheathing started to dry out.

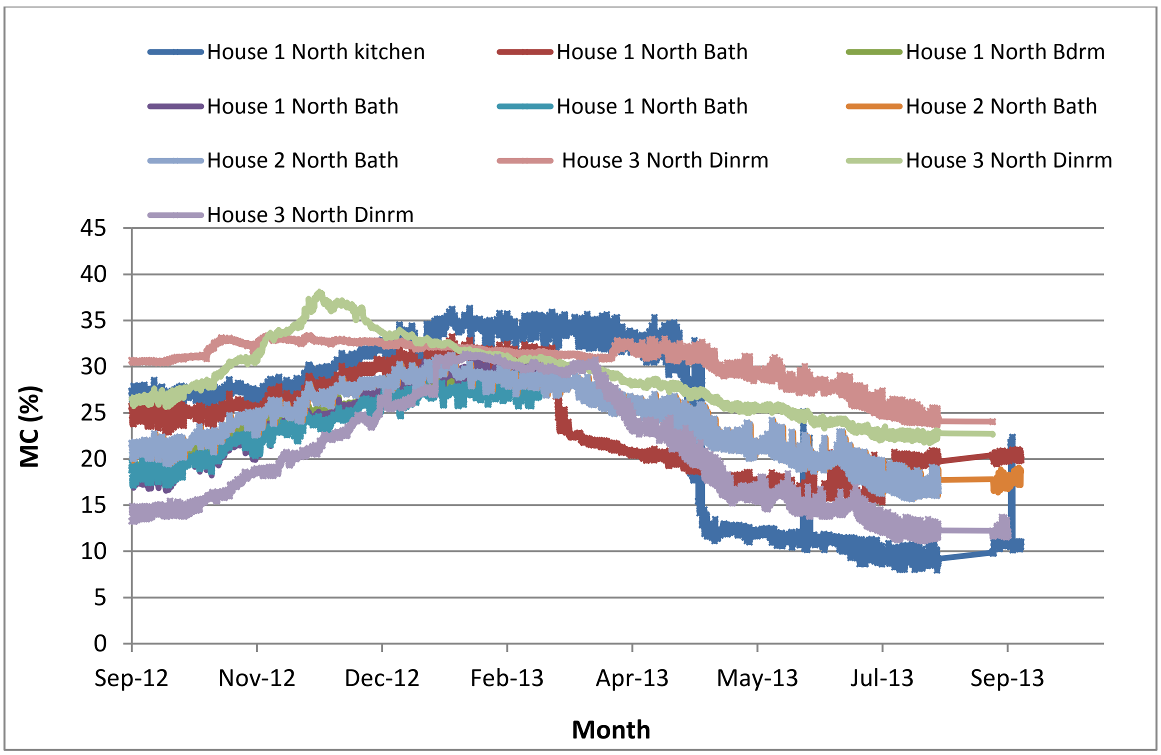

Figure 28: Moisture content at different locations on North elevation

One sensor location at North wall in the kitchen/dining room (house #3) showed exceptionally high MC levels. The MC peaked to 37% and was more than 30% for the whole winter season. Although it dried out eventually in summer, but took longer time due to limited exposure to sun. It should be noted that this location is below the electrical/gas meters in House #3 which were not waterproofed at all. The sheathing membrane was installed on plywood sheathing and the seams were taped with tuck tape.

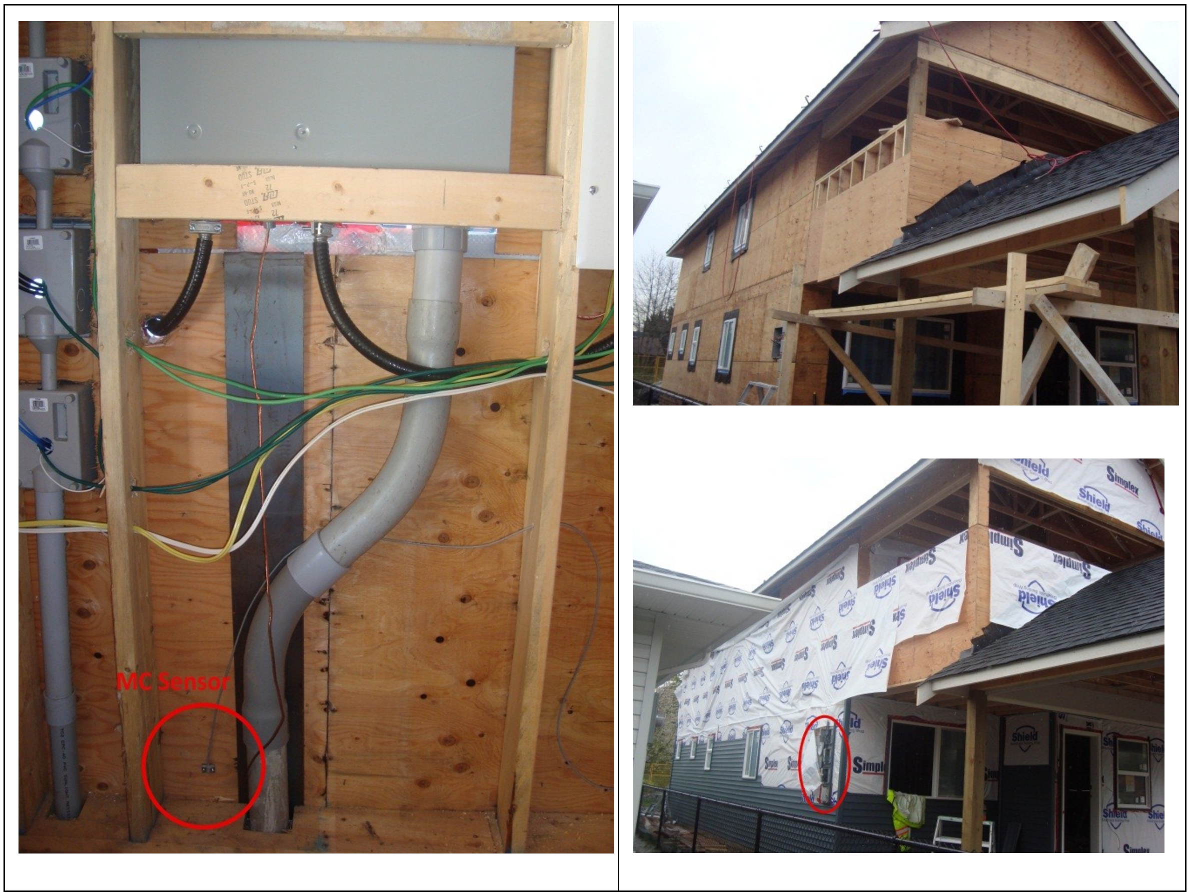

Figure 29: High MC measurements due to poor detailing

MC levels are more than fibre saturation(28%) for the winter months (November – March) at most locations on North elevation. These MC levels when compared with the typical seasonal moisture content ranges (Figure 30) expected for wood frame rainscreen walls in BC’s coastal climate, indicates that these walls are within cautionary seasonal range and are at the borderline MC levels for the winter months.

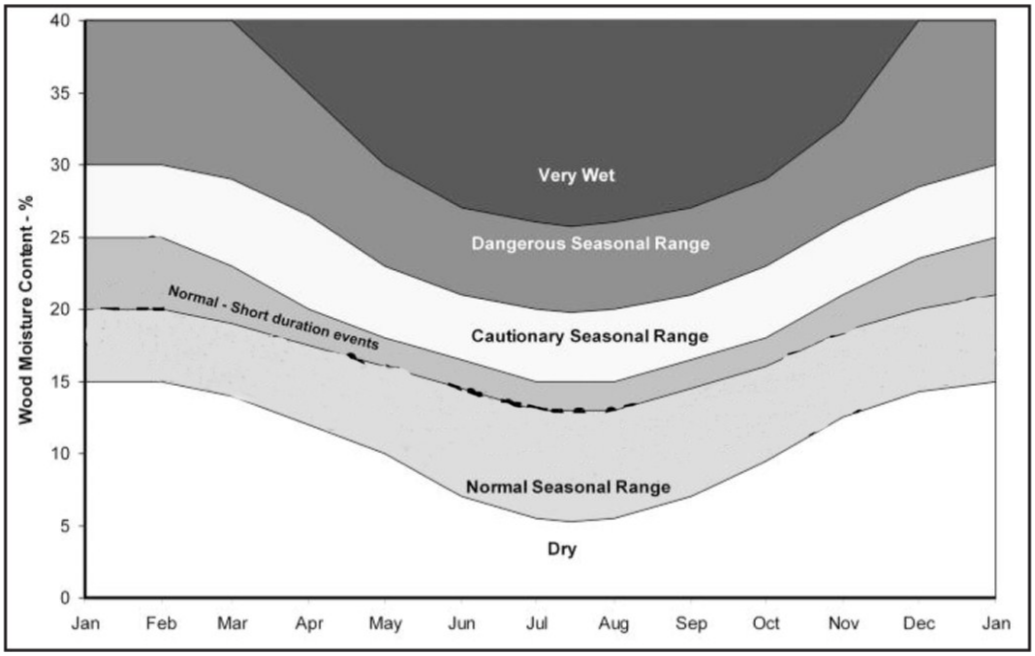

Figure 30: Typical seasonal moisture content ranges expected for wood frame rainscreen walls*(Reference: Rainscreen walls: Long-term performance and field monitoring in coastal BC, Finch et. al. 2008)*

The west elevation walls also had high moisture contents. Figure 31 shows the hourly variation of MC on this orientation. Sensors in House #2 stopped transmitting data after three months. The sensors could not be fixed due to unwillingness of the occupant to give access to the house. Three months of data shows wetting cycle during winter months. Since Houses #1 and #2 have large trees on west orientation, the walls have limited drying capability. It should be noted that sensor at the northwest corner has the highest MC. This is due to the collective effect of limited sun exposure at north and west elevations.

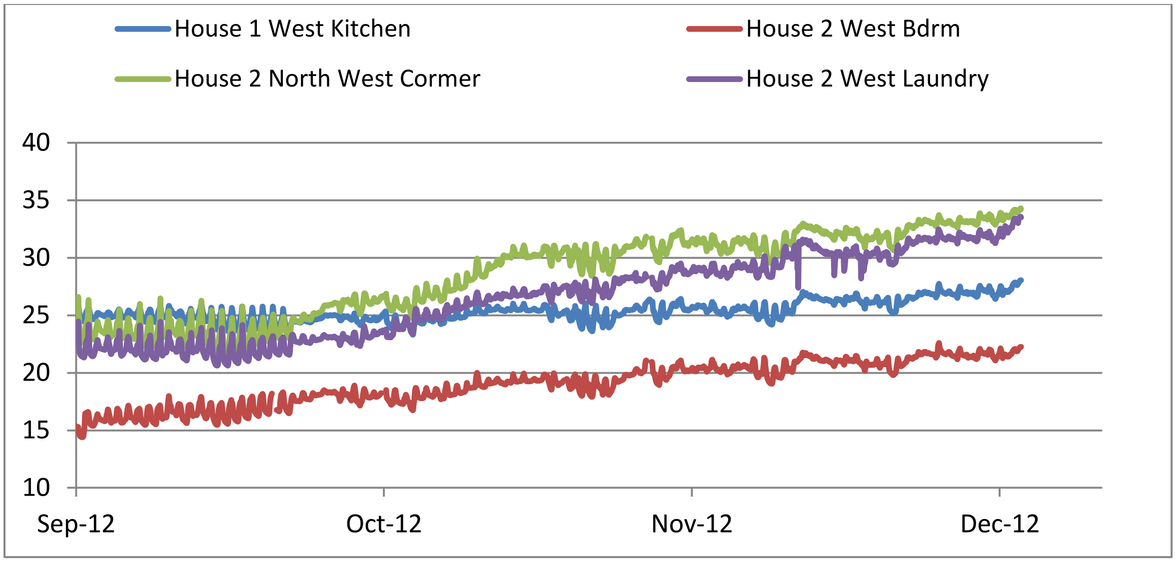

Figure 31: Moisture content on west elevation in Houses 1 & 2.

Figure 32 shows the hourly variation of moisture for the monitoring period on west elevation at House #1. This sensor was located below dining room/kitchen window. Similar to other west elevation locations, MC level was higher than fibre saturation (28%) in winter months. But the moisture dried out later in summer.

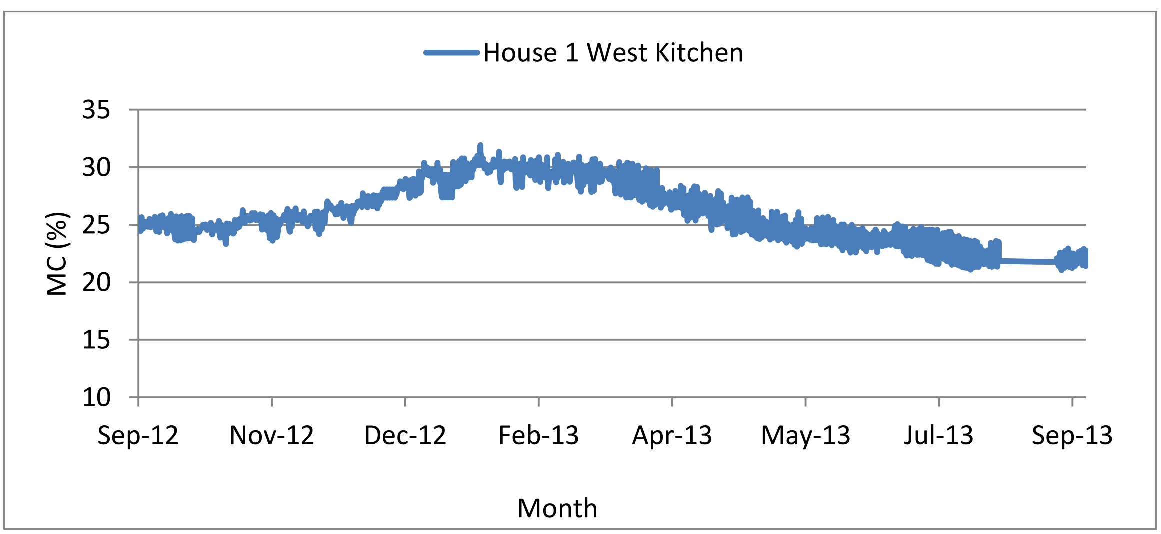

Figure 32: Moisture content on west elevation in House #1.

The south elevation of the houses is critical in terms of durability as the wind driven rain comes mostly from South on this reserve. But as shown in Figure 33, MC is lower as compare to other elevations; and moisture dried faster. It should be noted that this elevation has the least number of penetrations. The sensors were placed at the base of the wall whereas on other elevations, they were placed mostly below windows.

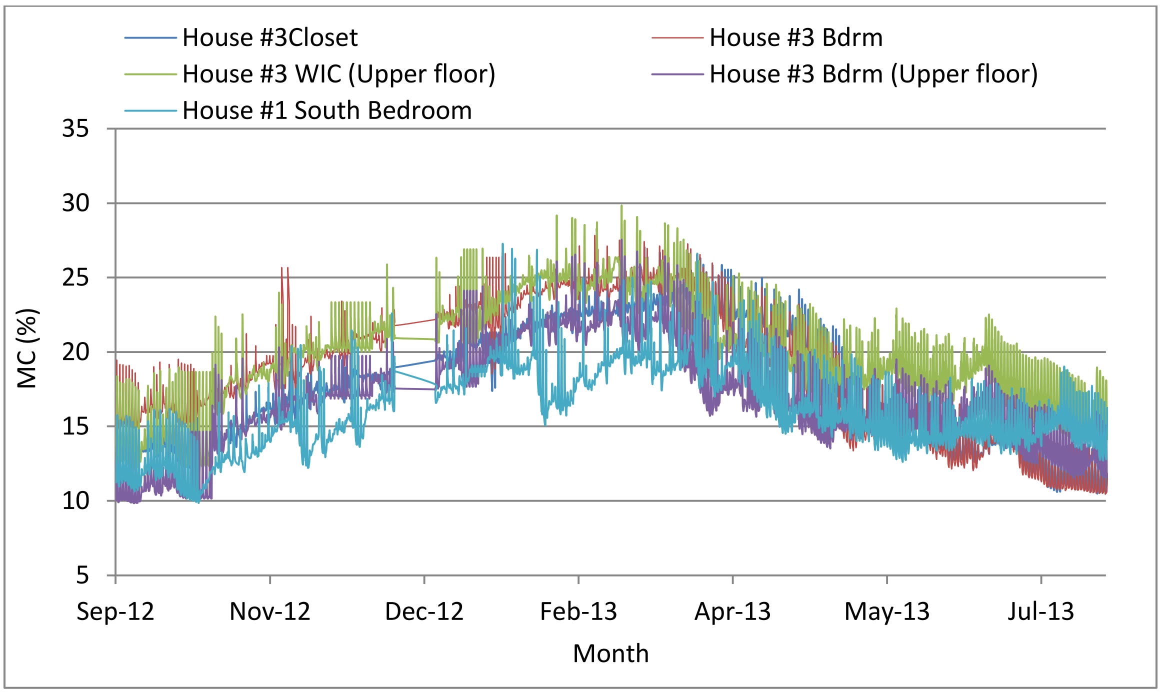

Figure 33: Moisture content on South elevation.

Generally, East elevation has the maximum drying capability. As expected, MC was low on East elevation for all the three houses. But at one location in East bedroom of House #1, MC was exceptionally high.

As shown in Figure 34, MC level under the window on the east-side wall of the bedroom is more than 35% between Jan-March months, which is in the dangerous seasonal range. These high MC levels correlated with rainy periods and the wind direction during this time was mostly from South/South-East directions. Thus, there is a possibility that rain penetration may have occurred at the window edges during this time period.

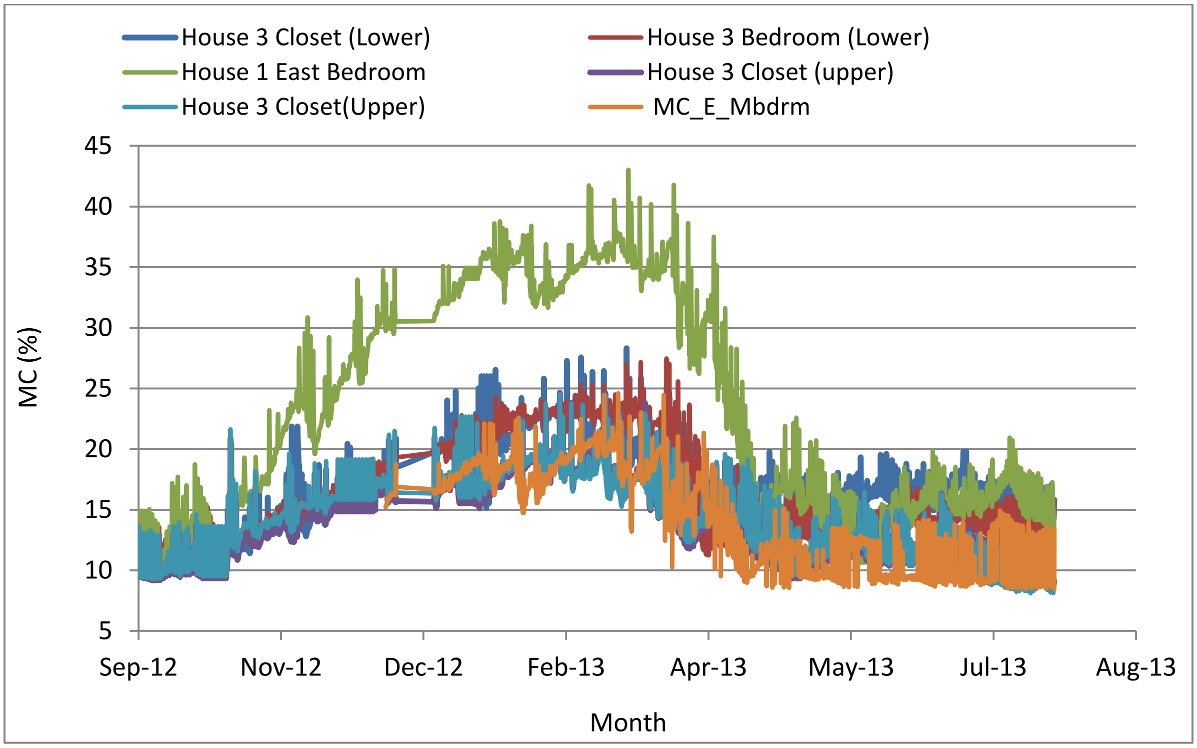

Figure 34: Moisture content on East elevation.

Moreover this location is near the change of planes in the building envelope as shown in Figure 35, where gable meets the wall. There is a possibility that the rain water penetrated through this interface. It should be noted that as the weather changed, MC levels decreased rapidly due to sufficient sun exposure at East elevations.

Figure 35: Location of MC sensor on the East Elevation of House#1

Another high MC level location was identified in House #3. The bathroom (lower floor) at North elevation showed peaks in MC levels as shown in Figure 37. The peak level in the month of May did not show any correlation with the rain. It is assumed that these sudden increases in MC levels are the result of condensation due to high humidity levels in the bathroom and air leakages through the wall penetrations in the wall.

Figure 36: Moisture content sensor below bathroom window near electrical outlet

The two locations discussed above need to be monitored further for the next winter season and if similar conditions persist, an engineering assessment has to be performed.

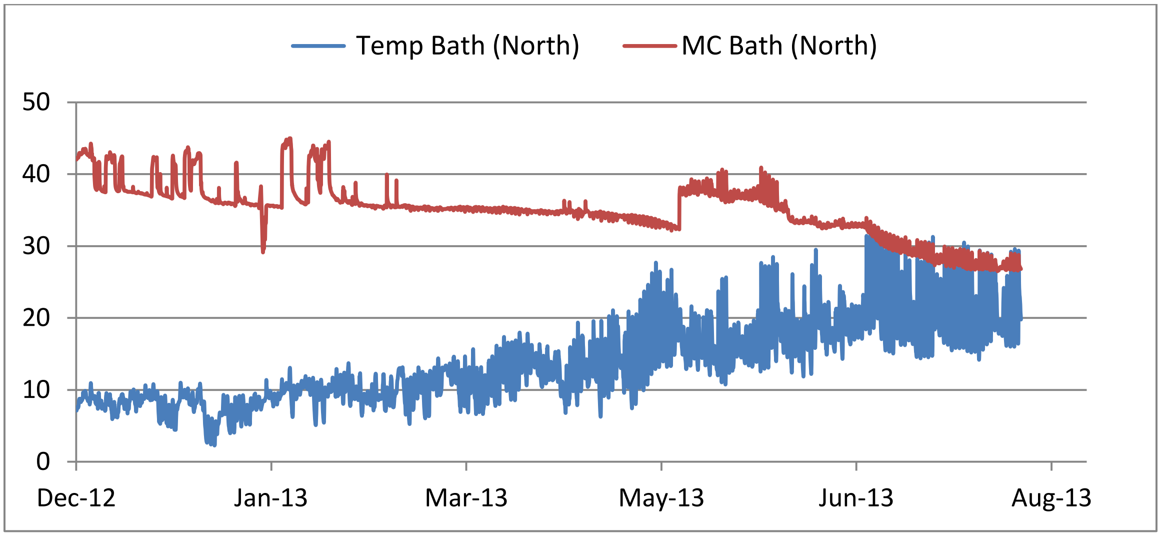

Figure 37: Sheathing MC and temperature variations in Bathroom under the window

In summary, seasonal wetting and drying trends were noted at all elevations. The drying period varied with the orientation. North and West elevations took longer time to dry due to limited sun exposure on North and presence of large trees on the west side of the houses respectively. Also, during winter, MC at both North and West orientations was generally more than the fibre saturation (28%).

All the three monitored houses have ventilated attics. Thus, outside air is the major source of moisture in the attic space. In wet coastal climates, attic ventilation is responsible for high sheathing moisture contents (Forest T.W. et. al. 2002). RH/T sensors in the attics showed that the air was saturated with moisture during the months of December, January, and February and is close to saturation in October, November, and March as shown in Figure 38. Roof sheathing MC readings showed a seasonal wetting and subsequent drying during the warmer seasons, but the wetting period was long and maintained MC above acceptable levels between December and March.

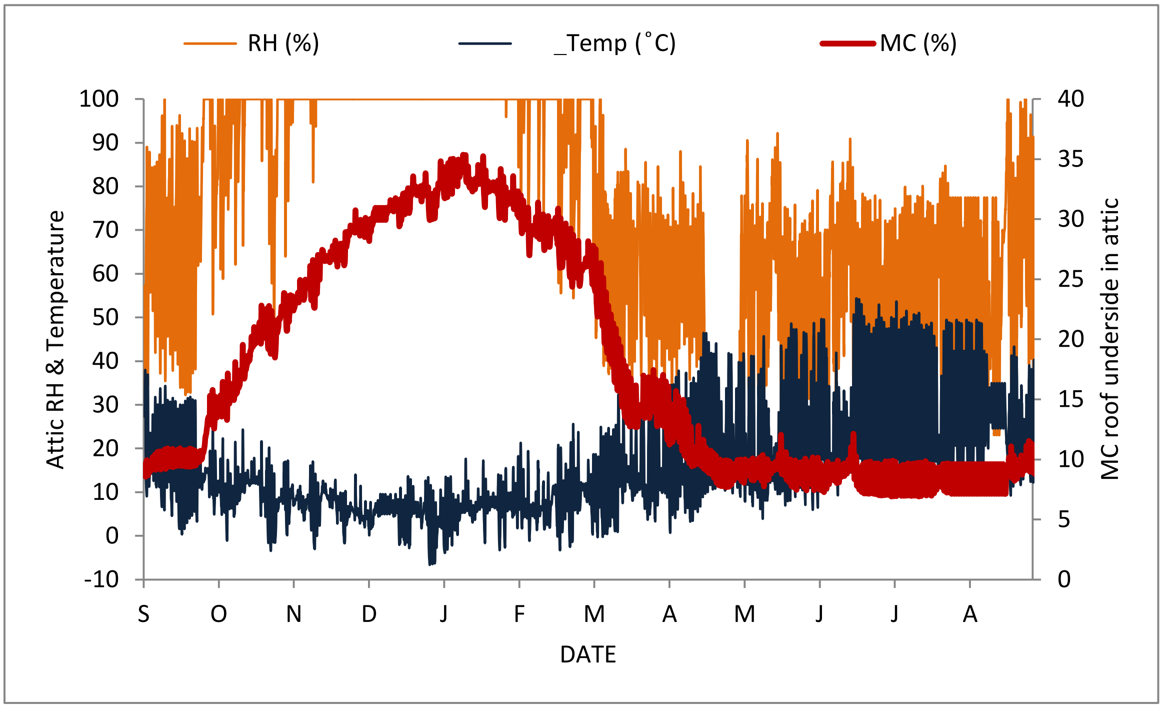

Figure 38: Temperature, RH and MC (roof sheathing) in the Attic of House #1

Condensation risks were evident on the roof sheathing when dew point of attic air was compared to the sheathing temperature. The dew point analysis in Figure 39, shows the instances when the sheathing temperature was less than the dew point temperature of the attic air during the critical months, from January to April. The red dots indicate instances when condensation could occur.

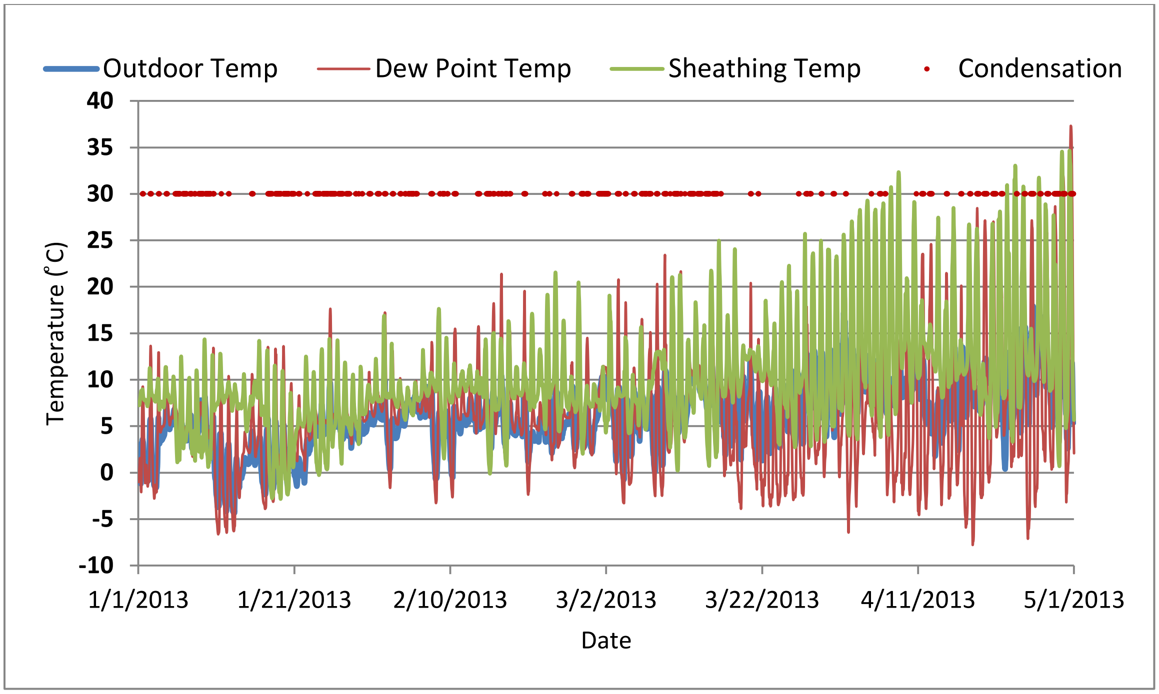

Figure 39: Hourly attic air dew point, sheathing temperature and outdoor air temperature

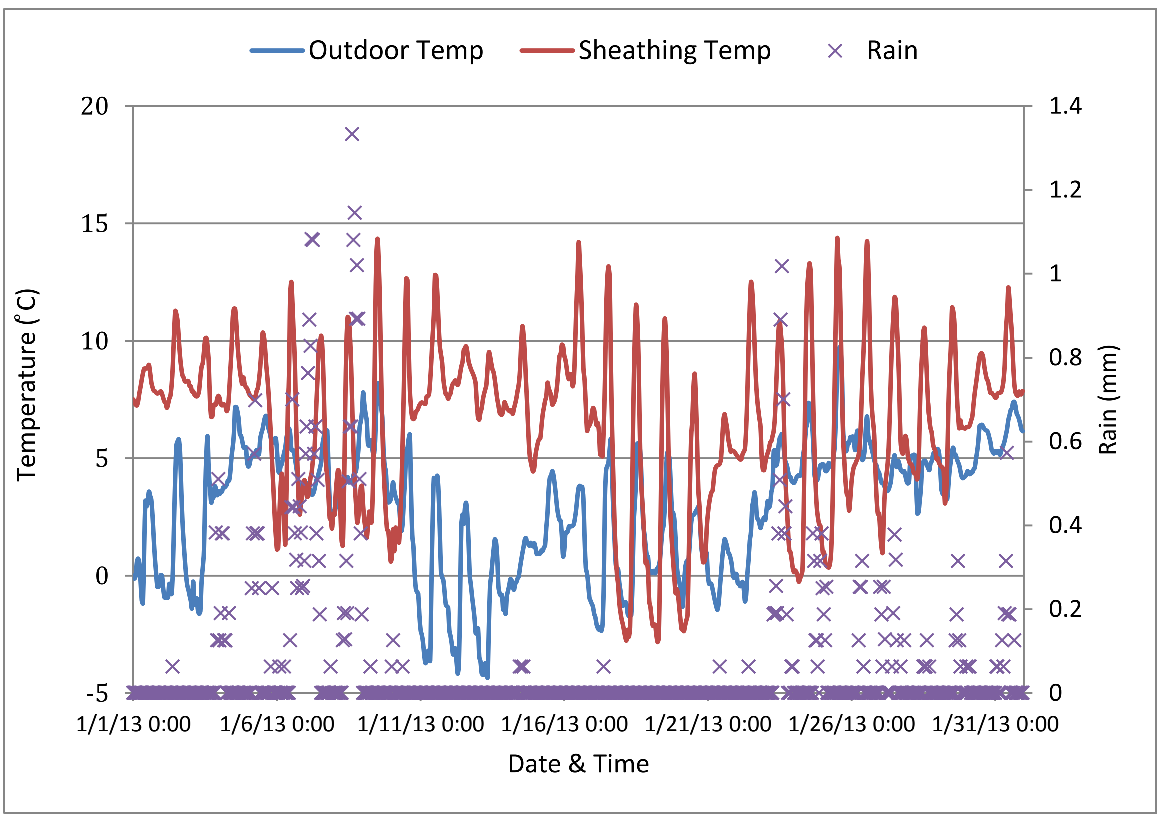

Figure 40: Undercooling of roof sheathing underside

In Figure 40, there are periods when the underside of the roof gets colder than the outdoor air. In all occasions it is evident that roof under cooling happens at night. The only possible cause for this under cooling is radiation heat loss from the roof to the sky in clear nights. Otherwise, it is expected that the attic temperature, and of course that of the underside of the roof will be warmer that the outdoor air. Rain data is superimposed in the Figure to attempt to correlate periods of no rain with roof under cooling. However, except for the three nights of January 19th through January 21th, no correlation is apparent from the Figure. The only possible explanation for this apparent discrepancy is that even though all nights are clear when roof undercooling happens, some of these days are rainy. By examining the rain data during the day and nights of January 7-11. January 19-21 and January 25-28, this hypothesis is confirmed.

5.3 INDOOR AIR QUALITY ANALYSIS

5.3.1 CRAWLSPACES

The crawlspaces in houses (#1 and #3) are heated via forced air heating system, whereas House #2 is slab on grade. The heating system seem to have effectively dried the initial construction moisture in winter and maintained air temperature and relative humidity levels within acceptable levels. In late summer and early fall months, the RH reached 75% but eventually came down to 60-65% range in winter when the forced air heating system started working. Figure 41 shows the temperature and RH variations in crawlspaces of two houses.

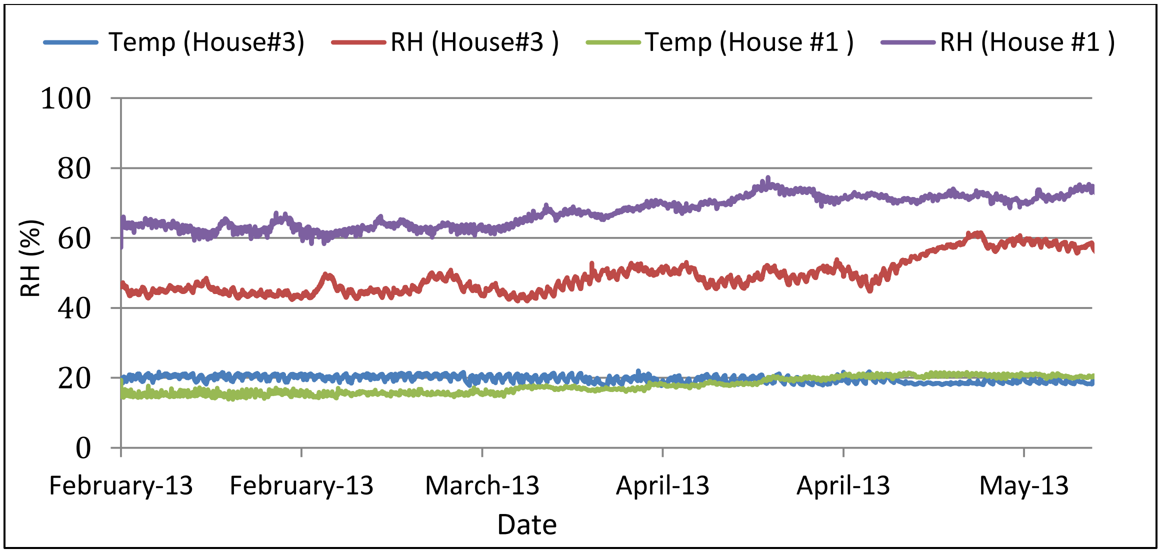

Figure 41: Temperature and Relative humidity variations in crawlspaces of two houses

Infrared temperature readings at the concrete foundation walls (before insulating them from the inside) showed wall temperatures ranging between 51.8°F (11°C) (close to the corners) and 59°F (15°C), which were close to the dew point of the indoor air. Therefore, potential for moisture condensation in these walls still exists. The walls were later covered with rigid expanded polystyrene insulation, which will make them even colder and more.

5.3.2 LIVING SPACES

Indoor temperature (T), relative humidity (RH), and carbon dioxide (CO_2) levels were monitored in the houses. In general, the temperature, RH, and CO_2 levels were acceptable and within the limits presented in Section 2 of this report; which, indicate that the indoor air quality of these three houses is acceptable. The following figures are examples of the indoor air quality data produced by the sensors. The analysis focuses on House#1 because this is the house where more complete data was obtained.

Figure 42 shows the relative humidity variations in House#1 & House#3. Overall RH levels were within comfortable limits (40-60%) for the occupants in winter; and did not risk microbial air borne contamination. Although few short periods of very low humidity (<30%) were noticed in January in house#2 (Manuscript 3), when the outdoor temperatures were the lowest. As weather got warmer, when occupants started opening windows, the indoor thermal conditions varied with the outdoor temperature (Figure 44), and the relative humidity peaked up to 75% in the summer months. RH in house #3 was always lower than House#1 since it has lower occupancy. Only one occupant lives in the house and this occupant did not have a habit of opening window.

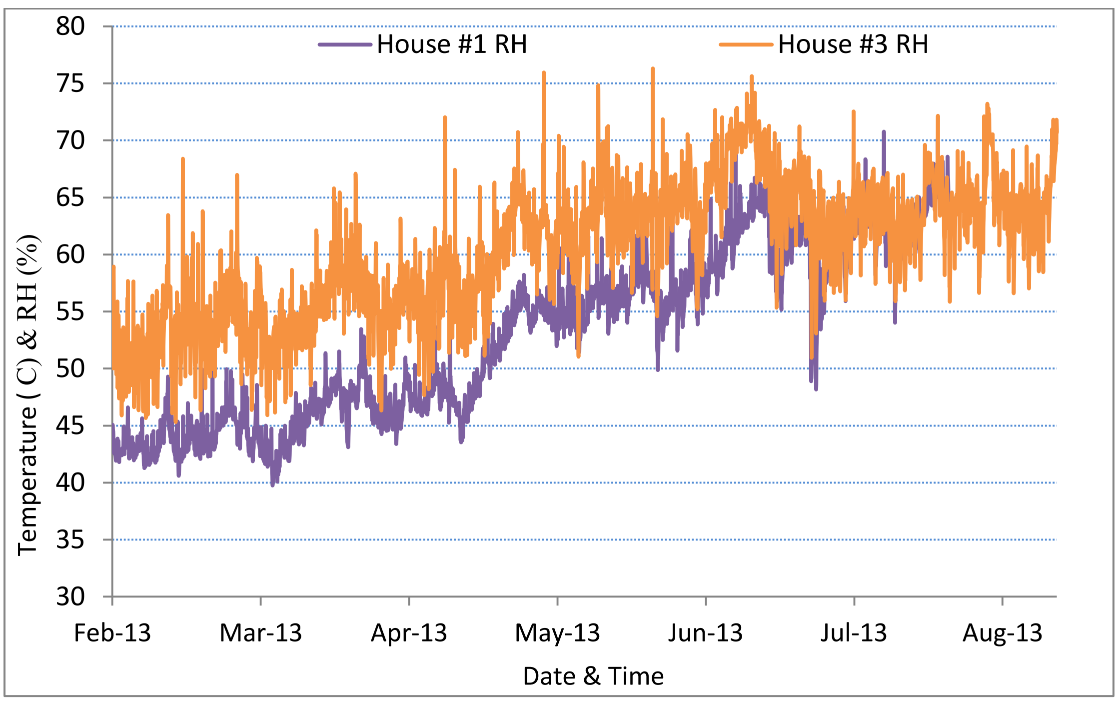

Figure 42: Hourly RH variations in House#1 and #3 during six months

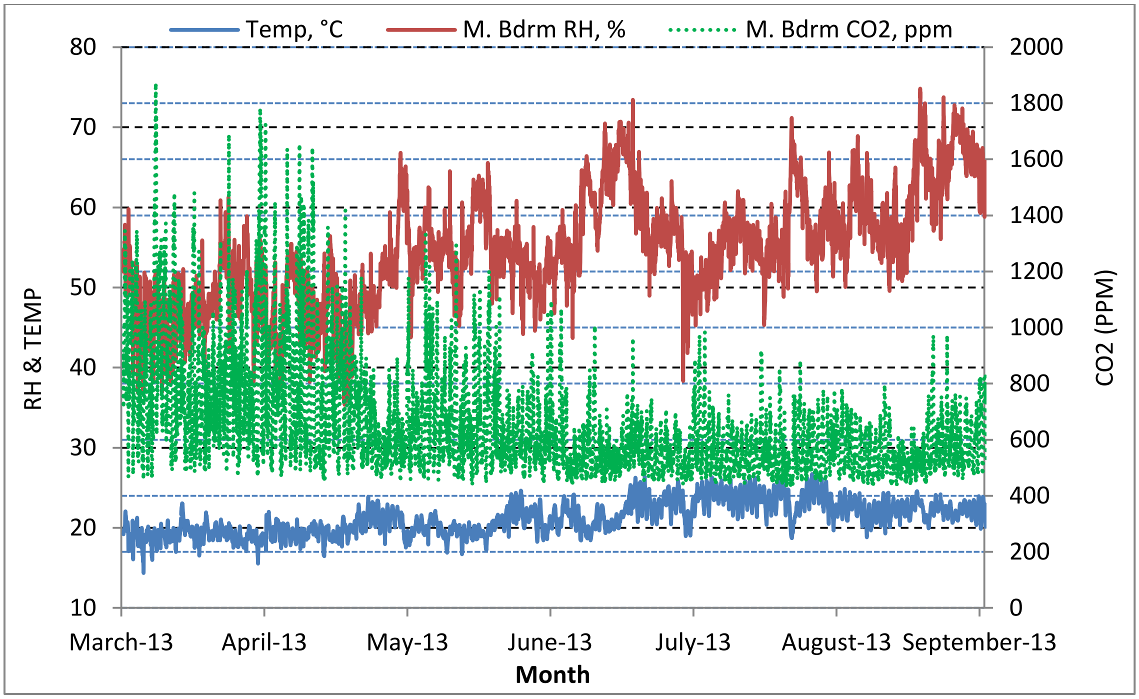

Figure 43: Hourly CO2, temperature and RH in master bedroom of house#1

Figure 43 shows that the temperature in the master bedroom of House #1 is maintained by the heating system close to 20°C in the winter and spring, and increases in the summer. Similarly, the RH is maintained controlled in the winter and spring between 40% and 60%, and increases in the summer. With the CO_2 levels the opposite happens. During the winter and spring CO_2 levels rise often above acceptable levels, whereas in the summer CO2 levels are quite good.

The above trends are typical of houses with tightly mechanically controlled indoor conditions in the cold season and no heating or cooling in the summer. This data demonstrates that the CO_2 levels do tend to deteriorate in the cold season because the houses do not have a dedicated ventilation system but one coupled with heating. Furthermore, the homeowners expressed that they have the habit of opening a bedroom window slightly in the mornings and close it when they get home. This makes the CO2 levels in the cold season fluctuate daily between close to an open-window outdoor value and a closed-window sleeping-time value.

Forced air heating systems in the houses performed well in maintaining uniform air temperature, relative humidity and CO_2 levels throughout the houses. Figure 44 shows the hourly indoor temperature variations at different locations in house #1 in comparison with the outdoor temperature. In winter, temperature was independent of the outdoor conditions and was maintained at a set point (20-22°C) around the house. In summer, when the forced air heating system was not working and windows were opened, the gap between indoor and outdoor temperatures was reduced.

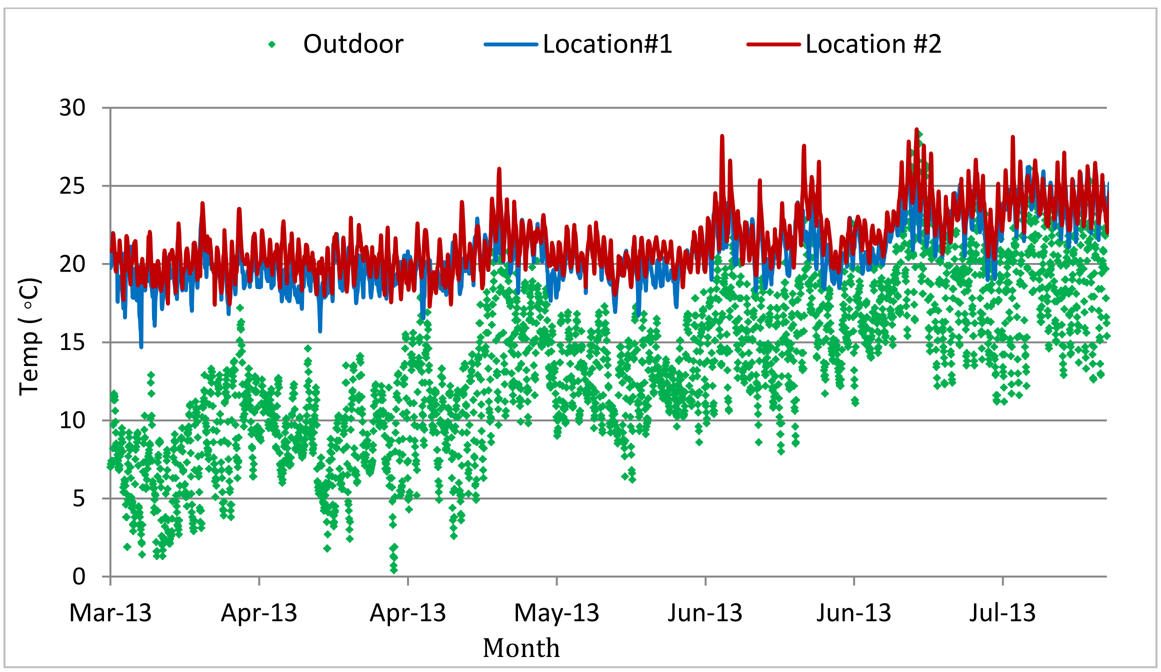

Figure 44: Hourly variations in temperature at different locations with the outdoor temperature

Figure 45 shows RH levels at different locations in House#1. The RH on the same floor of the house showed uniform variations, but was consistently higher in the lower level kitchen.

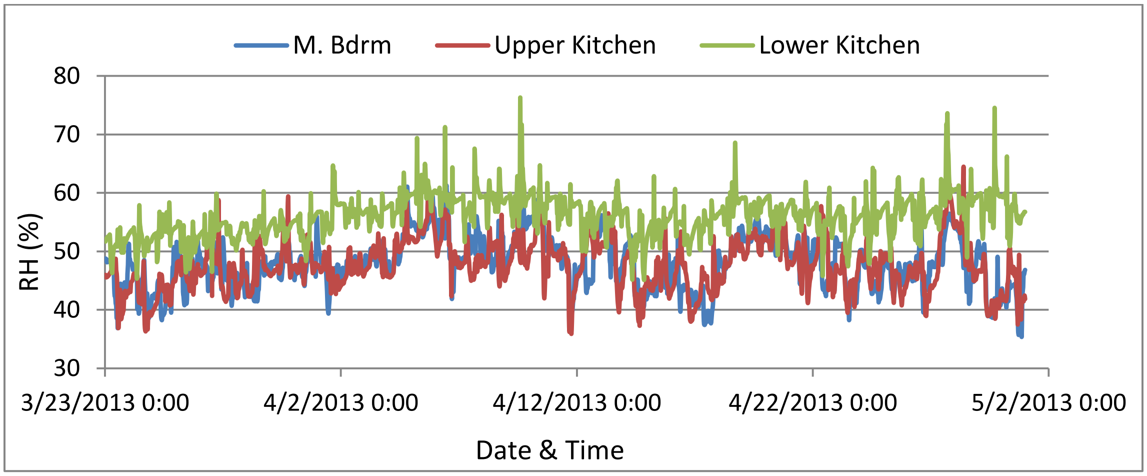

Figure 45: Comparison of RH levels in different locations in House #1

It should be noted that an occupant, a retiree, stay at home most of the time and live in the lower portion of the house. Homeowner questionnaire indicated that this occupant felt cold and kept most of the windows closed throughout the year.

Similarly, CO2 levels showed uniform variations in different parts of the houses. Figure 46 presents the comparison of CO_2 concentrations in Master Bedroom and upper kitchen in House#1. CO2 seems to be uniformly distributed, but peak concentrations (1400-1800 ppm) were observed in Master bedroom.

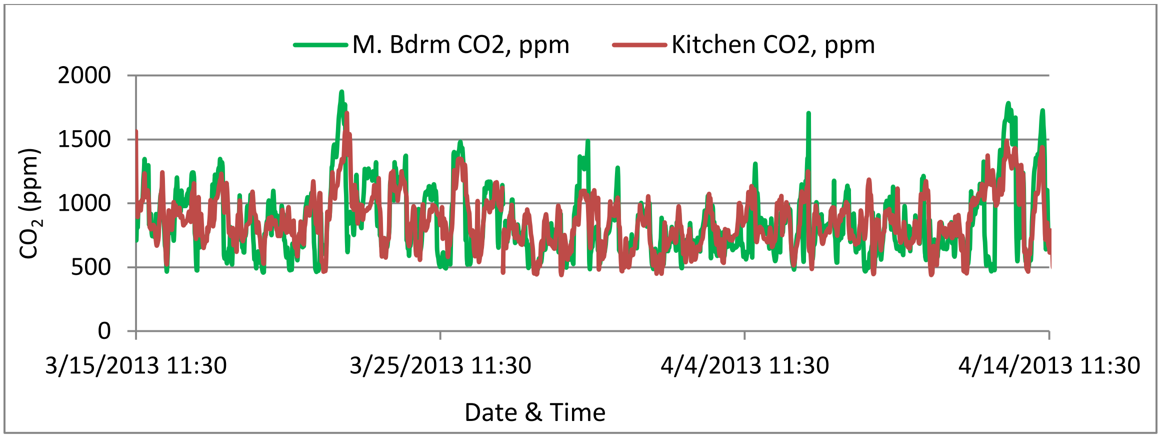

Figure 46: CO2 levels in different locations in House#1

Figures 47 & 48 takes a closer look at RH and CO_2 levels in house#1 during a week of March. RH and CO_2 levels reflect the shift in occupancy at day and night between the master bedroom and the kitchen. The master bedroom has higher RH and CO_2 in the evening and night when the occupants are in their bedroom and decreases rapidly around 7am when the occupants leave the bedroom and occupy kitchen for breakfast.

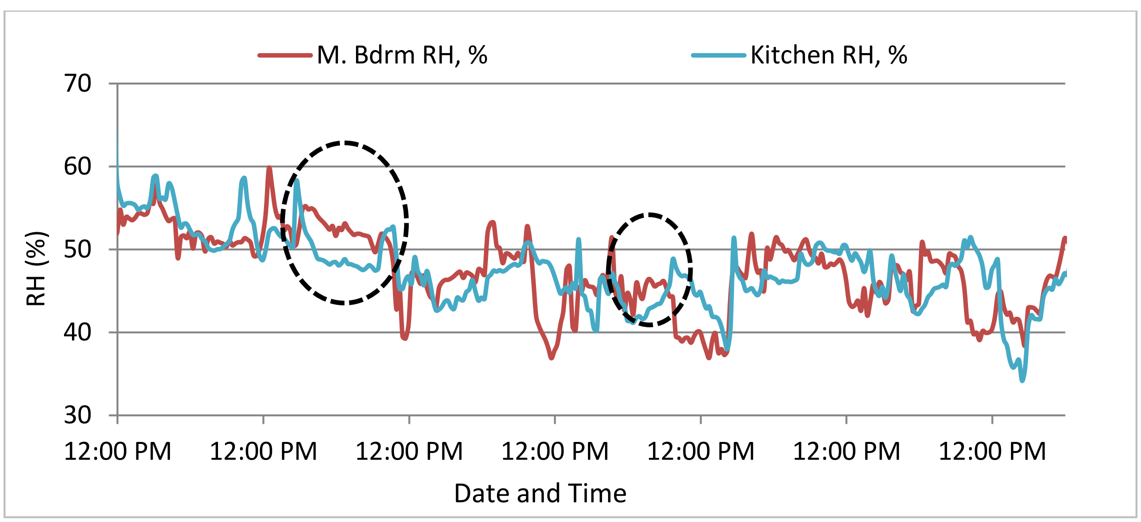

Figure 47: RH variations in Kitchen and Master Bedroom

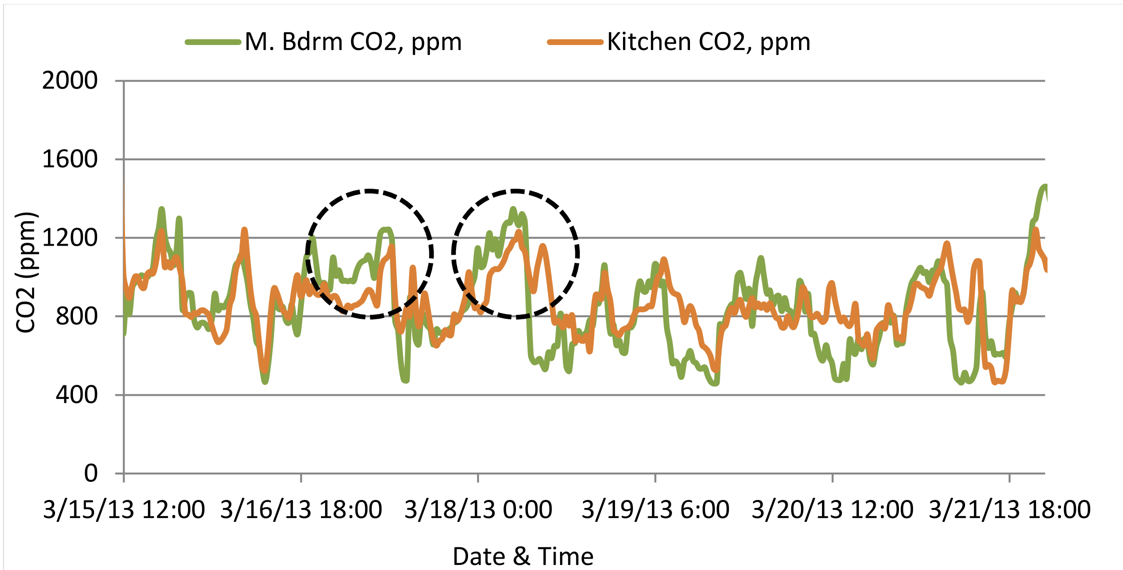

Figure 48: CO2 variations in Kitchen and Master Bedroom

CO_2 seem to respond better than RH to bedroom occupancy at night; whereas, as expected, relative humidity seems to be more responsive to moisture generating activities in the morning. The RH and CO_2 patterns in relation to occupancy, occupant behaviour and lifestyle have been discussed in detail in the manuscript#2.

5.4 ENERGY PERFORMANCE ANALYSIS

As discussed in section 4.6, an energy model was developed for House #1. The model was fine-tuned and calibrated with air tightness tests and questionnaires to occupants. It was then validated by comparing simulated energy use with utility bills collected from the homeowners, and using readings on the air handling unit on/off operation. Figure 49 shows the validation of the model that compares the simulated energy consumption with the actual consumption, obtained from utility bills.

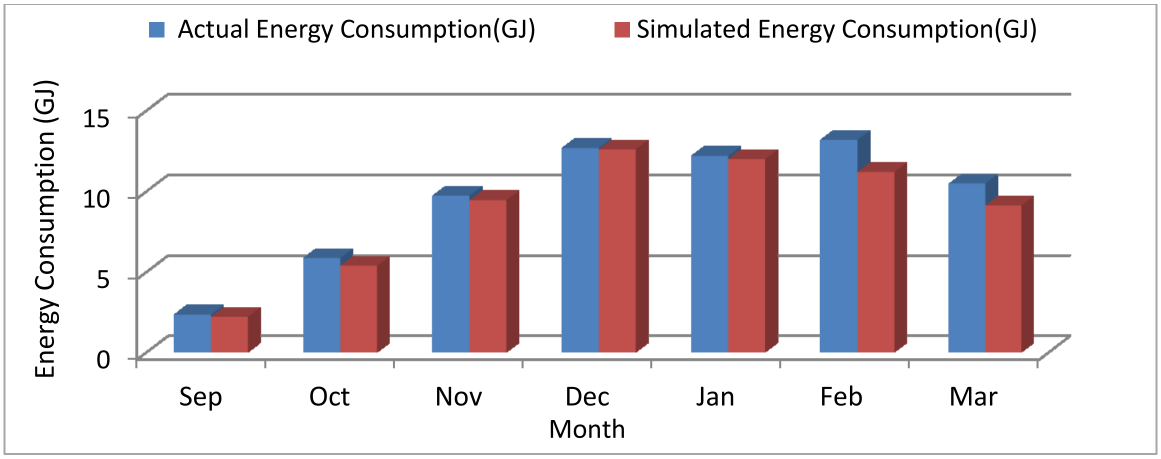

Figure 49: Comparison of actual energy vs simulated energy consumption

Occupant questionnaire indicated that the homeowners have a habit of opening windows whenever they want fresh air, and they like to keep kitchen window slightly open when they were not at home. The energy penalty due to this habit was evident, when the simulated and actual energy consumptions were compared for February and March months, when occupants started opening the windows as shown in Figure above.

The energy model predicted that the house will consume 78.9GJ (22.1MWh) of energy annually. 70% of this energy is consumed for space and domestic hot water heating and one fourth of the total heat losses are due to ventilation which include both air infiltration and mechanical ventilation.

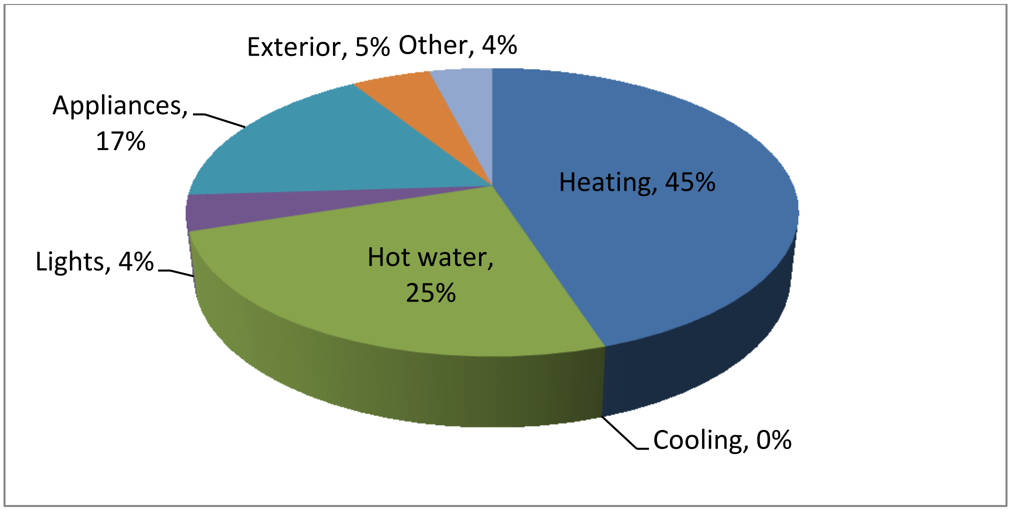

Figure 50: Energy consumption breakdown for House#1

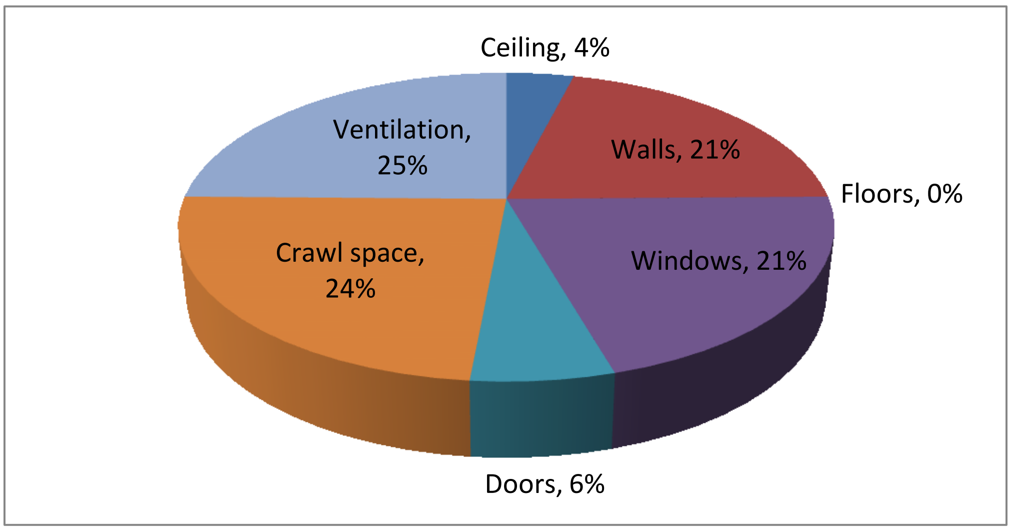

Figure 51: Heat losses from House #1

Since ventilation (both infiltration and mechanical) constitutes a major portion of energy consumption, it is desirable to improve the building envelope air-tightness and evaluate existing mechanical ventilation system. The ventilation in the monitored houses is supplied via make up air in the forced air heating systems. To study other ventilation alternatives, the validated model was used to compare the annual energy consumption and ventilation heat losses (%) of current heating/ventilation system with other potentially better systems.

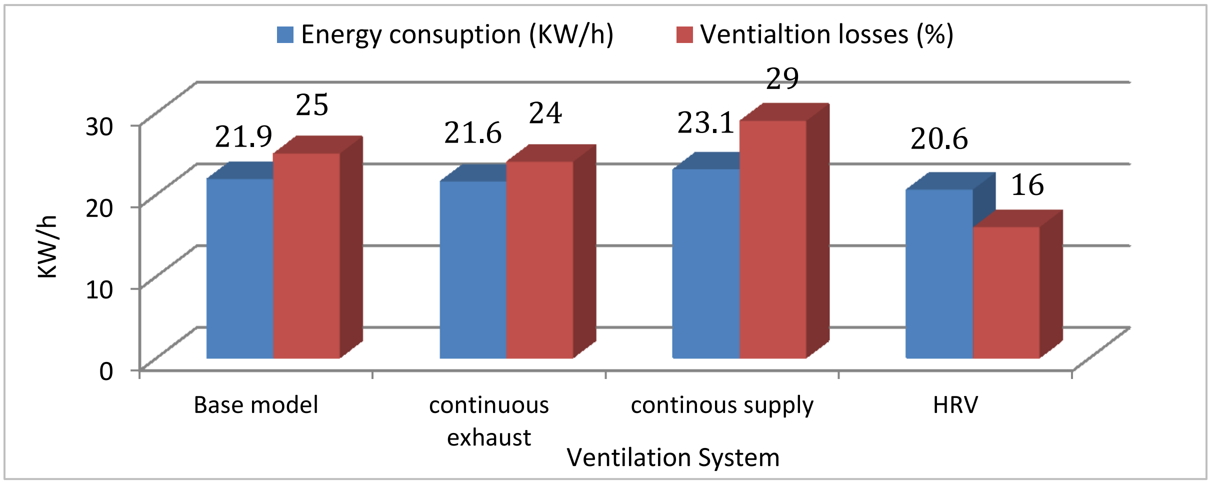

Figure 1 Comparison of energy consumption in different kinds of ventilation systems

Three ventilation options: Continuous exhaust, Continuous supply and HRV systems were evaluated to provide the required air change rate (33L/s) for the whole house ventilation (ASHRAE Standard 62.2, *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*). Simulations show that HRV ventilation system is the most economical one with the least ventilation heat losses as shown in Figure 47. But, it should be noted that occupant behaviors like opening windows would eventually override energy benefits of this ventilation system.

5.5 VENTILATION ANALYSIS

A computer model was used to compare the indoor air quality delivered by three alternative ventilation systems: continuous supply, exhaust and balanced versus the current ventilation system. The model and its assumptions are described in section 4.6. Since occupants open windows for almost eight months in a year, it was difficult to know the effectiveness of the mechanical system. Thus, the model was calibrated by comparing predicted CO_2 versus measurements for the duration when the windows were closed (October-December) to eliminate the open-windows factor from the analysis. This period is critical for IAQ and was used for assessing the effectiveness of alternative ventilation systems. Figure 53 shows the predicted and measured CO2 concentration in the upper floor kitchen. The predicted values are mostly in agreement with the measured values except at the peak values. Possible explanation for the under-predicted CO2 levels is the higher occupancy and longer cooking periods due to visitors in the house.

The comparison between predicted and actual CO2 concentrations in the bedroom for the month of March, clearly indicates the effect of opening windows. Figure 54 shows a rapid decline in the measured CO2 levels in the bedroom in the morning. This decline is due to the fact that occupants used to open bedroom window before they leave for work in the morning (between 7-8am in the morning).

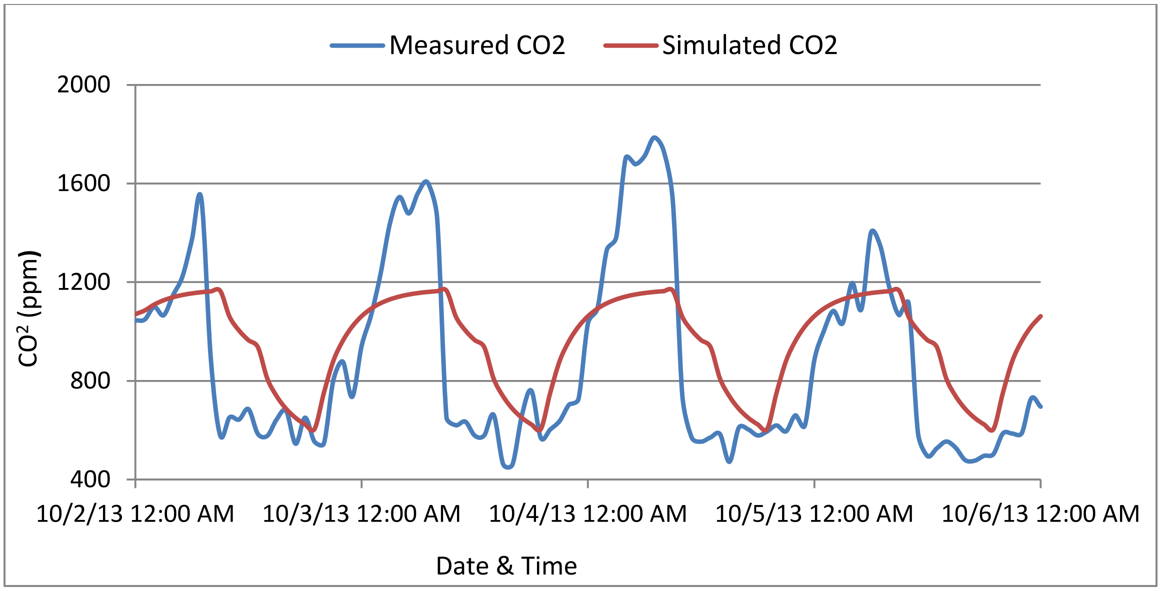

Figure 53: Comparison of simulated and measured CO2 levels in the kitchen

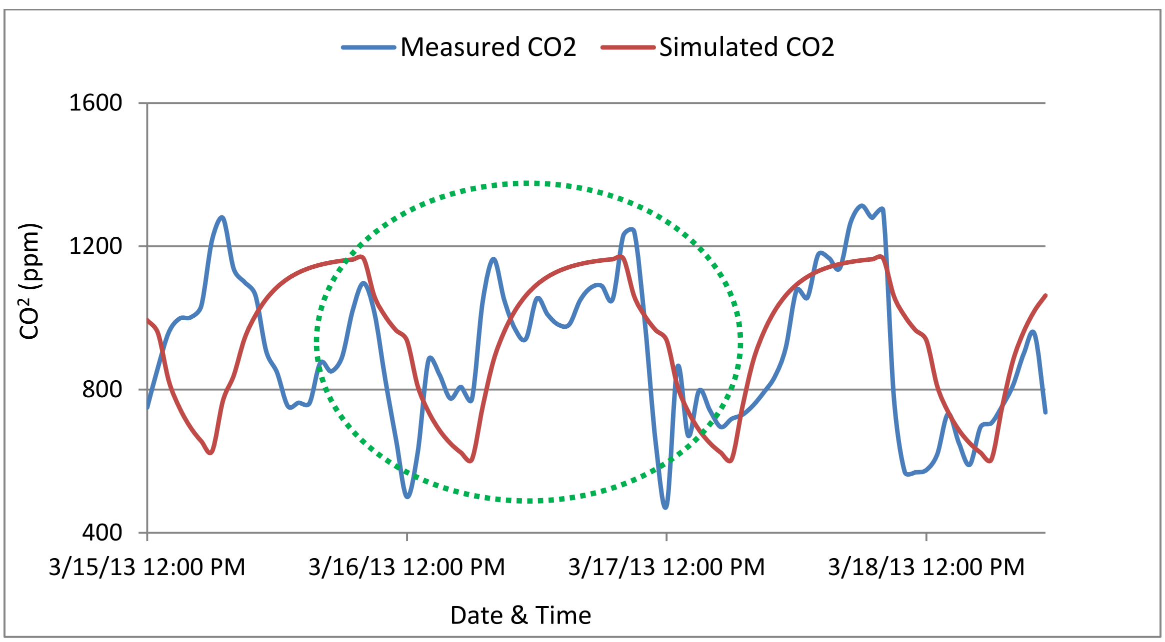

Figure 54: Comparison of simulated and measured CO2 levels in the Master Bedroom

The simulations predict that the house will be slightly de-pressurized when the forced air heating system is off. Thus, there is a potential risk of unwanted pollutant penetration from outdoors, attics and garages, given that there were noticeable leakages from the attic and garage in blower door tests. To minimize the risk of potential envelope contaminants from migrating into the house, the envelope needs to be air-tight and a dedicated ventilation system needs to be designed to improve IAQ.

The calibrated model was used to explore alternative ventilation systems for IAQ performance. Three ventilation systems: continuous supply, exhaust and balanced were compared with the performance of existing ventilation system. Figure 55 presents the comparison of CO2 concentrations in the kitchen.

The three alternative ventilation systems are able to maintain better indoor air quality than the current system because the current system is coupled with the heating demand in the house. Therefore, only whenever the thermostat calls for heating the house gets fresh makeup air at the return, and when the furnace is not operating, the house ventilation is leakage-based.

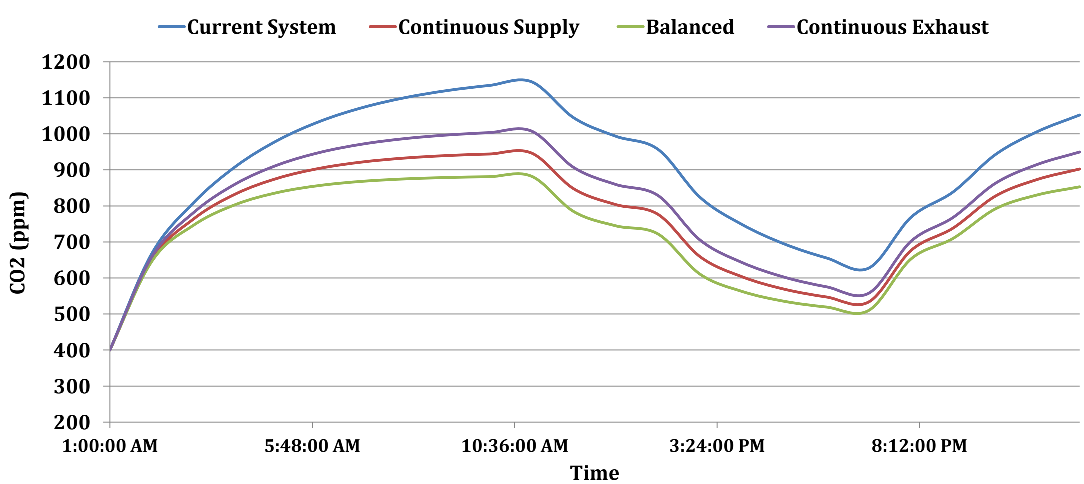

Figure 55: Comparison of simulated CO2 levels with different ventilation systems

From the IAQ simulations, a balanced ventilation system provides the best indoor air quality as it maintains the lowest levels of CO_2 and distributes uniform ventilation air to different areas in the house via forced air heating system ducts. Moreover, it keeps the house air pressure balanced and eliminates the risk of unwanted pollutant penetration from outdoors, attics and garages due to pressure differentials.

CHAPTER 6 – DISCUSSION AND RECOMMENDATIONS

6.1 LESSONS LEARNED FROM THE PILOT STUDY

The houses are performing well overall and there is no sign for immediate alarm to the homeowners or the builders. The construction is fairly good except few details and workmanship which should be improved to prevent chances of water penetration into the building envelope.

Waterproofing details around the penetrations like hose bibs, electrical outlets, electrical /gas meters etc. are not up to the mark based on good practice guidelines and needs improvement. Similarly window penetrations are not waterproofed adequately along the sill and at sill-jamb corners. At few locations, waterproofing is completely missing.

Foundation walls of all three houses are dampproofed to prevent moisture penetration through the concrete, but there is no capillary break between the concrete wall and the wood framing. Dampproofing stops at the grade level and there is an exposed concrete wall between grade and the wood framing. This allows moisture to penetrate from the exposed concrete to the wood framing. A good practice to block moisture penetration is to install a gasket between concrete and wood.

For air and vapour barrier continuity, 6-mil poly is used as air/vapour barrier in these houses. This makes the detailing around the penetrations more critical. Visual reviews indicated that at several locations poly had cuts and there were gaps in the air/vapour barrier around the penetrations, which were evident during blower door test as air leakage around these penetrations was noticeable.

At roof to wall transitions, negatively lapped building paper was located in House #2. It is possible that there are more locations, where building paper/sheathing membrane is negatively lapped. A negatively lapped sheathing membrane allows the incidental water which has penetrated through the first layer of protection (cladding) to penetrate behind the membrane and deteriorate plywood sheathing.

The assessment of results from the data analysis indicates the envelope moisture levels are high during winter, which is normal in the wet marine climate of BC, but it eventually dries in warmer months. North elevated walls have the highest level of moisture content and their drying period is longer as compared to other elevations. South and east walls have lower MC levels due to higher solar radiation. The effect of external obstructions (large trees) to solar radiation is evident on west elevated walls. They had high MC levels and took longer time to dry.

The moisture content of certain walls needs close attention as noted in the previous chapter. The north wall in House #3 below electrical/gas meters showed high MC levels [Figure 28]. It should be noted that the penetrations at these meters were not waterproofed at all [Figure 29]. Similarly, another location at north elevated wall in House#3 showed high MC levels [Figure 37]. This location is below master bathroom window in close proximity to the electrical outlet [Figure 36]. There is a possibility that air/vapour barrier is not continuous around the outlet and moisture-laden air leaks and condenses at the inner face of the plywood sheathing. MC at these locations eventually dried in summer, but it took longer time to dry as north oriented walls get limited solar radiation.

The sensor on east elevated wall in House #1 also showed exceptionally high moisture levels [Figure 34]. This sensor is located below a window and is near the change of planes in the building envelope [Figure 35], where gable meets the wall. There is a possibility that rain penetrated through this interface. It should be noted that the sheathing membrane could be negatively lapped at this location which is similar to the roof-wall transition in House #2 discussed above. Rain may have penetrated through the deficient interface detail and reached behind the negatively lapped sheathing membrane. As this location is on east elevation with plenty of sun exposure, moisture dried rapidly.

Above discussed locations are critical in terms of envelope durability in these houses. An engineering assessment would need to be conducted if higher values of moisture content persist in the next winter season also.

The attic also needs close attention because the moisture levels were very high and sustained for a long period. A high risk of moisture condensation on the underside of roof sheathing was evident. These conditions will likely result in mold growth and a proliferation of mold spores in the attic. Although, attics are not part of the envelope, they are connected, unintentionally through cracks, mostly through recessed light fixtures in the ceiling, with noticeable air flows during the blower door test. A preventive solution needs to be devised such as sealing the ceiling cracks and minimize air flow between conditioned space & attics.

The indoor environmental data (CO_2, RH/T) indicate that forced air heating systems are performing well to maintain uniform temperature & CO_2 levels; and keep indoor moisture levels within acceptable range for good indoor air quality. The CO_2 levels were more than 1000ppm in fall and spring months (swing season), when windows were closed and HVAC system had limited operation. The instances of higher values of CO_2 were observed in bedrooms and common areas during night time and higher occupancy periods respectively, which could result in occupant discomfort.

RH/T data in all the three houses showed no signs of risk for microbial air borne contamination due to excessive moisture in the indoor environment. CO_2 and RH/T sensors give clear indication that the owners in one house are opening the windows at times which is not convenient from an energy point of view.

The sensors in the crawl spaces suggest that foundation moisture is drying out and these seem to be performing well. Additional sensors at the corners of the foundation walls would help find out if there is a risk for moisture condensation at these locations.

A breakdown of the results from the energy simulation indicated that the heating and ventilation are mainly driving the energy consumption and occupant behaviors like opening windows are causing energy penalties. A feedback to the occupants on the items they can control to reduce energy consumption could make a difference.

For example, knowing the energy impacts from opening windows may lead the homeowners change that habit.

Ventilation simulations indicated that there is a risk of unwanted pollutant penetrations from outdoors, attics and garages, given that there are noticeable leakages from the attic and garage. The houses need to be air-tightened to improve the IAQ, prevent mold growth and increase energy efficiency. A dedicated ventilation system is desirable.

6.2 RECOMMENDATIONS FOR PERFORMANCE IMPROVEMENTS IN HOUSES

Based on the lessons learned from the pilot study, recommendations for improvements in the monitored as well as the future houses on the reserve are suggested. It is assumed that builders and band leaders are not prone to make radical changes in the construction practices; thus only simple and affordable solutions to improve overall performance of the houses were recommended.

6.2.1 BUILDING ENVELOPE

Moisture content of the plywood sheathing in exterior walls during winter as discussed in the previous chapter is in seasonal cautionary range. Apart from seasonal wetting and drying of plywood sheathing, the exterior walls had MC more than fibre saturation point (28%) at many locations for an extended period of time (2-3 months). These high MC levels were mostly due to construction moisture, air leakage condensation (i.e. moisture-laden indoor air leakage through the penetrations with deficient air/vapour barrier detail), deficient envelope details and high outdoor relative humidity (typically 80-100% during winter). Studies have shown that RH in the cavity behind the cladding follows outdoor relative humidity and temperature conditions, and is also influenced by solar radiation and orientation (Finch et. al. 2007). Few deficient details had the possibility of wetting due to rain water leakage. Better construction practices (air-tight envelope), construction moisture control and keen emphasis on the building envelope construction, specifically the vulnerable interface locations (wall-window, wall balcony, roof-wall) and critical north elevations can improve moisture levels in the building envelopes. These vulnerable locations need better waterproofing details. Figure 56 shows some examples of good waterproofing details around penetrations, at window rough openings and at the base of walls.

The attics are the main concern in these houses as high moisture levels sustained for a long period. There are risks of condensation on the underside of roof sheathing which could result in mold growth. Preventive solutions like making the ceiling more air tight; applying treatments and coatings to create unfavorable conditions for mold growth; providing insulating boards and mold resistant sheathing outboard ventilated spaces to keep the roof structure warm and dry; or insulating the underside of roof sheathing with foam insulation to stop mold spores from getting in contact with the roof sheathing are recommended (Roppel et. al. 2013).

Waterproofing detail around a vent

Detail around an electrical outlet

Detail at the base of wall

Waterproofing at the Sill

Figure 56: Examples of waterproofing details

In the long run, for the exterior walls, builders should consider adding semi-permeable rigid exterior insulation to maintain the plywood sheathing warm and protected, while letting any moisture that may be trapped in the wall escape to the exterior. This would also make the houses more energy efficient. For example, a 2X6 wall with R-21 Batt insulation in combination with exterior semi-permeable 1" XPS will increase overall effective R-value from R15.9 to R21(HPO 2011), which in-turn will reduce energy consumption by 14% as shown in the Figure 57 in house#1.

6.2.2 ENERGY EFFICIENCY AND IAQ

The energy model simulations indicated that major portion of the energy loss is due to air infiltration and mechanical ventilation. Energy losses due to infiltration should be reduced by improving air tightness in both existing and future homes. Building envelope should be durably sealed, and all joints, seams and penetrations should be caulked, gasketed and weather stripped. Studies have shown that it is possible to achieve 20-30% reductions in blower door test numbers by limiting infiltration via simple weatherization in the existing homes (Allison Bailes 2012). Assuming, the envelope airtightness is reduced from ACH4.5 TO ACH3 in existing houses, energy simulations predict 15% reductions in energy consumption as shown in Figure 57.

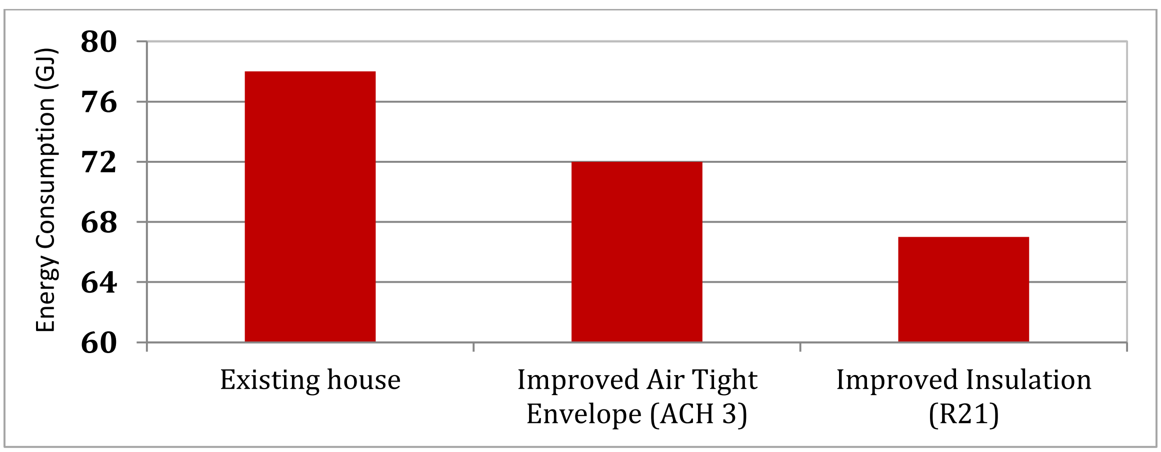

Figure 57: Monthly Energy consumption in existing vs improved building envelope tightness

Apart from saving energy costs (IRC 2009, IECC, BC Building Code 2012), air sealing will also reduce cold drafts, condensation risks in envelope and unwanted air infiltration of pollutants from garage and outdoors. Isolating the attic from living space will help to reduce chances of mold spore penetration. Air leakage in the envelope allows indoor moisture to penetrate into the envelope and condense on the plywood sheathing/roof sheathing and hence, result in higher risk of mold. Higher moisture content in the wall elevates mold growth and worsens the situation further.

Air tight envelope as assumed above will be beneficial from energy consumption perspective, but it will also compromise indoor air quality, given that the CO2 levels in the houses are already more than 1000ppm. As the envelope gets tighter in both existing and future homes, indoor relative humidity and pollutant control will become more important. Hence sufficient mechanical ventilation will be required in these renewed air tight enclosures for acceptable indoor air quality. Also, a dedicated ventilation system will minimize the need to open windows by the occupants; hence will help to minimize the energy penalties. Next section explores different ventilation strategies which are recommended for the existing and future homes on the reserve.

6.2.3 MECHANICAL VENTILATION

The existing houses on the reserve do not have a dedicated whole house mechanical ventilation system. Manually operated bathroom and kitchen intermittent exhausts are used for spot ventilation only. The houses rely on infiltration and forced air heating system for ventilation, which is not an effective ventilation strategy (CMHC 1999) since fresh air is drawn from the air duct only when there is a heating call from the thermostat. This results in inconsistent ventilation, especially in swing seasons.

Options for better ventilation systems for improved energy performance as well good indoor air quality, as discussed in chapter 5, indicates that balanced heat recovery ventilation system is a promising choice. But this system is not recommended because of its high cost as a refurbishment for these houses. Also, the low envelope thermal and air leakage performance of the houses combined with the mild climate do not justify the heat recovery.

Exhaust ventilation system could be a cost effective ventilation solution in the existing houses on the reserve. A continuous running exhaust fan in one of the bathrooms can be used for whole house ventilation. But, this ventilation strategy will only work when the houses are airtight and well-sealed from attics and garages; and outdoor air is allowed through vents or window trickle ventilators.

Since future houses on the reserve are also expected to have forced air heating systems; continuous supply ventilation, via central air handler fan, is recommended as it can provide year-round filtered and conditioned fresh air throughout the house. This system, also known as, the central fan integrated systems (CFIS) has been tested rigorously by Building Science Corporation professionals and has been used in Building America program for decades. The detailed design methodology and economic evaluation of this system has been discussed in Lstiburek et al (2001).

A schematic of this system is presented in Figure 58 (Rudd 2003). The system has a 6" diameter insulated duct connected from outdoors to the return side of the central air distribution fan with two specialized control processes:

- **Fan Cycling:** Fan cycling control assures that the central air handler fan will run enough to distribute ventilation air and evenly mix air throughout the house, even when there is no demand for heating or cooling. But rather than operate the fan continuously or by a simple timer, the FanCycler method factors in prior operation, i.e. it does not run the central fan for ventilation when operation for heating or cooling has already accomplished the necessary ventilation and mixing. In this way, the FanCycler method saves energy as well as wear and tear on equipment. Figure 58a shows the schematic of aircycler FRV as shown in the manufacturer's manual.

- **Ventilation Damper Cycling:** A motorized ventilation damper integrated with the fan cycling control limits over-ventilation during long heating or cooling cycles and saves the energy of unnecessarily conditioning the extra outside air. The damper opens when the fan is on unless enough time has already expired for the introduction of ventilation air.

There are several central fan integrated ventilation system controllers commercially available in the market (FanCycler.com). Like other ventilation systems, this system works best when the building envelope is air- tight.

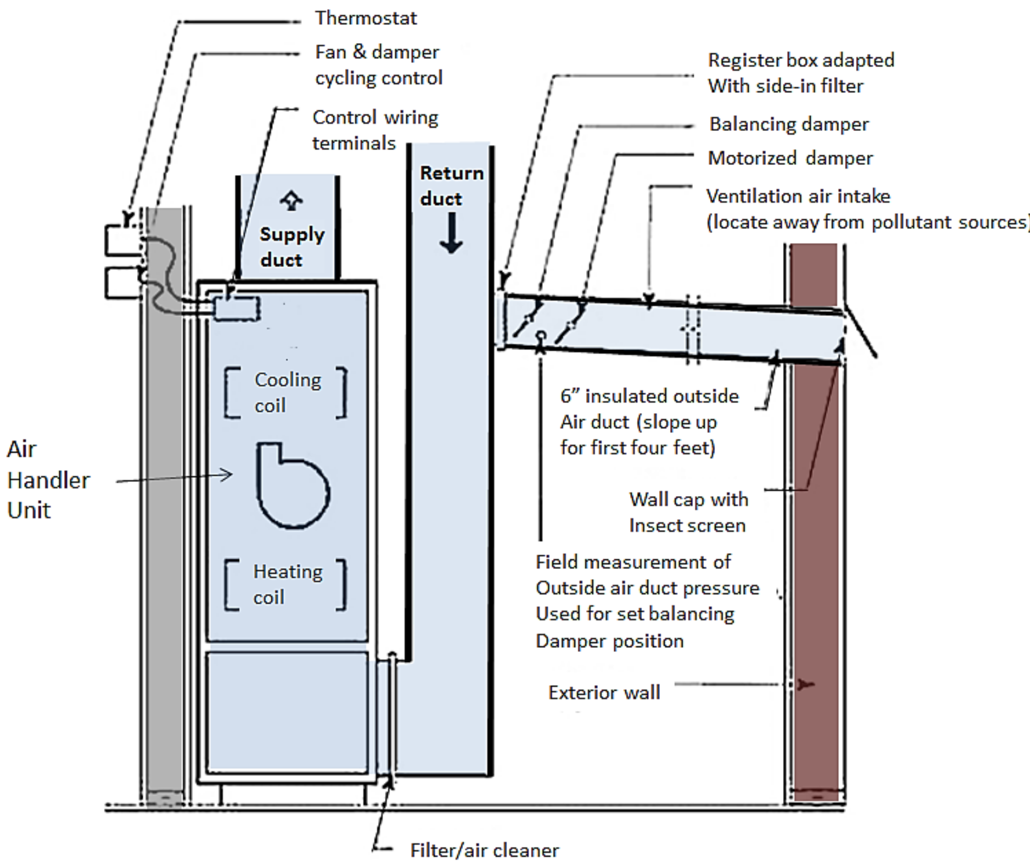

Figure 58: Schematic of Central Integrated Fan System (CFIS)

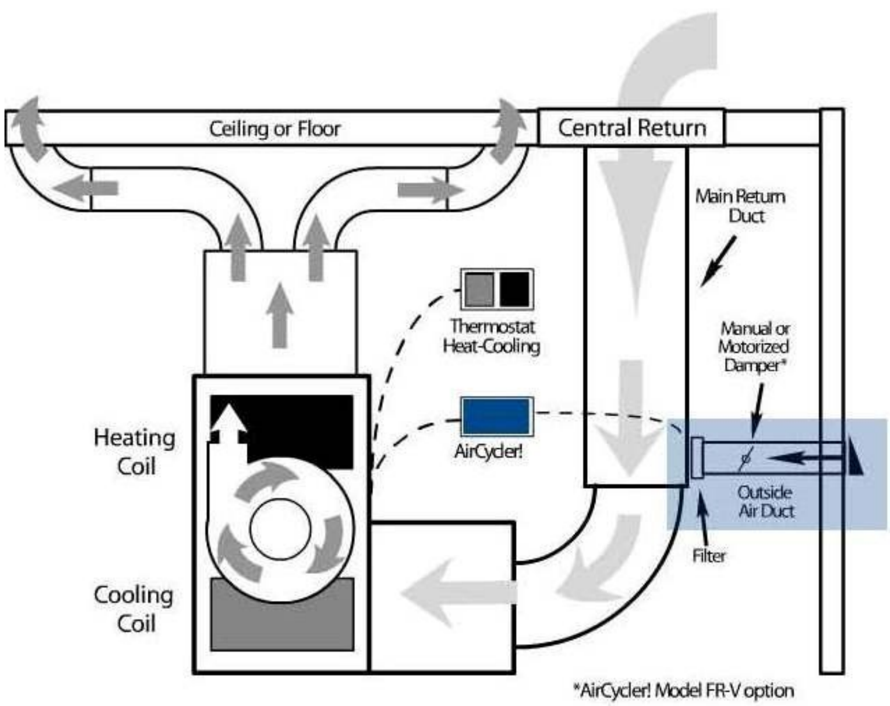

Figure 58a: Schematic of AirCycler FRV

6.3 CONCEPTUAL ARCHITECTURE OF THE MONITORING SYSTEM INTEGRAL TO HOMES

Based on the knowledge gained from this pilot study, a conceptual architecture of the monitoring system integral to homes was developed. Figure 58 illustrates the components of a ***Health Monitoring System*** integral to homes. The system consists of two components that provide feedback to the Occupants and learn from the behaviors. (1) ***The Sensory System*** that includes indoor environment, energy, and envelope sensors. And (2) ***The Reasoning System*** with three engines: the *Occupants Behaviors Inference Engine*, that infers occupants' behaviors from sensory data; The *Building Performance Inference Engine*, that infers performance; and the *Learning Engine*, that learns from occupants' changing behaviors, from the sensory data, and from actual energy performance data obtained from the Smart Meter (if one is installed). The dotted lines indicate feedback from the ***Health Monitoring System*** to the occupants; and from the occupants and the smart meter to the *Learning Engine*. The goal of the reasoning system is to infer occupants' behaviors and house performance from a limited number of sensors, and give feedback to occupants so that they can change behaviors, adapt, and take control of the house performance. Thus, through sensing, reasoning, and feedback to occupants the need for a complex and expensive electromechanical control system can be avoided, perhaps leaving automated source control only for kitchen and bathroom exhaust fans.

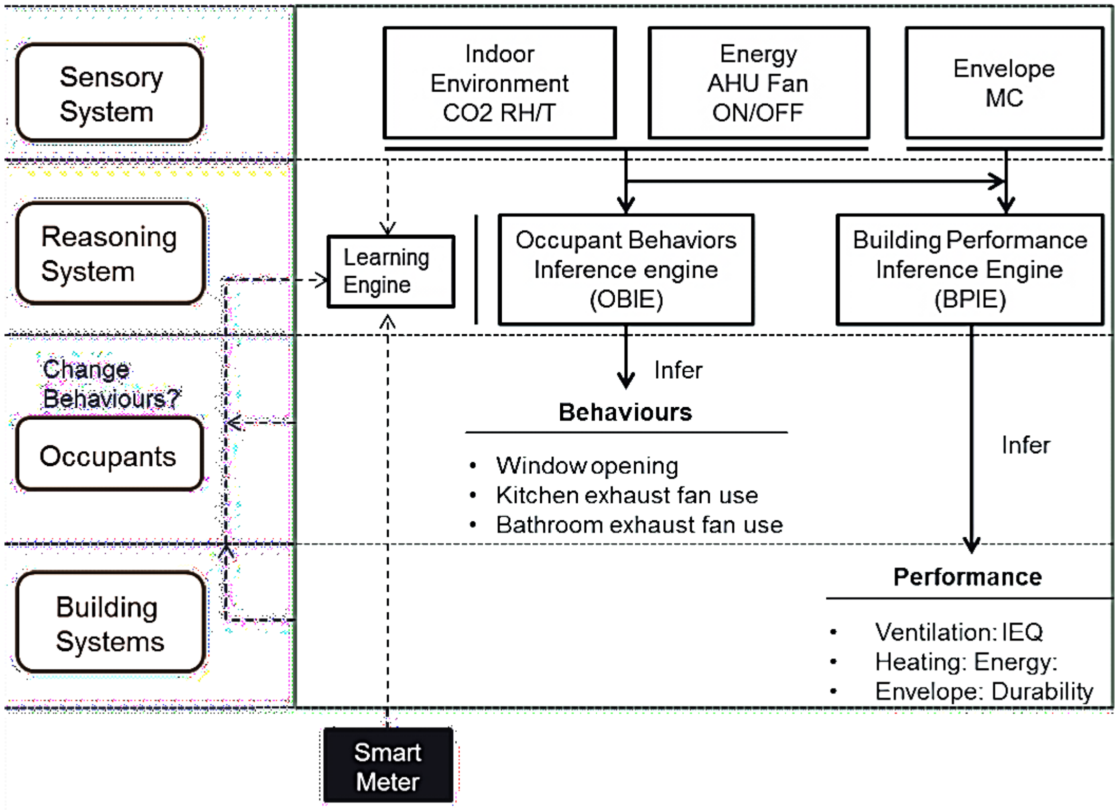

Figure 59: Conceptual Architecture of the Health Monitoring System Integral to Homes.

The *health monitoring system* is building science knowledge/principles based. This knowledge needs to be managed stochastically given the many uncertainties and dynamic nature of the boundary conditions. The system would be designed, fine-tuned and commissioned for each particular typology of houses, heating and ventilation system, and boundary conditions. The reasoning algorithms would be calibrated by memorizing characteristics of time-series generated sensor data during the learning phase, where the house is assumed to behave normally. This phase would subsequently help identify anomalous behaviors. It is envisioned that once operational, the system would learn from experience and fine-tune itself. An unexpected challenge from this project was having an occupant who is heavy smoker and carves wood in his house. Given that smoke produces co2, it was thought that co2 could be a good surrogate for the presence of smoke. However, apparently, the combination of gases and fine particulate matter from tobacco smoke affected the co2 sensor readings. Even with the advent of more sophisticated sensors, such as voc sensors, it is believed that a residential *health monitoring system* needs to be kept as simple as possible, and cannot be meant to prevent health risks that are more conveniently handled through source control. It is for the sake of simplicity, that the *reasoning system* is proposed, i.e. to eliminate the need for an unnecessary number of sensors

CHAPTER 7– CONCLUSIONS

7.1 CONCLUSIONS FROM THE PILOT STUDY

This pilot project demonstrates the value of a well-planned and deployed remote sensing system integral to homes to provide holistic feedback to homeowners and builders so that they can manage their homes more proactively. It demonstrates that this monitoring system is feasible and can help in collecting much needed data from the remote First Nation communities. The study also emphasize that occupant's behavior can have a significant impact and is critical for the design of any resilient residential indoor environmental monitoring system.

7.2 OUTCOMES

The project gave valuable feedback to homeowners and builders on the construction, indoor air quality and energy efficiency of the existing homes on the Reserve. Recommendations were given to improve existing homes with simple and affordable solutions. Also suggestions and recommendations were provided to improve construction (efficient and durable wall assemblies), & heating and ventilation systems in future homes on the Reserve.

It is a first step towards building partnership with First Nation Communities to help improve quality of their homes, and collaboration with the industry in the future, to optimize heating & ventilation systems for improved energy efficiency & indoor air quality on the First Nation Reserves.

Also, this study builds up efforts towards the development of a permanent real-time home quality monitoring/response platform in future.

7.3 CHALLENGES

Main challenges were faced in this research project are as follows:

1. **Technology:** The wireless sensor technology, especially CO2 sensors, is still evolving and there are several challenges like power and maintenance requirements, costs and adequate calibrations issues. The remote sensing system used in this project was used for the first time in residential setting (individual houses). Initially there were lots of challenges in downloading the data wirelessly. After much troubleshooting, sensing system started working well.
2. **Lack of co-operation from Homeowners:** Although in the beginning, homeowners were motivated and agreed to co-operate, but later they were not willing to help and provided only limited access to their houses (house #2 & #3).
3. **CO2 sensors:** CO2 sensor in the house#3 had to be de-commissioned as it out-of calibration after few days of installation. The occupants in this house smoke indoors and carve wood inside the house. It is assumed that these activities effected the sensor. After several attempts in troubleshooting, homeowners got frustrated and were not willing to give access to their house.

4. Few RH/T sensors in the attics did not work as expected. Due to limited access to attics, we were left with limited number of sensors and the data analysis was based on limited available sensors.

7.4 FUTURE WORK

As agreed with the homeowners and with the Squamish First Nation, the monitoring took place over a period of one year. However, it would have been convenient to extend the monitoring period to two years to be able to appreciate two cycles of wetting and drying. As construction moisture dries, it is expected that during the second winter the moisture content does not rise as much as during the first winter. This would have given a better indication of the long term performance of the houses. Future monitoring studies should take this factor into consideration.

Moisture transport modeling calibrated with monitoring data, would have helped to better understand the factors that produce high moisture contents in the walls of these houses, and help assess and quantify how to prevent this. Future studies can use the data produced in this study to model and calibrate moisture transport simulations.

This research is a pilot project to study the feasibility of a permanent real time monitoring system integral to homes and its significance in the performance improvements in First Nation homes. Future work will also include remote monitoring of statistically representative sample of homes, located in the remote regions. Also collaborations with manufacturers to test alternative heating &

ventilation technologies, and other researchers to develop intelligent sensing systems & controls algorithms will be established in the future.

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APPENDIX A- MANUSCRIPTS

Manuscript 1

Sensitive Homes: Remote Sensing and Monitoring Integral to Homes

LoveleenAtwal *Student Member ASHRAE*

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Gamal Mustapha

ABSTRACT

Aboriginal families are significantly more likely to live in poor housing conditions than the general population. Furthermore, in Canada, most of these houses are often located in colder regions, which challenge the construction, the indoor air, and the energy consumption. Poor housing is also related to poor child health outcomes. The overarching goal of this research is to develop a health monitoring system integral to homes that acts as preventive early warning system before problems become serious and sometimes irreversible. The underlying premise is that higher value can be gained from a system that combines different types of monitored data, such as indoor, construction, and energy, in building awareness and enabling better informed decision-making by homeowners. This paper presents the results from a pilot study to generate preliminary knowledge on the key challenges faced in attempting to develop and deploy such a system in remote regions. In the study, the indoor environment and the construction moisture of three new homes from the urban Squamish First Nations reserve in Vancouver are being monitored. The construction is typical of local urban reserve homes. The indoor parameters monitored are relative humidity, temperature, and carbon dioxide. The construction parameters monitored are the envelope moisture content and temperature. Expectedly, preliminary indoor environmental data indicate the houses are performing well. However, warning signals from the construction need close attention. Furthermore, occupants, unaware of the energy penalties, seem to be driving higher ventilation rates. Consequently, validated energy simulation models were used to inform occupants on the price of excessive ventilation habits. Squamish home builders were given a performance report, with alternatives to address current issues and improve performance in future houses. The results from the pilot study demonstrate the value of a holistic monitoring system integral to homes. Further work is required to address the practical aspects of the technologies involved and to elaborate on the knowledge to implement a monitoring platform to make the systems operational on a wider scale.

INTRODUCTION

Aboriginal families are significantly more likely to live in poor housing conditions than the general population, owing to usually lower construction quality, a lack of maintenance, and overcrowded living conditions (National Council on Welfare, 2007). Furthermore, in Canada, most of these houses are often located in colder remote regions. Shortage of skilled workers, unavailability of local building materials and dependence on fossil fuels for heating and electricity in the remote regions, coupled with rising population and shorter building season, challenges the construction, the indoor air quality and the energy consumption. Poor housing is also related to poor child health outcomes including higher infant mortality rates, Sudden Infant Death Syndrome, respiratory deceases (UNICEF 2009), and increase in life threatening infections, injuries, mental illness and chronic illness (National Collaborating Centre for Aboriginal Health, 2010).

This research follows a holistic approach for house health monitoring that attempts to characterize a healthy house from indoor air quality and envelope moisture data, and couple these with house energy consumption data. The overarching goal of this research is to develop a health monitoring system integral to homes. Such a system, as opposed to an ad-hoc temporary one, would be designed, planned, and fine-tuned for the house, just like the electrical system, to keep track of the quality of the house over time. A key part of such a system is the strategic placement of moisture content sensors in the walls to monitor envelope moisture as a function of the dynamically changing indoor and outdoor conditions. Such an integral home monitoring can act as preventive early warning system before problems become serious and sometimes irreversible. The underlying premise in this research is that higher value can be gained from a system that combines different types of monitored data, such as indoor, construction, and energy, in building awareness and enabling better informed decision-making by homeowners and builders. For example, moisture dependent microbiological contamination, in particular, and its health impacts are prevalent in Canadian homes (Lawton et al. 1998); monitored high CO2 levels signaling inadequate ventilation (dilution) cannot detect air borne microbial contaminants from construction moisture (source). Thus, the source of the air quality problem may remain undetected for a long time, and worsen, with serious consequences to the construction and the occupants.

The objective of the paper is to use a pilot study to generate preliminary knowledge on the key challenges faced in attempting to develop and implement such a system. In the study, the indoor environment and the construction moisture of three new homes from the urban Squamish reserve in Vancouver are being monitored. The construction is typical of local urban reserve homes, which do not require stringent home inspections by city officials. The building codes and best practice guidelines (HPO 2011) for coastal climate of British Columbia are not followed strictly; therefore, they are believed to be more vulnerable to durability issues than a conventional home. For example, some use of face-sealed wall assemblies along with the lack of emphasis on interface details e.g. window to wall interface, wall penetrations and balcony-wall interface make these homes vulnerable to water ingress due to wind-driven rain.

In this study, the indoor parameters relative humidity, temperature, and carbon dioxide; and the construction parameters moisture content in walls, attics and crawlspaces are monitored. Note that the paper does not attempt to demonstrate that such a small sample of houses is representative of all Canadian or First Nations' homes, or of homes in remote regions. Instead, it attempts to use a sample of typical new first Nation's homes to test the hypothesis on the need and value, particularly in remote regions, of having a holistic health monitoring system integral to homes.

PREVIOUS WORK

Many of the factors affecting house health performance are interrelated and vary with time. On one hand, various researchers have studied the trade-offs between ventilation and energy performance (Walker and Sherman 2008; Laverge et al. 2011). On the other hand, with regards to the relation between ventilation and the presence of microbiological contaminants, the results are conflicting. While controlled ventilation helps control indoor humidity levels and dilute these contaminants, uncontrolled air leakage, possibly driven by exhaust ventilation, can potentially bring moisture laden contaminants from damp envelope locations, and from out-of-the-envelope crawl spaces and attics. Lawton et al. (1998) monitored a group of houses in southern Ontario, and found that houses with higher levels of microbiological indoor contaminants had, on average, higher leakage-based air change rates. This demonstrates that, occupancy-related, CO_2 is not a good surrogate for construction-related microbial indoor air quality. This paper proposes combining CO_2 data with materials moisture contents and temperature (MC/T) data to produce a more complete assessment of the cleanness of the indoor air and the likelihood of microbial sources.

Associations between persistent dampness and adverse health effects have been acknowledged. However, relationships between persistent dampness, microbial exposure, and health effects cannot be quantified precisely at the moment (WHO 2009). As a consequence, no quantitative health-based exposure guideline or thresholds are recommended for acceptable levels of microbial contamination (IOM 2004). In light of this, ASHRAE (2012) and AIHA (2013) recommend keeping buildings and their systems as dry as possible, given their normal functions, to limit the potential for microbial growth and reduce dampness-related health risks. The moisture content (MC) of materials is the key parameter for assessing the risk of microbial growth on their surfaces; however, its extreme spatial variation over short distances (a few centimeters), and its dependence on the materials and the quality of the construction, limit its applicability as a universal indicator of dampness risk (ASHRAE 2012). Nevertheless, a premise of this project is that from the type of construction and building location, experts can identify the hidden envelope areas, surfaces, and materials that are more likely exposed and vulnerable to dampness. Such knowledge can then be used to lay out a dampness-warning MC sensor system. Building on this premise, this paper proposes a more holistic assessment of residential performance that combines monitored data from: the indoor environment, the construction, the occupants' behaviors, and the energy system to provide a more informed view of the residential performance for occupants, builders, and possibly to policy makers. To the authors' knowledge no such holistic approach has been proposed in the past.

METHODOLOGY

Three new houses were made available for our pilot study by the Squamish First Nations band in agreement with the homeowners. The houses are typical 2-storey, wood-frame construction single houses identified as house#1 [2,500 ft^2 (232 m^2)], house#2 [2,000 ft^2(186m^2)], and house#3 [1,800 ft2 (167m^2)] with ventilated attic, conditioned crawl space and a combined forced air heating/ventilation system with outdoor air intake at the return side. Research methodology includes:

4 Sensing system layout planning and instrumentation – The houses were instrumented with a wireless remote sensing system. A weather station was also placed on the roof of the nearby community center.

5 Testing, measuring, and questionnaires - Air tightness tests were conducted in the houses, as well as air flow measurements at the supply and return grilles of the forced air system. Information on house operation was obtained by an administered occupant-questionnaire and by direct inspection on our regular site visits.

6 Monitoring – The houses will be monitored for one year starting in September of 2012 when occupancy started. So far, nine months of data have been collected (up to May 2013).

7 Energy modeling& Analysis – An energy model was created and fine-tuned with air tightness tests, air flow measurements at the forced air system's supply and return grilles, and questionnaires to occupants. The model was validated by comparing simulated energy use with utility bills data, and using readings on the air handling unit on/off operation. The validated energy model was then used to assess the impact of the occupants' behaviours on energy performance, and to compare the energy and indoor air quality performance of the current heating/ventilation system with other potentially better systems.

8 Integrated assessment of the results – The value of a health monitoring system was evaluated in terms of its capability to provide data that can be used to assess holistically the health of the house during its service life.

THE MONITORING SYSTEM

A distributed data acquisition system was used with battery-powered data loggers deployed in strategic locations to acquire data from cabled nearby groups of sensors. Sensors were deployed in groups of 8 or less in order to minimize sensor cabling and number of data loggers used (each data logger support 8 channels of either resistance or voltage inputs). The data loggers transmit the data wirelessly to a central gateway computer placed in house#3, which, in turn, uses Internet to transmit data to a central platform combining a repository and analytical tools.

In each home, a relative humidity and temperature (RH/T) sensor was located in the family area, attic and the crawl space. A CO2 sensor was also placed in the family area and master bedroom. Moisture content (MC) sensors were placed in selected areas of the following locations: the underside of the roof sheathing; the walls underneath the windows, particularly close to the corners and the bottom plate; the envelope bathroom walls; and the floor joists at the crawl space. The majority of the MC wall sensors were placed on north facing walls, because these walls have the lowest drying potential. One ON/OFF switch type sensor was placed in the air handling unit in one house.

RESULTS: ANALYSIS AND DISCUSSION

This section presents selected monitoring data from the pilot study. The data has not been statistically processed because it has no statistical meaning given the size of the sample. Furthermore, this study does not claim that these houses are representative of houses in remote cold regions. The premise that these houses have typical problems, given the climate; quality and the type of construction; and that the occupants play a role in exacerbating these and sometimes even causing more problems, these houses provide a good experimental setting for challenging the proposed sensing system, with challenges that can be generalized to houses in remote regions.

Monitoring results

The houses have been monitored for nine months so far, from September of 2012 to May of 2013. However, in order to better appreciate the patterns on the data, this section presents monitoring data from the last five months (January to May, 2013),with emphasis on winter months (Jan-March) which are most critical from indoor air quality, energy, and durability points of view. It should be noted that in house#3 the owner is a heavy smoker that spends most of the time in the house carving wood. Unfortunately, in that house the CO2 sensor went out of calibration. After several unsuccessful attempts to fix the sensor the homeowner got frustrated; this forced us to decommission the sensor.

Figures 1 and 2 present weather station data with typical values for a moderate marine climate; in Figure 1 the relative humidity remains high and tends to follow an inverse relation with the temperature. In Figure 2, the solar radiation is low and the rain is not as intense as expected for this period of the year.

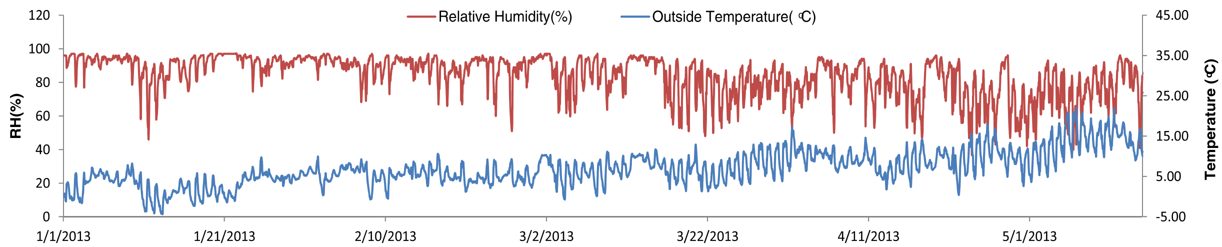

Figure 1 Hourly averaged outdoor temperature and relative humidity.

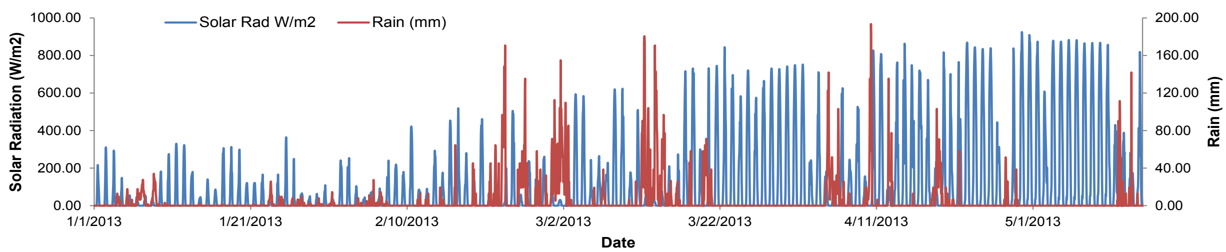

Figure 2 Hourly rainfall and solar radiation.

In general, the houses have good ventilation with uniform CO2 levels(excluding the house with the decommissioned CO2 sensor). Peaks of CO2 between 1400-1800 ppm were observedduring night-time in bedrooms and higher occupancy periods in common areas. These high levels of CO2 can cause discomfort (body odor) and impaired performance in occupants (Persily A K 1996). Figure 3 takes a closer look at indoor CO2, temperature and relative humidity (RH) for months of March and April in house#1. In this case, as confirmed with a questionnaire, as the weather got milder, the occupants opened the windows whenever they felt they wanted "fresh air". This is reflected in the low readings, sometimes below 600 ppm. The patterns are similarly observed in the relative humidity and temperature readings.

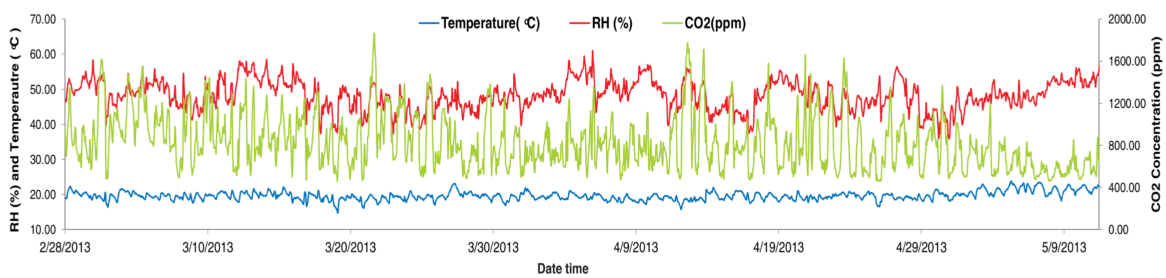

Figure 3 Hourly CO2, temperature and RH in master bedroom of house#1.

Figure 4 shows the temperature and relative humidity in the heated and ventilated crawl space in house #2. In this case a longer period was selected (October/2012 to May/2013) to appreciate the drying out foundation moisture in winter. The temperature fluctuates more in crawlspace than in the rest of the house because it is unoccupied and has no thermostat control. At first sight the crawl space appears to be performing well. Infrared temperature readings at the foundation walls show wall temperatures ranging between 51.8°F (11°C) (close to the corners) and 59°F (15°C), which are close to the dew point of the indoor air. Therefore, potential for moisture condensation in these walls exists.

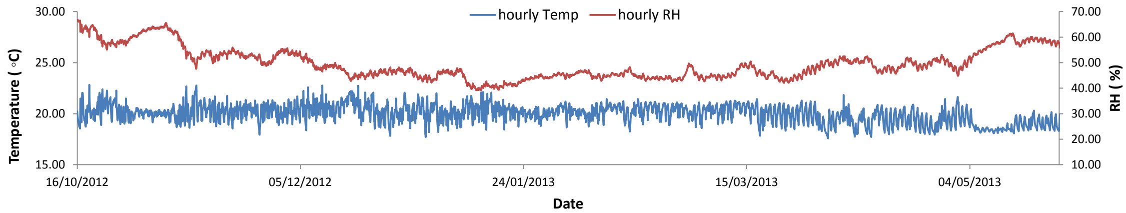

Figure 4 Hourly temperature and relative humidity in crawlspace of house #2.

In Figure 5, the attic air is saturated with moisture during the months of December, January, and February and close to saturation in October, November, and March. This is confirmed with the moisture content (MC) data at the underside of the roof sheathing. Note that the attic is not part of the envelope. However, it is connected unintentionally through cracks, with noticeable air flows during the blower door test. Even though the MC readings show a seasonal wetting and subsequent drying during the warmer seasons, the wetting period is long and maintains MC above acceptable levels between November and March. Comparing Figure 5 with Figures 1 and 2, it can be appreciated that more sun and higher temperatures are driving moisture evaporation from the roof sheathing.

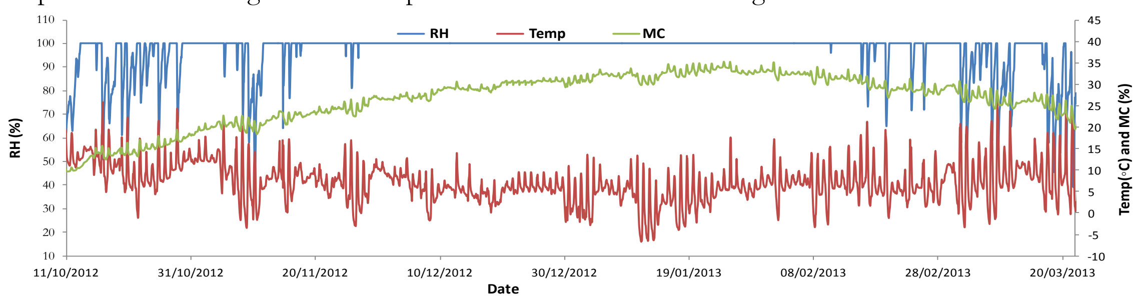

Figure 5 Hourly temperature, RH, and Moisture Content in the Attic of house#1.

Figure 6 shows the MC at selected representative wall locations. The Figure shows that the MC has been maintained relatively stable up until the beginning of March, when drying is observed. However, in all cases except for the south wall, the MC is higher than the 28% limit for fungal germination, and 19% limit for fungal growth; in the east wall the MC is above the 35% limit for fungal spores flourishing and growth (HPO 2011).

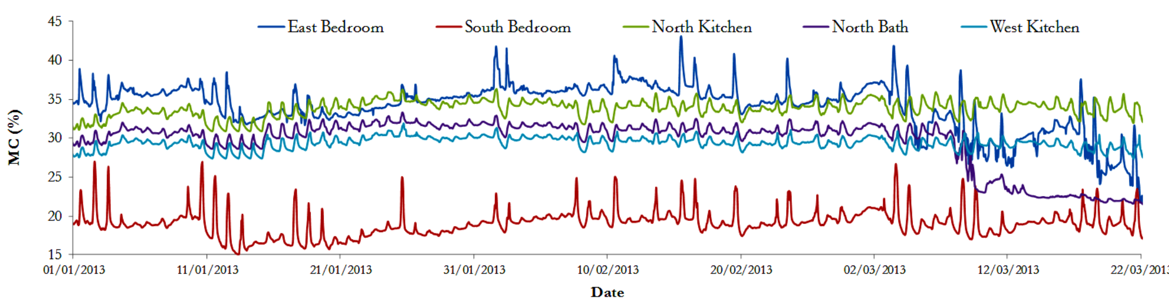

Figure 2 Hourly MC on various elevations.

Sensor data was cross-validated using additional sensors whenever possible. Figure 7 shows the comparison of CO2 concentrations in the kitchen of House#1 from two different kinds of sensors (Sensor #1: Telaire 7000 CO2 sensor; Sensor #2: Cozir-A CO2 sensor (2000ppm)). It should be noted that these sensors were placed at different heights on the wall. Both sensors showed similar variations in CO2 values, but sensor#1 installed at lower height showed higher values as expected (since the CO2 is heavier than air, it tends to have higher concentrations at lower levels).

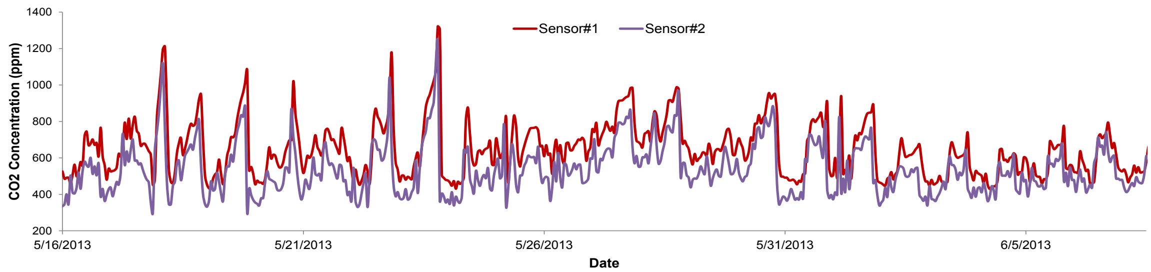

Figure 7 Comparison of two CO2 sensors for validation

IAQ-Energy Analysis

An energy model was created for house#1. The model was calibrated with blower door and air flow measurements at the outdoor air intake, the air supply grilles, and the returns of the forced air system, and with the use of a questionnaire to the occupants. Due to space constraints, details of the modeling are not given in this paper. Figure 8 shows the validation of the model that compares the simulated energy consumption with the actual consumption, obtained from utility bills.

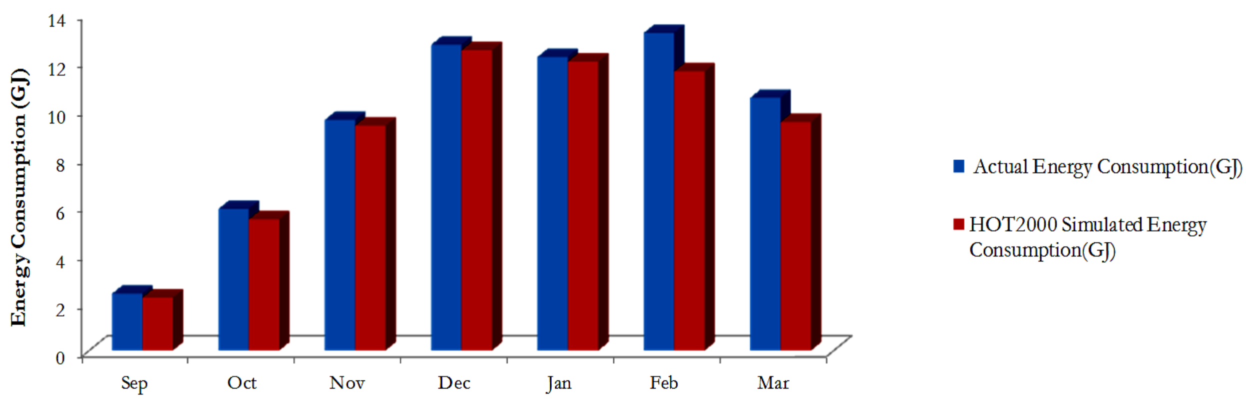

Figure 8 Comparison of simulated vs. actual energy consumption.

The energy model predicted that the house will consume 78.9GJ (22.1MWh) of energy annually. 70% of this energy will be consumed for space and domestic hot water heating (Figure 9) and one fourth of the total heat losses will be due to ventilation which included both air infiltration and mechanical ventilation.

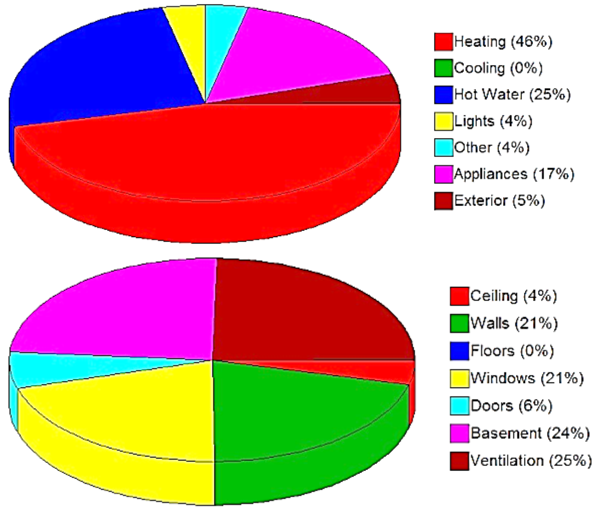

Figure 9 Components of annual energy consumption (left) and components of annual heat loss (right).

Three ventilation systems were evaluated to provide the required air change rate for the whole house (ASHRAE 2010): Continuous central exhaust fan, continuous supply fan, and dedicated HRV (Heat Recovery Ventilator). Figure 10 shows the comparison of annual energy consumption and ventilation heat losses (%) in above simulated systems.

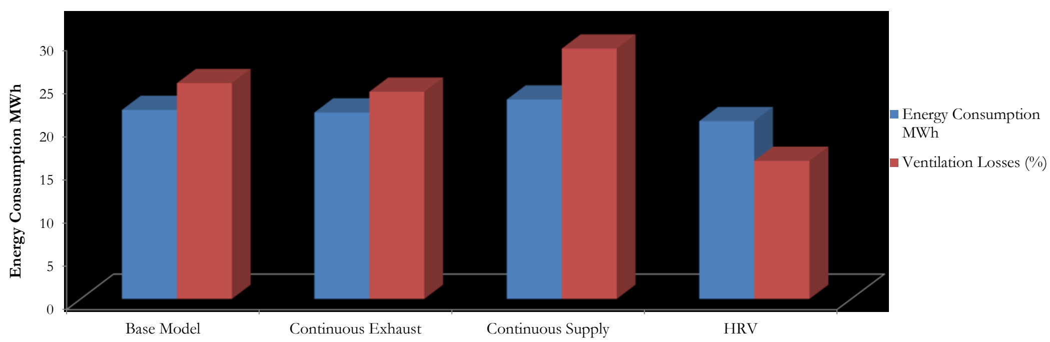

Figure 10 Comparison of different ventilation systems.

Simulations show that HRV ventilation system is the most economical one, while supplying balanced uniform air distribution to the house. Exhaust ventilation is considered more adequate for cold climates than supply ventilation. For the marine climate of Vancouver any of the options above would work from a durability point of view. However, window opening by the occupants would override any ventilation system operation assumption.

Integrated analysis of the results from the pilot study

Overall, the houses seem to be performing well and there is no sign for alarm to the owners or the builder. The indoor environmental data (CO2, RH/T) indicate that the houses have good ventilation (CO2) in general. Instances of higher values of CO2 could be related to increased occupancy which could result in occupant discomfort. RH/T data show no signs of risk for microbial air borne contamination due to excessive moisture. In house#1, CO2 and RH/T sensors give clear indication that the owners in one house are opening the windows at times when is not convenient from an energy point of view. The energy penalty can be calculated and is appreciated in Figure 8. The sensors in the crawl spaces suggest that foundation moisture is drying out and these seem to be performing well. Additional sensors at the corners of the foundation walls would help find out if there is a risk for moisture condensation at these locations. The attic needs close attention because the moisture levels are high and sustained for a long period. A preventive solution needs to be devised such as sealing the ceiling cracks and possibly improving the attic ventilation. Similarly, the moisture content of certain walls needs close attention. An engineering assessment would need to be conducted if higher values persist. A breakdown of the results from the energy simulation, cross-validated continuously with utility data (e.g. Figure 9) give feedback to the occupants on the items they can control to reduce energy consumption. For example, knowing the energy impacts from opening windows may lead the homeowners change that habit, particularly when reasonable CO2 levels are sensed.

CONCEPTUAL ARCHITECTURE OF THE HEALTH MONITORING SYSTEM INTEGRAL TO HOMES

Figure 11 illustrates the components of a ***Health Monitoring System*** integral to homes, created using the knowledge gained from the pilot study. The system consists of two components that provide feedback to the Occupants and learn from the behaviors. (1) ***The Sensory System*** that includes indoor environment, energy, and envelope sensors. And (2) ***The Reasoning System*** with three engines: the *Occupants Behaviors Inference Engine*, that infers occupants' behaviors from sensory data; The *Building Performance Inference Engine*, that infers performance as indicated in Figure 10; and the *Learning Engine*, that learns from occupants' changing behaviors, from the sensory data, and from actual energy performance data obtained from the Smart Meter (if one is installed). The dotted lines indicate feedback from the ***Health Monitoring System*** to the occupants; and from the occupants and the smart meter to the *Learning Engine*.The goal of the reasoning system is to infer occupants' behaviors and house performance from a limited number of sensors, and give feedback to occupants so that they can change behaviors, adapt, and take control of the house performance. Thus, through sensing, reasoning, and feedback to occupants the need for a complex and expensive electromechanical control system can be avoided, perhaps leaving automated source control only for kitchen and bathroom exhaust fans.

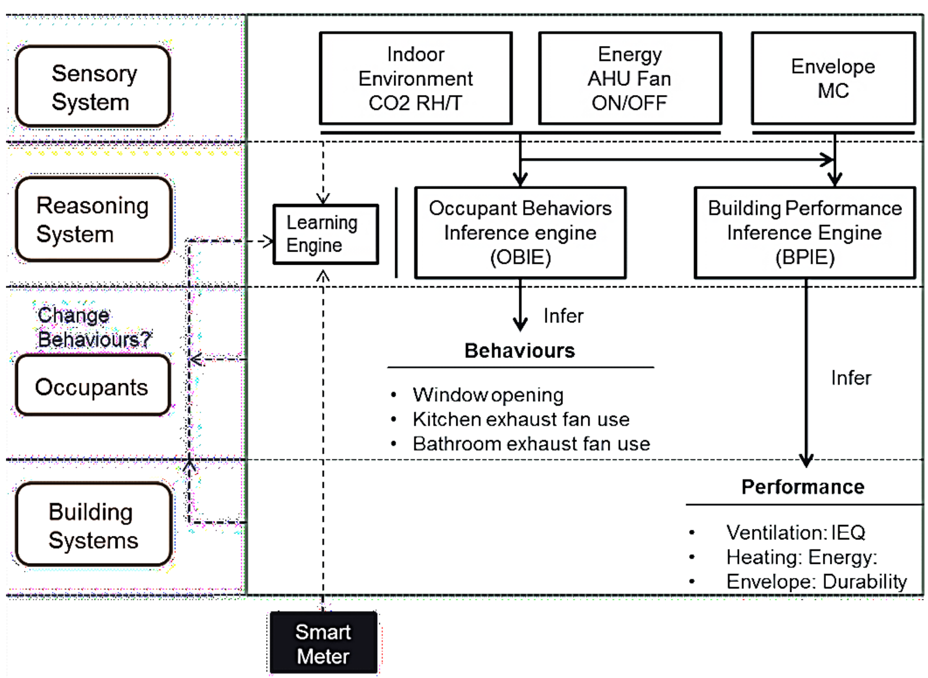

Figure 11 Conceptual Architecture of the Health Monitoring System Integral to Homes.

The ***Health Monitoring System*** is building science knowledge/principlesbased. This knowledge needs to be managed stochastically given the many uncertainties and dynamic nature of the boundary conditions. The system would be designed, fine-tuned and commissioned for each particular typology of houses, heating and ventilation system, and boundary conditions. The reasoning algorithms would be calibrated by memorizing characteristics of time-series generated sensor data during the learning phase, where the house is assumed to behave normally. This phase would subsequently help identify anomalous behaviors. It is envisioned that once operational, the system would learn from experience and fine-tune itself. An unexpected challenge from this project was having an occupant who is heavy smoker and carves wood in his house. Given that smoke produces CO2, the authors thought that CO2 could be a good surrogate for the presence of smoke. However, apparently, the combination of gases and fine particulate matter from tobacco smoke affected the CO2 sensor readings.This needs to be confirmed. Even with the advent of more sophisticated sensors, such as VOC sensors, the authors believe that a residential ***Health Monitoring System*** needs to be kept as simple as possible, and cannot be meant to prevent health risks that are more conveniently handled through source control. It is for the sake of simplicity, that the ***Reasoning System*** is proposed, i.e. to eliminate the need for an unnecessary number of sensors.

CONCLUSIONS, LIMITATIONS AND FURTHER WORK

The pilot project demonstrates the value of a well-planned and deployed remote sensing system integral to homes to provide holistic feedback to homeowners and builders on durability, indoor air quality and energy efficiency, so that they can manage their homes more proactively. This system can provide valuable information for improvements in construction and mechanical systems in future homes. This study emphasize that occupant's behavior can have a significant impact and is critical for the design of any resilient residential indoor environmental system.Higher need for such a system would be felt from communities in remote regions where the conditions are harsher and professional help is scarcer. This paper presents the initial steps in the development of an integral remote sensing system. The challenges are great, particularly in the sensor technology development, power and maintenance requirements, and cost. These challenges were not explored in this paper. However, the technologies are advancing fast and hopefully they will become widely available soon. In the meantime, the pilot study is still in progress and will be used to help elaborate on the knowledge and reasoning components of the remote sensing system. The pilot study will be expanded further on statistically representative sample of houses. Partnerships with the manufacturers and researchers will be established to test alternative heating and ventilation technologies; and develop intelligent sensing systems and control algorithms.

ACKNOWLEDGEMENTS

The authors are grateful to the British Columbia Institute of Technology (BCIT) as well as the BC Homeowner Protection Office (HPO) for funding this research project and making it possible. The authors also wish to express appreciation to the Squamish community for their logistic support and particularly to the homeowners for giving us access to their homes.

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Manuscript 2

INDOOR AIR QUALITY AND ENVELOPE MONITORING OF FIRST NATION HOMES ON AN URBAN RESERVE: A PILOT STUDY

ABSTRACT

First Nations Communities have higher risk of respiratory disorders due to environmental tobacco smoke, overcrowding and substandard housing. Limited information is available on the performance of First Nation homes and there is a need to monitor the indoor environment and building envelope performance. The overarching goal of this pilot study is to gain knowledge on the indoor air quality, durability and energy efficiency of selected homes on an urban reserve, under the typical marine boundary conditions of British Columbia, and use this knowledge to recommend performance improvements in future homes on the reserve. A related goal was to gain preliminary knowledge on the impact of occupants on the performance of the houses. For this study, a permanent real-time remote sensing and monitoring system was installed in three homes on the reserve and the indoor, envelope and outdoor weather conditions were monitored for one year. The monitored data was analyzed to identify environmental loads and to infer knowledge by correlating data from multiple sensors. The emphasis was to identify indoor humidity, temperature and air quality patterns in relation to occupancy and weather; envelope moisture performance in relation to indoor and outdoor conditions; indoor humidity and air quality thresholds based on effects on people and construction; and weather effects on indoor conditions. Indoor environment and envelope data indicate the houses are performing well. However, building envelope leakage and occupants, unaware of the energy penalties, are driving higher ventilation rates, hence, compromising the energy efficiency. Conclusions from the pilot study emphasized the need to make these homes air tight for improvements in energy consumption and consequently, install a dedicated mechanical ventilation system to maintain indoor air quality in the renewed air tight enclosure. This project is the first step towards developing data and knowledge for characterization of the homes on the reserve using real time health monitoring integral to homes. Further work will include monitoring larger group of houses, more representatives of remote aboriginal communities.

INTRODUCTION

First Nations Communities have higher risk of respiratory disorders (Evers et al. 1985; Harris et al. 1998; Sin et al. 2004) due to environmental tobacco smoke, overcrowding and substandard housing (Kovesi 2006, Clark et. al. 2002). Recently, efforts have been made to identify exposure pathways to environmental contaminants among First Nation Communities in Canada (AFN 2011, FNFNES 2011). However, indoor contaminants, which are the major source of exposure, given that people spend most of their time indoors, were not included as potential sources in these studies. Limited information is available on the performance of First Nation homes in the literature and there is a need to monitor the indoor environment and building envelope performance.

This pilot study aimed to gain knowledge on the indoor air quality, durability and energy efficiency of homes on a Squamish Nation reserve in West Vancouver, British Columbia (BC). The marine climate of BC, with long wetting and shorter drying periods, challenges the building envelope resiliency; and wind driven rain is the major factor in building envelope failures. Construction of homes on this urban First Nation reserve is typical of conventional homes, but due to Construction of homes on this reserve is typical of conventional homes, but due to absence of stringent inspections from city officials, these homes are believed to be more vulnerable to outdoor weather conditions. The focus of this paper is on the building envelope performance and indoor air quality. The premise that occupant behavior and lifestyle influences indoor air quality and is the major driving factor in energy consumption in a home, the study also aims to gain the preliminary knowledge on the impact of occupants on the performance of houses on the reserve.

For this research, a permanent real-time remote sensing and monitoring system was installed in three homes on the reserve and the indoor, envelope and outdoor weather conditions were monitored for one year (For detailed description of monitoring system and characteristics of the homes, readers are advised to refer Atwal et. al. 2013). The indoor parameters: relative humidity, temperature, and carbon dioxide; and the construction parameters: moisture content (MC) in walls, attics and crawlspaces were monitored. It should be noted that this study does not attempt to characterize First Nation Homes based on a small sample of homes; instead it aims to use permanent monitoring system integral to homes to identify predominant environmental loads in these houses and infer knowledge by correlating data from multiple sensors. The knowledge gained from the study will be used to recommend performance improvements in both existing and future homes on the reserve.

BACKGROUND

A house is a system and its performance depends on many interrelated factors which vary with time. Structural integrity and durability, indoor air quality and energy efficiency of a house depends on dynamic indoor and outdoor conditions, construction, mechanical systems and occupant behaviors. Recently many studies have focused on the effects of occupant behavior on energy performance (Peng et.al. 2012, Santin et.al. 2011, Fabi et. al 2012) and efforts have been made to include occupant behavior as an integrated part of energy simulations (Clevenger et. al. 2006). Apart from energy performance, occupant behavior and habits also have a profound impact on indoor air quality. This paper proposes the use of a holistic monitoring system to simultaneously study the envelope, indoor air quality and energy performance of the house, with the focus on occupant behavior and lifestyle.

METHODOLOGY

Three new homes were selected for the pilot study after consultations with the Squamish First Nation band in agreement with the homeowners. The research methodology includes:

- **Monitoring:** The houses were instrumented with a permanent real-time monitoring program designed to monitor in-situ performance of the exterior wall assemblies and interior environmental conditions for one year (Atwal et. al. 2013).

- **Testing, Survey and Questionnaire**: Blower door tests were conducted to characterize air tightness of the house; and air flows were measured at the supply and return grilles of the forced air heating system. Supplementary questionnaires and onsite inspections were conducted to capture occupancy loads, lifestyle and uses of the house.
- **Energy modeling and analysis**: An energy model was created and fine-tuned with air tightness tests, air flow measurements and questionnaires to occupants. The model was validated by comparing simulated energy use with utility bills data, and using readings on the air handling unit on/off operation. The validated energy model was then used to assess the impact of construction, and occupants' behaviors on energy performance.
- **Data Analysis:** The monitored data was analyzed to identify environmental loads and infer knowledge by correlating data from multiple sensors.

RESULTS: ANALYSIS AND DISCUSSION

This section presents data analysis from the pilot study. The data has not been statistically processed as it has no statistical meaning given the size of the sample. The premise that these houses are prone to durability and indoor air quality issues, given the climate; quality and type of construction; and that the occupants play an important role in exacerbating these, the houses provide a good experimental setting for identifying indoor humidity, temperature and air quality patterns in relation to occupancy and weather; envelope moisture performance, and weather effects on indoor conditions.

Following sub-sections will discuss the monitoring results based on envelope, indoor air quality and energy performance. The houses were monitored for one year, from September 2012 to October 2013. However, in order to better appreciate the patterns on the data, this section will emphasize on winter months which are the most critical from durability, indoor air quality and energy points of view. Figure 1 shows the weather station data, representing temperature and relative humidity distribution, on the reserve during monitoring period. As expected, the distribution shows a relatively moderate climate, with a significant portion of the year at high relative humidity, between temperatures 0˚C and 11˚C.

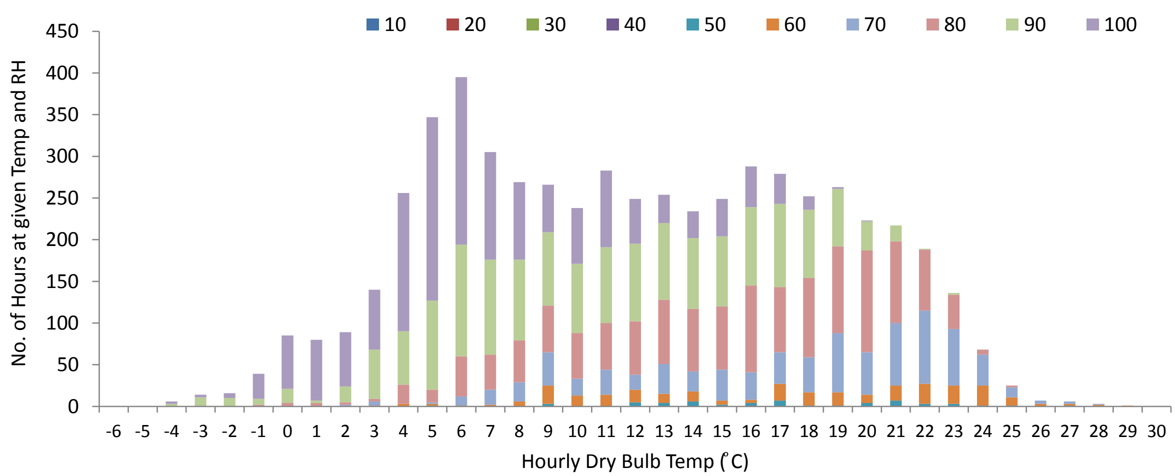

FIGURE 1: Outdoor Temperature and Relative Humidity Distribution at the reserve

The wind driven rain rose for the reserve location as shown in the Figure 2 shows that the direction of wind driven rain is predominantly from the South. The majority of the rain occurred from September to March months; whereas the summer months were comparatively dry. It is important to mention that during the monitored year, the Lower Mainland region experienced less precipitation than normal.

Envelope Performance

Moisture Content (MC) in the plywood sheathing was considered the primary performance measure for building envelope durability in this study. The moisture content/temperature sensors were installed strategically on the critical locations like the underside of the roof sheathing; the walls underneath the windows, particularly close to the corners and the bottom plate; the envelope bathroom walls; and the floor joists at the crawl space.

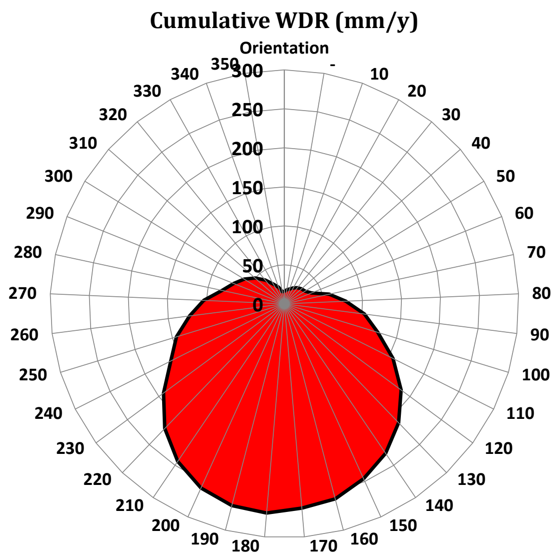

FIGURE 2: Wind driven rain rose

Overall, these sensors did not show correlation between moisture fluctuations and rainwater leakage into the wall cavity, except at few locations discussed later in this section. MC rather followed the exterior temperature and humidity, solar radiation and building orientation. For instance, Figure 3 presents the sheathing MC levels on different wall orientations, with the corresponding outdoor temperature, relative humidity and rain periods for a selected period (Jan-March). These locations clearly do not indicate sudden peaks in MC levels expected due to rain water penetration.

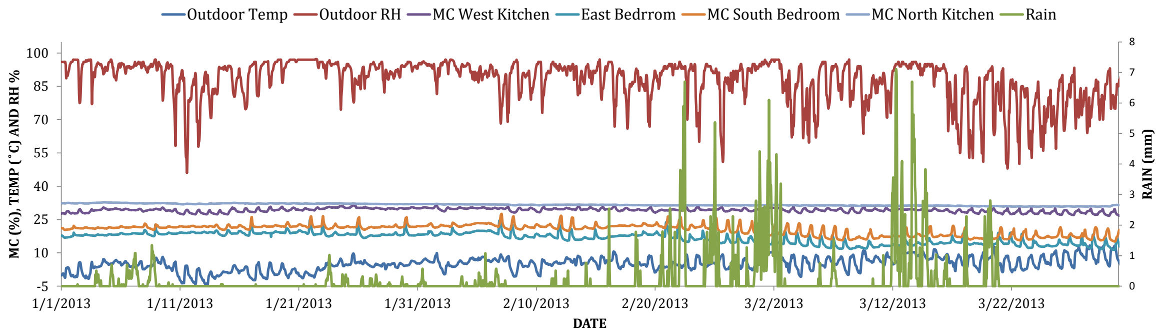

FIGURE 3: Measured sheathing moisture content at different orientations in comparison with outdoor RH and rain periods

Over the monitoring period, as shown in Figure 4, sheathing MC levels at all orientations, except south facing walls, were higher than industry-recognized threshold levels of 19% during winter, which, eventually dried in warmer months. South-facing walls with direct solar exposure had dryer sheathings; whereas North and West elevations took longer time to dry due to limited sun exposure on North and presence of large trees on the west side of the house respectively. The MC levels were as high as 35% at some locations in winter months, but the durability risks due to fungi decay propagation were not established as the temperatures were not favorable for fungi growth (between 10-35˚C).

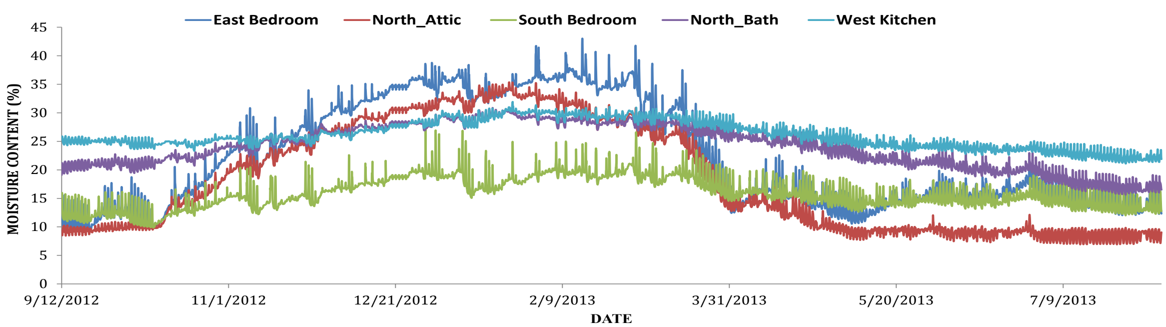

FIGURE 4: Sheathing Moisture content on all four orientations

Figure 4 shows that the MC level under the window on the east-side wall of the bedroom is exceptionally high (>35%) between Jan-March months. These high MC levels correlated with wind driven rain mostly from South/South-East directions. Thus, it is assumed that rain penetration occurred at the window edges. Moreover, this location is near the change of planes in the building envelope, where gable meets the wall. There is a possibility that the rain water penetrated through this interface. It should be noted that as the weather changed, MC levels decreased rapidly due to sufficient sun exposure at East elevations. Two other sensor locations: North wall in the kitchen and dining room of the house#2 showed exceptionally high MC levels as shown in Figure 5. It peaked to 37% and sustained at more than 30% for the whole winter season.

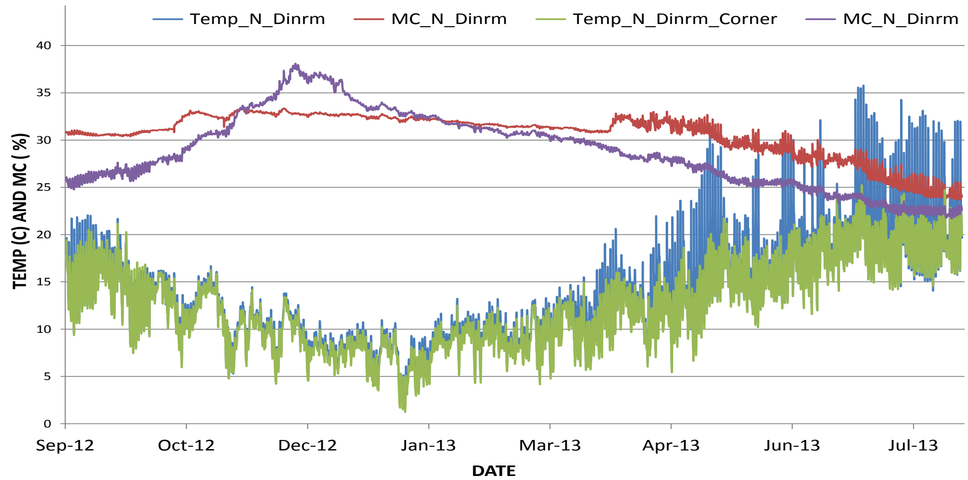

FIGURE 5: Sheathing MC Variations and temperature at North elevation under the window

Attic

All the three houses have ventilated attics, thus outdoor air is the main source of moisture. Also, in wet coastal climates, attic ventilation is responsible for higher sheathing MCs (Forest T.W. et. al. 2002). The attic air in these houses was saturated with moisture during the months of December, January, and February and close to saturation in October, November, and March as shown in Figure 6. Roof sheathing showed a seasonal wetting and drying trend. But, the wetting period was long and maintained MC above acceptable levels between November and March.

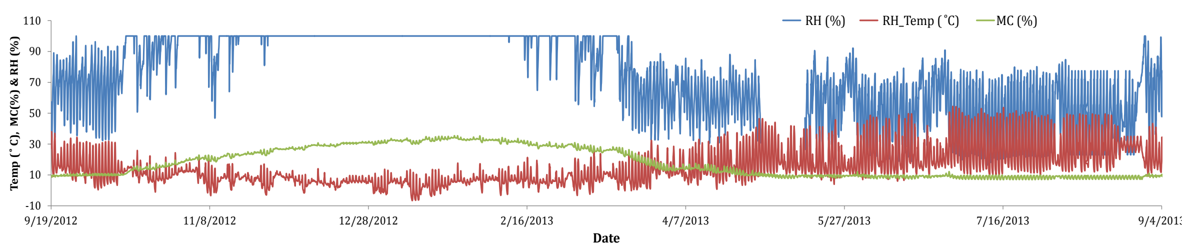

FIGURE 6: Hourly temperature, RH, and Moisture Content (roof sheathing) in the Attic

Condensation risks were evident on the roof sheathing when dew point of the attic air was compared to the sheathing temperature between January and March months. Figure 7 shows the selected periods in January, when roof sheathing temperatures were less than the dew point of attic air. The attic condensation can decrease the effectiveness of insulation over time; and can cause significant damage to structural elements in the attic such as rafters or trusses.

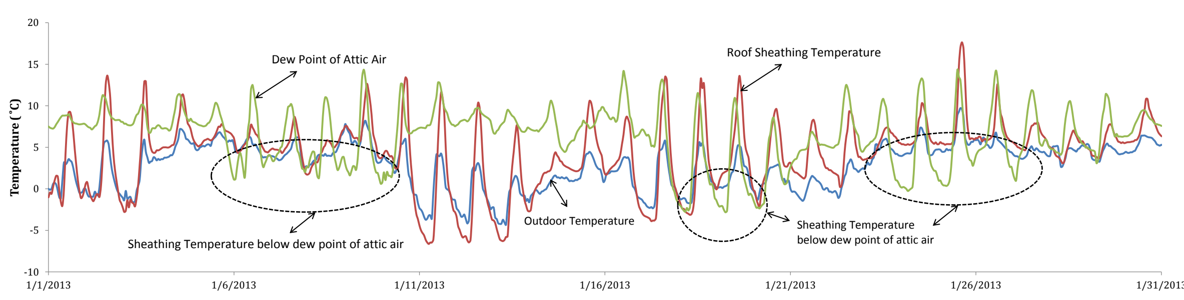

FIGURE 7: Hourly attic air dew point, sheathing temperature and outdoor air temperature

Crawlspace

Figure 8 shows the air temperature and relative humidity in the heated crawlspaces in two houses. Forced air heating dried the initial construction moisture in winter and maintained relative humidity levels within acceptable levels. But, infrared temperature readings at the foundation walls showed wall temperatures ranging between 51.8°F (11°C) (close to the corners) and 59°F (15°C), which were close to the dew point of the indoor air. Therefore, potential for moisture condensation in these walls exists. In late summer and early fall months, the RH reached 75% but eventually came down to 60-65% range in winter when the forced air heating system started working.

Indoor Air Quality

The indoor temperature, relative humidity and CO_2 levels were considered the performance measures for the indoor air quality in this study. Monitored data indicated that the indoor moisture levels in all three houses were mostly within acceptable limits and the temperature was maintained between 20-22°C. Figure 9 shows the indoor temperature and relative humidity variations in the House#3. Overall the RH levels were within comfortable limits (30-60%) for the occupants and did not risk microbial air borne contamination. Although few short periods of very low humidity (<30%) were noticed in January, when the outdoor temperatures were the lowest. As weather got warmer, occupants opened windows. As a result, the indoor thermal conditions varied with outdoor temperature, and relative humidity peaked up to 75% in the summer months.

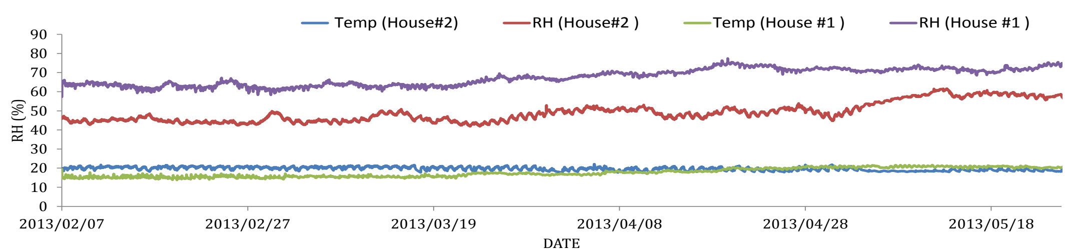

FIGURE 8: Hourly temperature and RH in crawlspaces of two houses

Forced air heating systems in the houses performed well in maintaining uniform air temperature, RH and CO_2 levels throughout the houses. Figure 10 shows the hourly indoor temperature variations at different locations in house #1. In winter, temperature was independent of the outdoor conditions and was maintained at a set point (20-22°C) around the house, while in summer, the gap between indoor and outdoor temperatures was reduced.

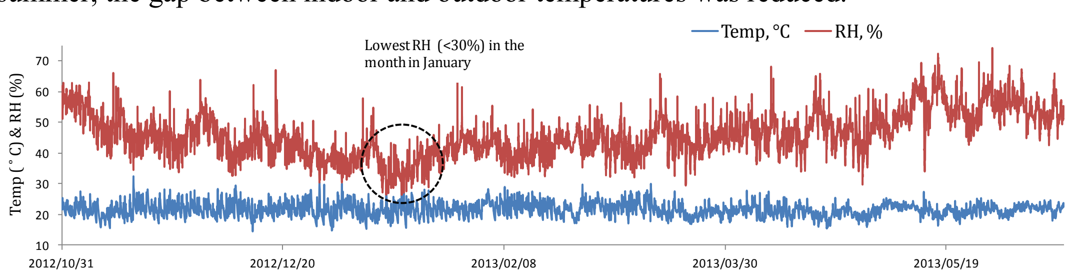

FIGURE 9: Measured indoor temperature and relative humidity in house #3

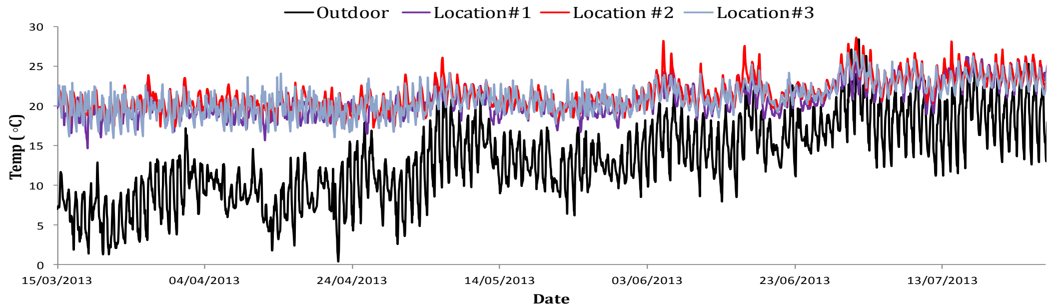

FIGURE 10: Hourly variations in temperature at different locations in House#2, as compared to outdoor temperature

Figure 11 shows the relative humidity measured at three locations in House#1. Location #3 (a ground level kitchen) measured higher RH values consistently than upper level locations (#1 & #2). It should be noted that an occupant, a retiree, stay at home most of the time and live in the lower portion of the house. Homeowner questionnaire indicated that this occupant felt cold and kept most of the windows closed throughout the year.

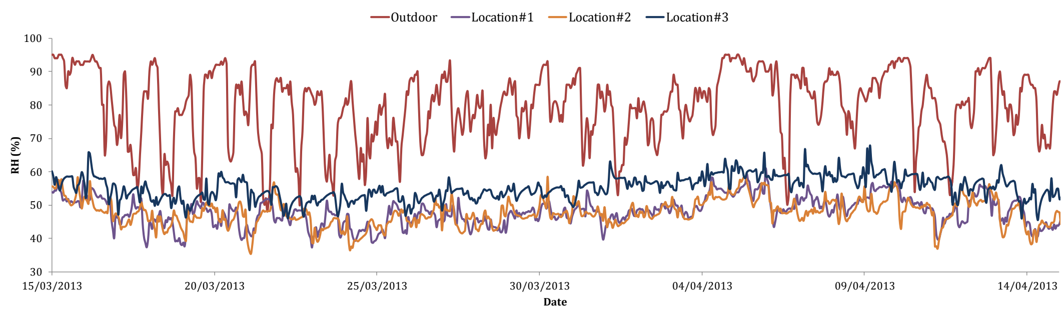

FIGURE 11: Measure relative humidity at different locations in House#1

Relative humidity as well as CO2 levels in upper level kitchen (location #1) and master bedroom (location #2) showed patterns in relation to occupant behavior and lifestyle. Occupant questionnaire indicated the cooking schedule is mostly in the mornings (between 6am-8am) and evenings (between 5pm-8pm). The house has five adult occupants. Four occupants leave house between 8:00-9:00am in the morning and return in the evening after 5:00 pm, whereas an older occupant lived at lower level as mentioned above.

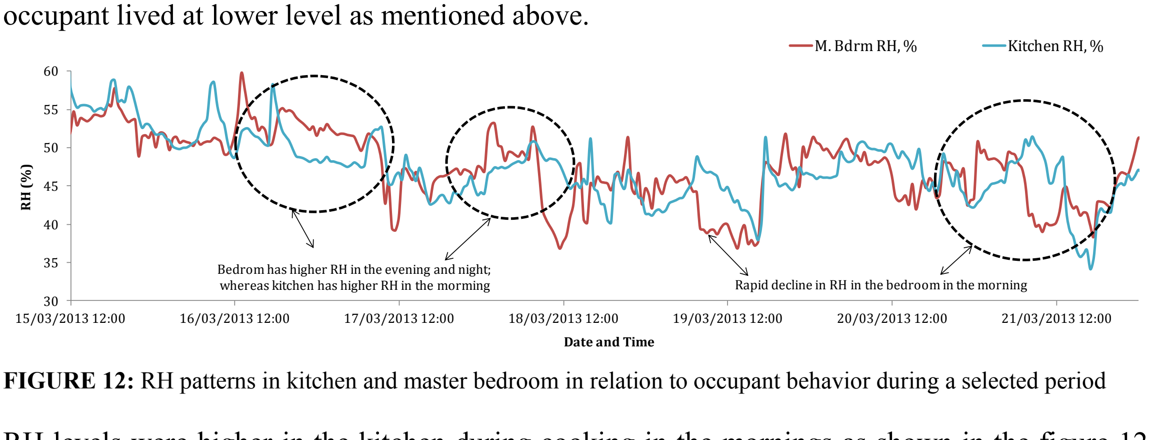

FIGURE 12: RH patterns in kitchen and master bedroom in relation to occupant behavior during a selected period

RH levels were higher in the kitchen during cooking in the mornings as shown in the figure 12, whereas these levels were comparatively higher in the master bedroom during night. Occupant's habit of keeping the bedroom window slightly opened before leaving the house in the morning caused RH levels to decline rapidly in the master bedroom as shown in the figure above.

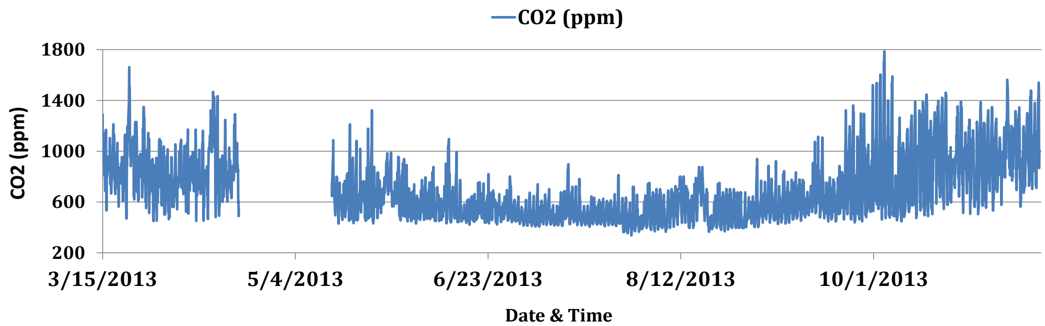

FIGURE 13: CO2 Concentrations in House #1

Figure 13 shows the CO_2 concentration in the house#1. The data is missing for the month of April as the sensor needed to be re-calibrated. The CO_2 levels were above 1200ppm in the fall season (end of September-November); higher than ASHRAE recommended level of 1000ppm for acceptable indoor quality. Peak concentrations between 1400-1800ppm were observed during night-time in bedrooms and higher occupancy periods in kitchen and common areas.

Figure 14 and 15 shows the CO_2 patterns in relation to occupancy and occupant behaviors. The concentrations were highest in the night in master bedroom which declined much faster during weekdays than in the weekends, as occupants spend more time in the bedrooms during weekends.

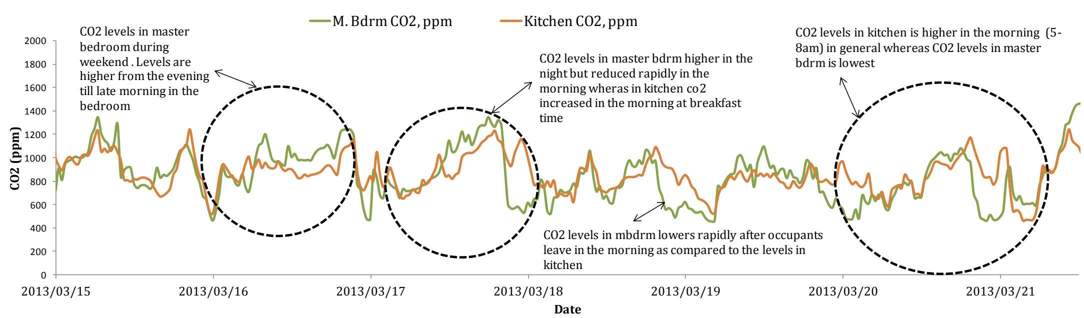

FIGURE 14: CO_2 patterns in kitchen and master bedroom in House#1 in relation to occupancy

Similarly, peak CO_2 levels were observed in the kitchen in the mornings during weekdays. Figure 15 shows RH and CO_2 variations during milder weather (May month). As confirmed with a questionnaire, occupants opened windows frequently which are reflected in low readings, sometimes below 600ppm. The peak concentrations were measured during mornings between 5-8 am.

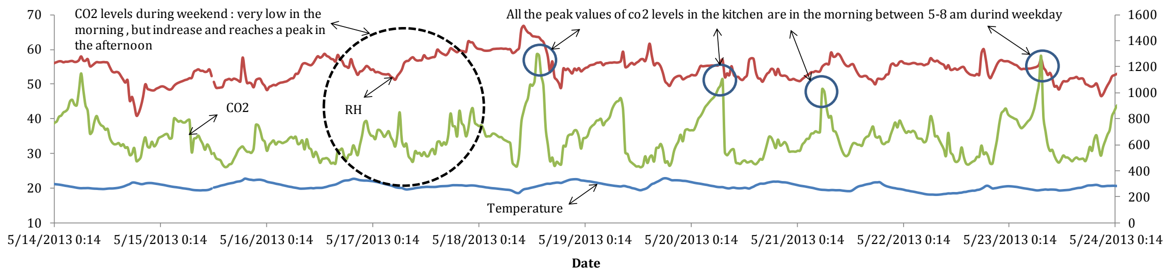

FIGURE 15: CO_2 and relative humidity patterns in kitchen in relation to occupancy and occupant behavior

Energy Performance

An energy model was created for house#1. The model was calibrated with blower door and air flow measurements at the outdoor air intake, the air supply grilles, and the returns of the forced air system, and with the use of a questionnaire to the occupants. The model was then validated by comparing simulated energy consumption with the actual consumption, obtained from utility bills. Due to space constraints, details of the modeling are not given in this paper (For energy modeling details, please refer to Atwal et. al 2013). The validated model indicated that heating and ventilation are the main drivers for energy consumption. Moreover, envelope air leakage (as measured during blower door tests) and occupant's habit of opening windows were causing high energy penalties. Simulations with improved envelope air tightness predicted 12% reductions in energy consumptions as shown in Figure 14.

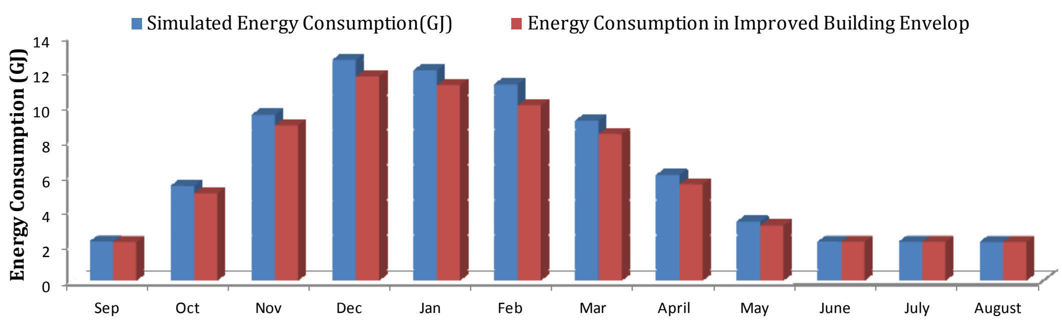

FIGURE 14: Energy consumption comparison between existing and improved building envelope tightness

LESSONS LEARNED FROM THE PILOT STUDY

The assessment of results from the data analysis indicates that the houses are performing well overall and there is no sign for immediate alarm to the homeowners or the builders. The envelope moisture levels are high during winter, which is normal in the wet marine climate of BC, but it eventually dries in warmer months. The moisture content of certain walls needs close attention. An engineering assessment would need to be conducted if higher values of moisture content persist in the next winter season also. The attic needs close attention because the moisture levels were very high and sustained for a long period. A high risk of moisture condensation on the underside of roof sheathing is evident. These conditions will likely result in mold growth and a proliferation of mold spores in the attic. Although, attics are not part of the envelope, they are connected, unintentionally through cracks, with noticeable air flows during the blower door test. A preventive solution needs to be devised such as sealing the ceiling cracks; applying treatments and coatings to create unfavorable conditions for mold growth; providing insulating boards and mold resistant sheathing outboard ventilated spaces to keep the roof structure warm and dry; or insulating the underside of roof sheathing with foam insulation to stop mold spores from getting in contact with the roof sheathing (Roppel et. al. 2013).

The indoor environmental data (CO2, RH/T) indicate that forced air heating systems are performing well to maintain uniform temperature & CO2 levels; and keep indoor moisture levels within acceptable range for good indoor air quality. The CO2 levels were more than 1000ppm in fall and spring months (swing season), when windows were closed and HVAC system had limited operation. The instances of higher values of CO2(1400-1800ppm) were observed in bedrooms and common areas during night time and higher occupancy periods respectively, which could result in occupant discomfort. RH/T data in all the three houses show no signs of risk for microbial air borne contamination .CO2 and RH/T sensors give clear indication that the owners in one house are opening the windows at times which is not convenient from an energy point of view.

The sensors in the crawl spaces suggest that foundation moisture is drying out and these seem to be performing well. Additional sensors at the corners of the foundation walls would help find out if there is a risk for moisture condensation at these locations. A breakdown of the results from the energy simulation indicated that the heating and ventilation are mainly driving the energy consumption and occupant behaviors like opening windows are causing energy penalties. A feedback to the occupants on the items they can control to reduce energy consumption could make a difference. For example, knowing the energy impacts from opening windows may lead the homeowners change that habit.

CONCLUSIONS, LIMITATIONS AND FURTHER WORK

This pilot project demonstrates the value of a sensory system to monitor and gain knowledge on the indoor air quality, envelope and energy performance of a group of houses. This knowledge can be used to give feedback to occupants and builders, and recommend improvements in existing as well as future homes. For energy performance improvements, these houses need to improve envelope air tightness. Further monitoring and airflow simulations will be needed to study the effects of improved air tightness on the indoor air quality in these homes. Increased air tightness also calls for a dedicated ventilation system incorporated in the current HVAC system in the existing as well as future houses. This project is a pilot study and first step towards developing data and knowledge for characterization of the homes on the reserve using real time health monitoring integral to homes. Further work is needed to monitor larger group of houses, more representative of remote aboriginal communities, for indoor environment and building envelope characterization.

ACKNOWLEDGEMENTS

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Manuscript 3

Topic B4: Ventilation

VENTILATION FOR A HOUSE AS A SYSTEM

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Keywords: Ventilation, Low income homes, House as a system, Mould, Remote Sensing monitoring system

SUMMARY

Low income First Nation homes face unique challenges of poor maintenance, low ventilation rates, indoor tobacco smoke, and inferior construction quality. These challenges are responsible for the poor indoor air environmental quality in these homes. A study was conducted to gain knowledge on the ventilation performance in three homes, and investigate energy efficient and cost effective solutions to improve the air quality of the houses. The indoor conditions were monitored during one year; as well as the envelope, and the weather. The data analysis combined with calibrated multi-zone airflow models pointed towards potential indoor air quality problems due to insufficient ventilation and potential risks of migration of mould spores from the envelope into the house. The solution proposed realizes the concept of a house as a system, which in this case analyzes the house ventilation in conjunction with construction quality, energy efficiency and cost-effectiveness. CO_2 contaminant dispersion modeling confirmed that a dedicated ventilation system delivers superior indoor air quality than the current system.

INTRODUCTION

Low income First Nation homes face unique challenges of poor maintenance, low ventilation rates, indoor tobacco smoke, inferior design and construction quality. These challenges are believed to be responsible for poor indoor air environment (National Council on Welfare, 2007); and are related to increase in life threatening infections, mental illnesses and higher infant mortality rates in Aboriginal communities (UNICEF 2009, National Collaborating Centre for Aboriginal Health, 2010). These communities are mostly located in remote and cold regions of Canada, which challenges the construction and indoor air quality of their homes. Limited information is available on how construction, mechanical equipment, climate, & occupant related factors affect the indoor environment in these homes. There is a need to monitor the actual performance and devise solutions to improve the quality of these homes, incorporating the unique challenges, construction & service life conditions.

A permanent real-time remote sensing and monitoring system was installed in three homes of a First Nations reserve in Vancouver. The indoor parameters relative humidity, temperature, and carbon dioxide; the construction parameters moisture content in walls, attics and crawlspaces; and the outdoor weather were monitored for one year. These homes do not have a dedicated whole house mechanical ventilation system. A forced-air heating system supplies make up air for ventilation, only when heating is required. Otherwise, the ventilation is leakage-based. The construction is typical of local urban reserve homes, which do not require stringent home inspections by city officials. The building codes and best practice guidelines for coastal climate of British Columbia are not followed strictly; therefore, they are believed to be more vulnerable to durability and indoor air quality issues than a conventional home.

This paper aims to assess the performance of the existing ventilation system in the houses and propose potentially better systems. The premise is that these houses have typical problems, given the climate, quality and the type of construction, and provide a good experimental setting for the characterization of the indoor air quality; and recommendations from the study could be generalized to future houses on the reserve.

NEED TO CONSIDER A HOUSE AS A SYSTEM

Housing performance depends upon many interrelated components that vary with time. Changing one component of a house without considering how it influences other components, often results in unintended negative consequences to the related systems. For example, improved envelope airtightness is advantageous for energy, comfort and durability; but it can also lead to increased indoor pollutants that are harmful and often trigger ailments, asthma and other respiratory illnesses among occupants (Wray et al. 2000). In recognition of these issues, ASHRAE Standard 62.2, *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings,* has required mechanical ventilation in residences since 2003. Ventilation improves perceived indoor air quality and occupant health.

While controlled ventilation helps control indoor humidity levels and dilute indoor contaminants; uncontrolled air leakage, possibly driven by exhaust ventilation, can potentially bring moisture laden contaminants from damp envelope locations and from out-of-the-envelope crawl spaces and attics (Airaksinen et al 2004b). Lawton et al. (1998) monitored a group of houses in southern Ontario, and found that houses with higher levels of microbiological indoor contaminants had, on average, higher leakage-based air change rates. Occupancy related CO2, usually used as an indicator for IAQ, is not a good surrogate for construction-related microbial indoor air quality. Hence, a complete assessment of the quality of the indoor air and the likelihood of microbial sources would need to rely on CO2 data combined with indoor relative humidity (RH) and envelope moisture content and temperature (MC/T) data. Associations between persistent dampness and adverse health effects have been acknowledged in literature (Bornehag et.al 2005). However, relationships between persistent dampness, microbial exposure, and health effects cannot be quantified precisely at the moment (WHO 2009). As a consequence, no quantitative health-based exposure guideline or thresholds are recommended for acceptable levels of microbial contamination (IOM 2004). In light of this, ASHRAE (2012) and AIHA (2013) recommend keeping buildings and their systems dry, given their normal functions, to limit the potential for microbial growth and reduce dampness-related health risks.

Occupants play an important role in the energy performance; and also, their behaviour has a profound effect on indoor air quality of a house (Lai et. al. 2013, Kabir et. al. 2011). Recently many studies have focused on the effects of occupant behaviour on energy performance and indoor air quality in residential buildings (Santin et.al. 2011, Fabi et. al 2012). Building on the premise that house should be considered as a system, this research attempts a holistic assessment of residential performance that combines monitored data from: the indoor environment, the construction, the occupants' behaviours, and the energy system to provide a more informed view of the residential performance for homeowners and builders, and propose improvements.

METHODOLOGY

Three new First Nations houses were studied. The houses are typical 2-storey, wood-frame construction single family houses identified as house#1 [2,500 ft^2(232 m^2)], house#2 [2,000 ft^2(186m^2)], and house#3 [1,800 ft2 (167m^2)] with ventilated attic, conditioned crawl space and a combined forced air heating/ventilation system with outdoor air intake at the return side. The research methodology includes the following tasks:

- Sensing system layout planning and instrumentation – The houses were instrumented with a wireless remote sensing system. A weather station was also placed on the roof of the nearby community center. Details of the monitoring systems are discussed in Atwal et al. (2013).
- Testing, measuring, and questionnaires - Air tightness tests were conducted in the houses, as well as air flow measurements at the supply and return grilles of the forced air system. Information on house operation was obtained by an administered occupant-questionnaire.
- Monitoring – indoor relative humidity, temperature, CO_2, and envelope moisture contents were monitored for a period of one year.
- Airflow modeling & Analysis – An Airflow model was created and fine-tuned with air tightness tests, air flow measurements at the forced air system's supply and return grilles, furnace on/off operations and questionnaires to occupants. The model was validated with CO2 data, as well as testing, measurements, and questionnaires. The validated model was then used to compare the indoor air quality performance of the current heating/ventilation system with other potentially better systems.

RESULTS: ANALYSIS AND DISCUSSION

Monitoring Results

Figure 1 presents the relative humidity, sheathing moisture content and temperature variations in the attic. The moisture level in the attic air is very high, and it sustained for a long period.

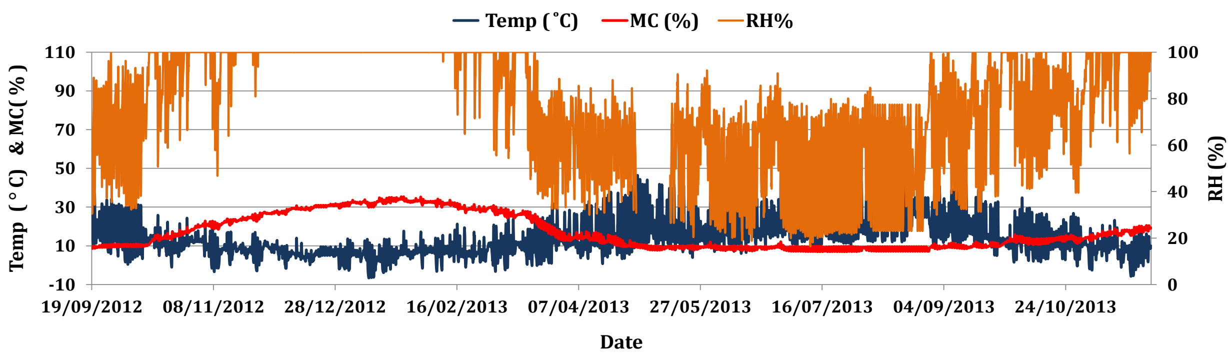

Figure 1. Hourly temperature, RH and Moisture Content in the Attic of house#1.

The attic air is saturated with moisture during the months of December, January, and February and is close to saturation in October, November, and March. This is confirmed with the moisture content data at the underside of roof sheathing. Although Moisture Content (MC) readings show a seasonal wetting with subsequent drying during the warmer seasons, the wetting period is long and maintained MC above acceptable levels (>28%) between November and March.

In Figure 2, the MC levels at the selected wall locations showed wetting and drying trends in winter and summer months respectively. Locations at North elevations were all above 28% during winter months (3 months) and took longest time to dry due to limited sun exposure. Drying at West elevations was longer than expected as these houses have large trees on the west side. South and east elevations were maintained below 20% in winter months. Except at one location on East elevation (below East Bedroom window), where MC levels were exceptionally high (>35%). It is assumed that water penetration occurred at this location.

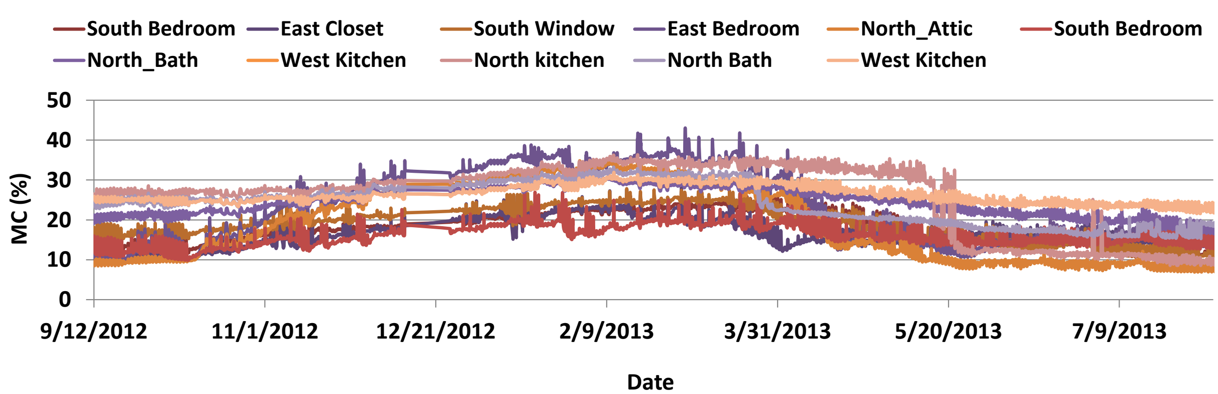

Figure 2. Hourly Moisture Content (MC) on different wall locations

Figure 3 shows the RH and temperature variations in House #2. RH levels were within 30-60% range in winter months when forced air heating system was running. As the outside temperature changed towards warmer side and occupants started opening windows, the RH levels followed outdoor RH values and recorded in the range 70-75%.

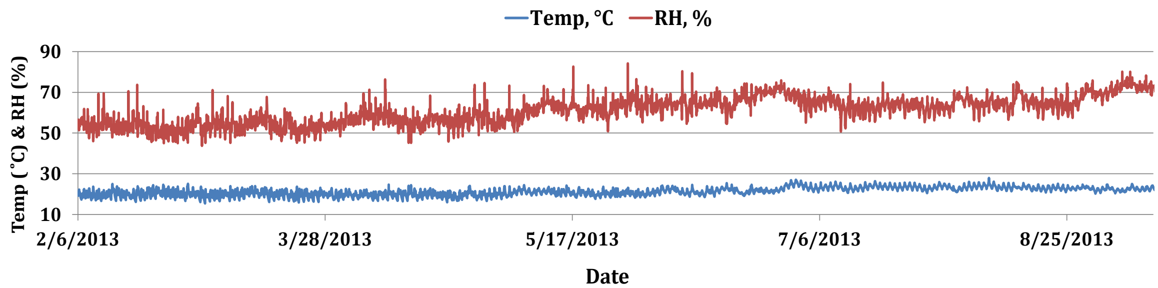

Figure 3. Indoor Relative Humidity & Temperature variations in House#2

Forced air heating/ventilation systems performed well in maintaining uniform temperatures, RH and CO_2 levels in all the three houses as shown in Figures 4 & 5 respectively. Figure 4 shows the RH at three different locations in house#1. The lower level kitchen measured higher RH values consistently than upper level locations. It should be noted that an occupant, a retiree, stay at home most of the time and live in the lower portion of the house. Homeowner questionnaire indicated that this occupant felt cold and kept most of the windows closed throughout the year.

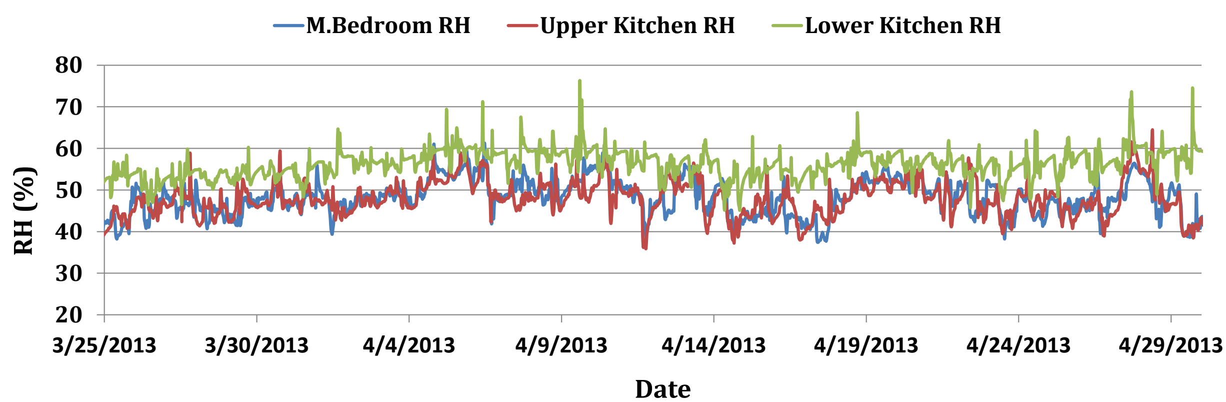

Figure 4. Measure relative humidity at different locations in House#1

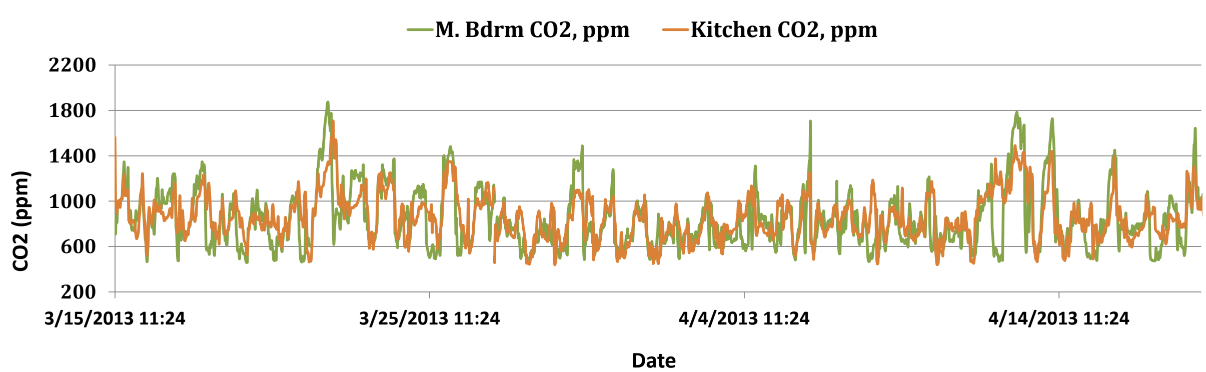

Figure 5. CO2 variations at two different locations in House #1

A closer look at the CO2 concentrations over the monitoring period indicated that these houses had low ventilation rates during swing seasons when forced air heating system was not operational. Due to space limitations this data in not included in this paper.

Multi-Zone Airflow Model

An airflow model was created for house#1 to evaluate the existing ventilation system. The model was fine-tuned and validated with air tightness tests, air flow measurements at the forced air system's supply and return grilles, and questionnaires to the occupants. Due to space constraints, details of the modeling are not given in this paper. The occupants in this house open windows for almost eight months in a year. This makes it difficult to know the effectiveness of the mechanical system. Thus, to eliminate the open-windows factor from the analysis, the model was calibrated by comparing predicted CO_2 versus measurements for the duration when the windows were closed (October-December), which is the most critical scenario for assessing the effectiveness of the ventilation system.

Figures 6 and 7 present the comparison between simulated and measured CO2 concentrations in the kitchen and master bedroom respectively. The predicted values are mostly in agreement with the measured values except at the peak values in kitchen when measured CO2 concentrations were higher due to increased occupancy and longer cooking periods, as confirmed with the questionnaire. The effect of opening windows is clearly visible in the rapid decline in measured CO2 levels in the master bedroom (Figure 7). The occupants in this house open bedroom window before they leave for work in the morning (approx. 8:30 am)

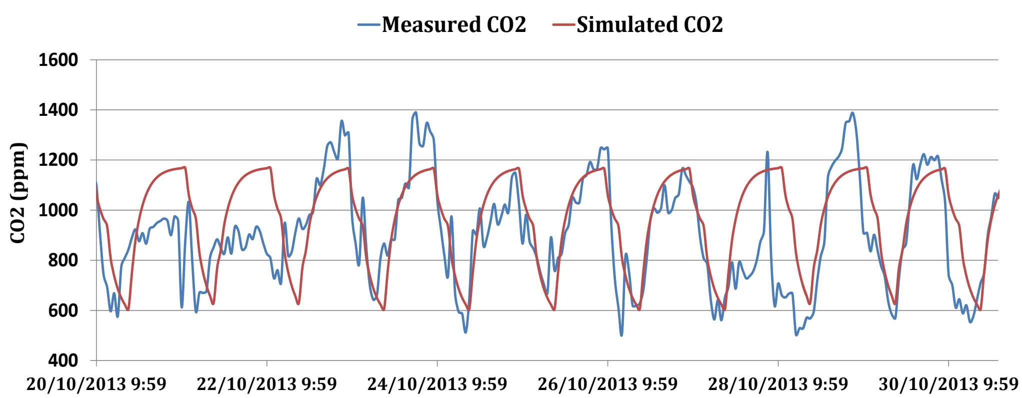

Figure 6. Comparison of simulated and measured CO2 levels in the kitchen

The airflow simulations predict that the house is slightly de-pressurized and the ventilation rates especially when HVAC system has a limited operation are not sufficient to maintain CO2 concentrations below 1000 ppm. Moreover, unintentional leakages through ceilings and garages will risk the unwanted pollutant penetrations into the living space.

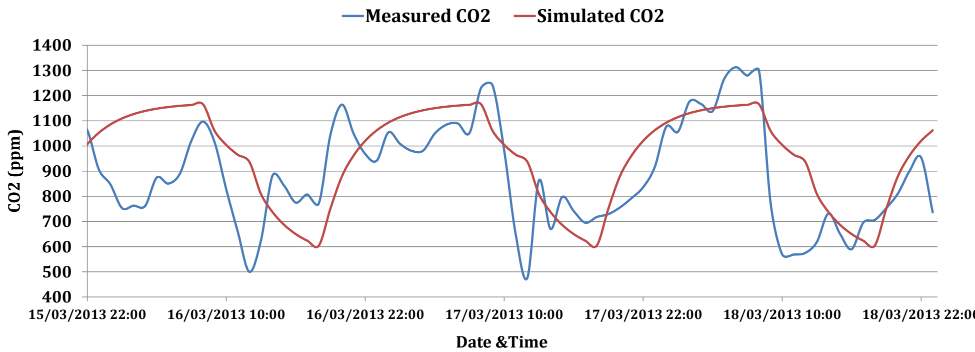

Figure 7. Comparison of simulated and measured CO2 levels in the Master Bedroom

Integrated Analysis of the Results from the Pilot Study

The monitoring data indicates that the houses are performing well overall and there is no immediate cause of concern. However, the attics have very high moisture levels sustained for a long period. There is a high risk for moisture condensation on the underside of roof sheathing, which will result in mould growth and a proliferation of mould spores in the attics. Large air flows were observed from the attic during blower door tests. Indoor data show no risk for microbial air borne contamination due to excessive moisture. CO_2 levels were more than 1000ppm in fall and spring months (swing season), when windows were closed and HVAC system had limited operation. The instances of higher values of CO_2 were observed in bedrooms and common areas during night time and higher occupancy periods respectively, which could result in occupant discomfort. Multi-zone airflow model showed that the pressure differentials along with unintentional leakages through ceilings and walls can lead to mould spores penetration into the living space from attics and envelope walls. Researchers have demonstrated the possibility of penetration of mould spores through the envelope into the house due to pressure differentials (Airaksinen et al 2004). To minimize the risk of potential microbial contamination from attic and damp envelope locations, the building envelope needs to be air-tight; thus increasing the need for dedicated ventilation.

Airflow simulations indicated that dedicated ventilation performs better than the current system. Figure 8 presents the comparison of CO2 concentrations with three alternative ventilation systems: continuous supply, continuous exhaust, and balanced heat recovery.

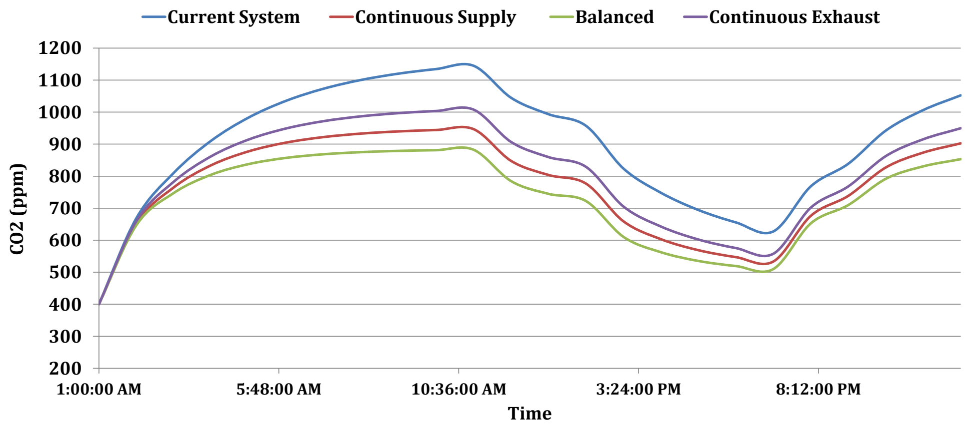

Figure 8. Comparison of simulated CO2 levels with different ventilation systems

The balanced heat recovery ventilation system is a promising option as it is the most energy efficient system (For energy model details, readers are requested to refer Atwal et.al 2013), and maintains lowest levels of CO2. Moreover, it minimizes the risk of unwanted pollutant penetration from the envelope and the garage due to pressure differentials. However, this system is not cost-effective for these houses due to the moderately cold climate and the poor thermal and leakage performance that do not justify heat recovery. Continuous exhaust ventilation is an alternative cost-effective and simple solution for these houses, provided infiltration is minimal; and the living space is adequately sealed from the attic and the garage.

CONCLUSIONS, LIMITATIONS AND FURTHER WORK

The pilot project demonstrates the value of a holistic assessment of performance of a house. It emphasizes the need to treat a house as an integrated system where improvements in one component (ventilation in this case) should be accompanied with others (airtightness, construction quality and energy efficiency or vice versa). Further work will include testing the actual performance of the different ventilation systems, so that they can be implemented on a wider scale in future houses on the Reserve.

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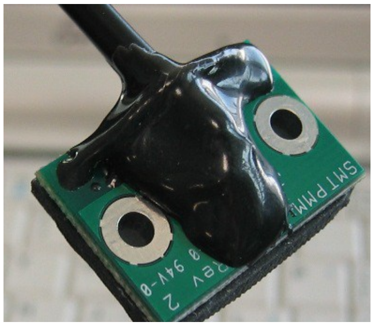
APPENDIX B

Table 1 below lists the equipment used in the project

Equipment and Reference	Functions
Point Moisture measurement sensor (PMM) http://smtresearch.ca/files/RS-1063%20PMM%20Datasheet%20Web.pdf	Measures moisture content (MC/T) and temperature in plywood sheathing.
COZIR- A-2000 Sensor http://www.co2meter.com/products/cozir-0-2-co2-sensor	High performance CO2 sensor used to measure ambient carbon dioxide up to 2000 parts per million (ppm).
HTM 2500 RH Sensor http://smtresearch.ca/files/RS-1082%20HTM2500%20Datasheet%20Web.pdf	Relative humidity and temperature sensor used for indoor and outdoor air quality analysis
SMT A2- Wireless Data Acquisition Unit http://smtresearch.ca/files/RS-1104%20SMT%20A3%20Datasheet%20Web.pdf	An interface which integrates moisture content, relative humidity and carbon dioxide sensors and transmits data wirelessly to SMT Building Intelligence Gateway (BIG) and then synchronizes with the cloud based Building Analytics software.
Building Intelligence Gateway (BIG) http://smtresearch.ca/files/RS-1061%20BIG%20Datasheet%20Web.pdf	Provide continuous monitoring and data collection of distributed sensors. It also provides local analysis of data as well as synchronization with SMT's on-line monitoring and reporting system, Analytics©.
Analytics: Monitoring Center http://smtresearch.ca/product/Analytics	An enterprise class transactional database system with an advanced web based front end which provide data collection, processing, analysis, and long term storage of sensor data.
HOBO U12-011 Data Logger http://www.onsetcomp.com/products/data-loggers/u12-011	Temperature/Relative Humidity data Logger used for high-accuracy monitoring of temperature and humidity for indoor air quality analysis
HOBO UX 90-004 Motor on/off Loggerhttp://www.onsetcomp.com/products/data-loggers/ux90-004	Records motor on and off conditions and is used to track usage & runtimes of motors, pumps, compressors, and other equipment

Telaire 7001 CO2 Sensor http://www.onsetcomp.com/products/sensors/tel-7001	Measures carbon dioxide and temperature for indoor air quality analysis.
Blower Door Test Equipment http://retrotec.com/residential/Products/BlowerDoors	Measures airtightness of small to medium sized buildings. It consists of three components: a calibrated, variable-speed fan, a pressure measurement instrument, manometer, and a mounting system, used to mount the fan in a building opening, such as a door or a window.
Thermo-Anemometer Model 8904 http://www.itm.com/shop/itemDetail.do?itm_id=144939&itm_index=0&item=8906	Simultaneously measures air velocity and temperature. Features include data hold, the ability to record minimum, maximum and average readings on a single point.It is ideal for HVAC inspection, energy audits and balancing applications.
Davies Vantage PRO Weather Station http://www.davisnet.com/weather/products/weather_product.asp?pnum=06152	Measures outdoor weather conditions such as temperature, relative humidity, rainfall, wind speed and direction and solar radiation



Point Moisture Measurement Sensor Datasheet

General Description

The Point Moisture Measurement (PMM) Sensor is used to perform a direct contact measurement of moisture content in material susceptible to moisture absorption. The PMM can be used to sense the moisture content of wood or relative moisture level of gypsum, concrete or masonry.

The design of the PMM ensures moisture probes are spaced apart consistently and contains an integrated temperature sensor for temperature correction of moisture content readings.

The PMM interfaces to SMT's wireless dataloggers. The dataloggers transmit readings to the Building Intelligence Gateway (BiG) where temperature compensation and wood species correction factors are applied.

Classical brass nail probes are available and function the same as the PMM except they do not have an integrated thermistor.

Features

- 3.5mm audio jack interfaces to the Mobile WiDAQ and A2 units.
- Leaded version interfaces to Industrial WiDAQ and A3 units.
- Sealed and rugged design allows for deployment in harsh construction environments
- Built in temperature sensor allows for temperature compensation.
- Temperature data is transmitted and recorded along with Moisture Content Data
- Low profile design allows for easy deployment.
- Different probe lengths are available.

Typical Application

Figure 1. Drive #6 3/4" SS Screw through guides into wood/gypsum.

Note: Ensure screw depth is less than sheathing width.

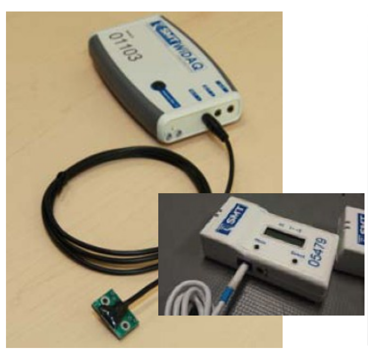


Figure 2. Plug audio jack into Mobile WiDAQ or A2. Screw into terminal blocks for Industrial WiDAQ and A3 models.

Figure 3. Dataloggers transmit data to the Building Intelligence Gateway (BiG) and sync with Building Analytics for archiving and further analysis.

Functional Specifications PMM

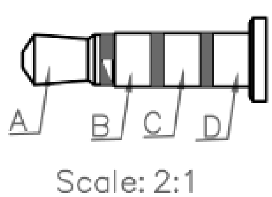
Electrical Characteristics	
Operating Voltage	2V to 12VDC
Resistance Measurement Range	Short to Infinite
Thermistor Measurement Range	-40°C to 125°C
Thermistor part number	Cantherm MF58104F3950
NTC Thermistor Beta Value	3950
BiG/Analytics Sensor Type	104JT

Environmental	
Operating Temperature	-40° to 50°C / -40° to 122°F
Application Temperature	5° to 50°C / 41° to 122°F
Storage Temperature	-40° to 50°C / -40° to 122°F
Storage Humidity	30% to 70% RH

Physical	
PCB Dimensions	30mm x 20mm x 10mm
3.5mm Audio Wiring	22 AWG 4 conductor stranded

Approvals/Regulatory	
PCB Flammability Rating	94V-0
Protective Backing Flammability Rating	UL94B

PMM-02 3.5mm Audio Jack Wire Diagram



PMM	Cable	Function
A	Red	Moisture
D	Black	Moisture
B	White*	Thermistor (Com)
C	Green	Thermistor

PMM-03 Connection to WiDAQ/A3

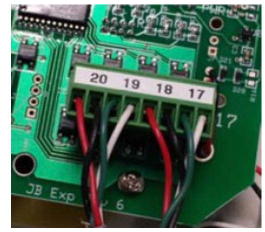
Wire colors depend on cable type used

Input 17: PMM1
Temp: Green/White*

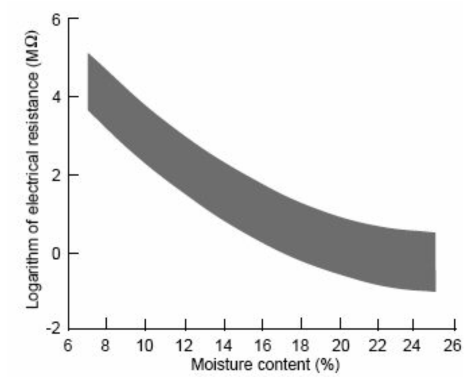
Input 18: PMM1
Moisture: Red/Black

Input 19: PMM2
Temp: Green/White*

Input 20: PMM2
Moisture: Red/Black



Moisture Content Calculation



Change in electrical resistance of wood with varying moisture content levels for most wood species; 90% of test values are represented by the shaded area.

$$MC = \left[\frac{R_s + \left(0.567 - 0.0260x + 0.000051x^2\right)}{0.881\left(1.0056^x\right)} - b \right] \div a$$

Where

- MC moisture content at 23°C
- R resistance to moisture based on above graph
- x temperature of the wood (°C), and
- a,b species correction regression coefficients

See moisture content notes and papers..

Ordering Information	
3.5mm Audo Jack 6' cable	PMM-02-006
Control Wire 30' cable	PMM-03-030
Moisture Probe #6 SS Screw	PMM-MP-3/4
	3/4 = Screw Length

Specifications are subject to change without notice

*Cable color may be white or yellow

Relative Humidity Sensor
HTM2500

General Description

Based on the rugged Humirel HTS2010 humidity sensor, the HTM2500 is a dedicated humidity and temperature transducer designed for applications where a reliable and accurate measurement is needed.

Typical Applications

- Building science research
  - Building envelope cavity validation
  - Indoor and outdoor air quality analysis
- Restoration
  - Verification of equipment status
  - Drying progress
- Industrial applications
  - Process control
  - Hygrostat

Features

- Hermetic Housing
- Humidity calibrated within ±2% @55% RH
- Integrated Thermistor – MF52 pearl-shaped precision NTC thermistor (leaded version)
- Small size
- Compatible with SMT Mobile and Industrial WiDAQ
- Full interchangeability
- High reliability and long term stability
- Not affected by water immersion
- Instantaneous de-saturation after long period in saturation phase
- Fast response time suitable for low voltage wireless applications.
- High resistance to chemicals
- Unique solid polymer structure

Ordering Information	
HTM2500 with 6' Audio cable	HTM2500-02-006
HTM2500 with 6' Leaded cable	HTM2500-01-006
HTM2500 with 30' Leaded cable	HTM2500-01-030

SMT Research Ltd. – 158-628 East Kent Ave South – Tel: 778.373.2071 – Fax: 204.480.8579
Website: www.smtresearch.ca Email: info@smtresearch.ca RS-1082 Rev B

Electrical Characteristics	
Operating Voltage (with SMT A3)	0V to 5VDC
Sensing Element	HTM2500

Environmental	
Operating Temperature	-30° to 70°C
Operating Humidity Range	0% to 100% RH
Storage Temperature	-40° to 85°C
Storage Humidity	0% to 100% RH

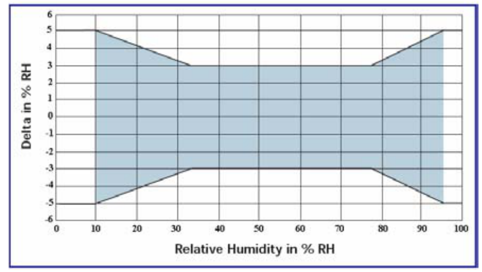
Humidity Characteristics	
Humidity Measuring Range	1% to 99% RH
RH Accuracy (10 to 95% RH)	±3 to ±5 %RH
A3 Supply Voltage	5VDC
Current Consumption	0.4mA
Temperature Coefficient (10°C to 50°C)	±0.1 %RH/°C
Average Sensitivity from 33% to 75% RH	+25 mV/%RH
Recovery time after 150 hours of condensation	10 seconds
Humidity Hysteresis	±1.5 %RH
Long term stability	±0.5 %RH/yr
Time Constant (at 63% signal, static) 33% to 76% RH	5 seconds

Thermistor Characteristics	
Rated Resistance R25	10 to 250 KΩ
B Value (25/50°C)	4150K
Operating Temperature	-55° to 125°C
Tolerance	1%

Approvals/Regulatory	
Passed Meas-France qualification process	Vibration, shock, storage temperatures, high temperature and humidity and ESD.
Chemical conditions tested	Salt atmosphere, SO2, NOx, NO, CO, Softener, Soap, Toluene, acids (H2SO4, HNO3, HCl), HMDS, insecticide, cigarette smoke. HTM255 is not light sensitive.

Specifications are subject to change without notice

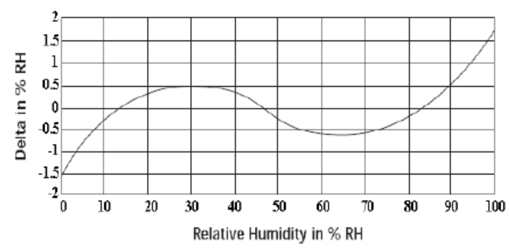
HTM2500 Error Limits at 23°C



Temperature coefficient compensation:

$$RH_{Cor}\% = RH_{read}\% \times \left(1 - (T_a - 23) \times 2.4E^{-3}\right)$$

HTM2500 Linearity Error



Non-linearity and temperature compensation

$$RH\% = \frac{-1.9206E^{-3}V_{out}^{3} + 1.437E^{-5}V_{out}^{2} + 3.421E^{-3}V_{out} - 12}{1 + (T_a - 23) \times 2.4E^{-3}}$$

HTM2500 on CAT5 Cable

CAT5 Cable	Function
White/Blue	Ground
Blue	+5V
White/Orange	RH
Orange	NC
White/Green	NC
Green	NC
White/Brown	Thermistor
Brown	Thermistor Com

COZIR™

Ultra Low Power Carbon Dioxide Sensor

COZIR is an ultra low power (3.5mW[4]), high performance CO_2 sensor, ideally suited for battery operation, portable instruments and HVAC. Based on GSS IR LED and Detector technology, and innovative optical designs, the *COZIR* offers the lowest power NDIR sensor available. Optional temperature, humidity and light sensing are available. *COZIR* is a third generation product from GSS – leaders in IR LED CO2 sensing.

- Ultra-low Power 3.5mW
- Measurement ranges from 2,000ppm to 10,000ppm
- Low noise measurement (<10ppm)
- Digital or Analog Output
- 3.3V supply
- Peak current only 33mA
- Optional Temperature and Humidity Output

Specifications

General Performance

Warm-up Time

- < 3s

Operating Conditions

- 0°C to 50°C (standard)
- -25°C to 55°C (extended range)
- 0 to 95% RH, non-condensing

Recommended Storage

- -30°C to +70°C

CO2 Measurement

Sensing Method

- Non-dispersive infrared (NDIR) absorption
- Patented Gold-plated optics
- Patented Solid-state source and detector

Sample Method

- Diffusion

Measurement Range

- 0-2,000ppm, 0-5,000ppm, 0-10,000ppm CO2. Up to 100% CO2 Available.
- Analog output 0-3VDC = 0-2000ppm

Accuracy

- ±50 ppm +/-3% of reading[1]

Non Linearity

- < 1% of FS

CO2Meter.com
CO2 Measurement Specialists
131 Business Center Drive
Ormond Beach, FL 32174
(386) 872-765 Sales
(386) 256-4910 Support
www.CO2Meter.com
Sales@CO2Meter.com

Pressure Dependence

- 0.13% of reading per mm Hg

Operating Pressure Range

- 950 to 1050 bar[2]

Response Time

- 3 secs to 2 mins (user Configurable)[3]
- Reading refreshed twice per second.[3]

Electrical/Mechanical

Power Input

- 3.25V to 5.5V DC
- Peak Current 33mA[4].
- Average Current <1.5mA[4].

Power Consumption

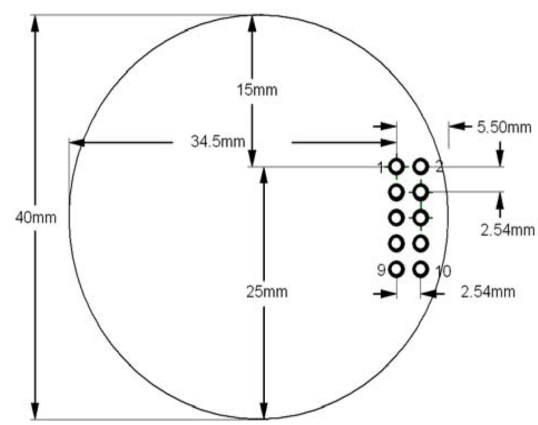
- 3.5 mW[4]

Wiring Connections

- 2x5 0.1" header.

View from underside (connector side)

1	GND	2	N/C
3	3.3V (nominal)	4	N/C
5	Rx	6	N/C
7	Tx	8	Nitrogen Zero
9	Analog (0.1 to 3.3V)	10	Fresh Air Zero



Optional Temperature & Humidity Measurement[5]

Optional Temperature and Humidity sensor only available as digital output

Sensing Method

Humidity: Capacitive

Temperature: Bandgap

Measurement Range

- -25 to +55 °C
- 0 to 95% RH

Resolution

- 0.08 °C , 0.08% RH

Absolute Accuracy[5]

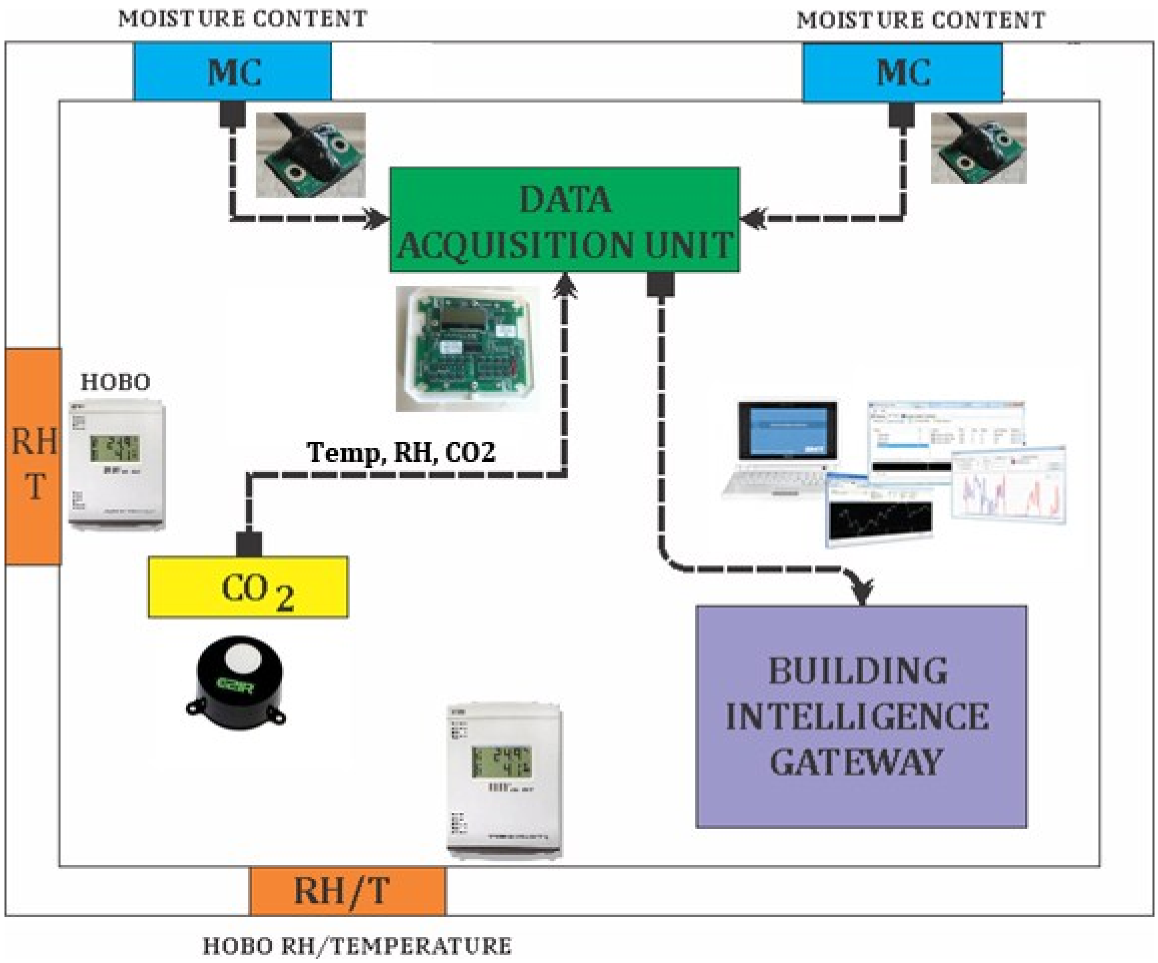
- +/-1 °C 0°C to 55°C.
- +/-3% RH 20°C to 55°C.
- +/-2 °C over the full temperature range.
- +/-5% RH over the full temperature range.

Repeatability

- +/-0.1 °C
- +/-0.1 % RH

APPENDIX C

General Equipment and sensor layout in a house



Below are some pictures taken during sensor installation and blower door test

House during construction and installation

Moisture Content Sensor near the bottom plate below a window

Data Acquisition Unit Box (Sensors are terminated in the box for connections to Data Acquisition Unit)

Moisture Content Sensor and Exterior RH/T sensor in the Attic

Finished Data Acquisition unit on the wall with a HOBO RH/T sensor for calibration

During Blower Door Test

Weather Station Installed on the roof of a building near monitored houses

APPENDIX D

SQUAMISH PROJECT

Date: ____________

Questionnaire to Home Occupants Survey No: ________ Home type: ________

Home Contact Information			
First name:		Last name:	
Phone 1:		Address:	
Phone 2:		City:	Zip:

Typical Weekday Occupants' Schedules

No	Age group	Shower time	Duration	Bath fan use	Periods at home during typical day	Typical home activities	Room(s)
1							
2							
3							
4							
5							
6							

Typical Weekend Occupants' Schedules

No	Age group	Shower time	Duration	Bath fan use	Periods at home during typical day	Typical home activities	Room(s)
1							
2							
3							
4							
5							
6							

Typical Weekday Cooking Schedule					**Typical Weekend Cooking Schedule**				
Type	Time	Duration	Method	Days/week	Type	Time	Duration	Method	Days/wknd
Breakfast					Breakfast				
Lunch					Lunch				
Dinner					Dinner				

Use Kitchen exhaust fan when cooking:

Always: ________ Most of the times: ________ Sometimes: ________ Never: ________

Laundry/Cleaning	Frequency:				Duration:			
Most likely days:				Times:				
Clothes drying:	Drier:		Outside:		In Laundry:			

	Weekday Thermostat Setpoints					Weekend thermostat Setpoints			
	Living	Room1	Room2	Room3		Living	Room1	Room2	Room3
Morning					Morning				
Afternoon					Afternoon				
Evening					Evening				
Night					Night				

Indoor Home Equipment & USE

	Weekday Equipment Use					Weekend Equipment Use			
	Living	Room1	Room2	Room3		Living	Room1	Room2	Room3
Morning					Morning				
Afternoon					Afternoon				
Evening					Evening				

Windows Opening

Period(s) of year: Approx. No of days per week:

	Weekday Typical Windows Opening Schedule					Weekend Typical Windows Opening Schedule			
	Living*	Room1	Room2	Room3		Living*	Room1	Room2	Room3
Morning					Morning				
Afternoon					Afternoon				
Evening					Evening				
Night					Night				

Problems Detected with home operation

	Problem	Specific location	Occurrence
Living			
Room1			
Room2			
Room3			
Bathroom			
Kitchen			
Laundry			
Other			